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System-Wide Water Resources Program

Gridded Surface Subsurface Hydrologic Analysis (GSSHA) User's Manual

Version 1.43 for Watershed Modeling System 6.1

Charles W. Downer and Fred L. Ogden

September 2006

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Charles W. Downer

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Fred L. Ogden

Department of Civil and Architectural Engineering
Department 3295, 1000 East University Avenue
Laramie, WY 82071-2000

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Abstract: The need to simulate surface water flows in watersheds with diverse runoff production mechanisms has led to the development of the physically-based hydrologic model Gridded Surface Subsurface Hydrologic Analysis (GSSHA). GSSHA is a reformulation and enhancement of the two-dimensional, physically based model CASC2D. The GSSHA model is capable of simulating stream flow generated by a variety of sources, including runoff due to infiltration excess and saturated sources areas and seeps, as well as direct interaction between streams and the saturated groundwater. The model employs mass-conserving solutions of partial differential equations. The hydrologic components are closely linked, assuring an overall mass balance. The model has been applied to a diverse variety of projects and has been proven useful for analysis of hydrologic and sedimentation processes, and can provide information needed for designed systems and the potential effects of projects, land-use change, environmental restoration, best management practices, climate change, and related issues. This manual describes the model formulation, model input, and provides information on the practice of hydrologic modeling with GSSHA, and hydrologic modeling in general.

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Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (USACE). Funding was provided by the System-Wide Water Resources Program (SWWRP) and the Hydrologic Systems Branch, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC).

This report was prepared by Dr. Charles W. Downer, Hydrologic Systems Branch, CHL, and Dr. Fred L. Ogden, Department of Civil and Architectural Engineering, University of Wyoming, under the general supervision of Mr. Earl Edris, Chief, Hydrologic Systems Branch, CHL, and Mr. Thomas W. Richardson, Director, CHL. Dr. Steven L. Ashby is Program Manager of SWWRP. The report was reviewed by Drs. Mark Jourdan and Jeffery D. Jorgeson, Watershed Group, Hydrologic Systems Branch, CHL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

This document and the software *GSSHA* are products of the Watershed Systems Group, Hydrologic Systems Branch, CHL, and SWWRP. For more information about *GSSHA*, contact: Barbara Parsons, Hydrologic Systems Branch, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. Information on GSSHA can be found on CHL's web site at *http://chl.erdc.usace.army.mil/*. For more information on SWWRP, visit the Program's Web site at: *https://swwrp.usace.army.mil/*.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
angstroms	0.1	nanometers
atmosphere (standard)	101.325	kilopascals
bars	100	kilopascals
British thermal units (International Table)	1,055.056	joules
centipoises	0.001	pascal seconds
centistokes	1.0 E-06	square meters per second
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
fathoms	1.8288	meters
feet	0.3048	meters
foot-pounds force	1.355818	joules
gallons (U.S. liquid)	3.785412 E-03	cubic meters
hectares	1.0 E+04	square meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
kilotons (nuclear equivalent of TNT)	4.184	terajoules
knots	0.5144444	meters per second
microinches	0.0254	micrometers
microns	1.0 E-06	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
mils	0.0254	millimeters
ounces (mass)	0.02834952	kilograms
ounces (U.S. fluid)	2.957353 E-05	cubic meters

Multiply	By	To Obtain
pints (U.S. liquid)	4.73176 E-04	cubic meters
pints (U.S. liquid)	0.473176	liters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
quarts (U.S. liquid)	9.463529 E-04	cubic meters
slugs	14.59390	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (force)	8,896.443	newtons
tons (force) per square foot	95.76052	kilopascals
tons (long) per cubic yard	1,328.939	kilograms per cubic meter
tons (nuclear equivalent of TNT)	4.184 E+09	joules
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter
yards	0.9144	meters

1 Introduction

The Watershed Systems Group (WSG) within the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Research and Development Center (ERDC) supports the U.S. Army and the U.S. Army Corps of Engineers (USACE) in both military and civil operations through the development, modification and application of surface and subsurface hydrologic models. The Department of Defense (DoD) is also charged with managing approximately 200,000 km^2 of land within the United States on military installations and flood-control and river improvement projects. The WSG provides the Army with predictions of stream flow and stage, inundated areas, saturated areas, soil moistures, groundwater levels, and contaminant fate and transport. Predictions are provided for anticipated changes in weather conditions, project alternatives, and land-use changes. The WSG uses a variety of models that are supported by the DoD graphical user interfaces (GUI) Watershed Modeling System (*WMS*) (Nelson 2001), Groundwater Modeling System (*GMS*) (Jones 2001), and Surface-Water Modeling System (*SMS*) (Zundel 2001). These GUIs are commonly referred to as the XMS system. The XMS interfaces support a variety of model classes, from simple lumped-parameter runoff models, to two-dimensional (2-D) overland, and three-dimensional (3-D) unsaturated groundwater models.

For many problems, the distributed modeling approach may offer substantial potential improvement in capability compared with traditional lumped-parameter hydrologic models such as the HQUSACE surface hydrologic model *HEC-1* (HQUSACE 1985). The U.S. Army, with additional support from the U.S. Environmental Protection Agency (EPA), funded the development of the physically-based, distributed parameter, Hortonian runoff model *CASC2D* (Ogden and Julien 2002; Downer et al. 2002a). Past experience with *CASC2D* has been favorable when the model has been properly applied, i.e., when Hortonian flow is the dominant process (Doe and Saghafian 1992; Doe et al. 1996; Ogden et al. 2000; Senarath et al. 2000; Downer et al. 2002). *CASC2D* Version 1.18b is linked with *WMS* Version 5.1 (BYU 1997a; 1997b), which greatly simplifies model setup, results analysis, and visualization.

While Army experience with *CASC2D* has generally been favorable, there are many instances where the assumptions inherent in the *CASC2D* model limit its applicability (Senarath et al. 2000; Downer et al. 2002a). Figure 1 illustrates hillslope hydrology with an emphasis on the different runoff and streamflow generating processes. When saturation excess runoff, groundwater discharge to stream, exfiltration, etc., contribute significantly to the streamflow, the application of Hortonian runoff models is ill advised and can lead to erroneous results (Loague and Freeze 1985; Loague 1990; Grayson et al. 1992; Smith et al. 1994; Loague and Kyriakidis 1997; Downer et al. 2002a).

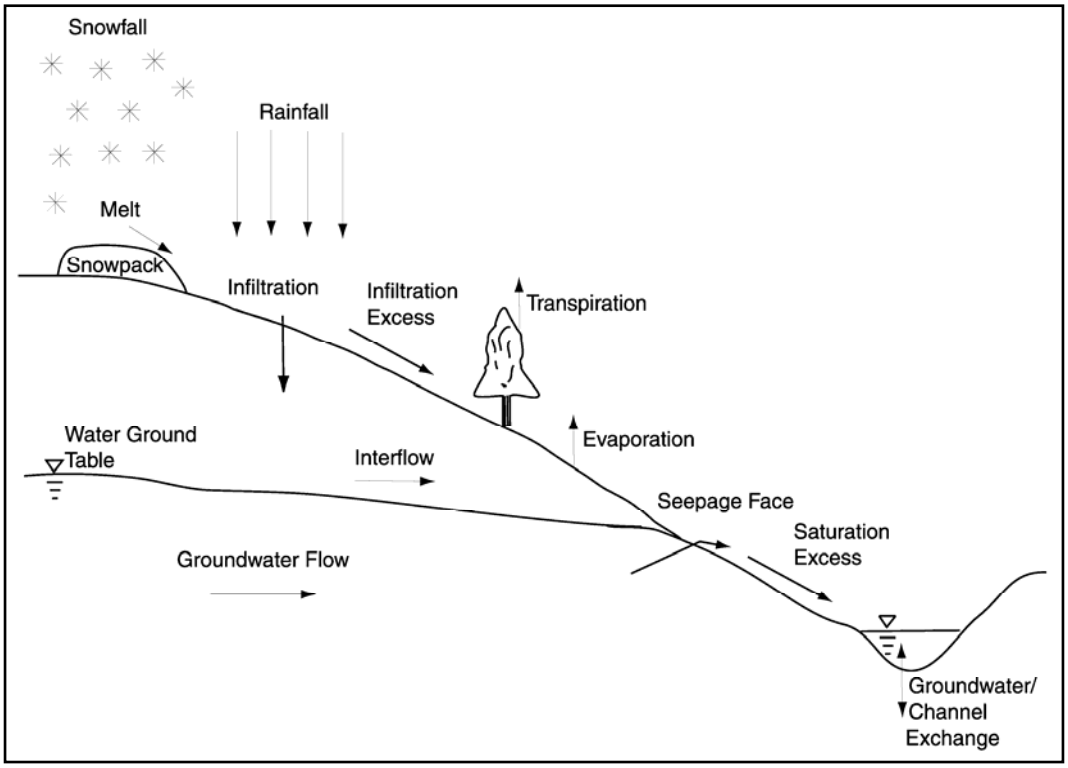


Figure 1. Hillslope hydrology.

History

The *GSSHA* model is a significant reformulation and enhancement of the *CASC2D* model. The *CASC2D* runoff model began with a 2-D overland flow routing algorithm developed and written in A Programming Language (APL) by Professor P.Y. Julien of Colorado State University. The overland flow routing module was converted from APL to FORTRAN by Dr. Bahram Saghafian, then at Colorado State University, with the addition of Green and Ampt infiltration and explicit diffusive-wave channel routing (Julien and Saghafian 1991; Julien et al. 1995). The FORTRAN

code was reformulated, significantly enhanced, and rewritten in the C programming language by Dr. Bahram Saghafian of the U.S. Army Construction Engineering Research Laboratory (CERL). Implicit channel routing was added to *CASC2D* by Fred L. Ogden (Ogden 1994), University of Wyoming, while acting as a post doc at Colorado State University. This version, named r.hydro.casc2d, is part of the *GRASS* GIS for hydrologic simulations (Saghafian 1993). Work began in 1995 to reformulate *CASC2D* with the addition of continuous simulation capabilities, including an interface with the Watershed Modeling System (*WMS*) interface developed by Brigham Young University (BYU). This version, known as *CASC2D* for *WMS*, is distinguished from its predecessors by the addition of a number of new capabilities, numerous improvements and bug fixes, and a more stringent copyright.

Purpose

The principal purpose of the *GSSHA* model is to correctly identify and realistically simulate the important hydrologic processes in watersheds. The model is intended to simulate different types of runoff production and determine the controlling physical processes in watersheds, i.e. infiltration excess, saturated source areas, and groundwater discharge. Development of the model was directed by the following requirements:

a. Model must be capable of explicitly calculating flows, stream depths, and soil moistures in a variety of hydrologic regimes and conditions including non-Hortonian watersheds.

b. Formulation must account for subsurface effects on streamflow.

c. Numerical algorithms must be robust.

d. Model must conserve mass.

e. Model must be capable of being extended to contaminant transport problems.

f. Simulation times must be short enough to allow real-time predictions for use at DoD training facilities.

g. Model must be supported by the standard DoD graphical user interface (GUI) *WMS*.

h. Source code must be available to the U.S. Army without restrictions or limitations on modification or publication of results.

Differences Between *GSSHA* and *CASC2D*

Despite the fact that *GSSHA* is derived from *CASC2D*, the formulation of *GSSHA* is fundamentally different from *CASC2D* in terms of the way the model updates individual processes in time. The formulation of *CASC2D* Version 1.18b used a short time-step "event" loop, nested within an hourly "evapo-transpiration" (ET) loop. In *CASC2D* simulations, when Hortonian runoff production ceases, the short time-step "event" loop is bypassed, effectively disabling all hydrodynamics other than evapo-transpiration from soil water. This formulation is not well suited for simulation of non-Hortonian watersheds, because the hydrodynamics of flows in the saturated and unsaturated zones cease to be "event" based. Rather, these processes continue independently from the occurrence of rainfall. Furthermore, with groundwater discharges to streams, channel hydrodynamics are also required to run continuously. To accommodate the inclusion of continuous processes, such as saturated and unsaturated groundwater flow, the nested-loop formulation of the *CASC2D* model (Figure 2), was discarded. The *GSSHA* formulation uses only one main loop (Figure 3). In *GSSHA*, each process has its own time-step and an associated update time. During each time-step the update time of each process selected by the user is checked against the current model time. When they coincide, the process is updated, and updated information from that process is transferred to dependent processes. The update time or time-step of dependent processes may be modified as part of the process update. In other words, any process in the model can effectively change the time-step of any other process. This formulation permits the efficient simultaneous simulation of processes that have dissimilar response times, such as overland flow, evapo-transpiration, and lateral groundwater flow. This scheme also allows a more integrated solution of processes coupled through boundary conditions and flux exchanges. Finally, the scheme has allowed considerable increases in computational efficiency through the use of larger time-steps when rates of change allow.

The *GSSHA* model is also fundamentally different from the *CASC2D* model because it extends the applicability of the model to non-Hortonian basins. The *CASC2D* formulation assumes that once water infiltrates into the soil, it either drains vertically or is removed by evapotranspiration. Soil water or groundwater is not considered in the context of non-Hortonian runoff production. The *GSSHA* formulation can simulate non-Hortonian runoff production.

The *GSSHA* model is backwards compatible with *CASC2D* V1.18 data sets. *CASC2D* V1.18, thus *GSSHA*, is not necessarily compatible with prior versions of *CASC2D* data sets. When trying to use older *CASC2D* data sets, make sure they conform to the standards described in this manual.

In summary, the *GSSHA* model is quite different from *CASC2D*. These differences are significant enough that *GSSHA* should be considered a different model. The published capabilities of *CASC2D* are still available with *GSSHA*. However, the range of applicability, numerical stability, and computational efficiency of *GSSHA* are considerably increased compared with *CASC2D*.

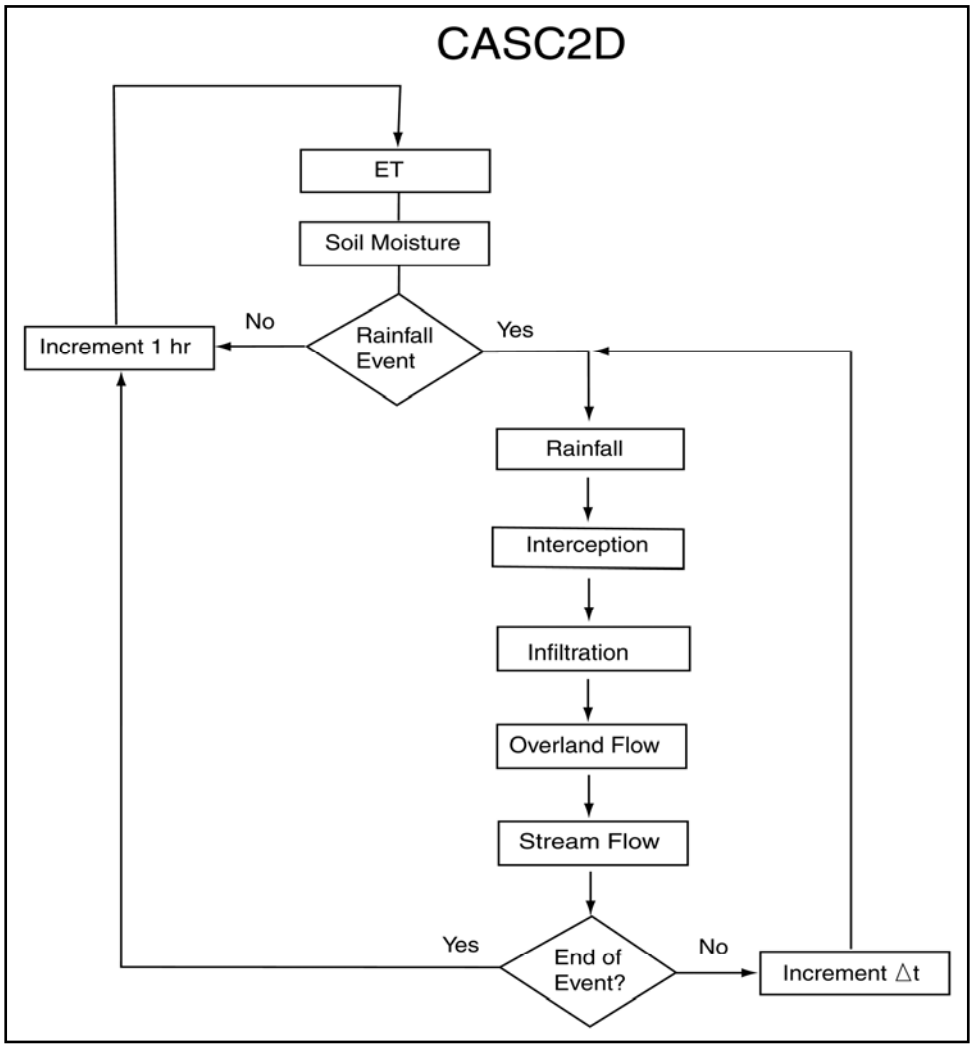


Figure 2. Simple *CASC2D* flowchart.

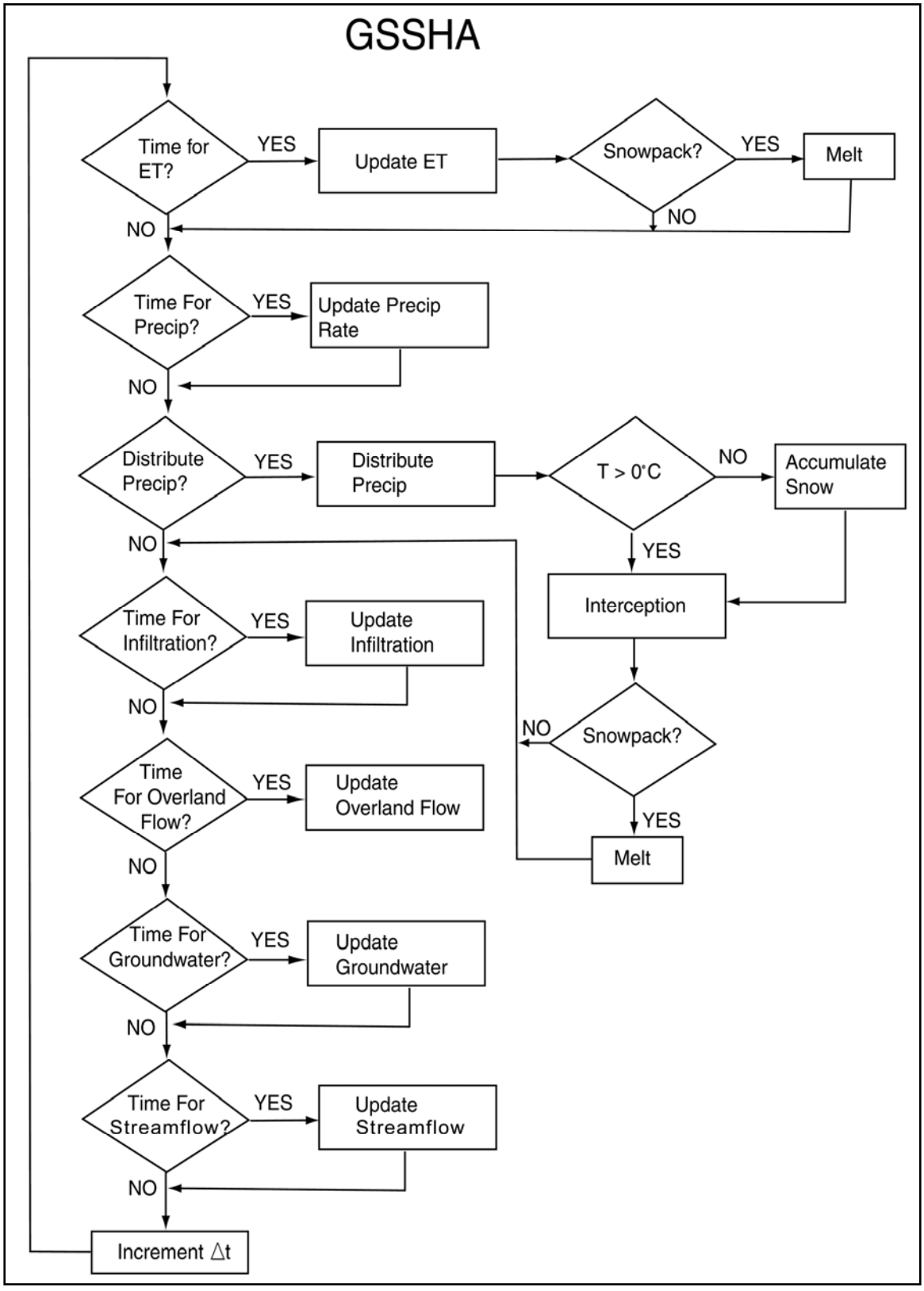


Figure 3. Simple *GSSHA* flowchart.

2 GSSHA Model Formulation

GSSHA is a physically-based, distributed-parameter, structured grid, hydrologic model that simulates the hydrologic response of a watershed subject to given hydrometeorological inputs. The watershed is divided into cells that comprise a uniform finite difference grid. Processes that occur before, during, and after a rainfall event are calculated for each grid cell and then the reponses from individual grid cells are integrated to produce the watershed response. Major components of the model include precipitation distribution, snowfall accumulation and melting, precipitation interception, infiltration, evapo-transpiration, surface-water retention, surface runoff routing, channel flow routing, unsaturated zone modeling, saturated groundwater flow, overland sediment erosion, transport and deposition, and channel routing of sediments.

During an event, rainfall is spatially and temporally distributed over the watershed. Rainfall may be intercepted by vegetation before reaching the land surface. Once an initial interception demand is reached, a fraction of the precipitation will reach the land surface. Upon reaching the land surface, precipitation may infiltrate due to gravity and capillary forces. Water remaining on the land surface may run off as 2-D overland flow, after a specfied retention depth representing microtopography has been reached. This water may eventually enter a stream and be routed to the watershed outlet as one dimensional (1-D) channelized flow. Between precipitation events, soil moisture accounting, evapo-transpiration (ET), and 2-D lateral groundwater flow may be occuring. When precipitation falls in the form of snowfall, the water equivalent volume remains on the land surface and is released as water according to an energy budget calculation.

Processes Simulated

GSSHA is a process-based model. Hydrologic processes that can be simulated and the methods used to approximate the processes with the *GSSHA* model are listed in Table 1. With the exception of channel routing, all processes and approximations in the original *CASC2D* model are also contained in the *GSSHA* model. The Preissmann channel routing routine (Cunge et al. 1980) was excluded because of known stability problems with the scheme when simulating transcritical flows (Mesehle and Holly 1997).

Also, the upwind explicit channel routing method was replaced with a similar up-gradient explicit method.

Table 1. Processes and Approximation Techniques in *GSSHA* Model.

Process	Approximation
Precipitation distribution	Thiessen polygons (nearest neighbor), Inverse distance-squared weighting
Snowfall accumulation and melting	Energy balance
Precipitation interception	Empirical 2 parameter
Overland water retention	Specified depth
Infiltration	Green and Ampt (GA), Multi-layered GA, Green and Ampt with Redistribution (GAR), Richard's equation (RE)
Overland flow routing	2-D diffusive wave - Explicit, - Alternating Direction Explicit (ADE), - ADE Predictor-Corrector (ADEPC)
Channel routing	1-D diffusive wave – up-gradient explicit
Evapo-transpiration	Deardorff, Penman-Monteith with seasonal canopy resistance
Soil moisture in the Vadose zone	Bucket model, RE
Lateral groundwater flow	2-D vertically averaged
Stream/groundwater interaction	Darcy's law
Exfiltration	Darcy's law
GA – Green and Ampt (1911), GAR – Green and Ampt with Redistribution (Ogden and Saghafian 1997), RE – Richards' equation (1931), ADE – Alternating Direction Explicit (Downer et al. 2000), ADEPC – Alternating Direction Explicit, Predictor-Corrector (Downer et al 2000).	

Time-Steps and Process Updates

In *GSSHA*, the user specifies the overall model time-step in seconds that the model uses to loop through the processes, check update times, and update processes. To avoid missing updates of processes, such as rainfall, that may be specified at 1-min intervals, the overall model time-step should be an integer divisible into 60 sec or an integer multiple of 60 sec (i.e., 5, 10, 15, 20, 30, 60, 120, 180, 300). Time-steps such as 7, 9, 13, 16, 21, 45, 90, 270 should not be used, as they may result in unexpected internal model behavior. The model time-step also must not be greater than the finest resolution of inputs, such as rainfall. Typical time-steps for *GSSHA*

range from 10 to 300 sec. Smaller time-steps may be required for particularly difficult problems.

The computational time-step is an important parameter affecting the performance of *GSSHA*. In addition to setting the pace of the model, the overall model time-step is used to set or initialize the temporal discretizations of many model processes. While many processes, such as channel routing, saturated and unsaturated groundwater flow, have internal model stability checks, overland flow routing does not. If the time-step is too large, the program may crash or produce inaccurate results. Very small time-steps result in inordinately long simulation times. The best way to determine the most efficient time-step is through a temporal convergence study, where the time-step is varied and the model behavior is observed. This allows the user to determine the maximum time-step that can be used with acceptable accuracy. As the time-step is increased, the outlet hydrograph will begin to shift in position in relation to simulations with smaller time-steps. As the time-step is further increased, the discharge at the outlet will oscillate; further increases in the computational time-step will result in program crashes. Results of a temporal convergence study, featuring hydrograph shifting, oscillations, and model crash, are shown in Figure 4.

The appropriate time-step strongly depends on watershed and rainfall characteristics. In general, shorter time-steps must be used for the following:

a. Higher intensity storms.

b. Finer horizontal grid resolution (grid spacing).

c. Steeper watershed slopes.

d. Larger watershed areas.

e. Smoother surfaces.

Shorter time-steps must be used when backwater effects are generated in flat areas in the digital elevation model (DEM). If the time-step is too long for any particular simulation, the surface-water depth in very flat areas may develop a checkerboard pattern due to oscillations in the water-surface level. This eventually results in a crash. If this occurs, the time-step should be decreased and the simulation repeated.

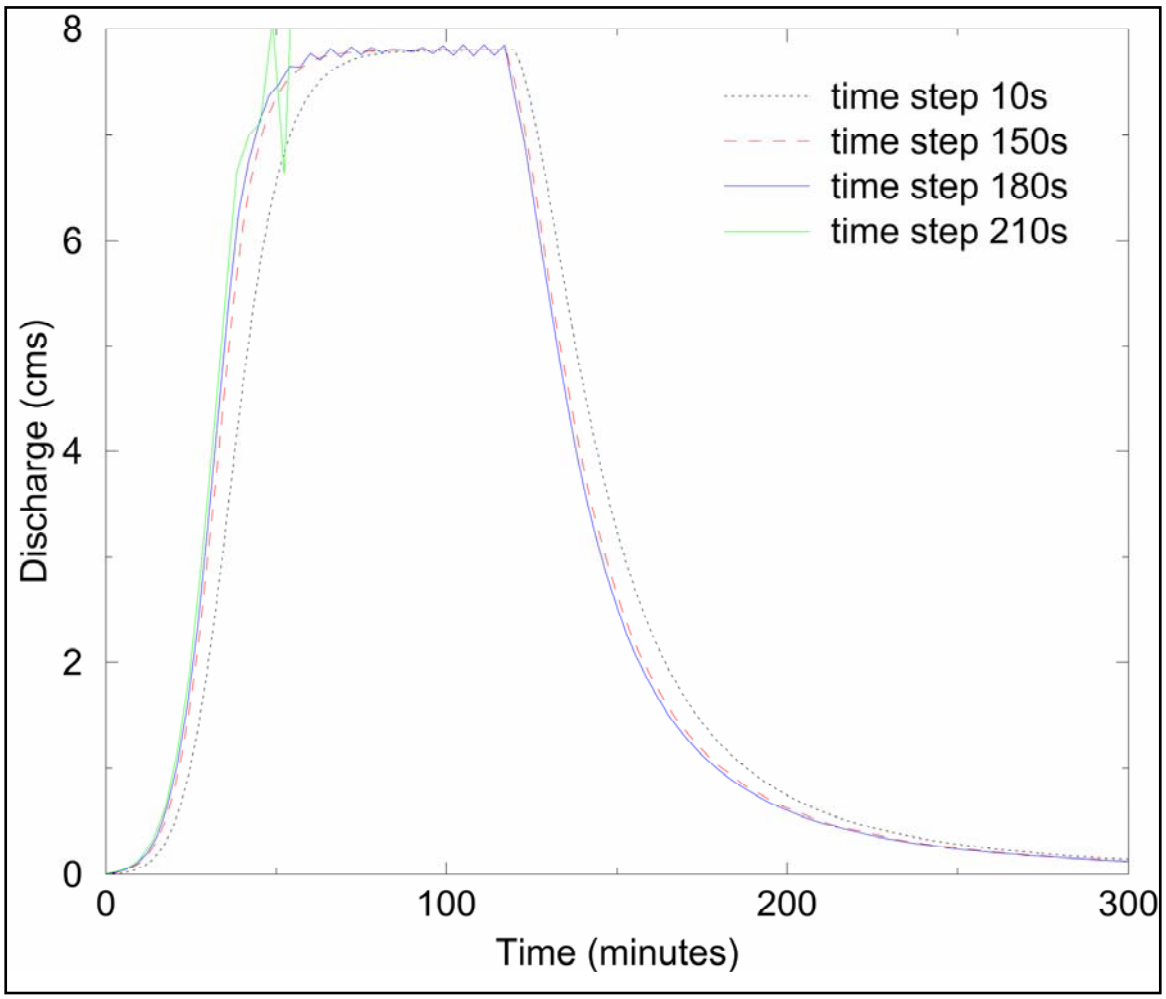


Figure 4. Example of temporal convergence study with hydrograph shifting at 150-s time-step, oscillations at 180 s, and oscillations leading to a crash at 210 s.

At the time of this publication, only the time-step for the saturated groundwater flow is specified in addition to the overall time-step. The ET time-step is fixed at 1 hr, the usual interval of hydrometeorological data available. To maintain stability, the time-step may be reduced internally for the explicit channel routing code, the unsaturated zone RE solver, and the groundwater solver. Internal time-step limitations in the model are described under the appropriate process sections. Rainfall updates are specified in the rainfall gage file and the interval between updates can vary as needed. Thus the overall time-step is limited by:

a. Stability issues in the overland flow scheme.

b. The smallest rainfall interval.

c. The groundwater time-step.

d. Must be integer divisible into the groundwater time-step and the smallest rainfall interval.

Guidance for time-steps is shown in Table 2.

Table 2. Recommended Time-Steps and Stability Criteria Used in *GSSHA* Model.

Process	Typical Time-step	Dependence	Stability Criteria
Overall model	1 s – 5 min	1) Overland flow scheme 2) Rainfall interval 3) Groundwater time-step	
ET	1 hr	Available hydrometeorological data	
Rainfall	1 min – 1 d	Available rainfall data	
Interception	1 min – 1 d	Rainfall interval	
GA Infiltration	1 s – 5 min	Same as overland flow scheme	
GA with Redistribution	1 s – 5 min	Same as overland flow scheme	
RE Infiltration	1 s – 1 hr	Dependent on change in water content ($d\theta/dt$)	$0.0025<d\theta/dt<0.025$ Set by user
Overland flow routing	1 s - 5 min	Stability of overland flow scheme	
Explicit channel routing	1s - 1 hr	1) Must be equal to or less than overland flow routing time-step during runoff 2) Equal to groundwater time-step when groundwater discharge only	Courant number less than 1/6
Saturated groundwater flow	10 min - 1 d	1) Equal to overland flow time-step during runoff 2) Must maintain channel stability during discharge to stream	Maximum number of cells added or subtracted from unsaturated zone

Inputs

GSSHA is a distributed-parameter, process-based model that requires the user to select the processes to be simulated and then provide the model with the data necessary to drive the selected options. Three types of input data are used. An ASCII text project file is used to provide the basic project information, select processes to be simulated, assign simulation parameters, and locate data files, tables and maps. Spatially distributed parameters are assigned with either maps of ASCII gridded data with a parameter value in each grid cell or with index maps and tables of parameter values that relate to the index maps. In *CASC2D*, maps containing values of all parameters for each grid cell are required. However, the data necessary to assign each parameter value in every cell is seldom available. Standard

practice in the application of *CASC2D* has been to use index maps based on available data to create the additional required maps. Land use, soil type, and vegetation data are used to create a master land use/soil type/vegetation map that is used to assign all parameters in each grid cell.

Realizing that the availability of such factors as overland roughness, hydraulic conductivity, and land surface albedo, are far from being readily available at the grid cell level, *GSSHA* provides on option to assign parameter values based directly on the index maps. Parameters for each index map are assigned using tables that reference the values in the index maps. This eliminates the need for a large number of maps currently required by *CASC2D*. A detailed description of using the index maps and mapping tables to build a *GSSHA* model is provided in Chapter 11. If available, the detailed maps containing parameter values in each cell, as described in Ogden (2000), may be input in lieu of the index maps and table.

Many distributed parameters may be assigned with a single uniform value in the project file, a table value linked to an index map, or with an ASCII map with a parameter value for every grid cell. While internally assigning parameter values, the *GSSHA* model looks for the most detailed information first, *GRASS* ASCII maps; the second most detailed information second, table values linked to index maps; and finally a single uniform value from the project file. Once data from one of these sources are located, the search ends and the parameter values are assigned inside the *GSSHA* model. While this rule is generally applicable, it is prudent not to specify multiple sources of the same parameter value in the project file. This avoids possible confusion and improper assignment of parameter values.

The Watershed Modeling System (*WMS*) interface, developed at the Environmental Modeling Research Laboratory (EMRL) at Brigham Young University, is recommended for developing input files and viewing output from the *GSSHA* model. The *WMS* produces *GSSHA* specific files from general Geographic Information System (GIS) data. *WMS* does not replace the functions of a GIS, though it can accept information in a variety of GIS formats. *GSSHA* relies on the *GRASS* ASCII data file format for storing spatially distributed data. The *GRASS* GIS is very helpful in the preparation of *GSSHA* data sets. Users of *ARC/INFO* and *ARCVIEW* can export data to *GSSHA* through the *WMS* interface. For more information about *WMS*, DoD and EPA personnel should contact: XMS Model Support,

Hydrologic Systems Branch, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research Development Center, 3909 Halls Ferry Road, Vicksburg, MS, 39180-6199, (601) 634-4286, *http://chl.erdc.usace.army.mil/*. Other users seeking information about *WMS*, should contact: Environmental Modeling Research Laboratory, 242 Clyde Building, Provo, Utah 84602, (801) 422-2812, FAX (801) 422-0150, *http://www.emrl.byu.edu*.

3 Project File

GSSHA simulations require a project file that contains command line instructions or "cards" which pass options to *GSSHA* for a particular simulation. The name of the project file is given at run time as a command line argument for *GSSHA*. The following section presents all project file cards followed by a brief description of each. The project file consists of a single card on each line, followed by its argument, if any. While some cards require no argument, others require values, character strings, file names, table names, or map names. Tables are files that contain ASCII input data in a tabular format. A map name is simply the name of a floating point *GRASS* ASCII file that contains raster data. An index map refers to a similar file that contains integers indexed to tabular values. Throughout the manual, project card names will be presented in **BOLD CAPITAL** letters; arguments appear as *CAPITAL ITALICS*.

The project file cards may appear in the project file in any order, except the first card must be **CASC2DPROJECT**. Extraneous or misspelled cards are ignored. A card may be commented out by preceding the card with a pound sign (hash mark) "#". When using the mapping table to assign parameter values for any process, the **MAPPING_TABLE** card is used. For project cards related to input parameters, the units, if any, of the input argument are presented. For optional inputs, the default value, if any, is also presented.

Required Inputs

The following tabulation lists all required project file cards, which must be present in a project file. In addition to these cards, a method of assigning rainfall and overland roughness values must also be selected from the choices.

Card	Argument	Description
CASC2DPROJECT	*none*	This card must appear first in the project file.
UNITS	*integer*	0- All units are as described in this document (metric units) 1- Elevation and grid size are in ft.
GRIDSIZE	*real*	The size of the square model grids (m if **UNITS** = 0 or, ft if **UNITS** = 1).
ROWS	*integer*	Number of rows in each raster map.
COLS	*integer*	Number of columns in each raster map.
TOT_TIME	*integer*	Total duration of the event simulation in minutes. Not required if **LONG_TERM** is specified.
TIME-STEP	*real*	Overall model time-step (s).
OUTSLOPE	*real*	Slope of the cell containing the watershed outlet. Must be positive. Not required if **CHAN_EXPLIC** is specified.
OUTROW	*integer*	The raster row where the catchment outlet is located. Not required **CHAN_EXPLIC** is specified.
OUTCOL	*integer*	The raster column where the catchment outlet is located. Not required **CHAN_EXPLIC** is specified.
ELEVATION	*map name*	Name of *GRASS* ASCII map containing watershed elevations (m if **UNITS** = 0 or, ft if **UNITS** = 1).
WATERSHED_MASK	*map name*	Name of *GRASS* ASCII map containing the watershed shape. Cells marked with 1 lie inside the watershed, while cells marked with a 0 lie outside. Must be the first card after CASC2DPROJECT for use with *WMS*.
HYD_FREQ	*integer*	Frequency (time-steps) that points are written to the output hydrograph file(s).
SUMMARY	*file name*	Output file summarizing information on options selected, inputs read, simulation results, mass conservation, and warnings generated during the simulation.
OUTLET_HYDRO	*file name*	Output file containing time series discharge at the catchment outlet. ($m^3\ s^{-1}$ if **UNITS** = 0 or, $ft^3\ s^{-1}$ if **UNITS** = 1)

Mapping Table - Optional

When using the mapping table to assign any of the distributed parameters, the mapping table card must be included.

Card	Argument	Description
MAPPING_TABLE	*filename*	Input ASCII file that assigns parameter values based on index maps.

Overland Flow - Required

Required inputs

Overland roughness coefficients must be assigned to every cell in the active grid. Overland roughness coefficients may be assigned as either a single uniform value, from a *GRASS* ASCII grid map, or from the mapping table. Only one option should be selected.

Card	Argument	Units	Description
MANNING_N	*real*	none	Constant value of Manning's roughness coefficient to be applied to the entire watershed. Mutually exclusive with **ROUGHNESS** and mapping table file assignment.
ROUGHNESS	*map name*		Name of *GRASS* ASCII map containing spatially-varied overland flow Manning's n values. Mutually exclusive with **MANNING_N** and mapping table file assignment.

Optional inputs

The user can select the overland flow routing scheme. An overland retention depth may also be specified at the discretion of the user. Retention depth can be assigned as a single uniform value, from the mapping table, or from a *GRASS* ASCII grid map. Only one option should be specified.

Card	Argument	Units	Default Value	Description
OVERTYPE	*integer*		1	Overland routing scheme: 1 - EXPLICIT, 2 - ADE, 3 - ADE-PC
RETENTION	*real*	mm	0.0	Specifies the uniform retention depth to be used for all overland flow cells. Mutually exclusive with **RETENT_DEPTH**, and mapping table file assignment.
RETENT_DEPTH	*map name or none*			Specifies distributed retention depth (mm) over the watershed. If followed by a map name, the file will be read in as the retention depth map. If no input is specified, then the retention depth map is generated from the mapping table file.
INITIAL_DEPTH	*map name*			Name of map that specifies initial depths, m, of every overland flow cell

Interception - Optional

Interceptions parameters may be assigned using the mapping table, or by assigning *GRASS* ASCII maps.

Card	Argument	Description
INTERCEPTION		Interception data present in the mapping table file.
STORAGE_CAPACITY	*map name*	Name of *GRASS* ASCII map containing values of the initial interception abstraction (mm). Mutually exclusive with mapping table file assignment.
INTERCEPTION_COEFF	*map name*	Name of *GRASS* ASCII map containing values of the interception coefficient. Mutually exclusive with mapping table file assignment.

Rainfall Input and Options - Required

The following tabulation lists all project file cards pertaining to rainfall input. Either, but not both, **PRECIP_UNIF** or **PRECIP_FILE** must be included in each *GSSHA* project file.

Card	Argument	Units	Description
PRECIP_UNIF	*none*		Specifies spatially and temporally uniform rainfall. Also requires: RAIN_INTENSITY, RAIN_DURATION, START_DATE, START TIME. Mutually exclusive with PRECIP_FILE.
RAIN_INTENSITY	*real*	mm hr^{-1}	Intensity of spatially- and temporally-uniform rainfall. Required only for PRECIP_UNIF.
RAIN_DURATION	*real*	minutes	Duration of spatially- and temporally-uniform rainfall. Required only for PRECIP_UNIF.
START_DATE	*integers*	year month day	Year, month, and day of the beginning of a simulation. Required only for PRECIP_UNIF. See section on rainfall input for format description.
START_TIME	*integers*	hr minute	Hour and minute of the beginning of a simulation. Required only for PRECIP_UNIF. See section on rainfall input for format description.
PRECIP_FILE	*table name*		Input ASCII file containing spatially and temporally varied rainfall rates (mm hr^{-1}). See the manual section titled *Precipitation Input* for a description of the file format. Exclusive with PRECIP_UNIF.
RAIN_INV_DISTANCE	*none*		Inverse distance squared rainfall interpolation. REQUIRED for PRECIP_FILE. Mutually exclusive with RAIN_THIESSEN.
RAIN_THIESSEN	*none*		Thiessen polygon (nearest neighbor) rainfall interpolation. Recommended particularly when rainfall rates are derived from radar estimates. REQUIRED for PRECIP_FILE. Mutually exclusive with RAIN_INV_DISTANCE.

Infiltration - Optional

Infiltration may be calculated using four different infiltration options. Green and Ampt (GA) (Green and Ampt 1911), a multi-layered Green and Ampt model, Green and Ampt with Redistribution (GAR) (Ogden and Saghafian 1997), and Richards' equation (RE) (Richards 1931). Only one of these four methods should be selected.

Card	Argument	Description
GREEN_AMPT	*none*	Specifies GA infiltration calculations.
INF_REDIST	*none*	Specifies GAR infiltration calculations.
INF_LAYERED_SOIL	*none*	Specifies three-layer Green and Ampt infiltration.
INF_RICHARDS	*none*	Specifies Richards' Equation be used for infiltration.

Green and Ampt (GA)

When **GREEN_AMPT** is selected, values of hydraulic conductivity, wetting front suction head, porosity, and initial moisture are required. Parameter values may be input using the mapping table file or with the series of *GRASS* ASCII maps using the cards listed in the following tabulation.

Card	Argument	Description
CONDUCTIVITY	*map name*	Name of *GRASS* ASCII map containing spatially varied values of soil saturated hydraulic conductivity (cm hr^{-1}). REQUIRED for GREEN_AMPT or INF_REDIST. Mutually exclusive with mapping table file assignment.
CAPILLARY	*map name*	Name of *GRASS* ASCII map containing spatially varied values of Green & Ampt wetting front capillary head parameter (cm). REQUIRED for GREEN_AMPT or INF_REDIST. Mutually exclusive with mapping table file assignment.
POROSITY	*map name*	Name of *GRASS* ASCII map containing spatially varied values of soil porosity. REQUIRED for GREEN_AMPT or INF_REDIST. Mutually exclusive with mapping table file assignment.
MOISTURE	*map name or none*	Used to assign the initial soil moisture content. If followed by a filename, the file will be read in as a *GRASS* ASCII initial soil volumetric water content map. If no input is specified, then the initial soil volumetric water content s will be input using the mapping table file. REQUIRED for GREEN_AMPT or INF_REDIST.

Green and Ampt with Redistribution (GAR)

When GAR is specified, the GA parameters plus two additional parameters must be provided: the pore-distribution index, and residual saturation.

These may be input in the mapping table file or by providing two *GRASS* ASCII maps using the following cards.

Card	Argument	Description
PORE_INDEX	*map name*	Name of *GRASS* ASCII map containing spatially varied values of the Brooks and Corey (1964) pore-distribution index. REQUIRED for **INF_REDIST**. Mutually exclusive with mapping table tile assignment.
RESIDUAL_SAT	*map name*	Name of *GRASS* ASCII map containing spatially varied values of the volumetric water content of the soil at residual saturation. REQUIRED for **INF_REDIST**. Mutually exclusive with mapping table file assignment.

Multilayered Green and Ampt

The multilayered GA parameters are assigned with the table described in Chapter 11, and referenced to an index map. The required project cards are listed in the following tabulation.

Card	Argument	Description
SOIL_TYPE_MAP	*index map name*	Name of *GRASS* ASCII map containing index numbers related to soil type.
SOIL_LAYER_INPUT_FILE	*table name*	Input ASCII file containing values GA parameter in three soil layers for each soil referenced to in the **SOIL_TYPE_MAP**.

Richards' Equation

When **INF_RICHARDS** is selected, additional cards are required. There are also a number of optional input and output cards, as described in the following tabulation.

Required inputs.

Card	Argument	Description
INF_RICHARDS	*none*	Specify Richards' equation for calculation of soil moisture, infiltration, and ET if doing **LONG_TERM** simulations.
RICHARDS_C_OPTION	*character string*	Type of water-content/head curve and hydraulic conductivity/head curve. **BROOKS** - Brooks and Corey (1964), as extended by Hutson and Cass (1987), into the wet profile; or, **HAVERCAMP** – Havercamp etal. (1977) as modified by Lappala (1987).
SOIL_TYPE_MAP	*index map name*	Name of *GRASS* ASCII map of soil type integer values corresponding to **SOIL_LAYER_INPUT_FILE**
SOIL_LAYER_INPUT_FILE	*table name*	Input ASCII file with soil layer input parameters.

Parameter assignment – required.

Select either **SOIL_LAYER_INPUT_FILE** or use mapping table.

Card	Argument	Description
SOIL_LAYER_INPUT_FILE	*table name*	Input ASCII file with soil layer input parameters.

Optional inputs.

Card	Argument	Default	Description
WATER_TABLE	*map name*	no water table	Simulate effect of water table on soil moisture. Specify filename of *GRASS* ASCII map that contains starting elevations of water table (m).
AQUIFER_DELTA_Z	*real*	none	Size of unsaturated cell to use in all cells below the soil column specified in SOIL_LAYER_INPUT_FILE or mapping table.
SEASONAL_RS	*none*	no seasonal canopy resistance	Vary the vegetation canopy resistance during the year.
RICHARDS_UPPER_OPTION	*character string*	*NORMAL*	Method used to calculate hydraulic conductivity at ground surface under ponded conditions: *NORMAL* – from cell-centered water content of first cell, *GREEN_AMPT* - saturated hydraulic conductivity (K_s) of cell 1 *AVERAGE* - average of K_s and *NORMAL*
GW_ASSIGN_THETA	*none*	do not assign initial theta, assume equilibrium values	Assign soil moisture from the file specified in SOIL_LAYER_INPUT_FILE card, if simulating the water table.
RICHARDS_ITER_MAX	*integer*	1	Maximum number of iterations on non-linear coefficients.
RICHARDS_WEIGHT	*real*	1.0	Weight on intercell hydraulic conductivities: 1.0 - forward 0.5 - centered 0.0 – backwards
RICHARDS_K_OPTION	*character string*	*ARITHMETIC*	Averaging method for intercell hydraulic conductivities, *GEOMETRIC* or *ARITHMETIC*
RICHARDS_DTHETA_MAX	*real*	0.025	Maximum allowable water content change during a time-step.

Optional output.

Card	Argument	Description
IN_THETA_LOCATION	*table name*	Input ASCII file that contains locations of cells to output time series moisture data.
OUT_THETA_LOCATION	*file name*	Filename to output time series moisture data every HYD_FREQ time-steps at cells specified in IN_THETA_LOCATION.

Channel Routing - Optional

Required inputs

The following cards are required for the simulation of channel routing.

Card	Argument	Description
CHAN_EXPLIC	*none*	Specifies explicit diffusive-wave 1-D channel routing.
CHANNEL_INPUT	*table name*	Input ASCII file containing channel network connectivity and cross-sectional information for each link/node.
SECTION_TABLE	*table name*	Input ASCII file containing cross section information for irregular, breakpoint channel cross sections. Required if look-up table cross sections are specified in **CHANNEL_INPUT** file.
LINKS	*map name*	Name of *GRASS* ASCII map containing the location of channel links within the watershed.
NODES	*map name*	Name of *GRASS* ASCII map containing the location of channel nodes within the watershed.

Initial condition and boundary condition - optional

Card	Argument	Description
EXPLIC_BACKWATER	*none*	Save explicit channel routing end of run values of channel depth (m) and discharge ($m^3\ s^{-1}$) for each cell in files specified by **WAT_SURF_PROFILE** and **DIS_PROFILE** cards
DIS_PROFILE	*table name*	Input ASCII file containing the start-up discharge in each link/node in the channel network. Written by running *GSSHA* with **EXPLIC_BACKWATER**.
WAT_SURF_PROFILE	*table name*	Input ASCII file containing the start-up water depth in each link/node in the channel network. Written by running *GSSHA* with **EXPLIC_BACKWATER**.
EXPLIC_HOTSTART	*none*	Start explicit channel calculations using the values of channel depth and flow saved in the files specified by **WAT_SURF_PROFILE** and **DIS_PROFILE** cards.
OVERBANK_FLOW	*none*	Allow water in channel to flow back onto overland flow plane.
HEAD_BOUND	*none*	Use lower boundary depth as specified by the **BOUND_DEPTH** card.
BOUND_DEPTH	*real*	Lower boundary depth (m).

Stream losses/gains – optional

General.

Card	Argument	Units	Description
STREAM_LOSS	*none*	none	Card is used to specify that stream losses be computed when the **WATER_TABLE** card is not included in the project file.

Parameters.

Used with **WATER_TABLE** or **STREAM_LOSS** card. These parameters may also be distributed along the channel by assigning in the **CHAN_INPUT** file.

Card	Argument	Units	Description
K_RIVER	*real*	cm hr^{-1}	Uniform hydraulic conductivity of streambed material. REQUIRES **WATER_TABLE** or **STREAM_LOSS**. May also be distributed in **CHAN_INPUT** file.
M_RIVER	*real*	cm	Uniform thickness of streambed material. Requires **WATER_TABLE** or **STREAM_LOSS**. May also be distributed in **CHAN_INPUT** file.

Optional output.

Card	Argument	Description
IN_HYD_LOCATION	*table name*	Input ASCII file specifying link/node pairs to write out time series data specified by **OUT_HYD_LOCATION, OUT_DEP_LOCATION**, or **OUT_CON_LOCATION**.
OUT_HYD_LOCATION	*filename*	Filename to output time series discharge data ($m^3\ s^{-1}$ or $ft^3\ s^{-1}$) at points **specified in IN_HYD_LOCATION. REQUIRED if IN_HYD_LOCATION** was specified.
OUT_DEP_LOCATION	*filename*	Filename to output channel depths (m) every **HYD_FREQ** time-steps at locations specified in the **IN_HYD_LOCATION** file.
IN_SED_LOC	*table name*	Input ASCII file containing a list of internal link/node locations where the user wants to save sediment hydrographs. Format identical to **IN_HYD_LOC** option. REQUIRES **SOIL_EROSION**.
OUT_SED_LOC	*filename*	Filename to output sediment flux hydrographs every **HYD_FREQ** time-steps at internal catchment locations specified in the **IN_SED_LOC** file. REQUIRED if **SOIL_EROSION** and **IN_SED_LOC** card are specified.
STRICT_JULIAN_DATE	*none*	Specifies all time series data use strict Julian format.
CHAN_DEPTH	*filename*	Filename to output **MAP_TYPE** map of channel depth (m) every **MAP_FREQ** time-steps.
CHAN_DISCHARGE	*filename*	Filename to output **MAP_TYPE** maps of channel discharge ($m^3\ s^{-1}$) every **MAP_FREQ** time-steps.
WMS_HYDRO	*Filename*	*WMS* filename to output outlet discharge data and internal hydrograph locations specified in **IN_HYD_LOCATION** every **HYD_FREQ** time-steps. File is readable to *WMS* v7.0+
INCLUDE_CHANNEL_DEPTH	*none*	Specifies channel depth (m), instead of the overland flow depth (m), be written to maps of overland flow depth.

Continuous Simulations – Optional

Continuous simulations require general information about the watershed location, selection of a method to calculate evapotranspiration (ET), hydrometeorological (HMET) data in one of three available formats, and the appropriate distributed data either from the mapping table file or from *GRASS* ASCII maps.

Required inputs

Card	Argument	Units	Description
LONG_TERM	*none*		Specifies continuous simulation. REQUIRES one of **ET_CALC_PENMAN** or **ET_CALC_DEARDORFF**. REQUIRES one of three HMET formats. Also REQUIRES **INF_REDIST** or **INF_RICHARDS**.
LATITUDE	*real*	decimal degrees	Latitude of catchment centroid.
LONGITUDE	*real*	decimal degrees	Longitude of catchment centroid.
GMT	*real*	hr	Number of hours difference between the time zone of the catchment and Greenwich Mean Time (e.g.,–6 for EDT).
SOIL_MOIST_DEPTH	*real*	m	Depth of the active soil moisture layer from which ET occurs (m).
EVENT_MIN_Q	*real*	$m^3 s^{-1}$	Threshold discharge for continuing runoff events.

Seasonal canopy resistance - optional

Card	Argument	Units	Description
SEASONAL_RS	*none*		Specifies that the values of canopy resistance vary seasonally

Method of calculating evapotranspiration – required, select one method

Card	Argument	Description
ET_CALC_PENMAN	*none*	Calculate evapotranspiration using the Monteith (1965) method. Mutually exclusive with **ET_CALC_ DEARDORFF**.
ET_CALC_DEARDORFF	*none*	Calculate evapotranspiration using the Deardorff (1978) bare-soil method. Mutually exclusive with **ET_CALC_PENMAN**.

Format of hydrometeorological (HMET) data – required, select one format

Card	Argument	Description
HMET_SURFAWAYS	*table name*	ASCII file with hourly HMET data formatted in the form of the NOAA/NCDC Surface Airways Data. Mutually exclusive with HMET_SAMSON and HMET_WES; one required for LONG_TERM.
HMET_SAMSON	*table name*	ASCII file with hourly HMET data formatted as per the NOAA/NCDC SAMSON CD-ROM data set. Mutually exclusive with HMET_WES and HMET_SURFAWAYS; one required for LONG_TERM.
HMET_WES	*table name*	ASCII file with hourly HMET data written using a simple format discussed in Chapter 9. Mutually exclusive with HMET_SURFAWAYS and HMET_SAMSON; one required for LONG_TERM.

ET parameter assignment – required, select mapping table or *GRASS* ASCII maps

Long-term simulation parameters must be assigned using either the mapping table or providing the *GRASS* ASCII maps as described in the following tabulation. Albedo and wilting point are required for **ET_CALC_DEARDORFF**. Transmission coefficient, vegetation height and canopy resistance are also required for **ET_CALC_PENMAN**.

Card	Argument	Description
ALBEDO	*map name*	Name of *GRASS* ASCII map containing short-wave albedo values (0.0 – 1.0).
WILTING_POINT	*map name*	Name of *GRASS* ASCII map containing values of the wilting point volumetric water content (0.0 - 1.0).
TCOEFF	*map name*	Name of *GRASS* ASCII map containing values of the canopy optical transmission coefficient. (0.0 - 1.0).
VHEIGHT	*map name*	Name of *GRASS* ASCII map containing values of the vegetation height in m. This value is used in calculating the aerodynamic resistance of the reference crop (m) and used in assigning root depth when using INF_RICHARDS.
CANOPY	*map name*	Name of *GRASS* ASCII map containing values of the canopy average stomatal resistance (s m^{-1}).

Saturated Groundwater Flow - Optional

Required inputs

These cards are REQUIRED to perform 2-D lateral groundwater simulations.

CARD	Argument	Units	Description
WATER_TABLE	*map name*		Specifies the simulation of the effect of the water table on the RE solver, gives *GRASS* ASCII map name of starting groundwater surface elevations (m).
GW_SIMULATION	*none*		Specifies the simulation of 2-D groundwater flow. **INF_RICHARDS** or **INF_REDIST** required.
GW_TIME-STEP	*real*	s	Time-step for groundwater computations
GW_LSOR_CON (successive over relaation by lines)	*real*	m	Convergence criteria for LSOR calculations
GW_RELAX_COEFF	*real*	none	Factor to overrelax or underrelax next estimate in LSOR calculations. Values greater than 1.0 overrelax, values less than 1.0 underrelax. Increase value to speed solution. Decrease value when solution does not converge.
AQUIFER_BOTTOM	*map name*		Name of *GRASS* ASCII map of bedrock elevations (m).
GW_BOUNDFILE	*map name*		Name of *GRASS* ASCII map that contains the boundary type of each cell. 0 – no flow 1 - no boundary, regular infiltration cell 2 - specified head, taken from **WATER_TABLE** file 3 - dynamic flux (well), not yet available 4 - river with calculated flux to/from groundwater 5 - river with specified head, value from channel solver 6 - static flux (well), value taken from **GW_FLUX_BOUNDTABLE**

Optional inputs

Card	Argument	Units	Default	Description
GW_ASSIGN_THETA	*none*			When simulating saturated groundwater, assign initial values of moisture in each cell of the unsaturated zone using values in the SOIL_LAYER_INPUT_FILE. INF_RICHARDS REQUIRED.[1]
GW_UNIF_POROSITY	*none*			Uniform porosity to be used in every cell in the groundwater problem
GW_POROSITY_MAP	*map name*			Name of *GRASS* ASCII map containing porosity values for each cell.[1]
GW_UNIF_HYCOND	*real*	cm hr^{-1}		Uniform hydraulic conductivity used in every cell in the groundwater problem.[1]
GW_HYCOND_MAP	*map name*			Name of *GRASS* ASCII map containing hydraulic conductivity (cm hr^{-1}) values for each cell in the groundwater problem[1]
K_RIVER	*real*	cm hr^{-1}		Hydraulic conductivity (cm hr^{-1}) of streambed material. Use in conjunction with CHAN_EXPLIC and GW_BOUNDFILE type 4. May also be distributed in CHAN_INPUT file.
M_RIVER	*real*	cm		Depth of streambed material (m). Use in conjunction with CHAN_EXPLIC and GW_BOUNDFILE type 4. May also be distributed in CHAN_INPUT file.
GW_FLUXBOUNDTABLE	*table name*			Input ASCII file containing location and pumping rate of wells in the grid. Locations should correspond to GW_BOUNDFILE.
GW_LEAKAGE_RATE	*real*	cm hr^{-1}	0.0	Rate of water loss out of the bottom of the shallow aquifer.

[1] Values for porosity (θ_S) and saturated hydraulic conductivity (K_S) may be specified in one of three ways:

a. Without specifying one of the two types of cards, θ_S and/or K_S values for each cell will be assigned the value of bottom layer of the SOIL_LAYER_INPUT_FILE for the soil type as specified in the SOIL_TYPE_MAP. This method is valid only with INF_RICHARDS.

b. Uniform values of θ_S or K_S may be specified using the appropriate card.

c. *GRASS* ASCII maps or θ_S or K_S values for each cell may be assigned by using the appropriate card.

If INF_REDIST is used in combination with GW_SIMULATION, either method b or c must be used.

Optional Output

CARD	Argument	Description
GW_OUTPUT	*filename*	Filename to output groundwater head (m) **MAP_TYPE** maps every **MAP_FREQ** time-steps.
OUT_WELL_LOCATION	*table name*	Input ASCII file containing the locations of observation wells. Values of groundwater head at each location in the file specified in **OUT_WELL_LOCATION** will be output every **MAP_FREQ** time-steps in the **GW_WELL_LEVEL** file.
GW_WELL_LEVEL	*filename*	Filename to output groundwater heads every **HYD_FREQ** time-steps at locations specified in **OUT_WELL_LOCATION**.

Soil Erosion - Optional

Soil erosion simulation - required

Card	Argument	Description
SOIL_EROSION	*none*	Specifies overland soil erosion calculations.

Soil erosion parameters – required, specify in mapping table or *GRASS* ASCII maps

Soil erosion properties must be assigned with either the mapping table or the *GRASS* ASCII maps as described in the following tabulation.

Card	Argument	Description
SOIL_ERODABILITY	*map name*	Name of *GRASS* ASCII map containing spatially-distributed values of the Universal Soil Loss Equation (USLE) soil erodability index (0.0 – 1.0)
SAND_MAP	*map name*	Name of *GRASS* ASCII map containing the percentage of sand in each grid cell (0.0 – 1.0).
SILT_MAP	*map name*	Name of *GRASS* ASCII map containing the percentage of silt in each grid cell (0.0 – 1.0).

Soil erosion factors – required, specify in mapping table or *GRASS* ASCII maps

Soil erosion factors must be assigned with either the mapping table or with the *GRASS* ASCII maps described in the following tabulation.

Card	Argument	Description
CROP_MANAGEMENT	*map name*	Name of *GRASS* ASCII map containing spatially distributed values of the USLE crop management factor (0.0 – 1.0).
CONSERVATION_PRACTICE	*map name*	Name of *GRASS* ASCII map containing spatially distributed values of the USLE conservation practice factor (0.0 –1.0).

Optional inputs

Card	Argument	Units	Default	Description
SAND_SIZE	*real*	mm	0.25	Representative grain-size for sand-size particles.
SILT_SIZE	*real*	mm	0.016	Representative grain-size for silt-size particles.
CLAY_SIZE	*real*	mm	0.001	Representative grain-size for clay-size particles.
WATER_TEMP	*real*	C^o	20	Water temperature
SED_POROSITY	*real*		0.4	Value of the porosity of channel bed sediments (0.0-1.0).
IN_SED_LOC	*table name*			Filename containing a list of internal link/node locations to output sediment hydrographs. Format identical to IN_HYD_LOC option. Valid only with CHAN_EXPLIC.

Output Files - Required

Required output

Card	Argument	Description
SUMMARY	*file name*	Output file summarizing information on options selected, inputs read, simulation results, mass conservation, and warnings generated during the simulation.
OUTLET_HYDRO	*file name*	Output file containing time series discharge at the catchment outlet. ($m^3\ s^{-1}$ if UNITS = 0 or, $ft^3\ s^{-1}$ if UNITS = 1)

Optional output

Card	Argument	Description
QOUT_CFS	*none*	Specifies outflow hydrograph ordinates in $ft^3\ s^{-1}$. The default is $m^3\ s^{-1}$.
QUIET	*none*	Suppress printing of information to the screen each time-step.
IN_HYD_LOCATION	*table name*	Name of input ASCII file containing the link/node pairs to write out hydrograph ordinates to the file specified by **OUT_HYD_LOCATION**.
OUT_HYD_LOCATION	*file name*	Filename to output discharge ($m^3\ s^{-1}$ or $ft^3\ s^{-1}$) every **HYD_FREQ** time-steps, at locations specified in **IN_HYD_LOCATION**. REQUIRED if **IN_HYD_LOCATION** was specified.
OUT_DEP_LOCATION	*filename*	Filename to output time channel depths (m) every **HYD_FREQ** time-steps at locations specified in the **IN_HYD_LOCATION** file.
OUT_SED_LOC	*filename*	Filename to output sediment flux every **HYD_FREQ** time-steps at internal catchment locations specified in the **IN_SED_LOC** file. REQUIRED if **SOIL_EROSION** and **IN_SED_LOC** card are specified.
OUTLET_SED_FLUX	*filename*	Filename to output outflow hydrograph ($m^3\ s^{-1}$) every **HYD_FREQ** time-steps. This output file contains 3 columns: 1st: time (min.); 2nd: sand flux; 3rd: suspended sediment flux. REQUIRED if **SOIL_EROSION** is specified.
IN_THETA_LOCATION	*table name*	Name of input ASCII file that contains locations of cells to output moisture data every **HYD_FREQ** time-steps.
OUT_THETA_LOCATION	*file name*	Filename to output time series moisture data every **HYD_FREQ** time-steps at cells specified in **IN_THETA_LOCATION.**
OUT_WELL_LOCATION	*table name*	Name of input ASCII file containing location of observation wells. Values of groundwater head at each location in the file specified in **OUT_WELL_LOCATION** will be output every **HYD_FREQ** time-steps in the **GW_WELL_LEVEL** file.
GW_WELL_LEVEL	*filename*	Filename to output groundwater heads every **HYD_FREQ** time-steps at locations specified in **OUT_WELL_LOCATION.**
STRICT_JULIAN_DATE	*none*	All time series data are output with strict Julian date.
OPTIMIZE	*filename*	Filename to output optimization information: peak discharge and discharge volumes at the watershed outlet and at any points specified in the **IN_HYD_LOCATION** file for each storm event.

Optional output maps

Card	Argument	Description
MAP_FREQ	*integer*	Frequency (in time-steps) that output time-series maps are written to. REQUIRED only if output maps are specified.
MAP_TYPE	*integer*	Specifies the format of output maps: 0 - ASCII *GRASS* maps. 1 - ASCII *WMS* maps. 2 - binary *WMS* maps. REQUIRED only if **MAP_FREQ** is required.
DISCHARGE	*filename*	Filename to output **MAP_TYPE** maps of the overland discharge ($m^3\ s^{-1}$) every **MAP_FREQ** time-steps.
DEPTH	*file name*	Filename to output **MAP_TYPE** maps of overland flow depth (m) every **MAP_FREQ** time-steps.
INCLUDE_CHANNEL_DEPTH	*none*	Specifies channel depth (m), instead of the overland flow 1depth (m), be written to **DEPTH** maps. REQUIRES **CHAN_EXPLIC**.
INF_DEPTH	*filename*	Filename to output **MAP_TYPE** maps of cumulative infiltrated depth (m) every **MAP_FREQ** time-steps. REQUIRES infiltration option.
SURF_MOIST	*filename*	Filename to output **MAP_TYPE** maps of soil surface volumetric water content every **MAP_FREQ** time-steps. REQUIRES infiltration option.
RATE_OF_INFIL	*file name*	Filename to output **MAP_TYPE** maps of infiltration rate ($cm\ h^{-1}$) every **MAP_FREQ** time-steps. REQUIRES infiltration option.
DIS_RAIN	*filename*	Filename to output **MAP_TYPE** maps of spatially distributed rainfall rate ($mm\ h^{-1}$) every **MAP_FREQ** time-steps.
CHAN_DEPTH	*filename*	Filename to output **MAP_TYPE** map of channel depth (m) every **MAP_FREQ** time-steps. REQUIRES **CHAN_EXPLIC**.
CHAN_DISCHARGE	*filename*	Filename to output **MAP_TYPE** maps of channel discharge ($m^3\ s^{-1}$) every **MAP_FREQ** time-steps. REQUIRES **CHAN_EXPLIC**.
VOL_SUSP_SED	*filename*	Filename to output **MAP_TYPE** maps of volume of suspended sediment (m^3) every **MAP_FREQ** time-steps. REQUIRES **CHAN_EXPLIC** and **SOIL_EROSION**.
MAX_SED_FLUX	*filename*	Filename to output **MAP_TYPE** maps of sediment flux ($m^3\ s^{-1}$) every **MAP_FREQ** time-steps. REQUIRES **SOIL_EROSION**.
NET_SED_VOLUME	*filename*	Filename to output **MAP_TYPE** maps of net volume (m^3) of erosion/deposition every **MAP_FREQ** time-steps. Erosion is negative, deposition is positive. REQUIRES **SOIL_EROSION**.
GW_OUTPUT	*filename*	Filename to output **MAP_TYPE** maps of groundwater head (m) every **MAP_FREQ** time-steps. REQUIRES **WATER_TABLE**.

4 General Considerations

Units

The **UNITS** flag argument is 0 if the grid size, bounding rectangle coordinates, and elevations in the elevation map are in units of meters. Otherwise, the **UNITS** argument should be 1, which specifies that the grid size, bounding rectangle coordinates and elevations are in units of feet. In this case, the coordinates are converted to meters. Internally, *GSSHA* uses metric units for all computations. Many inputs require metric units, and the model does not have built-in coordinate conversion. Furthermore, the model was developed based on the Universal Tranverse Mecator (UTM) coordinate system, as described in Chapter 4. For these reasons, users are strongly urged to input all data in metric units.

With few exceptions, the units used for input and output in *GSSHA* are in SI units. Units for particular processes are consistent with those found in the literature. For instance, hydraulic conductivity is specified in units of cm h^{-1}, while rainfall rates are specified in mm h^{-1}. The particular units expected of each input are given in the project file card descriptions.

Grid Size

Distributed models are used over a wide range of grid sizes, from 10 to 1,000 m. The selection of an appropriate grid size for a *GSSHA* model requires consideration of both the available data and computational effort required. Typical grid sizes range from 10 to 250 m. The selection of the grid size for a given watershed determines the total number of grid cells used to describe the watershed, setting the computational effort and memory required. Note that if the grid size is halved, the memory required and computational time increase by a factor of 4. In general, smaller grids are less sensitive to subgrid variability for Hortonian runoff (Ogden and Julien 1993). Therefore, smaller grids are generally “better,” if the data exist to assign relevant watershed characteristics to each grid cell. However, smaller grid sizes do not guarantee superior model performance. As with the time-step, the most appropriate grid size can be determined with a convergence study, where the effects of increasing or decreasing the grid size can be observed on model output.

Total Event Simulation Time

This project file card is used to specify the total *GSSHA* event simulation time in minutes. If the volume of water remaining on the surface at the end of the simulation is greater than 5 percent of the rainfall volume, the total simulation time is too short to capture the entire runoff hydrograph, and a warning is printed in the run summary (**SUMMARY** card) file. The **TOT_TIME** card is ignored for continuous simulations. For continuous simulations the end of an event is the time at which the outflow discharge falls below the discharge specified by the **EVENT_MIN_Q** project file card. For simulations with saturated or unsaturated groundwater, the **EVENT_MIN_Q** is used only for accounting purposes.

Coordinate System

GSSHA performs calculations on raster grids and data can be input with *GRASS* ASCII raster data. While any logical, and consistent, coordinate system can be used, the preferred coordinate system for raster based data is the UTM map projection. The UTM system breaks the entire earth into zones six degrees of longitude wide. The zones that cover the continental United States are listed in the following tabulation.

ZONE	WEST LIMIT	EAST LIMIT
10	126° W	120° W
11	120° W	114° W
12	114° W	108° W
13	108° W	102° W
14	102° W	96° W
15	96° W	90° W
16	90° W	84° W
17	84° W	78° W
18	78° W	72° W
19	72° W	66° W

The standard specification of the UTM system includes (Davis et al. 1981):

- The reference ellipsoid is Clarke 1866 in North America.
- The origin of longitude is the central meridian.
- The origin of latitude is the equator.

- The unit of measure is the meter.
- A false easting of 500,000 m is used for the central meridian of each zone.
- The scale factor at the central meridian is 0.9996.
- The zones are numbered beginning with 1 for the zone between 180° W and 174° W meridians and increasing to 60 for the zone between meridians 174° E and 180° E.
- The latitude for the system varies from 80° N to 80° S.
- In the southern hemisphere, a false northing of 10,000,000 m is used.
- The scale error is 1/2500 on the central meridian.

The UTM coordinate system was chosen because of its global applicability and widespread acceptance. Note that watershed data that lie in two zones must be merged into one zone. The data should be merged into the zone that contains the majority of the watershed area. This is accomplished using a GIS.

Map Headers

Many spatially varied inputs for *GSSHA* are input, or can be input, as ASCII *GRASS* GIS raster maps. Raster maps are defined as maps that assign attributes to areas, as opposed to vector maps, which assign attributes to lines or polygons. *GSSHA* requires that all raster grid cells are square.

Each raster map must have a header that conforms to the following example:

```
north: 4156000.0
south: 4135000.0
east:  601800.0
west:  575000.0
rows:  105
cols:  134
```

The entries for north, south, east, and west are the coordinates of the bounding rectangle that contains the entire watershed. The rows and columns entry in the header respectively contain the number of rows and columns in the watershed. Note that for this particular example header, that (north-south)/rows = 200 m, and (east-west)/columns=200 m. Therefore, the grid size of this particular model is 200 m, and the raster cells are square, as required by *GSSHA*. As the coordinate values in the map header are not used to determine geographic position on the globe, any values for

north, south, east, and west may be used in the map headers provided that the grid size is accurate, the grids are square, and your maps are consistent. If the grid size calculated from the bounding rectangle, rows, and columns is not equal to the value specified in the project file using the **GRID_SIZE** project file card, *GSSHA* will not run. The header in each *GRASS* ASCII map must be identical. This requirement forces the user to ensure that all maps are of the same geographic region and grid size.

The header is followed by rows and columns of space delimited data values. These values can be either integer or real, depending on the data type. For example, the mask, channel link, channel node, and index maps are by definition integer maps; maps containing the land surface and bedrock elevations contain real values.

Watershed Mask

The required **WATERSHED_MASK** project file card is used to input the name of the file containing the mask map. The mask map is used to define the watershed boundaries within the rectangular grid and reduces memory requirements by an amount directly proportional to the ratio of mask area over the bounding rectangle area. The watershed mask is a map containing only 0s and 1s, where 0 and 1 represent grid cells that are outside and within the watershed, respectively. For instance, a watershed that is approximately the shape of Texas would have the following a mask map file:

```
north: yyyyyyy.y1
south: yyyyyyy.y2
east:  xxxxxx.x1
west:  xxxxxx.x2
rows:  15
cols:  12
0 0 0 0 1 1 1 0 0 0 0 0
0 0 0 0 1 1 1 0 0 0 0 0
0 0 0 0 1 1 1 0 0 0 0 0
0 0 0 0 1 1 1 0 0 0 0 0
0 0 0 0 1 1 1 1 1 1 0 0
0 0 0 0 1 1 1 1 1 1 1 1
0 0 0 0 1 1 1 1 1 1 1 1
0 0 0 0 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1
0 1 1 1 1 1 1 1 1 1 1 1
0 0 0 1 1 1 1 1 1 1 1 0
0 0 0 0 1 0 1 1 1 1 0 0
0 0 0 0 0 0 1 1 1 0 0 0
0 0 0 0 0 0 1 1 1 0 0 0
0 0 0 0 0 0 0 1 0 0 0 0
```

If the watershed mask contains a 0 in a particular grid cell, *GSSHA* ignores data in all input maps for that particular grid cell. In the preceding map, there are a total of 15x12=180 grid cells. There are 85 grid cells with a 1 in the watershed mask. In this example, *GSSHA* would only allocate memory for 85 of the 180 grid cells for each map, representing a decrease of 53 percent of memory required to store the data for each map. Errors in watershed delineation (hence, mask creation) will propagate through all data sets input to and output from *GSSHA*. The watershed should be delineated with care. *WMS* creates the watershed mask as part of the watershed delineation processes. *GRASS* users can use the **r.watershed** command to create the mask. During each simulation, the *GSSHA* model writes out the watershed mask with the internal number assigned to each grid cell in *GRASS* ASCII format in a file called **maskmap**. This file is useful for deciphering error messages from *GSSHA* that refer to the grid cell number where the problem occurred.

Elevation Map

Elevation data are input for every active grid cell in a *GRASS* ASCII map file specified with the **ELEVATION** project file card. The elevation data are perhaps the most important inputs for *GSSHA* modeling. The quality of the elevation data plays a major role in success of *GSSHA* simulations. Elevations in the grid are derived from digital elevation model data (DEM).

DEMs always contain errors. Large flat areas in the DEM may be due to the limited vertical resolution of elevation data from which the DEM was derived. Extensive flat areas usually cause problems for the 2-D explicit diffusive-wave overland flow routing used in *GSSHA*. Digital dams, pits, and depressions in the DEM may be artifacts of the interpolation scheme used to rasterize digitized contours, or due to coarse resolution in regions of concave topography.

In addition, the grid size used in a *GSSHA* model is normally coarser than the available DEM data. Elevation data in the grid must be somehow interpolated from the DEM data and lumped into larger areas. This process can introduce additional error in the elevation of grid cells. As a rule, the user must crosscheck the elevation values with in-field observations or topographic maps of the area. Digital topographic maps are often available and can be displayed as a background image in *WMS*.

One way to discover potential errors in the elevation data is to perform a simulation with the most basic *GSSHA* model: a single event with uniform rainfall, overland flow, a relatively short time-step, and no other options. Surface depth output maps should be written frequently (see **DEPTH** and **MAP_FREQ** project file cards). If the simulation finishes without an error, the surface depth maps should be examined to determine where most water accumulates and whether such accumulations are justified by the topographic map of the watershed. Alternatively, the model may crash. The location of grid cells where problems occurred will be printed on the screen and also at the bottom of the run summary file.

Manual editing of the elevations in the grid is often necessary to impose the actual drainage trend observed in the topographic map. Digital dams, pits, and depressions must be removed since they trap surface runoff that would otherwise contribute to the outlet discharge. Using grids with raw elevations requires shorter computational time-steps, while properly prepared grids, particularly those with coarser resolution, allow use of longer time-steps. If channel routing is performed, care should also be taken to ensure that overland flow runoff reaches grid cells that contain channel links. If the stream network is delineated independently from the DEM, e.g. from a digital line graph (DLG), then the elevations of the grid cells containing channel nodes should be checked to insure they are not higher than those of the surrounding cells. Otherwise the overland flow will not be correctly passed to the channels.

WMS offers the option of importing and displaying vector stream location files (DLG) to aid in stream channel delineation. *WMS* users can also automatically delineate streams from the DEM using the tools in the *WMS* software. *GRASS* users may use the **r.watershed** command to automatically delineate the streams. As either automatic delineation relies on the DEM to determine stream locations, there may be substantial differences from the DLGs. If an automated method is used to locate the stream locations from the DEM data and the grid resolution used in the GSSHA model is coarser than the available DEM data the stream may not fall in the lowest elevation grid cells. However the stream is located, the elevations of the cells containing the stream may need to be manually adjusted to ensure proper overland-channel interaction.

Optimizations

Senarath et al. (2000) demonstrated that the *CASC2D* model could be effectively parameratized by use of an automated calibration procedure, such as the shuffled complex evolution (SCE) method (Duan et al. 1992). Output that allows optimizations based on event peak discharge and event discharge volume can be produced by using the **OPTIMIZE** card. This card specifies a file that contains the peak discharge and discharge volume for each event in the rainfall file. Peak discharge and volume are written for the outlet and also at any locations in the stream network specified in the **IN_HYD_LOCATION** file. Output is the same as specified in the **UNITS** card. The default is metric. The last line contains the total outlet discharge volume for the entire simulation. The output format is:

Event #	Peak at outlet	Discharge volume at outlet	Peak at first stream gage	Discharge volume at first stream gage	Peak at next stream gage	Discharge volume at next stream gage

5 Surface-Water Routing

GSSHA uses similar two-step explicit finite volume schemes to route water for both 1-D channels and 2-D overland flow, where flows are computed based on heads, and volumes are updated based on the computed flows. Compared with more sophisticated implicit finite difference and finite element schemes, the algorithm used in *GSSHA* is simple. The friction slope between one grid cell and its neighbors is calculated as the difference in water-surface elevations divided by the grid size. Compared with the kinematic wave approach, this diffusive wave approach allows *GSSHA* to route water through pits or depressions, and regions of adverse slope. The Manning formula is used to relate flow depth to discharge. Use of the Manning formula implies that the flow is both turbulent and that the roughness is not dependent on flow depth. Neither of these assumptions may be valid on the overland flow plane. While being simple, the method is powerful because it allows calculations to proceed when only portions of the stream network or watershed are flowing. This is an important attribute as rainfall may occur on only a portion of the watershed.

Several modifications were made to both the *CASC2D* channel routing and overland flow schemes to improve stability and allow interaction between the surface and subsurface components of the model. The combination of improvements in overland and channel routing stabilities has allowed increases in typical model time-steps from 5-30 sec to 1 to 3 min (Downer 2002; Downer et al. 2000). The improved formulations also results in reduced amounts of smoothing required of the DEM and channel thalweg elevations to maintain stability of the surface routing algorithms.

Channel Routing

Explicit channel routing formulation

The 1-D channel routing scheme is depicted in Figure 5. Intercell flows, $Q_{i-1/2}$ and $Q_{i+1/2}$ (m^3s^{-1}) in the longitudinal, x, direction are computed from depths, *d*, at the *n* time level using the Manning equation for the head discharge relationship:

$$Q_{i+1/2}^{n} = \frac{1}{n} A_i^n (R_i^n)^{2/3} (S_{f_{i+1/2}}^{n})^{1/2} \quad (1)$$

where: n is roughness coefficient, A is the area (m^2), R is the hydraulic radius, and S_f is the friction slope, calculated in the x direction as:

$$S^n_{f_{i+/2}} = S_{o_{i+1/2}} - \frac{d^n_{i+1} - d^n_i}{\Delta x} \tag{2}$$

where: S_{ox} is the land surface slope in the x direction. If negative flow occurs (flow in the upstream direction), the head in the downstream cell is used to calculate the flow as:

$$Q^n_{i+1/2} = \frac{1}{n} A^n_{i+1} (R^n_{i+i})^{2/3} (S^n_{f_{i+1/2}})^{1/2} \tag{3}$$

Since the flow direction may change at any point in the stream, especially in ephemeral streams near the beginning of rainfall events, the flow direction is determined around each node and the locally upstream cell properties are used to compute the flow. This simple local determination of the upstream cells prevents crashes in channels with adverse slopes when little or no water is present in the upstream cell. This method also allows better simulations of backwater effects.

Internode fluxes are used to calculate the volume, V, in each node as:

$$V^{n+1}_i = V^n_i + \Delta t (q^{n+1}_{lat} \Delta x + q^{n+1}_{recharge} \Delta x + Q^n_{i-1/2} - Q^n_{i+1/2}) \tag{4}$$

where: q_{lat} ($m^2 s^{-1}$) is the amount of lateral inflow from the overland flow cells adjacent to the node, and $q_{recharge}$ ($m^2 s^{-1}$) is the exchange between the groundwater and channel. These new volumes are used to compute nodal values of A, d, and wetted perimeter at the $n+1$ time level. Calculations proceed from the upstream boundary to the downstream boundary.

Several modifications were made in the implementation of the channel routing scheme to accommodate groundwater/channel interactions. These modifications permit continuous interaction between channel nodes and the saturated groundwater cells. The channel routing scheme was modified to allow water to remain in the channel after channel routing ends, and for water to be present in the channel when channel routing begins. Because groundwater may discharge to the stream at any time, channel routing is initiated any time a minimum amount of water is in the channel network. If the channel routing scheme indicates there is no flow in the

channel, channel routing is halted during periods outside precipitation events. Fluxes between the stream and the groundwater are still computed and adjustments to the stream volumes are made without routing. If groundwater discharges to the stream, channel routing will resume, but at the groundwater time-step, which is typically larger than the channel routing time-step.

Because *GSSHA* uses a finite volume representation of channel flow, the standard stability criterion, Courant number < 1.0, does not strictly apply. Maintaining stability is dependent on volume changes during each time-step. Experience with the scheme indicates that stability can be maintained with a time-step limitation that keeps the maximum Courant number everywhere in the network less than 1/6. Groundwater and overbank fluxes can induce instability and additional controls in the channel routing scheme are added to further reduce instability. If the channel routing scheme becomes unstable (negative depth occurs in one or more cells), despite the more restrictive control on the Courant number, the time-step is reduced and the channel routing calculations are repeated. The channel routing time-step may be automatically reduced to a value as low as 1/1000 of a second. Allowing the time-step to become small during periods of sharp transition allows a larger overall model time-step to be used. For each call of the channel routing function the overall model time-step is used as the beginning channel routing time-step. The time-step is only reduced when the stability controls are activated, and then only for that call of the channel routing routine.

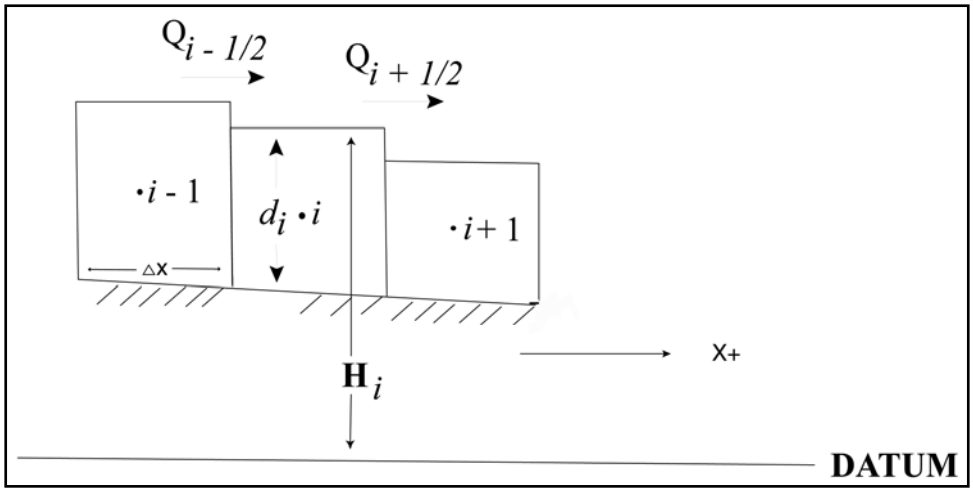


Figure 5. Explicit channel routing scheme.

Boundary conditions

The upstream boundary condition in each first order link is a no-flow condition. The default watershed outlet condition is normal flow, calculated using the channel slope at the watershed outlet. The downstream boundary condition can also be a specified head. The outlet boundary type is changed to a head by using the **HEAD_BOUND** project card. The boundary depth, m, is specified with the **BOUND_DEPTH** project card. When the head boundary is specified the depth at the outlet remains at the specified depth for the entire simulation period. Flows entering the outlet cell exit at the same rate. The head boundary condition is desirable when the condition at the outlet of the basin is a known head instead of normal depth. This might occur when the basin empties into a larger water body such as a river, pond, or lake, or when a hydraulic structure is near the watershed outlet. The up-gradient method of computing internode discharges allows the head boundary condition influence to propagate upstream.

Initial conditions

The default for the explicit scheme is to start simulations from the dry bed condition. A new feature for the explicit channel routing scheme is the ability to save water-surface profiles and flows from one simulation and use them as the initial condition of another simulation. To save the last set of values of depths and flows from the channel routing code the **EXPLIC_BACKWATER** project card is used. The **WAT_SURF_PROFILE** and **DIS_PROFILE** project cards are used to provide the file names for output of the surface-water profile, m or ft, and the discharge profile, $m^3\ s^{-1}$ or $ft^3\ s^{-1}$, respectively, for every node in the stream network. To begin a simulation from the saved values, the **EXPLIC_HOTSTART** project card is used along with the **WAT_SURF_PROFILE** and **DIS_PROFILE** project cards. Both options can be used in the same simulation. In this case the **WAT_SURF_PROFILE** and **DIS_PROFILE files** are overwritten at the end of the simulation.

Describing stream network

The stream network in *GSSHA* is described with a series of links and nodes. A node is a single computational element in the stream network. A

link is a channel segment comprised of two or more computational nodes. Three files are required to describe the channel network in *GSSHA*:

- Links map (**LINKS**) - GRASS ASCII map locating the channel links on the overland flow plane
- Nodes map (**NODES**) – GRASS ASCII map locating the channel nodes on the overland flow plane
- Channel input file (**CHAN_INPUT**) – ASCII text file describing link connectivity and assigning attributes to every channel node.

The links and nodes maps describe the topology of the stream network and contain the information needed to provide channel connectivity with the overland flow plane and the saturated groundwater grid. The **CHAN_INPUT** file contains the information necessary to connect the stream network and assign attributes to each of the stream nodes. *WMS* can create the links and nodes maps and **CHAN_INPUT** file in the required format. Output from the *GRASS* command **r.watershed** cannot be directly used in conjunction with *GSSHA*. The link numbers assigned by **r.watershed** must be renumbered. The nodes map may be constructed by renumbering the link map. The rules that govern the creation of the link map, nodes map, and **CHAN_INPUT** file are listed as follows:

1. General Rules.
   a. Streams may run in the x-y directions only, not diagonally.
   b. Looped reaches cannot be simulated.
   c. Link types may not be mixed within a link.
   d. Internal boundary condition link types (e.g., weirs) do not appear in the link or nodes maps.
   e. The **CHAN_INPUT** file contains the internal boundary links.
   f. Internal boundary condition links contain two nodes, one upstream, and one downstream, of the internal boundary condition.
   g. The link types currently supported by *GSSHA* are shown in Table 3.
2. Required Numbering Scheme.
   a. First order stream links are numbered first.
   b. The first link must be numbered 1.
   c. Link numbers must always increase in the downstream direction. Upstream links must have smaller numbers than downstream links.
   d. Link numbers must change at junctions.
   e. Link numbers may not be skipped.
   f. Node numbers increase in the downstream direction.

g. The most upstream node in a link is node 1.

Upstream and downstream links overlap one node. The first node in the downstream link is the same as the last node in the upstream link. In the **CHAN_INPUT** file this node must be explicitly contained in both the upstream and downstream links, such that the upstream link in the **CHAN_INPUT** will contain one more node than the nodes map. An exception to this rule is the most downstream link containing the outlet.

Table 3. Different Link Types Supported in GSSHA.

Link Type	Description	# Parameters per cross section	# Nodes
1	Fluvial link, trapezoidal cross section	5	>= 2
30	Fluvial link, trapezoidal cross section, sediment transport	6	>= 2
12	Fluvial link, trapezoidal cross section, subsurface parameters	7	>= 2
31	Fluvial link, trapezoidal cross section, sediment transport, subsurface parameters	8	>=2
9	Fluvial link, dual side slopes trapezoidal cross section	6	>= 2
14	Fluvial link, dual side slopes trapezoidal cross section, subsurface parameters	8	>=2
8	Look-up table (breakpoint) cross sections	2	>= 2
13	Look-up table (breakpoint) cross sections, subsurface parameters	4	>= 2
11	Overflow weir	8	2

Links map.

The links map can best be illustrated by example. In this example, a channel input data file is constructed for a fictitious watershed. The channel has the links described in Table 4. Typically, cross sections are measured in the main stem and larger tributaries. Smaller tributaries, which may be ephemeral, are input as trapezoidal channels.

With reference to the **LINKS** map shown in Figure 6, assume that links 1 and 2 drain into link 3, which drains into link 4, and then link 5. Links 7 and 8 drain into link 9. Link 5 changes into link 6 because of a change in some cross section property. Links 6 and 9 flow into link 10, which is immediately upstream from a weir that is link 11. Finally, link 12, the most downstream link, lies below the weir, link 11. The **LINKS** map contains a continuous sequence of link numbers, except for internal boundary

conditions, such as link 11, which are assumed so small that they do not collect lateral inflow from the overland flow plane. For this reason weirs do not appear in the links map.

```
north: 192346.52
south: 190146.52
east:   39471.00
west:   37471.00
rows:  22
cols:  20
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
0  0  0  1  0  0  0  0  0  0  0  0  0  0  2  0  0  0  0  0
0  0  0  1  0  0  0  0  0  0  0  0  0  2  2  0  0  0  0  0
0  0  0  1  1  0  0  0  0  0  0  0  2  2  0  0  0  0  0  0
0  0  0  0  1  1  1  0  0  0  0  0  2  0  0  0  0  0  0  0
0  0  0  0  0  0  1  1  1  0  0  0  2  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  1  0  2  2  2  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  1  1  3  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  3  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  3  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  4  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  4  0  0  0  0  0  0  0  0  0
0  0  7  7  7  0  0  0  0  0  4  0  0  0  0  0  0  0  0  0
0  0  0  0  7  7  0  0  0  0  5  0  0  0  0  0  0  0  0  0
0  0  0  0  0  7  7  0  0  0  5  5  0  0  0  0  0  0  0  0
0  8  8  8  0  0  7  0  0  0  0  5  6  0  0  0  0  0  0  0
0  0  0  8  8  8  9  9  0  0  0  0  6  6  0  0  0  0  0  0
0  0  0  0  0  0  0  9  9  9  0  0  0  6  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  9  9  9  9 10 10 10  0  0  0  0
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 12  0  0  0  0
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 12 12 12 12  0
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 12  0
```

Figure 6. Example links map.

Nodes map.

With the exception of the internal boundary conditions, nodes in each link are numbered from 1 to the number of grid cells spanned by that link. Internal boundary conditions have two nodes not present in the **NODES** map. With the exception of the link leading to the watershed outlet, all links must have an extra node to provide connectivity to the downstream link. Even though the **NODES** map, Figure 7, may show link 1 to have 13 nodes, it actually has 14. This implied extra node for link 1, shared between the most downstream node of link 1 and the most upstream node of link 3, provides the connection between link 1 and link 3. The number of nodes in each link in this example is shown in the following tabulation.

```
north: 192346.52
south: 190146.52
east:   39471.00
west:   37471.00
rows:  22
cols:  20
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
0  0  0  1  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0
0  0  0  2  0  0  0  0  0  0  0  0  0  3  2  0  0  0  0  0
0  0  0  3  4  0  0  0  0  0  0  0  5  4  0  0  0  0  0  0
0  0  0  0  5  6  7  0  0  0  0  0  6  0  0  0  0  0  0  0
0  0  0  0  0  0  8  9 10  0  0  0  7  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0 11  0 10  9  8  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0 12 13  1  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  2  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  3  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  0  2  0  0  0  0  0  0  0  0  0
0  0  1  2  3  0  0  0  0  0  3  0  0  0  0  0  0  0  0  0
0  0  0  0  4  5  0  0  0  0  1  0  0  0  0  0  0  0  0  0
0  0  0  0  0  6  7  0  0  0  2  3  0  0  0  0  0  0  0  0
0  1  2  3  0  0  8  0  0  0  0  4  1  0  0  0  0  0  0  0
0  0  0  4  5  6  1  2  0  0  0  0  2  3  0  0  0  0  0  0
0  0  0  0  0  0  0  3  4  5  0  0  0  4  0  0  0  0  0  0
0  0  0  0  0  0  0  0  0  6  7  8  9  1  2  3  0  0  0  0
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  2  3  4  5  0
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  6  0
```

Figure 7. Example nodes map.

Table 4. Number of Nodes in Each Link for Example Watershed Stream Network.

Link Number	Link Type	Number of in nodes map	Number of nodes in channel input file
1	1 fluvial-trapezoidal	13	14
2	1 fluvial-trapezoidal	10	11
3	1 fluvial-trapezoidal	3	4
4	8 fluvial-breakpoint	3	4
5	8 fluvial-breakpoint	4	5
6	8 fluvial-breakpoint	4	5
7	1 fluvial-trapezoidal	8	9
8	1 fluvial-trapezoidal	6	7
9	9 fluvial, dual trapezoidal	9	10
10	8 fluvial-breakpoint	3	4
11 (weir)	2 overflow weir	0	2
12 (outlet)	8 fluvial-breakpoint	6	6

Channel input file.

The channel input file consists of the three following parts:

1. Channel routing constants
2. Channel network connectivity
3. Individual node information

These three sections are assembled in the listed order to produce the channel input file.

Channel routing constants. The first portion of the channel input file is used to pass physical constants and simulation parameters to the model including the length of each node, Δx (m), and the computational time-step, Δt (s). At present, the time-step, Δt, and node length, Δx, must be identical to the computational time-step and raster grid size used in the overland flow routing portion of *GSSHA*. The program must be told the number of links, and the number of nodes in the longest link in the network for dynamic memory allocation. In our example problem, the number of links is 12, and the maximum number of nodes is 14 (in link 1). Recall that all links except the outlet link must have an extra node for connectivity purposes. The total number of links is called "nlinks", and the largest number of nodes in any link in the network is called "maxnodes." In this example, the constants and parameters given in Table 5 are used.

Table 5. Channel File Input Constants.

Parameter	Value	Units	Description
Δx	100.0	m	Fluvial node length. Required to be the same as the overland plane raster grid size (**GRIDSIZE** in project file).
Δt	30.0	s	Channel routing time-step. Required to be the same as the overland flow computational time-step (TIME_STEP in project file).
nlinks	12	none	Number of links in the channel network.
maxnodes	14	none	Number of nodes in the longest link in the network.

This data constitutes the first portion of channel input file and is arranged into a header which must have the form (note floating point and integers):

```
100.0
30.0
12
14
```

Channel network connectivity. The second portion of the input file describes link types as well as the network topology. This is accomplished using a line-input format, one line for each link in the network. Each line

contains six integer values arranged in columns, as shown in Table 6. The links should appear in ascending numerical order.

Table 6. Connectivity Information Format.

Column	Data Description
1	Link number
2	Link type
3	Number of links upstream from this link (min. 0, max 2)
4	Upstream link #1 (0 if no upstream links present)
5	Upstream link #2 (0 if no or only one upstream link)
6	Downstream link number (0 for outlet link)

Assuming the link types are as given in Table 4, the second portion of input file for describing link types and connectivity appears as follows:

```
 1  1  0   0  0   3
 2  1  0   0  0   3
 3  1  2   1  2   4
 4  8  1   3  0   5
 5  8  1   4  0   6
 6  8  1   5  0  10
 7  1  0   0  0   9
 8  1  0   0  0   9
 9  9  2   7  8  10
10  8  2   6  9  11
11  2  1  10  0  12
12  8  1  11  0   0
```

Note that only the outlet link has 0 downstream dependencies. Recall that the weir (link 11) does not appear in the link map, so the location and topology of this internal boundary condition with respect to other links is described via the preceding connectivity information. Examine link number 10. It is of link type 8 (fluvial-breakpoint), has two upstream dependencies (links 6 and 9), and flows into link 11.

Individual nodes information. The third portion of the input file contains the individual hydraulic property information for each node in the stream network. There is a block of data for each link. Link blocks must appear in the correct sequential order, starting with 1 and progressing to the highest link number. Each link block consists of a line containing the link and node number followed by a line of information for each node.

Channel cross sections may be either trapezoidal, dual slope trapezoidal, or natural channels represented by breakpoint cross sections. Different cross-section types may be mixed in the channel network. Typically, small streams in the upland areas are modeled with trapezoidal cross sections; larger streams in the lower reaches of the catchment are modeled with breakpoint cross sections. Data for the development of breakpoint cross sections can be derived from field surveys of cross section, detailed topographic maps, or high resolution digital elevation models. Coarse resolution DEMs should not be relied upon to develop channel cross-section geometry.

The hydrodynamic channel routing in *GSSHA* is sensitive to channel cross sections, more so than the longitudinal slope. More time should be spent developing accurate cross sectional descriptions than to getting a highly accurate longitudinal profile. Smooth transitions in channel cross sectional properties between all connecting fluvial links often play a vital role in the success of simulations. Abrupt changes in cross sections can lead to numerical mass conservation errors. It may be necessary to create transition links between measured breakpoint and trapezoidal cross sections when adjoining links vary greatly in cross section. It may also be necessary to assign different channel cross sections within a link. Sometimes it is necessary to provide a different cross section for every node in a link or along the entire channel. The Manning's roughness parameter used in the model is largely a calibration parameter. Physically realistic literature values may be used as initial guesses and as bound on the calibration (e.g., Chow 1959; Barnes 1967).

a. Trapezoidal cross section (link type 1). Trapezoidal cross sections are symmetrical, assumed to be infinitely deep, and have a constant side slope. Trapezoidal cross sections are defined by the following:
   (1) Manning's N - Manning's roughness coefficient, n (dimensionless)
   (2) Bottom width (m)
   (3) Channel depth (m)
   (4) Side slope, *z* (change in *X* with a change in *Y* of 1).

This information is entered for each node and each node can have different values for any or all of the parameters. Changes in the cross section between nodes in a single link, such as a constriction in the channel, can be described by editing the appropriate node data for bottom width and side slope (or even the roughness coefficient if necessary).

Assume that link 1 (which has 14 nodes as per Table 4) is well described as a trapezoidal channel with Manning's n of 0.019, a bottom width of 3.5 m, and a side slope of 5.0 m. In this example, the cross section does not change within the link. The link block for link 1 will appear as (with example thalweg elevations):

```
1 14
0.019 3.50 0.00 5.0 643.38
0.019 3.50 0.00 5.0 643.04
0.019 3.50 0.00 5.0 642.82
0.019 3.50 0.00 5.0 642.45
0.019 3.50 0.00 5.0 642.21
0.019 3.50 0.00 5.0 641.92
0.019 3.50 0.00 5.0 641.57
0.019 3.50 0.00 5.0 641.41
0.019 3.50 0.00 5.0 641.17
0.019 3.50 0.00 5.0 640.94
0.019 3.50 0.00 5.0 640.71
0.019 3.50 0.00 5.0 640.48
0.019 3.50 0.00 5.0 640.22
0.019 3.50 0.00 5.0 639.99
```

There are data for 14 nodes in link 1, with 14 lines of cross sectional data in the block after the one line header.

Similarly, if we assume that link 2 is well described as a trapezoidal channel with Manning's n of 0.023, a bottom width of 2.75 m, and a side slope of 4, the link block will look like (with example thalweg elevations):

```
2 11
0.023 2.75 0.00 4.0 645.77
0.023 2.75 0.00 4.0 645.10
0.023 2.75 0.00 4.0 644.49
0.023 2.75 0.00 4.0 643.87
0.023 2.75 0.00 4.0 643.41
0.023 2.75 0.00 4.0 642.89
0.023 2.75 0.00 4.0 642.21
0.023 2.75 0.00 4.0 641.49
0.023 2.75 0.00 4.0 640.54
0.023 2.75 0.00 4.0 640.33
0.023 2.75 0.00 4.0 639.99
```

There are 11 lines of node data in this link block. Notice that the elevations of the last two nodes in link blocks 1 and 2 are the same because node 14 in link 1 and node 1 in link 2 are at the same location.

Link 3 is also a trapezoidal cross section, and would be expected to be larger because links 1 and 2 flow into it. Assume that link 3 has a roughness coefficient of 0.018, a bottom width of 4.10 m, and a side slope of 5.5.

According to Table 4, there are four nodes in this link. The link block would appear as (with example thalweg elevations):

```
3 4
0.018 4.10 0.00 5.5 639.99
0.018 4.10 0.00 5.5 639.82
0.018 4.10 0.00 5.5 639.18
0.018 4.10 0.00 5.5 638.73
```

It is required that the bed elevation of all channel inverts at each junction be equal so the elevation of the downstream end of links 1 and 2 must be equal to the bed elevation of the upstream end of link 3 (Figure 8).

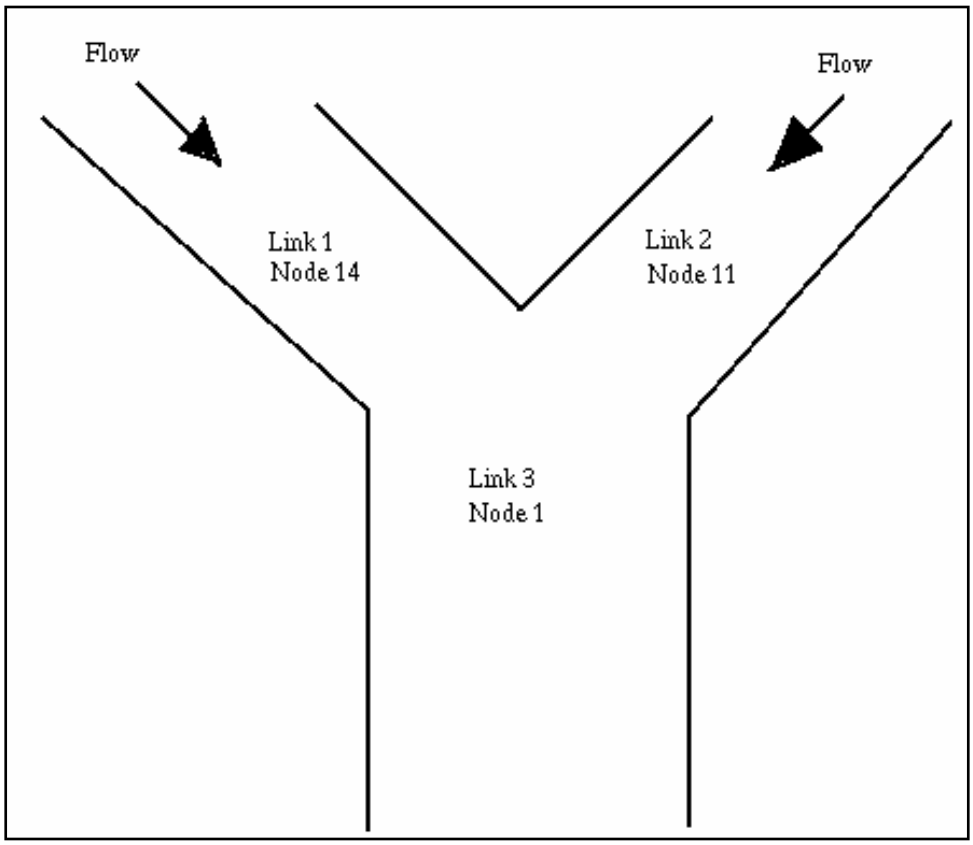


Figure 8. Example of channel junction.

b. Dual side-slope trapezoidal cross section (link type 9). Dual side slope trapezoidal channels are also symmetrical, assumed to be infinitely deep, with the second slope extending to infinity. This is a particularly useful form of cross sectional representation, allowing the simulation of both in-bank and out-of-bank flows. A dual side-slope trapezoidal cross section link block contains the standard header (link number, number of links), followed by node data consisting of:

(1) Manning's n (dimensionless)
(2) Bottom width (m)
(3) Channel depth (m)
(4) First (in-bank) side slope (dimensionless)
(5) Second (out of bank) side slope (dimensionless)
(6) Thalweg elevation (m)

As listed in Table 4, link 9 in our example is a dual side slope cross section with 10 nodes. Assuming that this channel has a roughness coefficient *n* of 0.016, bottom width of 5.1 m, a bank-full depth of 2.7 m, an in-bank side slope of 3.0, and an overbank side slope of 8.0, the link block appears as:

```
9 10
0.016 5.1 2.70 3.0 8.0 647.51
0.016 5.1 2.70 3.0 8.0 646.07
0.016 5.1 2.70 3.0 8.0 644.87
0.016 5.1 2.70 3.0 8.0 642.64
0.016 5.1 2.70 3.0 8.0 640.71
0.016 5.1 2.70 3.0 8.0 638.69
0.016 5.1 2.70 3.0 8.0 636.50
0.016 5.1 2.70 3.0 8.0 635.19
0.016 5.1 2.70 3.0 8.0 634.20
0.016 5.1 2.70 3.0 8.0 633.11
```

c. Breakpoint cross section (link type 8). Breakpoint cross sections are described with a table containing parameters computed at various channel depths for each surveyed cross section. In breakpoint section link blocks, only the number of the table associated with each node, and the thalweg elevation of the node, appear. If every node in link 4, our first breakpoint link, could be adequately described by the cross section information in Table 1, then the link block would look like:

```
4 4
1 638.73
1 638.34
1 637.89
1 637.29
```

Similarly, links 5 and 6, which are also defined as breakpoint links in Table 4, have link blocks that appear as:

```
5 5
1 637.29
2 636.81
2 636.22
2 635.73
2 635.20
```

```
6 5
2 635.20
2 634.75
3 634.08
3 633.64
3 633.11
```

The table numbers can vary for each node in the link. As with all links, the thalweg elevation at the downstream node of each link is the same as that at the upstream node of the downstream link. When there are only two channels at a junction, the cross sections in each should be the same otherwise the channel routing code will likely oscillate, resulting in mass conservation errors.

d. Weir links (link type 2). The present version of *GSSHA* channel routing includes support for weirs. Future plans call for support of bridge crossings, culverts, reservoirs, and lakes. Internal boundary conditions, such as weirs, are defined at nodes and are given a unique link number. Weirs cannot be used as the outlet boundary condition for the channel network. For watersheds with a weir at the outlet, place a short fluvial link downstream from the weir. The input values required for a weir are:
   (1) Free flowing discharge coefficient (dimensionless) - typical 0.9
   (2) Flooded coefficient (dimensionless) - typical 0.8
   (3) Crest width (m)
   (4) Crest elevation (m)

The crest elevation of the weir must be greater than the elevation of the upstream node.

In the example, link 11 is an overflow weir link. While this link has no nodes appearing in the node map for overland flow connectivity, it does have two nodes in the channel input file. The meaning of the columns in the weir node input section is presented in Table 7.

Table 7. Parameter Description for Weirs.

Node Entry	Column	Description
1	1	Forward flow direction discharge coefficient
1	2	Reverse flow direction discharge coefficient
1	3	0.0 (reserved for future use)
1	4	Crest length (m)
1	5	Elevation of weir crest (m)
2	1-4	0.0 (reserved for future use)
2	5	Thalweg elevation just downstream from weir (m)

The first (upstream) node represents the crest of the rectangular weir. The second (downstream) node represents the bed of the channel just downstream from the weir. Assume that this weir has a crest elevation of 233.47 m, a crest width of 8.3 m, a discharge coefficient in the forward direction of 0.92, a discharge coefficient for flow in the reverse direction equal to 0.85, and the channel bed elevation immediately downstream from the weir is 228.71 m. The link block entry in the channel input file for this weir appears as:

```
11 2
0.92 0.85 0.00 8.3 233.47
0.00 0.00 0.00 0.0 228.71
```

Assembling channel input file. In this section, the three portions of the channel input file are put together to form an example channel network.

```
----------------------Begin channel input -----------------------
100.0
30.0
12
14
 1 1 0  0 0  3
 2 1 0  0 0  3
 3 1 2  1 2  4
 4 8 1  3 0  5
 5 8 1  4 0  6
 6 8 1  5 0 10
 7 1 0  0 0  9
 8 1 0  0 0  9
 9 9 2  7 8 10
10 1 2  6 9 11
11 2 1 10 0 12
12 8 1 11 0  0
1 14
0.019 3.50 0.00 5.0 643.38
0.019 3.50 0.00 5.0 643.04
```

```
0.019 3.50 0.00 5.0 642.82
0.019 3.50 0.00 5.0 642.45
0.019 3.50 0.00 5.0 642.21
0.019 3.50 0.00 5.0 641.92
0.019 3.50 0.00 5.0 641.57
0.019 3.50 0.00 5.0 641.41
0.019 3.50 0.00 5.0 641.17
0.019 3.50 0.00 5.0 640.94
0.019 3.50 0.00 5.0 640.71
0.019 3.50 0.00 5.0 640.48
0.019 3.50 0.00 5.0 640.22
0.019 3.50 0.00 5.0 639.99
2 11
0.023 2.75 0.00 4.0 645.77
0.023 2.75 0.00 4.0 645.10
0.023 2.75 0.00 4.0 644.49
0.023 2.75 0.00 4.0 643.87
0.023 2.75 0.00 4.0 643.41
0.023 2.75 0.00 4.0 642.89
0.023 2.75 0.00 4.0 642.21
0.023 2.75 0.00 4.0 641.49
0.023 2.75 0.00 4.0 640.54
0.023 2.75 0.00 4.0 640.33
0.023 2.75 0.00 4.0 639.99
3 4
0.018 4.10 0.00 5.5 639.99
0.018 4.10 0.00 5.5 639.82
0.018 4.10 0.00 5.5 639.18
0.018 4.10 0.00 5.5 638.73
4 4
1 638.73
1 638.34
1 637.89
1 637.29
5 5
1 637.29
2 636.81
2 636.22
2 635.73
2 635.20
6 5
2 635.20
2 634.75
3 634.08
3 633.64
3 633.11
7 9
0.019 3.50 0.00 5.0 651.55
0.019 3.50 0.00 5.0 651.02
0.019 3.50 0.00 5.0 650.61
0.019 3.50 0.00 5.0 650.09
0.019 3.50 0.00 5.0 649.73
0.019 3.50 0.00 5.0 649.17
0.019 3.50 0.00 5.0 648.66
0.019 3.50 0.00 5.0 648.01
0.019 3.50 0.00 5.0 647.51
8 6
0.023 2.75 0.00 4.0 651.73
0.023 2.75 0.00 4.0 650.91
0.023 2.75 0.00 4.0 650.46
0.023 2.75 0.00 4.0 649.94
```

```
0.023 2.75 0.00 4.0 648.86
0.023 2.75 0.00 4.0 647.91
0.023 2.75 0.00 4.0 647.51
9 10
0.016 5.1 2.70 3.0 8.0 647.51
0.016 5.1 2.70 3.0 8.0 646.07
0.016 5.1 2.70 3.0 8.0 644.87
0.016 5.1 2.70 3.0 8.0 642.64
0.016 5.1 2.70 3.0 8.0 640.71
0.016 5.1 2.70 3.0 8.0 638.69
0.016 5.1 2.70 3.0 8.0 636.50
0.016 5.1 2.70 3.0 8.0 635.19
0.016 5.1 2.70 3.0 8.0 634.20
0.016 5.1 2.70 3.0 8.0 633.11
10 4
4 633.11
4 632.02
4 630.58
4 629.80
11 2
0.92 0.85 0.00 8.3 233.47
0.00 0.00 0.00 0.0 228.71
12 6
4 228.71
4 228.47
4 227.83
4 227.15
5 226.54
5 226.44
---------- End channel input file ----------
```

Breakpoint cross section look-up table. If link type 8 (breakpoint look-up table x-sections) are present in the channel input file, a separate file that contains the look-up table values must be specified with the **SECTION_TABLE** project file card. The first line of this file must contain two integers: the number of look-up tables contained in the file, and the number of rows in the longest look-up table in the file. In our example, there are five tables. Assume that the longest table contains six equally spaced heights. The first line of the **SECTION_TABLE** will be:

```
5 6
```

This line is followed by five repeating look-up table data sets. Each of these has the table number as the first line. The second line contains an integer, a real number, and an optional string which must be enclosed in double quotes “like this.” The integer equals the number of equally spaced heights contained in the table; the real number is the depth spacing (m) between look-up table values, and the string is for a description of the table. For Table 1, if there are five depths, each spaced by 0.7 m, the first two lines appear as:

```
1
5 0.70 "Table #1 - reach between Eagleville and Timnath"
```

The depth spacing must be constant within each table, but can vary between tables. Each table entry must contain "num_heights" lines, each with four entries. To impose zero cross-sectional area, topwidth and conveyance at zero depth, the first line must be:

```
0.0 0.0 0.0 0.0
```

The subsequent lines must have four columns, containing the following values at each depth interval:

a. Depth, D (m)
b. Cross sectional area, A (m^2)
c. Top width, TW (m)
d. Channel conveyance, $K = AR^{2/3}/n$, ($m^{8/3}$)

For a channel network with five surveyed cross sections the file specified by the **SECTION_TABLE** card may look like:

```
5 5
1
5 0.70 "Table #1 - reach between Eagleville and Timnath"
0.00 0.00 0.00 0.00
0.70 3.05 6.37 22.12
1.40 8.02 9.27 137.94
2.10 17.36 18.26 324.88
2.80 35.62 42.66 626.82
2
4 0.50 "Table #2 - reach between Coralville and Dallas"
0.00 0.00 0.00 0.00
0.50 2.27 3.89 11.13
1.00 6.45 8.19 91.29
1.50 13.71 14.66 223.98
3
4 0.80 "Table #3 - reach between Wiley and White Fish"
0.00 0.00 0.00 0.00
0.80 5.19 9.87 22.37
1.60 16.40 17.56 121.14
2.40 26.88 34.44 519.77
4
3 0.40 "Table #4 - reach between White Fish and Rome"
0.00 0.00 0.00 0.00
0.40 1.98 2.25 8.55
0.80 3.11 7.65 88.77
5
5 1.00 "Table #5 - any text can be put here"
0.00 0.00 0.00 0.00
1.00 5.98 10.43 101.01
2.00 10.12 56.33 748.92
```

```
3.00 56.43 132.88 1356.78
4.00 188.87 409.61 3945.76
```

For further clarification, consider look-up Table 4, corresponding to cross-sectional properties of the four most upstream nodes of link 12. Look-up Table 4 has three entries, each separated by 0.4 m of depth. At a depth of 0.80 m, the channel has a top width of 3.11 m, a cross sectional area of 7.65 m^2, and a conveyance of 88.77 $m^3\ s^{-1}$. The conveyance is used to calculate the discharge using:

$$Q = KS_0^{1/2} \tag{5}$$

where S_0 is the bed slope. A spreadsheet or other data analysis programs can be used to produce look-up tables. *WMS* contains a cross section calculator for the sole purpose of calculating cross section look-up tables from surveyed *x-y* cross-section data. For breakpoint cross sections, if the flow depth exceeds the range of the cross section data, the cross sections are extrapolated. If extrapolation occurs at any time during a simulation, a warning is printed in the *GSSHA* run summary file.

Longitudinal channel profile smoothing

When available, channel cross sectional geometry and longitudinal profile data collected from extensive field surveys can be input into *GSSHA*. In lieu of detailed streambed profiles, the DEM may be used as an indicator of channel slope, assuming that over large reaches, the slope of the channel thalweg is on the order of the same slope as the land surface. This assumption is not true in the case of extremely sinuous channels. Channel slopes extracted from the grid elevations are skewed by errors in the DEM and from errors in interpolating from the DEM to the resolution of the grid. These errors may result in regions of adverse channel slope, undulating streambed elevations, or sharp transitions in channel slope. These conditions will require a reduction in computational time-step for the explicit diffusive wave routing method. It may be impossible to simulate channel flow with in a channel with many uncorrected DEM derived errors.

Extensive regions of adverse slope are rare in natural channels. It is recommended that regions of adverse slopes be removed from the *GSSHA* channel network, unless field observations or obvious geologic controls indicate that they are justified. Smoothing of the channel thalweg profile

should be done to remove stream sections of adverse slope, undulating streambed elevations, zero slope, and sharp slope transitions.

Ogden et al. (1994) developed a method of smoothing stream channel profiles based on the realization that in regions of concave topography near streams, DEMs are likely to be positively biased. For such conditions filling depressions along stream paths is probably erroneous. A more accurate approach is to remove higher regions to connect depressions. *WMS* provides tools to smooth the channel thalweg profile both manually and with an automated version of the Ogden et al. (1994) algorithm.

Changes to the stream thalweg elevation alone will not result in proper simulations of channel-groundwater exchange or channel-overbank exchange. To properly simulate these processes, the correct elevations, or at least the correct difference in elevation, of the channel thalweg and overbank area are needed.

Losing and gaining streams

The calculation of stream losses from streams in arid regions with coarse textured substrate can be specified by including the **STREAM_LOSS** card in the project file. When simulating either a static or moving water table, streams may be either losing or gaining streams, and the **STREAM_LOSS** card need not be included in the project file. In either case, the hydraulic conductivity (K_{rb}) (cm hr^{-1}) and thickness (M_{rb}) (cm) of the substrate must be specified. Uniform values can be specified in the project file with the **K_RIVER** and **M_RIVER** cards. Including these values in the project file results in every node in every stream link, regardless of specified type, having these uniform values of streambed parameters. Alternately, the values can be specified in the **CHAN_INPUT** file for every node in a losing/gaining stream channel section. The links must be specified as one of four types of losing/gaining link types:

a. 12 – trapezoidal section with stream loss/gain
b. 13 – breakpoint section with stream loss/gain
c. 14 – dual side slope trapeziodal with stream loss/gain
d. 31 – erodable trapezoidal section with stream loss/gain

For each link type the values of K_{rb} and M_{rb} must be appended to the end of the line for each node in each link block. For example, with a trapezoidal section (link type 12) the following inputs are required:

a. Manning's n - Manning's roughness coefficient, n (dimensionless)
b. Bottom width (m)
c. Channel depth (m)
d. Side slope (change in *X* with a change in *Y* of 1)
e. Thalweg elevation (m)
f. K_{rb} (cm hr^{-1})
g. M_{rb} (cm)

If the **STREAM_LOSS** card is included but without **K_RIVER** and **M_RIVER** cards and without any link types 12, 13, 14 or 31 in the **CHAN_INPUT** file, then no stream losses will be computed. If link types 12, 13, 14 or 31 are used for some, but not all, of the links in the **CHAN_INPUT** file then the other links in the stream network will be assigned the uniform values **K_RIVER** and **M_RIVER.** If **M_RIVER** or **K_RIVER** are not specified then there will be no stream losses computed from these stream links. The default values for **M_RIVER** and **K_RIVER** are 1.0 and 0.0, respectively.

Calculation of the flux term is discussed in Chapter 8. The explicit channel routing code was modified to allow water to remain in the channel after channel routing ends, and for there to be a starting volume of water in each cell at the beginning of channel routing. When simulating groundwater, channel routing continues after a storm event ends until no water is moving in the channel or only a very small amount of water is left in the stream channels. If the stream discharges to the groundwater after channel routing has ceased, the volume of the stream is updated each groundwater update call. No channel routing is performed under these conditions. However, if the groundwater is discharging to the stream, channel routing will resume, but at the groundwater time-step.

Sediment transport in channels

Sediment transport in the channel network can be performed as described in Chapter 10. Sediment transport in the channel network requires that link type 30, erodable channels, or link type 31, erodable channels with subsurface parameters, be used for every node in the channel network. Erodable channels have the same inputs as the trapezoidal channel, link type 1 in Chapter 5, with an additional value for the maximum allowable bed erosion (m). Each node should have a line in the link block for each link in the **CHAN_INPUT** file with the following values, in the following order:

a. Manning's n - Manning's roughness coefficient, n (dimensionless)
b. Bottom width (m)
c. Channel depth (m)
d. Side slope (change in *X* with a change in *Y* of 1).
e. Thalweg elevation (m)
f. Maximum erosion (m)

For erodable trapezoidal channels with subsurface parameters, link type 31, values of K_{rb} and M_{rb} are appended to each line in the link block.

Overland Flow Routing

Overland flow routing formulation

Overland flow in *GSSHA* employs the same methods described for 1-D channel routing, except the calculations are made in two dimensions. Flow is routed in two orthogonal directions in each grid cell during each time-step. The watershed boundary represents a no flow boundary for the overland flow routing and when a grid cell lies on the watershed boundary, flow is not routed across the boundary. In *GSSHA*, $\Delta x = \Delta y$. Intercell fluxes in the x and y directions, *p* and *q*, respectively, are computed in cell *ij* from the depth, d_{ij}, at the n^{th} time level using the Manning equation for the head discharge relationship in the x and y directions, respectively, as

$$p_{ij}^{n} = \frac{1}{n}(d_{ij}^{n})^{5/3}(S_{f_x}^{n})^{1/2} \tag{6}$$

$$q_{ij}^{n} = \frac{1}{n}(d_{ij}^{n})^{5/3}(S_{f_y}^{n})^{1/2} \tag{7}$$

Depths in each cell are calculated at the *n+1* time level based on the flows for each cell (Julien and Saghafian 1991):

$$d_{ij}^{n+1} = d_{ij}^{n} + \frac{\Delta t}{\Delta x}(p_{i-1,j}^{n} + q_{i,j-1}^{n} - p_{ij}^{n} - q_{ij}^{n}) \tag{8}$$

In addition to this original formulation in the *CASC2D* model, two additional methods of solving the equations have been added, an alternating direction explicit scheme (*ADE*) and an *ADE* scheme with an additional predictor-corrector step (*ADEPC*) (Downer 2002; Downer et al. 2000). Both the *ADE* and *ADEPC* methods employ the up-gradient difference

technique, Equation 3, for flows in the upstream direction (Downer 2002). Fluxes other than intercell fluxes, direct evaporation (DET), infiltration, exfiltration, are accounted for before overland routing is computed.

In the *ADE* method, intercell flows are first calculated in the x direction according to Equation 6. Depths in each row are updated based on the flows in the x direction:

$$d_{ij}^{n+1/2} = d_{ij}^{n} + \frac{\Delta t}{\Delta x}(p_{i-1,j}^{n} - p_{ij}^{n}) \tag{9}$$

Intercell flows in the y direction are computed using the updated depths:

$$q_{ij}^{n+1/2} = \frac{1}{n}(d_{ij}^{n+1/2})^{5/3}(S_{f_y}^{n+1/2})^{1/2} \tag{10}$$

Depths in each column are updated based on the flows in the y direction:

$$d_{ij}^{n+1} = d_{ij}^{n+1/2} + \frac{\Delta t}{\Delta x}(q_{i,j-1}^{n+1/2} - q_{ij}^{n+1/2}) \tag{11}$$

With the *ADEPC* method additional steps are added to improve accuracy and stability. As before, during each sweep, by rows or by columns, an estimate of heads is made based on the calculated flows, Equations 9 and 11. Next, using the updated depths, updated estimates of flow are computed at the *n+1* time level

$$q_{ij}^{n+1} = \frac{1}{n}(d_{ij}^{n+1})^{5/3}(S_{f}^{n+1})^{1/2} \tag{12}$$

The original flows and the updated flows are then averaged to come up with an estimate of flows for the time-step:

$$q_{ij}^{n+1/2} = (q_{ij}^{n} + q_{ij}^{n+1}) / 2.0 \tag{13}$$

These flows are then used to update the original depths, Equations 9 and 11. This procedure is essentially the MacCormack method (MacCormack 1969) except up-gradient differences are used in both the predictor and corrector steps. A similar method was successfully implemented by Wang and Hjelmfelt (1998).

In benchmark tests using the three methods: original explicit (*EXPLICIT*), *ADE*, and *ADEPC*, in an contrived watershed consisting of two converging planes (open book), the Goodwin Creek Experimental Watershed (GCEW) (Senarath et al. 2000), and Poplar Creek (Downer et al. 2002a), the ADE and ADEPC methods ran with significantly larger time-steps (Downer et al. 2000). Depending on the test case, time-steps could be increased from 20 percent to 240 percent with commensurate decreases in simulation times.

The routing scheme is selected using the **OVERTYPE** card. The default value is *EXPLICIT*. The most efficient scheme to use depends on the particular watershed. The *ADEPC* scheme can generally handle rougher terrain and typically requires less smoothing of the DEM, but the additional computational steps result in greater computation time, unless use of the *ADEPC* scheme permits substantially greater time-steps than with one of the other two methods. For smoothed DEMs or in watersheds with smoother terrain, the *ADE* and *EXPLICIT* methods usually can be employed, with a resulting savings in execution time.

Overland flow hydraulic roughness

The *GSSHA* model requires that Manning roughness coefficients be assigned to every cell in the watershed mask. There are three ways to specify the hydraulic roughness of the overland flow planes in *GSSHA*. The first method is to apply a constant value over the entire watershed through the **MANNING_N** project file card. The second method is to use the **MAPPING_TABLE** to assign roughness coefficients using tabled values referenced to an index map. The third method is to produce a *GRASS* ASCII map of roughness coefficient, and provide the name of this map to *GSSHA* using the **ROUGHNESS** project file card. Table 8 provides typical values of the Manning roughness coefficient for overland flow over various surfaces:

Table 8. Values of overland flow roughness coefficient.

Land Use or Cover	Recommended n-value	Range
Concrete or asphalt	0.011[a]	0.01-0.013[a] 0.05-0.15[d]
Developed/industrial	0.0137[b]	-
Bare sand	0.01[a]	0.010-0.016[a]
Graveled surface	0.02[a]	0.012-0.03[a]
Bare clay-loam (eroded)	0.02[a]	0.012-0.033[a]
Gullied land	-	0.320-0.357[c]
Bare field – no residue	0.05[a]	0.006-0.16[a]
Range (natural)	0.13[a]	0.01-0.32[a]
Range (clipped)	0.10[a]	0.02-0.24[a]
Grass and pasture	-	0.05 – 0.15[a]
Pasture	- -	0.235-271[c] 0.30-0.40[d]
Clover	-	0.08 – 0.25[a]
Small grain	-	0.1 – 0.4[a]
Row crops	-	0.07 – 0.2[a]
Cotton/soy	-	0.246-0.261[c]
Grass (bluegrass sod)	0.45[a]	0.39-0.63[a] 0.30-0.50[d]
Short grass prairie	0.15[a]	0.10-0.20[a,d]
Dense grass	0.24[a]	0.17-0.30[a]
Bermuda grass	0.41[a]	0.30-0.48[a]
Lawns		0.40-0.50[d]
Forest	0.192[b]	0.184-198[c]
Sparsely vegetated	0.150[b]	0.05-0.13[d]
Dense Growth		0.40-0.50[d]

Notes: [a]Engman (1986), [b]Downer (2002b), [c]Senarath et al (2000), [d]HEC (1985)

These values should be considered guidelines. Manning roughness coefficients are typically assigned from literature values and then adjusted through calibration. Additional sources of literature values are Loing et al. (1989); Engman (1986); and Ree et al. (1977). If calibrated values differ significantly from published values, there may be appropriate justification. Typical Manning roughness coefficient values for open channel flow are considerably smaller than overland flow values because of deeper flow depths in the channel.

Runoff retention

Natural land surfaces contain microtopography, small depressions, that retain water prior to runoff. The water held in the grid cell, or retention storage, never becomes direct runoff and can only be removed from the land surface as infiltration or direct evaporation. In certain regions, the retention storage can be significant. Retention storage is input as a depth (mm) in each grid cell and may be optionally input to *GSSHA* as:

a. A uniform value using the **RETENTION** card
b. As a table of values related to index maps by using the **MAPPING_TABLE** project card
c. As an ASCII *GRASS* map through the use of the **RETEN_DEPTH** project file card

Specifying initial depths on watershed

Initial depths on the overland flow plane at the beginning of the simulation may be specified by use of the **INITIAL_DEPTH** project file card. This card is used to specify an ASCII *GRASS* map containing initial overland depth values, m. This feature is rarely used.

Simulations without channel routing

It might be desirable to perform simulations without channel routing in very small watersheds lacking a defined channel network, or in the beginning stages of developing a *GSSHA* model of a watershed. It is always prudent to build a *GSSHA* model one process at a time. Getting just the overland flow portion of the model to run is always the first step in building a model. For these reasons, *GSSHA* may be used without channel routing. Because the channel network normally provides the outlet point, the overland cell containing the outlet must be specified during simulations without channel routing. Normally this grid cell will have the lowest elevation in the watershed. The row and column containing the outlet grid cell are specified using the **OUTROW** and **OUTCOL** cards, while the slope of the outlet grid cell is specified using the **OUTSLOPE** card. If channel routing is enabled through the inclusion of **CHAN_EXPLIC** in the project file, the **OUTROW**, **OUTCOL**, and **OUTSLOPE** cards are not required, and ignored if present.

6 Precipitation

Rainfall is always a required input. Rainfall may be input as spatially and temporally uniform, at a specified rate for a specified duration, for a single event, or rainfall may be input as spatially and temporally varying for any number of rainfall events. The second method requires a separate rainfall data input file.

Spatially and Temporally Uniform Precipitation

Spatially and temporally uniform rainfall is specified with project file cards. Place the **PRECIP_UNIF** card in the project file, and specify the rainfall rate (mm hr^{-1}) and duration (minutes) with the **RAIN_INTENSITY** and **RAIN_DURATION** cards, respectively. Since *GSSHA* normally determines the starting date and time of a simulation from the rainfall input file, this information must be provided in the project file using the **START_DATE** and **START_TIME** cards. For example, the following five lines entered in a project file specify a rainfall rate of 27 mm h^{-1}, for a duration of 60 min, starting on 12 June 1996 at 13:30. Note that the date/time format in *GSSHA* input is always year, month, day, hour, and minute.

```
PRECIP_UNIF
RAIN_INTENSITY          27
RAIN_DURATION           60
START_DATE        1996  6     12
START_TIME        13    30
```

The use of spatially- and temporally-uniform rainfall is mutually exclusive with continuous simulations using the **LONG_TERM** project file card. Do not attempt to specify both **PRECIP_UNIF** and **LONG_TERM** in the same project file.

Spatially and Temporally Varied Precipitation

Assignment of spatially and temporally varied rainfall requires the creation of a rainfall input file. Like the project file, the rainfall input file is card based. The precipitation input file can contain multiple events. The following rainfall cards, Table 9, are recognized by *GSSHA*, and valid for use only in the precipitation input file (not in the project file):

Table 9. Types of Rainfall Inputs.

Card	Argument	Description
EVENT	*"character string"*	Denotes the beginning of a new event in the precipitation input file. The optional character string can be used to annotate the file. Card-REQUIRED, argument-OPTIONAL. Optional string MUST be in double quotes.
NRGAG	*integer*	Denotes the number of gages that recorded data for this event. The card and argument are REQUIRED for each EVENT.
NRPDS	*integer*	Denotes the number of periods of rain rate observations for this EVENT. The card and argument are REQUIRED for each EVENT.
$COORD_1$ • • • $COORD_{NRGAG}$	*real real "char string" "char string"* • • • •	Denotes the UTM coordinates of the gage, in the format *easting northing*. Two optional strings, which must be in double quotes are provided to annotate the file. One COORD card is REQUIRED for each gage. The number of COORD cards in an EVENT must equal NRGAG.
$GAGES_1$ • • • $GAGES_{NRPDS}$	*date time* $val_{1,1}..val_{1,NRGAG}$ • • • *date time* $val_{NRPDS,1}..val_{NRPDS,NRGAG}$	Rain accumulations (mm) recorded at the end of the sampling period. The number of GAGES cards in each EVENT must equal NRPDS. Each GAGES card must have the date and time of the recording, and be followed by NRGAG real values of rain accumulation during that period.
$RADAR_1$ • • • $RADAR_{NRPDS}$	*date time* $val_{1,1}..val_{1,NRGAG}$ • • • *date time* $val_{NRPDS,1}..val_{NRPDS,NRGAG}$	Rain rates (mm h^{-1}) recorded at the end of the sampling period. The number of RADAR cards in each EVENT must equal NRPDS. Each RADAR card must have the date and time of the recording, and be followed by NRGAG real values of rain rate.
$RATES_1$ • • • $RATES_{NRPDS}$	*date time* $val_{1,1}..val_{1,NRGAG}$ • • • *date time* $val_{NRPDS,1}..val_{NRPDS,NRGAG}$	Rain rates (mm h^{-1}) recorded at the beginning of the sampling period. The number of RATES cards in each EVENT must equal NRPDS. Each RATES card must have the date and time of the recording, and be followed by NRGAG real values of rain rate.
$ACCUM_1$ • • • $ACCUM_{NRPDS}$	*date time* $val_{1,1}..val_{1,NRGAG}$ • • • *date time* $val_{NRPDS,1}..val_{NRPDS,NRGAG}$	Cumulative amount of rainfall (mm) recorded at the end of the sampling period. The number of ACCUM cards in each EVENT must equal NRPDS. Each ACCUM card must have the date and time of the recording, and be followed by NRGAG real values of cumulative rainfall. The values *must* increase monotonically for each gage.

The following information on developing rainfall input should also be noted:

a. In a given EVENT, the rainfall data source type (GAGES, RADAR, RATES, ACCUM) may NOT change.

b. The data source type may change from one EVENT to the next.
c. The number and location of rain gages may change from one event to the next.
d. If only one gage is present, rainfall interpolation is impossible. The location of the gage is irrelevant and the gage coordinates are ignored. Rainfall is applied uniformly in space. This provides a means to apply a temporal distribution of rain in a spatially uniform fashion. Such temporally varying, spatially uniform rainfall distributions are commonly used in flood frequency analysis, i.e., TP40.
e. A separate line with its own time of recording is used to input each instance of rainfall, allowing varying temporal resolution rainfall data to be input. This feature is particularly useful when using radar-rainfall estimates, since the temporal resolution can vary considerably.
f. Avoid using precipitation data with temporal resolution coarser than 1 hr.
g. The finest temporal resolution of *GSSHA* rainfall input is 1 min. Rainfall rates change on integer minutes. Seconds are not allowed in the time field.
h. The COORD card must be followed by the easting and northing of the rain gage. Easting and northing must be in coordinates in the same frame of reference as the header of all ASCII *GRASS* input maps. If the gage and map coordinates are not in the same system, the gages will not be placed at the correct location in relation to the watershed.
i. If used, the optional strings *must* be enclosed in double quotes "like this."
j. Tabs or spaces are used to delimit the file. Do not use commas.
k. To improve readability, line feeds are allowed in the data file.

The following is an example of a multiple-event precipitation input file using radar-rainfall estimates for the first event and rain gage data for the second event (unlikely but illustrative):

```
EVENT "Event of 30 June 1995- rainfall stops on July 1st"
NRPDS 5
NRGAG 3
COORD 205150.0 4750212.0 "center of radar pixel #1"
COORD 205045.0 4750104.0 "center of radar pixel #2"
COORD       205320.0 4751173.0 "center of radar pixel #3"
RADAR 1995 06 30 22 56   0.00  0.00  0.00
RADAR 1995 06 30 23 18  10.75  2.25  5.80
RADAR 1995 06 30 23 39  21.16  1.80 41.50
RADAR 1995 06 30 23 57  12.13 20.90 20.70
RADAR 1995 07 01 00 09  11.71 16.50  2.30
EVENT "Event of 4 July 1995- new raingage network data"
NRPDS 4
```

```
NRGAG 4
COORD 204555.0 4751268.0      "location of raingage #1"
COORD 205642.0 4750491.0      "location of raingage #2"
COORD       205921.0 4750330.0      "location of raingage #3"
COORD       206170.0 4749611.0      "location of raingage #4"
GAGES 1995 07 04 09 47   0.0   0.0   0.0   0.0
GAGES 1995 07 04 10 01  38.0   2.0   0.0   0.0
GAGES 1995 07 04 10 16  16.0  14.0   3.0   0.0
GAGES 1995 07 04 10 35  19.0  20.0  16.0   8.0
```

Interpolation Between Gages

The rainfall interpolation technique for spatially varied rainfall is specified with either the **RAIN_INV_DIST** or **RAIN_THIESSEN** project cards. No interpolation method can create information without creating uncertainty. All interpolation methods estimate the spatially varied field from point measurements, introducing uncertainty. The Thiessen polygon method is simply a nearest-neighbor approach, while the inverse distance squared method produces smooth fields based on the assumption that the influence of a measured value decreases with the distance from the point of measurement squared. The spatial variability of instantaneous rainfall is correlated at a scale of only several kilometers at most. Use caution. It is not appropriate to use rain gage data at distances greater than the correlation length of the rainfall rate field. For example, the use of 15-min rain gage data from a gage that is 30 km from the catchment is completely unrealistic, making calibration impossible. If you have no rain gages in the catchment separated by less distance than the correlation length of the rainfall field, you do not have enough data to calibrate *GSSHA*.

For example, Ogden and Julien (1993) calculated the correlation length of radar-estimated rainfall rates from multiparameter observations of convective rainfall. Putting aside the discussion of the appropriateness of the correlation length as indicator of spatial structure due to the anisotropy and nonstationary of rainfall, the calculated correlation length was on the order of 2.5 km. This means that a rain gage network with intergage distances greater than this distance will not capture the true spatial variability of rainfall. There is also a chance that significant rainfall will be completely missed by such a network.

The U.S. National Weather Service network of WSR-88D next generation (NEXRAD) weather radars offer the potential of providing rainfall estimates in locations where there are no rain gages. There are numerous error sources that affect the conversion of radar observations into rainfall rate estimates. Discussions of radar errors are beyond the scope of this

manual. NEXRAD precipitation estimates can be used in *GSSHA*, by formatting the data into a *GSSHA* precipitation file using the RADAR precipitation type card. When using NEXRAD rainfall estimates, *GSSHA* assigns a rain gage at the center of each radar data pixel. When combined with Thiessen polygon rainfall interpolation, this reproduces the original radar pixels. The use of inverse-distance squared interpolation should not be used with radar data.

Interception

The interception of rainfall by the vegetation is modeled in *GSSHA* using the two parameter method published by Gray (1970). An initial quantity of rainfall (mm), entirely intercepted by foliage, is specified with the **STORAGE_CAPACITY** project card. The fraction of rainfall retained as intercepted water after satisfying the storage capacity is specified with the **INTERCEPTION_COEFF** card. These two cards are used to specify *GRASS* ASCII maps of the required parameters. Alternatively, both storage capacity and the interception coefficient may be assigned use the mapping table and an index map based on vegetation.

In *GSSHA*, the interception rate (i) is expressed as:

$$i(t)=r(t) \text{ while } I < a$$
$$i(t)=b*r(t) \text{ while } I > a$$

where:

- r (t) denotes rainfall intensity at time t,
- a is the storage capacity,
- b is the interception coefficient,
- and I is the cumulative interception depth.

Storage capacity and interception values are usually inferred from vegetation or land cover. Values of storage capacity and interception coefficient values can be found in Gray (1970) or Bras (1990).

7 Infiltration

Water ponded on overland flow plane cells will infiltrate into the soil as conditions permit. Infiltration is dependent upon soil hydraulic properties and antecedent moisture conditions, which may be affected by previous rainfall, run on, ET, and the location of the water table. In *GSSHA*, the unsaturated zone that controls infiltration may be simulated with a 1-D formulation of Richards' equation (RE), which simulates infiltration, ET, and soil moisture movement in an integrated fashion. Infiltration may also be simulated using traditional Hortonian Green and Ampt (GA) (Green and Ampt 1911) approaches which are simplifications of RE. There are three optional GA based methods to calculate infiltration for Hortonian basins: a) traditional GA infiltration, b) multilayer GA, and c) Green and Ampt infiltration with redistribution (GAR) (Ogden and Saghafian 1997). The traditional GA and multilayer GA approaches are used for single event rainfall when there are no significant periods of rainfall hiatus. The GAR approach is used when there are significant breaks in the rainfall, or for continuous simulations.

RE is a general equation and can be applied in any type of watershed or conditions. However, the simpler methods based on the GA equation are preferred when runoff is Hortonian, i.e., occurs due to infiltration excess, where the rainfall/run-on of water is greater than the possible infiltration rate. For fine textured soils the GAR method has been shown to closely mimic the RE solution (Ogden and Saghafian 1997) and when applied in basins identified as Hortonian, the GAR method has been shown to produce results comparable with the RE (Downer and Ogden 2003).

However, when Hortonian flow is not the predominant streamflow producing mechanism, application of GA type models is ill advised and can result in erroneous results (Downer et al. 2002a). For cases where Hortonian flow is not the predominate process generating streamflow the RE should be used, and coupled with the saturated groundwater solution as appropriate. Representation of the soil column below each cell with Richards' equation is presented. Formulation and application of the GA model is well described in other sources (i.e., Maidment 1993) as well as the GAR method (Ogden and Saghafian 1997). Formulation, solution, and

application of the multilayered GA model as applied in the *GSSHA* model is presented in Chapter 7.

Richards' Equation

Detailed modeling of the soil water profile in the vadose, or unsaturated zone, is a key addition in the *GSSHA* model. It is this dynamic area that controls the flux of water between the surface and groundwater and partitions rainfall into infiltration, runoff, groundwater recharge and ET. The most rigorous way to model these complicated and integrated phenomena is to use Richards' equation in the solution of the problem. While many have described RE as being infeasible for use in hydrologic predictions the equation has been successfully used in field scale and watershed scale models of soil moisture and runoff (Lappala et al. 1987; Hutson and Waggenet 1989; Dawes and Hatton 1993; Refsgaard and Storm 1995; and others). Simpler methods, such as GA and GAR, which are approximations of RE do not provide detailed soil moisture profiles or simulate the movement of water from the groundwater to the unsaturated zone. Accurate representation of layered soils or soils with a water table is also difficult with these approximations (Short et al. 1995). To simulate infiltration with Richards' equation use the **INF_RICHARDS** option in the project file.

Processes in the unsaturated zone important to surface-water hydrology, infiltration, ET, and groundwater recharge, are largely oriented in the vertical direction (Refsgaard and Storm 1995). *GSSHA* solves the one-dimensional (vertical direction) head-based formulation of Richards' equation

$$C(\psi)\frac{\partial \psi}{\partial t} - \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z} - 1\right)\right] - W = 0 \qquad (14)$$

where:

C = the specific moisture capacity
ψ = the soil capillary head (cm)
z = the vertical coordinate (downward positive) (cm)
t = time (hr)
K (ψ) = the effective hydraulic conductivity (cm)
W = a flux term added for sources and sinks (cm hr^{-1})

The head-based formulation allows solution of Richards' equation in both saturated and unsaturated conditions (Haverkamp et al. 1977). The head-based approach has been successfully implemented in the field scale unsaturated flow models VS2D (Lappala et al. 1987), LEACHM (Hutson and Wagenet 1989), and SWAP (van Dam and Feddes 2000) and in the surface-water hydrology models TOPOG_IRM (Dawes and Hatton 1993) and MIKE SHE (Refsgaard and Storm 1995). With a head-based formulation, rainfall, evaporation and groundwater recharge can all be modeled without a change in variable. Known mass balance problems associated with solution of the head-based formula (Celia et al. 1987; Ross 1990; Pan and Wierenga 1995; Celia et al. 1990) have largely been eliminated by the development of new solution techniques (Kirkland et al. 1992; Rathfelder and Abriola 1994; Pan and Wierenga 1995).

In *GSSHA*, RE is solved using an implicit finite difference approach, which maps directly to the overland flow finite difference grid. The soil column below each overland flow cell is subdivided into multiple unsaturated zone cells (Figure 9).

A 1-D approximation of the unsaturated zone imposes some limitations on the application of the model. Lateral flow in the unsaturated zone may be significant for a perched water table that does not extend to the soil surface. Lateral flow of unsaturated water may also occur in the absence of a perched water table (Zaslavsky and Sinai 1981). Lateral flow in the unsaturated zone under either saturated or unsaturated conditions is most significant for steep slopes. Solution of the multidimensional RE is difficult and the additional computational burden is not commonly justified if the purpose of the model is to simulate surface-water hydrology. Aspect ratio problems are also avoided because of the 1-D formulation employed. Other conditions in the unsaturated zone that are not explicitly simulated are macro-pores and hysteresis.

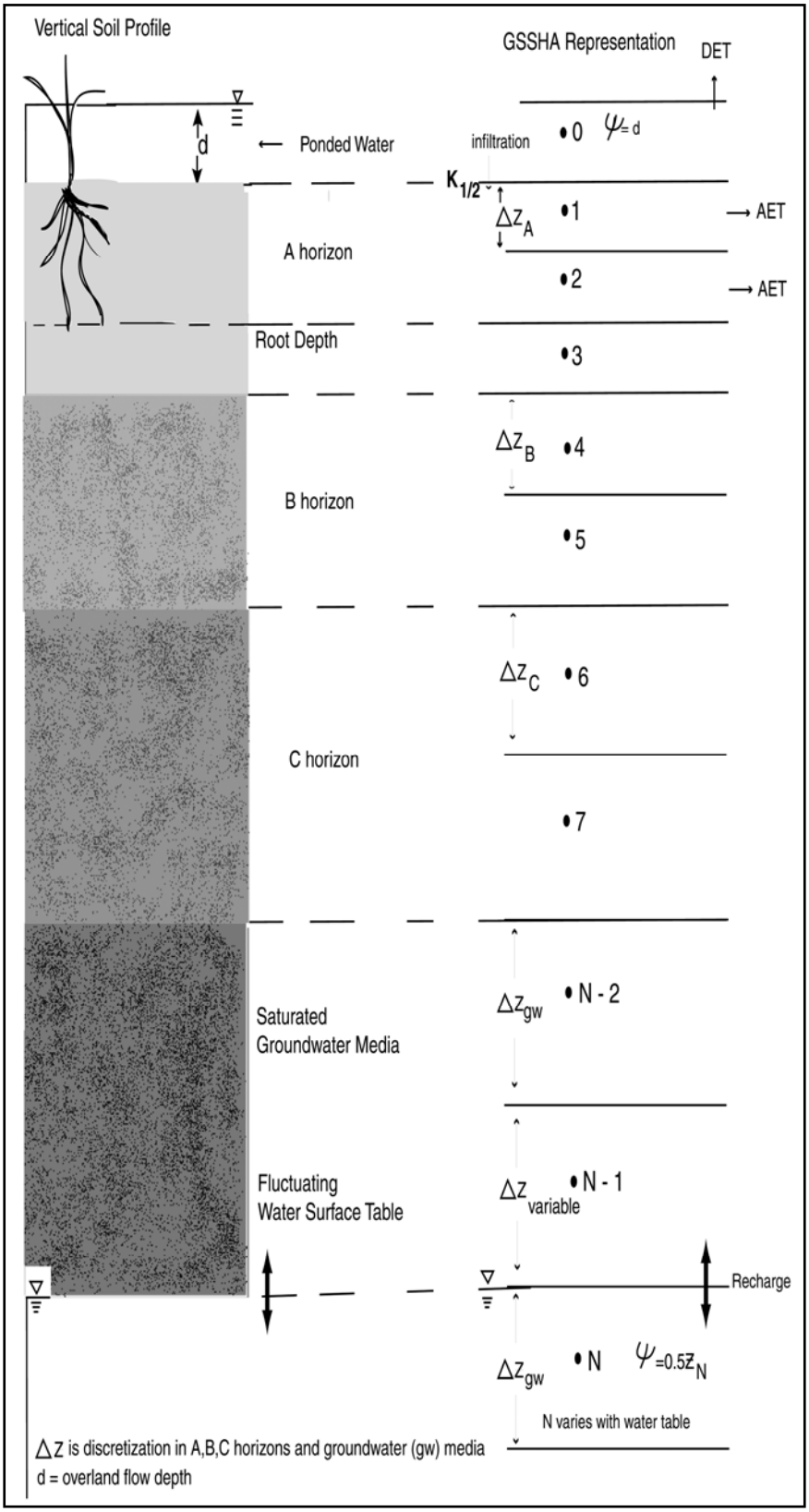


Figure 9. *GSSHA* representation of unsaturated zone.

Discretization

The soil column must be subdivided into cells to numerically solve Richards' equation. The discretization used in the *GSSHA* model is shown in Figure 9. The soil column is defined in three layers, namely A, B, and C horizons. The soil properties and discretization can vary in each layer. Any size cell can be used in the discretization, however, if very large cells are used the solution may be poor. As discussed in Downer (2002a) and Downer and Ogden (2004), cells on the order of 1 cm are generally needed in the top 10 cm of soil to accurately model the infiltration process. If larger cells are used in dry soils a large volume of water must be added to the cell before significant infiltration can occur because the hydraulic conductivity will be very low. This can result in significant underestimation of infiltration, as discussed in Downer (2002a) and Downer and Ogden (2004). The grid size for each soil in the **SOIL_TYPE_MAP** in each soil layer is specified in the **SOIL_LAYER_INPUT_FILE** or in the mapping table.

The solution scheme employed is implicit, central difference in space and forward difference in time, and is thus second order accurate in space, first order accurate in time. For *j* being the cell numbering scheme, increasing downward, such that *j* is the cell of interest, *j*-1 is the cell above, and *j*+1 is the cell below, and n represents the time level, Figure 9. The following discretization is used for nonboundary cells:

$$C_j^n \frac{\psi_j^{n+1} - \psi_j^n}{\Delta t} = \frac{1}{\Delta z_j}\left[K_{j+1/2}^n \left(\frac{\psi_{j+1}^{n+1} - \psi_j^{n+1}}{\Delta z_{j+1/2}} \right) - K_{j-1/2}^n \left(\frac{\psi_j^{n+1} - \psi_{j-1}^{n+1}}{\Delta z_{j-1/2}} \right) \right] + W_j^n \qquad (15)$$

where:

C = water capacity
ψ = pressure head in the cell (cm)
K = hydraulic conductivity in the cell (cm hr^{-1})
W = source term (cm hr^{-1})
Δt = time-step (hr)
Δz = grid size (cm)

Values for variables represented between cells, or at the cell interface, are represented by *j-1/2* and *j+1/2* for the interfaces above and below, respectively. Internodal distances, $\Delta z_{j-1/2}$, $\Delta z_{j+1/2}$, are defined as the distance

between the center of cells *j* and *j-1* and *j* and *j+1*, respectively, computed as:

$$\Delta z_{j-1/2} = \frac{\left(\Delta z_{j-1} + \Delta z_j\right)}{2.0} \tag{16}$$

Intercell hydraulic conductivities may be calculated two ways, an arithmetic weighting of the values or a geometric average. The intercell hydraulic conductivity weighting method is selected with the **RICHARDS_K_OPTION** project card with the argument being either *ARITHMETIC* or *GEOMETRIC*; the default is *ARITHMETIC*. In using the arithmetic weighting, a weighting factor, α , is used to determine how much weight is placed on upper and lower cells. The value of α is specified with the **RICHARDS_WEIGHT** project card; the default value is 1.0. If α = 1, then only the value from the *j-1* cell is used; this is commonly referred to as backwards difference, or upwinding. If α = 0 only the *j+1* value is used. This is commonly referred to as forward difference, or downwinding. If α is 0.5 then equal weight is applied to both the *j-1* and *j+1* cells. Lappala (1981) recommends that backward difference be used for modeling the infiltration process. The geometric average is best when there are large changes in the hydraulic conductivity between cells and is generally applicable in all situations.

Nonlinear coefficients

In Richards' equation, hydraulic conductivity and water capacity values are dependent on the water content of the cell. The method to describe these relationships must be specified with the **RICHARDS_C_OPTION** project card. The possible arguments are *BROOKS* for the Brooks and Corey method (1964) and *HAVERCAMP* for the Havercamp method (Havercamp et al. 1977). The Brooks and Corey method (1964) as extended by Hutson and Cass (1987) may be used to estimate relative hydraulic conductivity from the soil pressure head as:

$$\begin{aligned} &\text{if } \psi < \psi_b \quad K_r = \left(\frac{\psi}{\psi_b}\right)^{-2-3\lambda} \\ &\text{and if } \psi > \psi_b \quad K_r = 1.0 \text{ if} \end{aligned} \tag{17}$$

where:

K_r = the relative hydraulic conductivity
ψ_b = the air entry or bubbling pressure
λ = the pore-size distribution index, which is the inverse of the ratio of the length of flow path through the soil matrix to the straight line length

With the Havercamp method (Havercamp et al. 1977) as modified by Lappala et al. (1987) the relative hydraulic conductivity is calculated as:

$$K_r = \frac{A}{A + |\psi|^B} \tag{18}$$

where: A and B are parameters fitted to laboratory determinations of hydraulic conductivity at different soil pressure heads.

The water capacity C is also dependent on the pressure head ψ. Water capacity is defined as the change in moisture with respect to head $\frac{\partial \theta}{\partial \psi}$. For Brooks and Corey if $\psi < \psi_b$ the relationship between moisture content and head is expressed as:

$$\Theta = \left(\frac{\psi_b}{\psi} \right)^{\lambda} \tag{19}$$

where: $\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$, θ is the moisture content, θ_r is the residual saturation, and θ_s is the saturated moisture content, or porosity. Rearranging and taking the derivative with respect to head yields:

$$\frac{d\theta}{d\psi} = -\lambda(\theta_s - \theta_r)\psi^{-\lambda-1}{\psi_b}^{\lambda} \tag{20}$$

In the original formulation of Brooks and Corey, if $\psi > \psi_b$, $\theta = \theta_s$, and C=0. This formulation permits changes in pressure head without a resulting change in water content for pressures greater than the bubbling pressure. Hutson and Cass (1987) extended the Brooks and Corey equation into the wet region where $\psi > \psi_b$ using the following formulation:

$$\psi = \frac{\psi_b (1-\Theta)^{1/2} \Theta_c^{-1/2}}{(1-\Theta_c)^{1/2}} \tag{21}$$

where: $\Theta_c = \frac{\theta_c - \theta_r}{\theta_s - \theta_r}$, and θ_c is the critical moisture content, the moisture content where the curve changes from the standard Brooks and Corey curve to the modified curve of Hutson and Cass. The critical moisture content is defined as $\theta_c = 2(1/\lambda)/(1+2(1/\lambda))\theta_s$ with the corresponding critical pressure head:

$$\psi_c = \psi_b \left[\frac{2(1/\lambda)}{1+2(1/\lambda)} \right]^{(1/\lambda)} \tag{22}$$

The moisture content can then be represented as

$$\theta = \left(1 - \left(\frac{\psi}{\psi_b} \frac{(1-\Theta_c)^{1/2}}{\Theta_c^{-1/\lambda}} \right)^2 \right) (\theta_s - \theta_r) + \theta_r \tag{23}$$

And, the water capacity is found by taking the derivative of the above equation.

$$\frac{d\theta}{d\psi} = -2\psi \left(\frac{(1-\Theta_c)^{1/2}}{\psi_b \Theta_c^{-1/\lambda}} \right) (\theta_s - \theta_r) \tag{24}$$

For the Havercamp equations the relationship between the water content and the pressure head is

$$\theta = \frac{\alpha(\theta_s - \theta_r)}{\alpha + |\psi|^\beta} + \theta_r \tag{25}$$

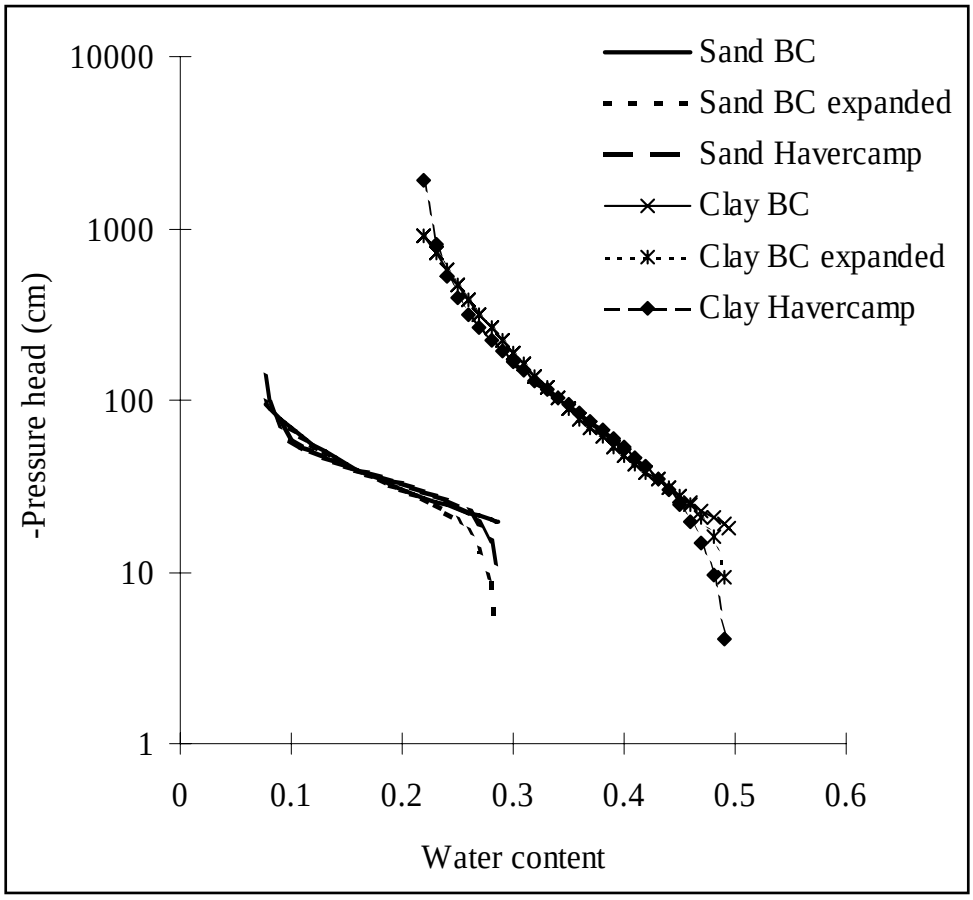
where: α and β are fitted parameters. According to Lappala (1981) the form of the equation can be expressed as:

$$\Theta = \frac{1}{1 + \left(\frac{\psi}{\alpha} \right)^\beta} \tag{26}$$

Differentiating with respect to pressure yields the water capacity

$$C = \frac{-(\theta_s - \theta_r)(\beta / \alpha)(\psi / \alpha)^{\beta-1}}{[1 + (\psi / \alpha)^{\beta}]^2} \quad (27)$$

The relationship between soil moisture and suction head as represented by



the different methods is shown in Figure 10.

Figure 10. Water retention curves (BC – Brooks and Corey).

Evapotranspiration source term

During long-term simulations potential evapotranspiration (PET) is calculated by either the Penman Monteith (Monteith 1965; 1981) or Deardorff (1977; 1978) equations and is applied to each soil column below the overland flow plane. Any water ponded on the surface of the overland flow cell is reduced up to the amount of the PET. Any remaining PET demand is applied to cells in the unsaturated zone down to the specified root depth (Figure 9). The actual evapo-transpiration (AET) is distributed over the

cells in the specified root zone in proportion to the size of each cell. The AET is computed from the PET by adjusting the PET for the soil moisture in each cell. AET depends on the soil moisture, hydraulic properties of the soil and plant characteristics. At water contents close to the field capacity there is no stress on plants and AET is equal to PET (Shuttelworth 1993; Dingman 1994). The field capacity is the water content at which the suction pressure prevents gravity drainage of the soil. Field capacity is not an actually physically measurable quantity and there are many descriptions of the conditions that correspond to the concept of field capacity. In *GSSHA*, if the water content in a cell is greater than 75 percent saturation, AET is equal to PET. At water contents below the wilting point, θ_{wp}, plant transpiration ceases and plants wilt (Dingman 1994), and AET is zero. At intermediate points AET will depend on PET and the water content. Many relationships to relate AET to PET have been suggested (Dyck 1983). In *GSSHA*, AET is calculated from PET for water contents greater than the wilting point using the relationship:

$$AET = PET\left(\frac{\theta - \theta_{wp}}{0.75(\theta_s - \theta_{wp})}\right)^P \tag{28}$$

The appropriate equation depends on vegetation, climate, and soil type. If the exponent, *P*, is 1 the relationship is linear, above 1 the curve is convex, and below 1 concave (Figure 11). Currently *P* is set to 1.0. Future versions will allow the power to be specified by the user to reflect the local conditions. The AET for each cell is added to the source term, *W*, for that cell in the RE solution.

Upper boundary condition

The upper boundary condition varies depending on the condition of the top cell: specified flux for no surface ponding, and specified pressure (head) when infiltration excess results in surface ponding. The first cell in the column, j=0 (Figure 9), is located above the ground surface, and a pressure is always specified for this cell. For a flux boundary condition, the pressure in the top cell is zero and the flux is added to cells via the source term, *W*. For a head boundary the pressure in the top cell is equal to the depth of ponded water. The typical sequence of events is described in the following paragraph.

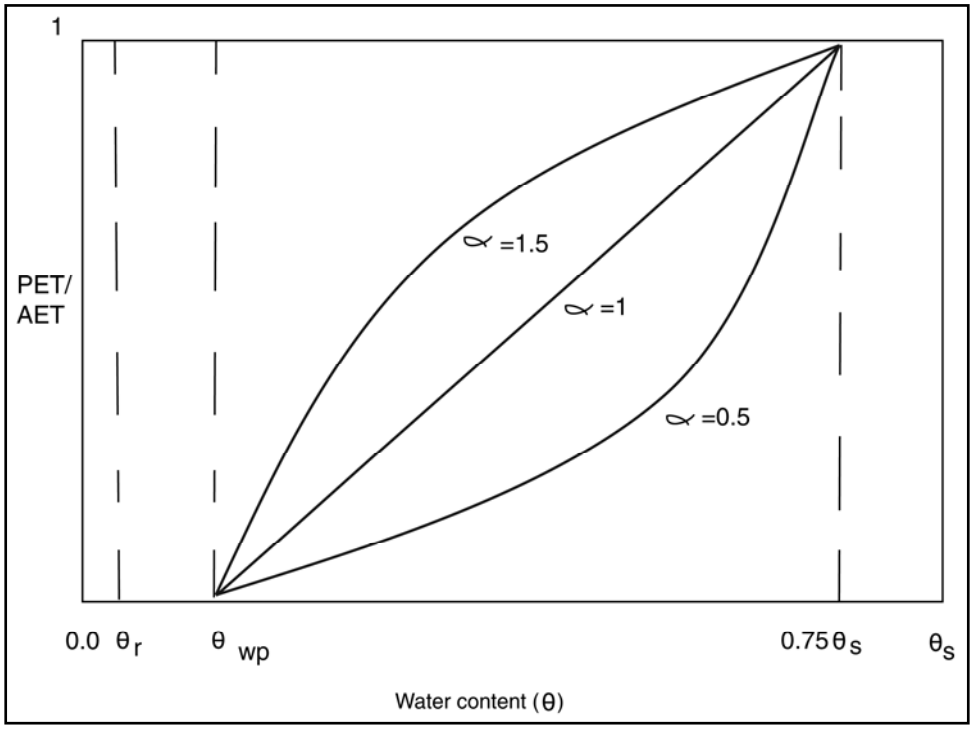


Figure 11. Relationship of actual evapotranspiration to potential evapotranspiration.

At the beginning of simulations and at times between rainfall events there is typically no ponded water on the overland flow plane. The upper boundary condition for the unsaturated zone is a negative flux, equal to the AET of the top cell, cell 1 in Figure 9. When rainfall, runoff or some other source of water is added to the overland flow cell a flux boundary condition is initially specified for the RE solution. A flux equal to the depth of ponded water divided by the current time-step is added to the source term, *W*, of the first non-boundary cell, cell 1 in Figure 9. New heads are calculated with this assumed flux. These heads are used to compute the inter-cell fluxes. The computed flux in cell 1 is compared to the source term. If the calculated flux is less than the specified (assumed) flux, then all the water cannot infiltrate into the soil column during the current time-step. In this case, water ponds on the soil surface and the upper boundary is changed to a specified head, the head being the depth of ponded water. Heads are re-computed using the head boundary. To save computation time, the upper boundary condition remains a specified head until the overland flow cell becomes dry. At this point the boundary condition changes back to a specified flux, and remains a specified flux until infiltration capacity of the soil column is again exceeded. Water that enters the top cell is infiltration. Any water that does not infiltrate can become runoff or direct ET (DET).

As discussed in Downer (2002a) and Downer and Ogden (2004), the assignment of the hydraulic conductivity at the ground surface, $K_{1/2}$ between j=0 and j=1 (Figure 9), has important implications in determining infiltration, infiltration excess, and ET. Three methods, specified with the **RICHARDS_UPPER_OPTION** project card and the appropriate argument, can be used to compute the hydraulic conductivity at the ground surface. The default option, *NORMAL*, is to use the cell-centered value of hydraulic conductivity in cell 1 (Figure 9). The cell-centered value of hydraulic conductivity is always used for a flux boundary condition. If the soil surface boundary condition is a head, hydraulic conductivity at the soil surface may be assumed to be the saturation value, selected by using the *GREEN_AMPT* argument, or an average of the saturation value and the cell-centered value, selected with the *AVERAGE* argument. The assumption is that there is always a very thin layer of saturated material at the soil surface any time water ponds. Either method results in increased infiltration compared to using the cell-centered value of hydraulic conductivity. As discussed in Downer (2002a) and Downer and Ogden (2004), testing at two watersheds indicated either alternative method allows the use of larger cell sizes in the unsaturated zone without seriously affecting calculated hydrologic fluxes.

Lower boundary condition

Three different lower boundary conditions can be specified. When the groundwater table is far from the ground surface the lower boundary condition is a zero head gradient. Water entering the *N-1* cell in the soil column exits at the incoming rate (Figure 9). This boundary condition is valid when the water table is so deep that its effect on processes in the upper soil column is negligible, and is the default option when a **WATER_TABLE** is not specified by the user. The lower boundary can also be a fixed water table, specified with the **WATER_TABLE** project card that specifies the name of a map containing starting groundwater elevations. When a fixed water table is simulated the top of the last cell, *N*, is just at the surface of the saturated groundwater (Figure 9). The pressure at the top of the cell is zero, and the pressure at cell's center is positive, calculated as $0.5\Delta Z_N$ (Figure 9). This groundwater boundary fluctuates when saturated groundwater is simulated. For a moving water table, the size of the last non-boundary cell, *N-1*, and the number of cells, *N*, changes as the water table rises and falls (Figure 9). A moving water table is specified by using the **GW_SIMULATION** card in the project file, and then supplying the required saturated groundwater inputs.

The unsaturated zone does not include the saturated zone. The flux between the saturated and unsaturated zones is calculated as part of the overall unsaturated solution. This separation of the saturated and unsaturated zones helps in determining mass balance errors and maintaining mass balance in both the saturated and unsaturated zones because water is either in one zone or the other. When water crosses the boundary between the saturated and unsaturated zones it is removed from one zone and placed in the other. Mass balance errors can occur for a variety of reasons including: model formulation, spatial and temporal discretization used, solution technique, and abrupt changes in material properties. In *GSSHA* the mass balance for each compartment, overland, stream, unsaturated, saturated, are calculated independently and integrated to compute an overall mass balance. Mass balance errors in any compartment may be controlled by reducing time-steps or increasing stability criteria, as needed. The methods used to link the saturated and unsaturated zones are further described in later sections.

Solution

Richards' equation is highly nonlinear because both the water capacity and the hydraulic conductivity depend on the pressure, or water content, of the soil. Numerical solution of RE requires some type of linearization. In *GSSHA* the RE is linearized by making the water capacity and intercell hydraulic conductivity constant during each time-step. With flux updating of the heads, as described by Kirkland et al. (1992), this provides a stable, accurate, and mass conserving solution for most conditions.

For N cells including the upper and lower boundary cells, $N-2$ equations are needed. The well-known Thomas algorithm (Thomas 1949) is efficient for solution of the resulting tri-diagonal matrix. After solving for heads in each cell, flux updating (Kirkland et al. 1992) synchronizes the heads and soil moistures, and improves the mass balance. Fluxes (cm hr^{-1}) across the top face of each cell, $f_{j-1/2,}$ are computed as:

$$f_{j-1/2} = K_{j-1/2}\left(1 - \frac{(\psi_j - \psi_{j-1})}{\Delta z_{j-1/2}}\right) \tag{29}$$

These are used to compute the change in water content of each cell as:

$$\Delta\theta_j = \Delta t\left(\frac{-f_{j+1/2} + f_{j-1/2}}{\Delta z_j} + S_j\right) \tag{30}$$

The new water content is:

$$\theta_j = \theta_j + \Delta\theta_j \tag{31}$$

Once the water content in each cell is updated, pressure heads in each cell are calculated based on the head-moisture content relationship and used in the next time-step. Kirkland (1991) found it necessary to restrict flux updating to cells that were both unsaturated and not immediately adjacent to saturated cells. Testing by the authors confirms this needed restriction. The reason for this requirement is that in saturated cells, head changes can occur without a change in water content. This deficiency in the formulation can cause errors in the solution and the mass balance. In this case, iterating on K_r and C can produce substantial improvements in accuracy and mass balance.

The maximum number of iterations is specified by the user using the **RICHARDS_ITERMAX** project card, the default being one. While iterating on the hydraulic conductivity and water capacity will almost always improve the solution and mass balance to some extent, iterating is particularly useful any time there are saturated cells in the unsaturated zone. Cells can become saturated when large changes in material properties exist between adjacent layers, when the upper boundary condition is a head, and when the saturated groundwater is rapidly rising. Experience indicates that when the top boundary is the head condition, the accuracy and mass balance are always improved by iterating on the nonlinear coefficients. When the top boundary condition is a head the maximum number of iterations changes from the default to five, unless the user has specified more iterations.

Picard iterations (Celia et al. 1990) are used any time the user specifies iterations or the upper boundary condition is a head. Heads at the $n+1$ time level are first calculated using values of K_r and C from the n time level. Water contents are calculated based on the fluxes, and heads are updated based on the water contents. K_r and C are then calculated based on the updated values of head and water content. The water contents and heads are set back to the n time level values and K_r^{n+1} and C^{n+1} are used to compute values of head at the $n+1$ time level. The procedure is repeated

until the convergence criterion is met or the maximum number of iterations is reached. The convergence criterion is applied independently to each soil column. The convergence criterion is the difference in head between iterations. The error is adjusted for the head in each cell because the error is most important for wet cells, where a small absolute error in head can cause a large error in the solution. The error for each cell is expressed as:

$$error = \frac{\psi_j^{k+1} - \psi_j^k}{\psi_j^{k+1}} * 100 \ \ percent \tag{32}$$

where k expresses the iteration number, which should not be confused with n, which represents the time level. Iterations for a particular soil column cease once the maximum change in head is less than 1 mm.

Time-step limitation

Because the discretization is implicit there is no inherent stability criteria for the scheme. However, a time-step limitation is desirable to keep the scheme accurate and mass conserving. The time-step limitation in *GSSHA* is adapted from Belmans et al. (1983). The time-step is limited such that a maximum change in water content, $\Delta\theta_{allow}$, is not exceeded. If the maximum change in water content in any cell, $\Delta\theta_{\max}$, exceeds $\Delta\theta_{allow}$ the time-step is reduced so that an exceedance during the next time-step is not likely. The following limitation is used:

$$\Delta t^{n+1} = \Delta t^n \frac{\Delta\theta_{allow}}{\Delta\theta_{\max}} \tag{33}$$

The maximum allowable change in water content is specified by the user, with a suggested range of 0.002 to 0.03 Belmans et al (1983). Smaller limitations will result in longer simulation times. In *GSSHA* each soil column has its own time-step limitation computation. This can greatly increase the speed of the model when rapid changes in water content occur in only a few soil columns. In this case, Δt for these few soil columns may be small while Δt for the bulk of the soil columns in the watershed is still large in comparison. The time-step is limited by specifying the maximum water content change allowable with the RICHARDS_DTHETA_MAX project card; the default value is 0.025.

Green and Ampt (GA)

The Green and Ampt equation, developed for infiltration into uniform soils, has proven useful in the field of hydrologic engineering. The Green and Ampt equation was successfully implemented in the physically based hydrologic model *CASC2D* for infiltration into uniform soils for multiple wetting fronts (Ogden and Saghafian 1997). The GA method is selected by placing the **GREEN_AMPT** card in the project file. Four soil hydraulic parameters are needed for modeling the infiltration process using the GA technique:

a. Soil saturated hydraulic conductivity, K_s (cm h^{-1})
b. GA soil capillary suction head parameter, ψ_f (cm)
c. Effective porosity, θ_e
d. Initial soil moisture content, θ_i

These values may be assigned by using the mapping table and an index map or with four *GRASS* ASCII maps. If using the mapping table and an index map the **MAPPING_TABLE** card is placed in the project file. The **MOISTURE** card is used with no argument. If using the *GRASS* ASCII maps to assign values to every cell in the watershed the **CONDUCTIVITY**, **CAPILLARY**, **POROSITY**, and **MOISTURE** cards are used to specify the *GRASS* ASCII map names as arguments. Assignment of parameters for all infiltration methods is discussed later.

Multilayer Green and Ampt

While the basic Green and Ampt model has been proven effective for modeling infiltration into soils, several important common natural phenomena cause the assumption of a vertically uniform soil to be overly restrictive. Conditions such as layered soils, nonuniform initial soil moistures, surface crust, lenses, and high-water tables all violate this basic assumption, yet are routinely encountered in the field. Therefore it becomes necessary to deal with these situations in some manner. The method used can have significant, if not overwhelming, effects on the hydrograph produced. This section discusses a methodology to incorporate a three layered soil profile into the *GSSHA* hydrologic model using Green-Ampt infiltration. Layering in soil may also be simulated with the Richards' equation, discussed earlier in this chapter.

Layered soils

In nature, layered soils are the norm rather than the exception. Everyone is familiar with the three-layer soil system consisting of a top, A, middle, B, and bottom, C, horizon (Figure 9). Typically, soils in the A horizon are loose and high in organic material. High biological activity increases the porosity and hydraulic conductivity of soils in this layer. Soils in the B horizon are typically less permeable, with lower organic content and reduced biological activity. Soils in the C and lower horizons tend to be even less permeable, with minimal biological activity. What is found in the field could vary greatly from this simple model. Erosion and sedimentation, both recent and in geologic time frames, can cause different layering effects. This can result in layers that become more porous with depth, or alternating porous and impermeable layers. Also, thin impermeable surface crusts can exist where compaction, raindrop impact or tillage occurs.

Regardless of the layering, when a wetting front moves from one layer to the next, the infiltration rate will be reduced. This is true regardless of the orientation of the layering. If a wetting front moves from a more porous to a less porous layer, the infiltration is reduced due to the reduced hydraulic conductivity. If the wetting front moves from a less porous layer to a more porous layer, the reduced wetting front suction causes the reduction in the infiltration rate. If the soils making up the lower layers are much coarser than the top layers, the wetting front may become unstable, and infiltration will be greatly reduced.

In a single layer infiltration model, the effect of layering must be addressed in some manner. Two possible approaches are: a) use the properties of the top soil to represent the entire column, or b) use some type of average values based on the depths of the layers.

Varying moisture contents

Soils do not have to be layered to cause problems with the Green-Ampt assumption of uniform soil properties. Soil moisture can also vary with depth. The variation in soil moistures with depth could be caused by layering or due to other reasons, such as interaction with the groundwater table. In the latter case, the soil will tend to be driest at the surface and saturated near the water table. During periods of evaporation, the soil moisture content may vary considerably with depth. This type of condition

can be roughly approximated with the three-soil layer model, where the only parameter that changes through the layers is the initial soil moisture.

Model formulation

For GA infiltration in *GSSHA*, infiltration occurs in what is assumed to a uniform soil profile with constant hydraulic parameters and initial soil moisture throughout the profile. The Green and Ampt routine has been expanded to allow for three different soil layers to be modeled. These layers can be of any thickness and hydraulic parameters. The assumption of a sharp wetting front still applies. As the wetting front crosses the layers there is assumed to be an instantaneous change in the initial moisture, porosity, and wetting front suction head. However, the effective hydraulic conductivity is calculated at each time-step based on the depth of the leading edge of the wetting front. The hydraulic conductivity, K (cm hr^{-1}), is calculated as the harmonic mean of the wetted layers. While the front is contained in the first layer, the hydraulic conductivity at any time n, K^n, is equal to K_1, the hydraulic conductivity of the A soil horizon.

After the wetting front passes into the second layer, the hydraulic conductivity is defined as:

$$K^n = \frac{\left(L_1 + \frac{F^n - L_1 MD_1}{M_2}\right)}{\left[\frac{L_1}{K_1} + \left(\frac{\frac{F^n - L_1 MD_1}{MD_2}}{K_2}\right)\right]} \tag{34}$$

where:

L_1 = thickness of the A horizon (cm)
L_2 = thickness of the B horizon (cm)
MD_1 = moisture deficit of the A horizon (dimensionless)
MD_2 = moisture content of the B horizon (dimensionless)
K_1 = saturated hydraulic conductivity of the A horizon (cm hr^{-1})
K_2 = saturated hydraulic conductivity of the B horizon (cm hr^{-1})
F^n = cumulative infiltration at the n time level (cm)

The moisture content *MD* is defined as the effective porosity θ_s minus the initial moisture content θ_i.

When the wetting front reaches the third layer, the effective hydraulic conductivity becomes

$$K^n = \frac{\left[L_1 + L_2 + \frac{F^n - (L_1 MD_1 + L_2 MD_2)}{MD_3} \right]}{\left\{ \frac{L_1}{K_1} + \frac{L_2}{K_2} + \left[\frac{\frac{F^n - (L_1 MD_1 + L_2 MD_2)}{MD_3}}{K_3} \right] \right\}} \tag{35}$$

where MD_3 (cm), and K_3 (cm hr^{-1}) are the moisture content and hydraulic conductivity, respectively, of the third soil layer.

Therefore the change in effective hydraulic conductivity is gradual, as would be expected in nature. The soil is assumed to be saturated at all points behind the wetting front.

The cumulative infiltration at the *n+1* time level is (Adapted from Chow et al. 1988):

$$F^{n+1} = F^n + K^n \Delta t + \psi_f MD \ln\left(\frac{F^{n+1} + \psi_f MD}{F^n + \psi_f MD} \right) \tag{36}$$

where: ψ_f, the wetting front suction head, and *MD* are for the layer containing the leading edge of the wetting front. This equation is solved iteratively by the Newton Raphson method. Once the cumulative infiltration is determined the infiltration rate, *f* (cm hr^{-1}) is calculated by:

$$f^{n+1} = K^n \left(\frac{\psi_f MD}{F^{n+1}} + 1 \right) \tag{37}$$

Actually, for this method the calculation of the effective hydraulic conductivity lags the calculation of the infiltration by one time-step. However, since the time-steps for *GSSHA* are small, on the order of 1 min, this should present minimal concern, because the hydraulic conductivity will change very little over such a short period.

In the case where rainfall rate is limiting, the cumulative infiltration is calculated as:

$$F^{n+1} = F^{n} + d^{n+1} \tag{38}$$

where: d^{n+1} is the depth of water ponded on top of cell before infiltration is calculated.

The infiltration rate is then

$$f^{n+1} = d^{n+1} / \Delta t \tag{39}$$

Inputs

The multilayered GA input represents an intermediate step in transforming from a map based input system to an index map and table based input system. The multilayer GA approach is selected by placing the **INF_LAYERED_SOIL** card in the project file. Multilayer GA requires the same inputs as the traditional GA approach except that the information must be specified in a table for all three layers. The table is specified with the **SOIL_LAYER_INPUT_FILE** card. This table is referenced to an index map that contains a unique integer number, starting with 1, for each soil type in the watershed. This *GRASS* ASCII map is specified with the **SOIL_TYPE_MAP** project card. The soil layer input file contains the number of soils on the first line, followed by the soil number and parameter values for each soil in the table. Soil numbers should start with soil 1 and increase monotonically. Every soil number in the table should correspond to a number in the **SOIL_TYPE_MAP**. As shown below, values in the table are separated by spaces or tabs, not commas:

```
Total # of Soils
Soil #
Ks1  Sf1  θs1  θi1  d1
Ks2  Sf2  θs2  θi2  d2
Ks2  Sf2  θs3  θi3  d3
```

The numbered subscripts refer to the soil layer number, 1 – top layer, 2 – middle layer, 3 – bottom layer.

For a watershed with three soil types, soil one a uniform clay, soil two a uniform sand, and soil three a sand with an embedded clay layer, the table might look like:

```
3
1
0.1 30.0 0.5 0.4 10.0
0.1 30.0 0.5 0.4 50.0
0.1 30.0 0.5 0.4 40.0
2
2.0 10.0 0.4 0.25 10.0
2.0 10.0 0.4 0.25 50.0
2.0 10.0 0.4 0.25 40.0
3
2.0 10.0 0.4 0.25 50.0
0.1 30.0 0.5 0.40 10.0
2.0 10.0 0.4 0.25 40.0
```

The corresponding **SOIL_TYPE_MAP** would contain the integers 1, 2, and 3 corresponding to the locations of the soils 1, 2, and 3 in the **SOIL_LAYER_INPUT_FILE**.

Green and Ampt With Redistribution (GAR)

The GAR method expands the capability of the GA method by redistributing soil moisture during periods of no- or low- intensity rainfall. This allows infiltration capacity to recover for the next burst of storm intensity, and makes the GAR method suitable for simulating multiple rainfall events in series. This method is selected with the **INF_REDIST** card in the project file. The technique for hiatus and posthiatus infiltration was developed by Ogden and Saghafian (1997), and is similar to the method developed by Smith et al. (1993).

The GAR technique requires two additional inputs to the four required for the GA method, residual saturation and pore-size distribution index (Brooks and Corey 1964). These may be input with in the mapping table or by specifying two additional maps. These two maps are listed in the project file using the **RESIDUAL_SAT** and **PORE_INDEX** cards, respectively. Assignment of parameters is discussed in Chapter 7.

Ogden and Saghafian (1997) performed a comparison of the GAR approach against a numerical solution of RE on each of the 11 U.S. Department of Agriculture (USDA) soil textural classifications for two pulses of rainfall separated by a period of no rainfall. It is important to note that the traditional GA is invalid for this case, unless the period of no rainfall is

long enough in duration for the soil moisture profile to equilibrate. Results for six soil textures are shown in Figure 12. These results and other analysis presented by Ogden and Saghafian (1997) indicate that the GAR approach is a reasonably good approximation to the numerical solution of RE for well-drained soils, subjected to multiple pulses of rainfall. The agreement between the two approaches is better for finer textured soils. Coarse textured soils dry faster at the surface because of moisture profile "bulging." The GAR approach cannot predict this phenomena, and therefore, overpredicts near soil-surface water contents after rainfall.

Parameter Estimates

It is best to use soil property and Green-Ampt infiltration parameters derived from field and laboratory measurements of infiltration on the study watershed. Even under controlled conditions infiltration measurements are very difficult. Hysteresis effects and the extremely nonlinear behavior of soil water retention make it very difficult to uniquely identify soil infiltration parameters. Hydrologic studies seldom have budgets sufficient to determine the needed parameters in the field.

Considerable prior research has been performed to relate soil infiltration parameter values to textural classification. Some highly relevant references are Rawls and Brakensiek (1983) and (1985), and Rawls et al. (1982) and (1983). Table 10 summarizes Rawls and Brakensiek soil parameter estimates as a function of USDA textural classification. It is important to note that the values listed in Table 10 were derived from the geometric mean of tests on a large number of soil samples. Hydraulic conductivies for all GA based approaches are half of the saturated values listed in Table 10 (Rawls et al. 1982). The variance of these values is large, indicating significant uncertainty or low correlation between textural classification and soil texture. However, these values are useful because they provide an initial estimate of infiltration parameters. The variances of the values in Table 10 are listed in the original papers, and are published in Maidment (1993).

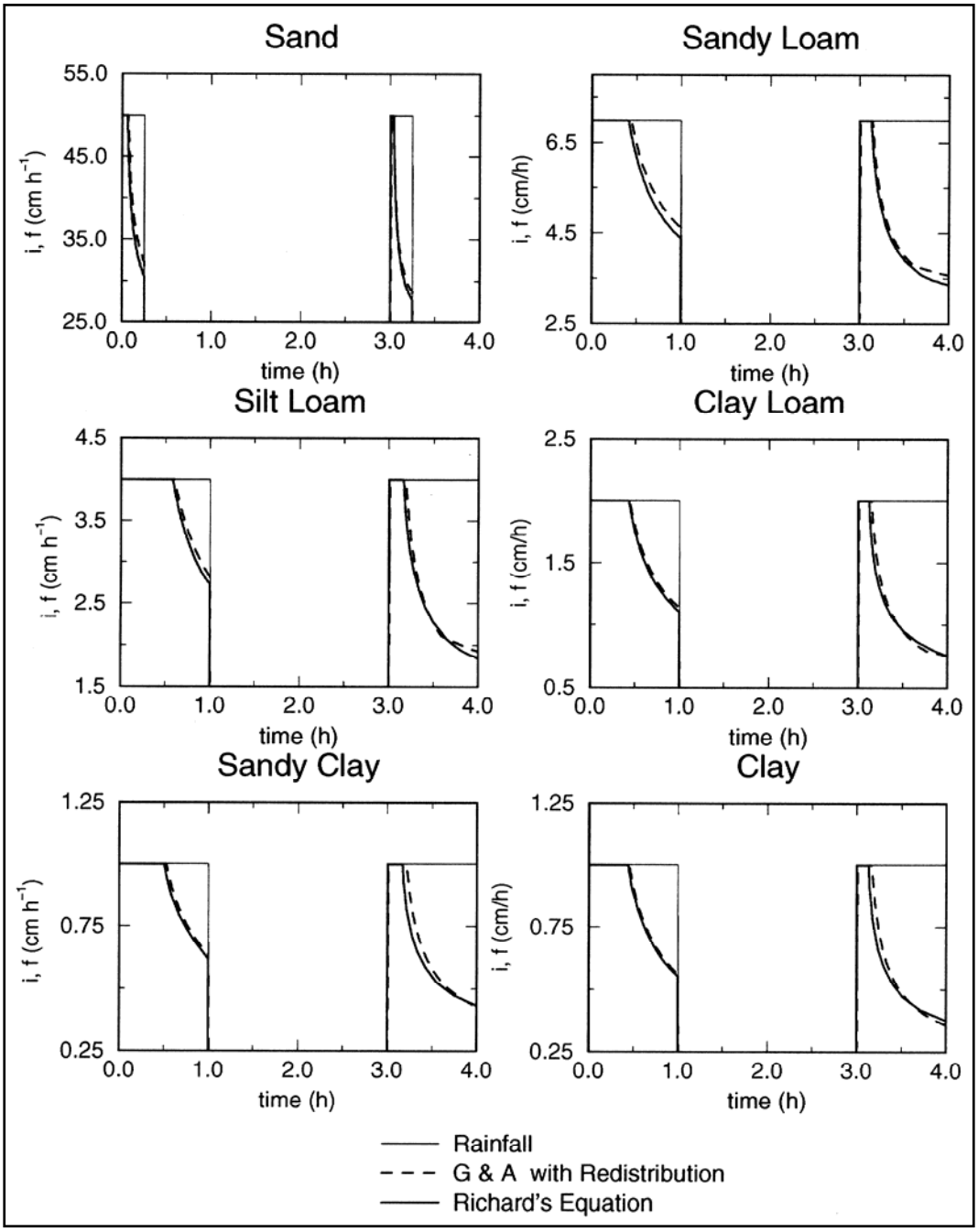


Figure 12. Comparison of GAR with numerical solution of RE on six soil textures (from Ogden and Saghafian 1997).

Table 10. Rawls and Brakensiek Soil Parameter Estimates.

USDA Textural Classification	θ_s	θ_e	θ_r	θ_{wp}	ψ_b (cm)	λ	K_s (cm h^{-1})	ψ_f (cm)
Sand	0.437	0.417	0.020	0.033	7.26	0.694	23.56	4.95
Loamy sand	0.437	0.401	0.035	0.055	8.69	0.553	5.98	6.13
Sandy loam	0.453	0.412	0.041	0.095	14.66	0.378	2.18	11.01
Loam	0.463	0.434	0.027	0.117	11.15	0.252	1.32	8.89
Silt loam	0.501	0.486	0.015	0.133	20.79	0.234	0.68	16.68
Sandy clay loam	0.398	0.330	0.068	0.148	28.08	0.319	0.30	21.85
Clay loam	0.464	0.390	0.075	0.197	25.89	0.242	0.20	20.88
Silty clay loam	0.471	0.432	0.040	0.208	32.56	0.177	0.20	27.30
Sandy clay	0.430	0.321	0.109	0.239	29.17	0.223	0.12	23.90
Silty clay	0.479	0.423	0.056	0.250	34.19	0.150	0.10	29.22
Clay	0.475	0.385	0.090	0.272	37.30	0.165	0.06	31.63

Standard practice in developing *GSSHA* models is to obtain digital soil textural classification data and use these data to develop an index map of soil types. Soil textural maps may be combined with land use or vegetation maps. Land use and vegetation can strongly influence soil hydraulic properties. The mapping table is used to assign initial parameters to the soil types in the index map. One or more of these parameters, typically K_s and ψ_f or ψ_b, are used as calibration parameters. As discussed by Senarath et al. (2000), calibration is best done using an automated calibration method, such as SCE (Duan et al. 1992), combined with long-term simulations. The possible parameter values are bounded by the range found in literature values, unless other factors, such as land use or vegetation, dictate otherwise. The range of values may be narrowed by making field and laboratory measurements of parameters.

8 Lateral Groundwater Flow Modeling in Saturated Zone

General

Simulation of saturated 2-D groundwater flow is selected by placing the **GW_SIMULATION** card in the project file. When groundwater simulations are performed, the starting water surface elevations (m) must be provided in a file specified with the **WATER_TABLE** card; the file containing bedrock elevations (m) is specified with the **AQUIFER_BOTTOM** card. The groundwater time-step must also be specified (s) using the **GW_TIME STEP** card, typically 300 – 1,200 s. A variety of boundary conditions can be specified with the **GW_BOUNDFILE** card. Saturated groundwater may be simulated using either the GAR or RE methods to calculate infiltration. The saturated groundwater solution was developed in conjunction with the RE unsaturated groundwater solution, and is intended to be used with RE. The GAR method was linked to the saturated groundwater model to provide a simple, quick, and approximate groundwater recharge estimate. This method is a useful screening tool, and can be used to help define parameter values before applying the more rigorous RE method. Whether GAR or RE is used affects how parameter values are assigned, as described in the following section.

Formulation

Trescott and Larson (1977) described the solution to the 2-D free surface groundwater problem, and the efficiency of various solvers. Their methods were largely followed in the development of this portion of the code; an exhaustive coverage need not be presented here. The overall approach, differences in approach, and integration into the *GSSHA* model are presented.

The controlling equation, as developed by Pinder and Bredehoeft (1968), is:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W(x,y,t) \qquad (40)$$

where:

T = the transmissivity ($m^2\ s^{-1}$)
h = the hydraulic head (m)
S = the storage term (dimensionless)
W = the flux term for sources and sinks ($m\ s^{-1}$)

It is assumed that off diagonal terms are not important and that transmissivity can be expressed as the product of the saturated hydraulic conductivity of the media (K) and the depth of the saturated media (b). For the free surface problem the head is the surface-water elevation (E_{ws}).

$$\frac{\partial}{\partial x}\left(K_{xx} b \frac{\partial E_{ws}}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} b \frac{\partial E_{ws}}{\partial y}\right) = S \frac{\partial E_{ws}}{\partial t} + W(x, y, t) \tag{41}$$

This equation can be represented using a block-centered finite difference five-point implicit scheme as:

$$\begin{aligned} &\frac{1}{\Delta x_j}\left\{\left[T_{xx(i,j+1/2,k)} \frac{h_{i,j+1}^{n+1} - h_{i,j}^{n+1}}{\Delta x_{j+1/2}}\right] - \left[T_{xx(i,j-1/2,k)} \frac{h_{i,j}^{n+1} - h_{i,j-1}^{n+1}}{\Delta x_{j-1/2}}\right]\right\} \\ &+ \frac{1}{\Delta y_i}\left\{\left[T_{yy(i+1/2,,k)} \frac{h_{i+1,j}^{n+1} - h_{i,j}^{n+1}}{\Delta y_{i+1/2}}\right] - \left[T_{yy(i-1/2,j,k)} \frac{h_{i,j}^{n+1} - h_{i-1,j}^{n+1}}{\Delta y_{i-1/2}}\right]\right\} \\ &= \frac{S_{i,j}^{n+1}}{\Delta t}\left(h_{i,j}^{n+1} - h_{i,j}^{n}\right) + W_{i,j}^{n+1} \end{aligned} \tag{42}$$

This representation varies from the original representation of Trescott and Larson (1977) in that the transmissivities and the storage terms are both time dependent and calculated implicitly using Picard iteration.

Solution

The equation is solved by successive overrelaxation by lines (LSOR) (for example Tannehill et al. 1997). LSOR was shown by Trescott and Larson (1977) to be capable of solving a variety of difficult groundwater problems, though not necessarily being the most efficient method. With LSOR, the 2-D problem is linearized by solving by rows or by columns. The user specifies solution by rows or by columns with the **GW_LSOR_DIR** project card, and the choice is made to align the direction of solution with the principal direction of flow, x (argument - 1) or y (argument - 2)

(Trescott and Larsen 1977). LSOR is an iterative method; the user selects the groundwater convergence criteria (m) with the **GW_LSOR_CON** project card. A typical value, the default, is 10^{-5} m. The user also selects an overrelaxation coefficient, ω, with the **GW_RELAX_COEF** card. During each iteration the head in each cell is adjusted by the over relaxation coefficient, ω, such that:

$$h^{k+1} = h^k + \omega(h^k - h^{k-1}) \tag{43}$$

where k denotes the iteration number. For ω greater than 1.0, the next head is projected out on a line determined from previous iterations. This speeds the convergence process but may also reduce stability. Typically, a value of ω of about 1.2 results the fastest solution. For very difficult problems ω may need to smaller than 1.0, and the solution is said to be underrelaxed.

For each iteration the transmissivities in both the x and y directions are calculated based on the updated saturated depth, b, determined from the heads, so that:

$$T^{k+1} = K_{gw} b^{k+1} \tag{44}$$

where K_{gw} is the lateral hydrualic conductivity of the porous media. This is a variation from Trescott and Larson (1977) who calculate the transmissivity based on the value of b from the last, n^{th}, time-step such that $T^{n+1} = K_{gw} b^n$. The storage term, S, in the equation is used to represent the change in volume with respect to the change in head:

$$S = \frac{\partial V}{\partial h} \tag{45}$$

where V is the volume. In 2-D applications it is common practice to represent the storage as the porosity of the saturated groundwater media. When RE is used to define the unsaturated zone the storage term, S, is not a constant but also depends on the head. The storage term is updated each iteration. The storage term is set to the porosity of the unsaturated cell above or below the groundwater surface elevation, depending on whether the groundwater is rising or falling. For time-steps when the groundwater moves more than one unsaturated zone cell, the storage term is calculated as a bulk storage term:

$$S^{n+1} = \frac{\sum(\Delta\theta_s)}{\sum \Delta z} \quad (46)$$

where $\sum \Delta z$ is the distance that the groundwater surface is anticipated to move during the *n+1* time-step or *k+1* iteration. The anticipated change in the groundwater surface elevation is determined from the source term, *W*, containing all fluxes in the cell and the storage capacity, *S*, of surrounding cells. An internal time-step limitation attempts to limit the movement of the groundwater surface to a single unsaturated zone cell. This added step helps maintains overall mass conservation. The actual storage available is $\theta_s - \theta$, but because water content is a discrete value in each cell, calculating storage as $\theta_s - \theta$ over $\sum \Delta z$ can result in a lack of convergence of the groundwater solution, which is implicitly calculating *h, S, b,* and *T* simultaneously. As discussed later in the section on coupling of processes, the difference in water volume between θ_s and $\theta_s - \theta$ is added to the source term during the next groundwater update, such that mass is conserved. This may result in a small time lag in the groundwater response.

When GAR is used to provide recharge estimates to the groundwater model, the storage term is constant, equal to the value moisture deficit of the soil, effective porosity minus soil moisture. The moisture deficit is updated every rainfall event.

Assignment of Parameter Values

The value of K_{gw} (cm hr^{-1}) may be specified as a constant value with the **GW_UNIF_HYCOND** or a map of spatially distributed values specified with the **GW_HYCOND_MAP** card. The porosity of the groundwater media below the specified unsaturated zone can be a uniform value, specified with the **GW_UNIF_POROSITY** card, or can be distributed by specifying a map of spatially distributed values using the **GW_POROSITY_MAP**. If neither uniform or distributed values of these parameters are specified with the previous cards, the values will be set to the those of the last soil layer of the soils in the unsaturated zone specified in the **SOIL_TABLE_INPUT_FILE** or mapping table files.

When GAR is used to provide estimates of recharge, only hydrualic conductivity need be specified, as the storage is computed using the GAR infiltration parameters.

Boundary Conditions

Each cell in the active domain is assigned a boundary condition with a map of integer values specified with the **GW_BOUNDFILE** project card. Boundary conditions around the border of the watershed may be constant head (type 2), constant flux (type 0) or a combination of both. Flux boundaries are represented by setting the transmissivity of flow boundary cells to zero and entering the flux in the source/sink term, *W*. For all non-head boundary cells (type 1), the unsaturated zone provides a flux to the source/sink term, *W*. The lower boundary is a flux term (cm hr^{-1}) that represents a leaky aquifer, specified with the **GW_LEAKAGE_RATE** project card. The default is zero. This single user-specified value is used in all cells.

Possible internal boundary conditions include constant head (type 2), constant flux (type 6), variable flux (type 3), river head (type 5) and river flux (type 4). The constant flux and variable flux boundaries are used to represent pumping wells of constant and variable rate, respectively. Water added/subtracted by pumping is added to the source/sink term, *W*. The possible boundary types are:

0 – no flow
1 – regular infiltration cell (no special boundary condition)
2 – specified head, taken from **WATER_TABLE** file
3 – dynamic flux, well, (not active)
4 – stream cell with calculated flux between stream node and groundwater cell
5 – stream cell with a specified head, value from stream routing solution
6 – static flux (well) value taken from the **GW_FLUX_BOUNDTABLE**

Stream boundary cells – type 4 and 5

When 1-D channel flow is simulated, grid cells containing stream channels may be represented as either head (type 5) or flux boundaries (type 4). For a head boundary, the elevation of the water surface in the stream node is used as a specified head in the groundwater solution. For a river flux boundary condition the flux between the groundwater cell and stream node is calculated during the channel routing update. Fluxes accumulated over multiple channel routing updates are accumulated and then added to the groundwater cell in the source/sink term, *W*. Additional inputs are required to simulate groundwater/stream interactions:

a. Thickness of the riverbed material, M_{rb}, (cm)
b. Vertical hydraulic conductivity of riverbed material, K_{rb} (cm hr^{-1})

These may be specified as uniform values using the **M_RIVER** and **K_RIVER** project cards, respectively. These may also be distributed along the stream network in the channel input file (cip file), specified with the **CHAN_INPUT** card. Four new channel link types have been added to *GSSHA* to allow interactions with the groundwater flow through the streambed material (Table 11).

Table 11. Groundwater/Stream Interaction Link Types.

Link Type	Description	Number of Parameters	Number of nodes
12	Fluvial trapezoidal cross section with subsurface parameters	7	>=2
13	Fluvial breakpoint cross section with subsurface parameters	4	>=2
14	Fluvial dual side slope trapezoidal cross section with subsurface parameters	8	>=2
31	Fluvial erodable trapezoidal cross section with subsurface parameters	7	>=2

The new link types are the same as link types 1 and 8, 9, and 30 but include individual **K_RIVER** and **M_RIVER** parameters for each node. The **K_RIVER** and **M_RIVER** flags specified in the project file become the default values, and are used for the subsurface parameters on all but these new link types, 12, 13, 14, and 31.

The lines for the nodes in link type 12 have the same order and number of parameters as link type 1, excepting that **K_RIVER** and **M_RIVER** are appended to the parameter list, in that order. For example, the link block for a trapezoidal channel link with 4 nodes, with an *n* of 0.19, 3.5 m bottom width, *z* of 5, K_{rb} of 1.5 cm hr^{-1}, and M_{rb} of 1.7 cm will look like:

```
2 4
0.019 3.50 0.00 5.0 643.38 1.5 1.7
0.019 3.50 0.00 5.0 642.98 1.5 1.7
0.019 3.50 0.00 5.0 642.65 1.5 1.7
0.019 3.50 0.00 5.0 641.37 1.5 1.7
```

The lines for the nodes in link type 13 have the same order and number of parameters as link type 8, except that **K_RIVER** and **M_RIVER** are appended to the parameter list, in that order. For example, for the same

channel with natural cross sections using lookup table 1, the link block will appear as:

```
2 4
1 643.38 1.5 1.7
1 642.98 1.5 1.7
1 662.65 1.5 1.7
1 641.37 1.5 1.7
```

The same pattern holds for link types 14 and 31, which are the same as link types 9 and 30, with the addition of the **K_RIVER** and **M_RIVER** parameters.

The flux through the riverbed is calculated based on the difference in elevation between the groundwater surface and the water-surface elevation in the stream node. McDonald and Harbaugh (1988) developed a simple method to compute flows between the channel network and saturated groundwater based on the Darcy equation. If the groundwater surface elevation is above the riverbed elevation but below the river water-surface elevation, the river discharges to the groundwater:

$$f = -\frac{K_{rb} / 3600}{M_{rb}}\left(E_r - E_{ws}\right) \tag{47}$$

where:

f = per unit area discharge (m s^{-1})
K_{rb} = hydraulic conductivity of the riverbed material (cm hr^{-1})
M_{rb} = depth of the riverbed material (cm)
E_r = elevation of the river water surface (m)
E_{ws} = elevation of the groundwater water surface (m)

The negative flux indicates that the discharge is into the groundwater. If the groundwater surface elevation is below the riverbed elevation the river leaks to the groundwater at the rate of:

$$f = -K_{rb}/3600$$

When the **STREAM_LOSS** card is used in the absence of a known or calculated water table location, this is used to compute the stream loss.

If the groundwater surface elevation is above the river water-surface elevation, the groundwater discharges to the river according to Equation 47. In this case, the flux will be positive, indicating flow is from the groundwater to the river. The unit flux, *f*, is multiplied by the top width and length of the channel segment. In calculating the top width an effective depth is defined. If the water-surface elevation in the channel is higher than the water-surface elevation of the groundwater, the channel depth is used in the calculation. When the groundwater level is higher than the water level in the stream, the effective depth used is the groundwater elevation minus the bed elevation.

The channel side slope properties are assumed to be the same as those of the channel bed. If properties vary significantly between the bed and the side slope an average or weighted average values should be input. This approach is highly empirical and the riverbed property values will require calibration to the system being modeled.

Static pumping wells – type 6

Static pumping rate wells may be placed in any cell in the watershed domain. Pumping wells are located by placing a value of 6 in the **GW_FLUX_BOUNDTABLE** at each desired well location. The **GW_FLUX_BOUNDTABLE** specifies the name of a file with the pumping rates. The **GW_FLUX_BOUNDTABLE** has the following format.

I location well 1	*J* location well 1	Pumping rate ($m^3\ d^{-1}$) well 1
I location well 2	*J* location well 2	Pumping rate ($m^3\ d^{-1}$) well 2
I location well 3	*J* location well 3	Pumping rate ($m^3\ d^{-1}$) well 3
...		
...		
...		
I location well *N-1*	*J* location well *N-1*	Pumping rate ($m^3\ d^{-1}$) well *N*-1
I location well *N*	*J* location well *N*	Pumping rate ($m^3\ d^{-1}$) well *N*

Values are separated by spaces or tabs, not commas. Groundwater extractions have a positive pumping rate; injections have a negative pumping rate. The number and *I*, *J* locations of the wells in table must match the number and location of wells in the **GW_BOUNFILE** file.

Coupling of Saturated Zone Model with Richards' Equation Model of Unsaturated Zone

In *GSSHA*, the saturated and unsaturated zones are linked though boundary conditions. When saturated groundwater is simulated, the lower boundary of the unsaturated zone is the saturated groundwater surface, as shown in Figure 9. Movement of the saturated groundwater surface according to the solution of the 2-D saturated flow equations requires a flexible spatial discretization for Richards' equation. In extreme cases the groundwater table may rise to the soil surface. In this case the unsaturated zone disappears, and only the saturated flow equations are solved.

When heads from the 2-D unconfined groundwater problem solution are used as the lower boundary condition of the unsaturated groundwater problem, the size of the unsaturated zone in each overland flow cell changes with each saturated groundwater update. Also, the storage term used in the saturated groundwater solution does not account for the water in the unsaturated zone. After solution of the saturated zone an extra step is required to account for the water that exists in the unsaturated zone.

Water is exchanged between the saturated and unsaturated zones through fluxes. Fluxes from the saturated zone to unsaturated zone are added to the source term of the *N-1* unsaturated cell during the next update for the unsaturated zone. The same procedure is used for fluxes to the saturated zone from the unsaturated zone. The formulation of the RE is exploited to correct any temporarily incorrect values of soil moisture or groundwater head. While this method works, it may induce a time lag in the solution. Making direct adjustments to the groundwater or the unsaturated zone while updating the other domain causes oscillations in groundwater levels, which may result in oscillations in stream discharge and ultimately, program crashes. Numerically, it is better to pass water through the source terms and let the calculations, which are solutions of diffusion equations, smooth out irregularities.

When the water table rises, the size of the *N-1* cell in the unsaturated zone is decreased and the moisture in the *N-1* cell is adjusted to account for the smaller cell size (Figure 9). If the size of the last cell becomes too small, less than a fourth the size of the *N-2* cell above it, the two cells are combined. The water content of the new cell is the total volume of water in the two cells divided by the size of the new cell, $\Delta Z_{N-1} + \Delta Z_{N-2}$. If the *N-1* cell becomes oversaturated the excess water is added back to the groundwater

as a source term during the next saturated groundwater update. Saturated cells stay in the unsaturated zone until the groundwater surface elevation is above the elevation of the cell. If the groundwater rises above the *N-1* cell, the *N-1* cell and any cells above it that are below the new groundwater level are removed from the unsaturated zone. The water in these cells is added back to the groundwater as a source term on the next saturated groundwater update.

When the groundwater table falls, the size of the *N-1* cell increases. The water content of the *N-1* cell changes to account for its increased size. If the size of the *N-1* cell increases to greater than 25 percent of the *N-2* cell, a new cell is created. If the groundwater falls rapidly more than one new cell may be created during a single groundwater time-step. Water in the *N-1* cell from the previous time-step, *n-1* time level, is distributed over the old *N-1* cell and any new cells. This may result in low water contents in these cells. The low water content in these cells places a demand on the saturated zone and water will be drawn from the saturated groundwater zone into the unsaturated zone to meet the demand. Very low water contents in new cells can cause computational problems in subsequent calculations because low hydraulic conductivities resulting from low water contents will prevent the movement of water in these cells. For this reason, the water content of new cells is compared to the saturation content and the water content corresponding to equilibrium with the groundwater table. If new cells are less than 75 percent saturated and the water content is less than the water content corresponding to equilibrium with the groundwater, the water content of the cell is increased to the equilibrium water content. Water for the new cells comes from the saturated groundwater domain, and results in a negative flux for the groundwater solution during the next time-step. This procedure may result in small oscillations in groundwater head, on the order of one unsaturated cell size.

When the water table rises to or above the ground surface of an overland flow cell, that cell becomes an exfiltration cell. Once a cell becomes an exfiltration cell, unsaturated groundwater calculations are no longer performed, and the overland flow plane becomes linked directly to the saturated groundwater. Exchange of water between the groundwater and the overland plane depends on the elevation of the land surface, depth of water on the overland flow plane, and the groundwater surface elevation. If the groundwater elevation is greater than the combined value of the elevation of the cell and the overland flow depth, the exfiltration depth,

d_{exfil} (m), onto the overland flow plane is computed each infiltration time-step as:

$$d_{exfil} = (E_{ws} - (E_{ov} + d_{ov}))\frac{\Delta t_{\inf}}{\Delta t_{gw}} S \tag{48}$$

where:

E_{ov} = the elevation of the cell (m)
E_{ws} = the elevation of the groundwater surface (m)
d_{ov} = the depth of water in the overland cell (m)
Δtinf and Δtgw = the time-steps (s) for infiltration and groundwater, respectively
S = the storage

If the groundwater elevation is less than the combined value of the ground elevation of the cell and the overland flow depth, exfiltration is into the groundwater, and is computed as:

$$d_{exfil} = -f_L \Delta t_{\inf} \tag{49}$$

where: f_L is the leakance (m s^{-1}) through the aquifer bottom, as specified by the user. If the calculated groundwater recharge is greater than the depth of water on the overland flow plane, then the recharge is set equal to the depth of water on the overland flow plane.

The upper boundary conditions for the saturated groundwater zone is the flux derived from solution of Richards' equation. During and after periods of rainfall, the unsaturated zone provides a positive flux, recharge, to the saturated zone. During dry periods, low soil pressure heads create a negative flux from the saturated groundwater zone to the unsaturated zone. If soils are shallow and evaporative demand is high, it is possible that the elevation of the groundwater surface may fall below the specified bottom of the aquifer. Two features are used to ensure that this condition is properly simulated. Multiple unsaturated cells are defined in the aquifer bedrock, increasing the possible number of cells in the unsaturated zone. The saturated hydraulic conductivity, K_s, of cells in the bedrock and immediately above the bedrock is reduced. In the last unsaturated cell above the bedrock, K_s is lowered to 10^{-2} K_s of the other cells in the saturated groundwater media. The vertical K_s is reduced to 10^{-5} cm hr^{-1} in the first cell in the

bedrock, and is further reduced to 10^{-6} cm hr^{-1} in additional cells in the bedrock. The lower hydraulic conductivity reduces the flow of water from the groundwater to the unsaturated zone. If the groundwater surface drops below the top of the bedrock, the lower boundary condition changes from $0.5\Delta Z_N$ to:

$$\psi_N = (E_{br} - E_{ws}) - 0.5\Delta z_N \tag{50}$$

where: E_{br} is the elevation at the top of the bedrock. As the groundwater level continues to fall, the head in the N cell becomes more negative, further reducing flow from the unsaturated zone.

Coupling of Saturated Zone Model to GAR Infiltration Model

The GAR routine described in Chapter 7 calculates infiltration and soil moisture based on the movement of multiple sharp wetting fronts that occur with rainfall burst followed by rainfall hiatus. The infiltration calculated by GAR can be used to provide a rough estimate of groundwater recharge to the 2-D saturated groundwater flow simulation. The groundwater recharge for each time-step is equal to the infiltration computed by GAR. In the model the groundwater recharge is computed each time-step as:

$$R = (F^{t+\Delta t} - F^t)A \tag{51}$$

where: R is equal to the recharge m^3, F is the total infiltration (m), and A is the area of the overland flow cell (m^2).

The simple “bucket” soil moisture accounting routine is used to calculate soil moistures between rainfall events. Soil moisture accounting begins at the end of the rainfall event, when the outlet discharge falls below the amount specified in **EVENT_MIN_Q**. At that time the soil moistures provided by the GAR method are sent to the soil moisture accounting routine and soil moisture calculations proceed until the next specified rainfall event. In the soil moisture accounting routine, the soil moisture is adjusted hourly for losses due to ET only. Even though water may be present on the overland flow plane, flowing and infiltrating, this does not affect the soil moisture accounting calculations. In this respect there is a disconnect between the ET calculations and the infiltration calculations. The storage term used in the saturated groundwater calculations in each

cell is assumed to be the effective porosity of the cell minus the initial moisture. The initial moisture is updated at the beginning of each rainfall event. When the groundwater elevations exceed the ground surface elevation, infiltration calculations for the cell cease, and the groundwater surface exchange is calculated as previously described. Any time exfiltration occurs, the infiltration and overland flow processes are initiated if they are not already active. These processes remain active as long as exfiltration occurs and until all water on the overland flow plane stops flowing and infiltrating. Infiltration is not calculated for cells in which exfiltration is occurring.

9 Continuous Simulations

GSSHA can be used to perform continuous simulations by specifying the **LONG_TERM** card in the project file, and providing the necessary input data. Continuous simulations require that one of two optional methods for calculating evapo-transpiration (ET) be selected, Deardorff (1978) or Penman-Monteith (Monteith 1965, 1981), as described in the next section. Hourly hydrometeorological observations are required for either method. The file containing the hourly values of hydrometeorological values is specified with the **HMET_*TYPE*** card. The ***TYPE*** can be **WES**, **SAMPSON**, or **SURFAWAYS**, as described later in this chapter. Any time long-term simulations are performed, snowfall accumulation and melting can be included in the simulations, as described in "Snowfall Accumulation and Melting." Infiltration must be calculated with either GAR or RE by use of the **INF_REDIST** or **INF_RICHARDS** cards, respectively. As described in "Sequence of Events during Long-Term Simulations," long-term simulations advance differently depending upon which method of calculating infiltration is chosen.

Computation of Evaporation and Evapotranspiration

The evaporation and evapotranspiration models incorporated in *GSSHA* allow calculation of the loss of soil water to the atmosphere, improving the determination of soil moistures. Two different evapo-transpiration options are included:

a. Bareground evaporation from the landsurface using the formulation suggested by Deardorff (1978)
b. Evapo-transpiration from a vegetated landsurface utilizing the Penman-Monteith equation (Monteith 1965, 1981).

Variants of these two representations are widely used in land-surface schemes of climate and distributed hydrologic models (e.g., Dickinson et al. 1986; Beven 1979).

To accurately compute fluxes of soil water to the atmosphere, energy fluxes between the atmosphere and the ground must first be computed. These energy, or radiation, fluxes, discussed in the next section, are the forcing terms in the evapo-transpiration calculations. Ground temperature

is an important component in both the Deardorff and Penman-Monteith formulations, and the fluxes computed in "Computation of Auxiliary Energy and Heat Fluxes" are used in the computation of the ground temperature as described in "Estimation of Ground Temperature." A detailed presentation of the Deardorff method in "Bare Ground Evaporation" describes how the computed fluxes and ground temperatures can be related to bare soil evaporation. "Evapo-transpiration" details how the computed fluxes are adjusted and applied for computation of evapotranspiration with the Penman-Monteith equation. Finally, "Parameter Values" describes the additional inputs needed for ET calculations.

Computation of auxiliary energy and heat fluxes

Realistic estimates of incoming and outgoing radiation fluxes are needed for accurate estimates of ET. The important components of the energy budget are long-wave radiation, short wave radiation, and heat conduction into the soil, which are all discussed in the following sections. Influences of soil, water, vegetation, and cloud albedos, atmospheric emissivities, and sloping-terrain effects on energy fluxes must be included in the calculations. The effects of albedos and emissivities are of great importance in determining radiation fluxes and warrant detailed representation (Pielke 1984).

Net incoming short-wave radiation.

The net incoming short-wave radiation can be represented as:

$$R_s = (1 - A)\left[R_{s,direct} + R_{s,diffuse}\right] \tag{52}$$

where: A is the albedo, and $R_{s,\,direct}$ and $R_{s,\,diffuse}$ are direct and diffuse contributions of short-wave radiation, respectively.

It is also imperative that short-wave energy influxes be modified to account for sloping terrain effects. As described by Young (1972), even in the Great Plains region of North America (one of the flattest places on earth), only 7 percent of the land area can be classified as flat in relation to solar radiation calculations. Despite the significance of terrain, most hydrologic and Global Climate Model (GCM) land-surface schemes ignore the sloping terrain effects when estimating the soil energy budgets. Pielke (1984) found substantial differences between the solar radiation values from north and south facing slopes. Pielke and Mehring (1977) found that

"the eastern slope of a 1-km mountain (with a slope of about 2°) to be about 1° to 2°C warmer in the morning and cooler by the same amount in the afternoon than the same location in the western slope." The direct incoming solar irradiance can be represented as:

$$R_{s,direct} = R_{s,horiz,direct,ground} \frac{\cos(\lambda)}{\cos(\zeta)} \tag{53}$$

where: λ is angle of incoming radiation, ζ is the local land surface slope in the azimuthal direction of the sun, and $R_{s,\ horiz,direct,ground}$ is the direct radiation on a horizontal ground surface, computed as:

$$R_{s,horiz,direct,ground} = K_t \left[1-(1-K)N\right] e^{-nam} R_{s,horiz,direct} \tag{54}$$

where: the transmission coefficient, K_t (dimensionless) is a function of density, type and condition of vegetation, N is the fraction of sky covered by cloud cover (0-1), n is a turbidity factor of air that varies from 2.0 (clear air) to 5.0 (smoggy urban areas), currently fixed at a value of 2.0 in the code. K is the fraction of cloudless sky insolation received on a day with overcast skies, and is given as:

$$K = 0.18 + 0.0853z \tag{55}$$

where z is the height to the cloud-base (km), fixed in the current formulation at 1.5 km. The molecular scattering coefficient, a, is defined as:

$$a = 0.128 - 0.054 \log_{10} m \tag{56}$$

The optical air mass, m, is calculated as:

$$m = \left[\sin(\lambda) + 0.1500(\lambda + 3.885)^{-1.253}\right]^{-1} \tag{57}$$

where: λ is the angle from the observer's horizon to the center of the solar disk, and is often referred to as the "solar elevation angle." Calculation of λ is discussed in the following equation.

If no measurements of $R_{s,horz,direct}$ are available, then they may be estimated based on the time of day and year, and the location of the watershed from:

$$R_{s,horiz,direct} = S_o \left(\frac{a^2}{r^2} \right) \sin(\lambda), \text{ if } \lambda < 90^o, \text{ and} \tag{58}$$

$$R_{s,horiz,direct} = 0, \text{ if } \lambda > 90^o \tag{59}$$

where the solar constant, S_o, has a value of 1376 W m^{-2} (Hickey et al. 1980). Following Paltridge and Platt (1976) the ratio of the actual earth-sun distance squared (a^2) to the average earth-sun distance squared (r^2) on any given Julian day m^* can be estimated using the following relationship:

$$\begin{aligned} \frac{a^2}{r^2} = {} & 1.000110 + 0.034221 \cos(d_o) + 0.001280 \sin(d_o) \\ & + 0.000719 \cos(2d_o) + 0.000077 \sin(2d_o) \end{aligned} \tag{60}$$

where:

$$d_o = \frac{2\pi m^*}{365} \tag{61}$$

where: m^* is the number of the day (i.e., ranging from 0 (January 1) to 364 (December 31)), and d_o is the Julian day fraction of the year converted to radians. The angle (i) between the direct solar radiation and the normal to the slope is defined as (Kondrat'yev 1969):

$$\cos(i) = \cos(\alpha) \sin(\lambda) + \alpha \cos(\lambda) \cos(\beta - \gamma) \tag{62}$$

The slope of the terrain (α) is given by:

$$\alpha = \tan^{-1} \left[\left(\frac{\partial z_G}{\partial x} \right)^2 + \left(\frac{\partial z_G}{\partial y} \right)^2 \right]^{1/2} \tag{63}$$

where: $\partial z_G / \partial x$ and $\partial z_G / \partial y$ represent the incremental slopes in the x and y directions. The zenith angle (λ) is defined by:

$$\sin(\lambda) = \cos(\phi) \cos(\delta_{sun}) \cos(h_r) + \sin(\delta_{sun}) \sin(\varphi) \tag{64}$$

where: angle ϕ is the latitude at the site of interest. The orientation of the sun's azimuth β relative to the azimuth of the terrain slope γ is given by $\beta - \gamma$. The trigonometric relationship for γ is:

$$\gamma = \frac{\pi}{2} - \tan^{-1}\left(\frac{\frac{\partial z_G}{\partial x}}{\frac{\partial z_G}{\partial y}}\right) \tag{65}$$

The trigonometric relationship for β is:

$$\beta = \sin^{-1}\left(\frac{\cos\ (\delta_{sun})\sin\ (h_r)}{\cos(\lambda)}\right) \tag{66}$$

where: δ_{sun} is the declination angle of the sun (varying between +23.5° on June 21 to -23.5° on December 22), and can be obtained by using the following formulation (Paltridge and Platt 1976):

$$\begin{aligned}\delta_{sun} = {} & 0.006918 - 0.399912\cos(d_o) + 0.070257\sin(d_o) \\ & - 0.006758\cos(2d_o) - 0.000907\sin(2d_o) \\ & - 0.002697\cos(3d_o) + 0.001480\sin(3d_o)\end{aligned} \tag{67}$$

where: δ_{sun} is in radians. The hour angle, h_r (0° ≡ noon) is represented mathematically when the sun is east of the observer's longitude as follows (Curtis and Eagleson 1982):

$$h_r = 15(T_s + 12 - \Delta T_1 + \Delta T_2) \tag{68}$$

where: T_s is the standard time at the site of interest (counted from midnight; i.e. from 0.00 to 23.59), ΔT_2 is the difference between true solar time and mean solar time in hours (small; hence is neglected in this analysis), and ΔT_1 is the difference between the standard and local longitudes (in hours) given as:

$$\Delta T_1 = \frac{i^*}{15}\ (\ \theta_s - \theta_L\ ) \tag{69}$$

where $i^* = 1$ for longitudes located to the east of Greenwich and $i^* = -1$ for those located to the west, and θ_S and θ_L are the longitudes of the standard-

and the observer-meridian, respectively. The standard-meridian is defined as the meridian where the observer's time zone is centered. When the sun is west of the observer's longitude the following relationship is used:

$$h_r = 15(T_s - 12 - \Delta T_1 + \Delta T_2) \tag{70}$$

The diffuse short-wave radiation is obtained by using the following relationship (Kondrat'yev 1965):

$$R_{s,diffuse} = R_{s,horiz,diffuse} \cos^2\left(\frac{\alpha}{2}\right) \tag{71}$$

Lee (1978) noted that the difference between $R_{s,diffuse}$ and $R_{s,horiz.,diffuse}$ is only 2 percent for slopes less than 30 percent. Lee (1978) also showed that for slopes less than 36 percent, the contribution to the total solar radiation by the reflection of total solar from surrounding sloped terrain is only 3 percent or less. The diffuse horizontal radiation, $R_{s,horiz.,diffuse}$ data are extracted from NOAA-NREL CD-ROMs, and hence atmospheric scattering and absorption effects are neglected.

Net incoming long-wave radiation.

The net incoming long-wave radiation can be represented as follows:

$$R_l = (1 - A)\ \sigma\ K^*\ E_a\ T_a^4 - \sigma\ E_g\ T_g^4 \tag{72}$$

where: A is the long-wave surface albedo, σ is the Stephan-Boltzmann constant with a value of 5.67 x 10^{-8} $Jm^{-2}s^{-1}K^{-4}$, T_g and T_a are the absolute ground and the air temperatures (Kelvins), respectively, K^* is the cloudiness-correction factor (dimensionless), and E_a and E_g are the emissivities of the air and the ground surfaces, respectively (dimensionless). Following Bras (1990), it is assumed that the ground surface acts as a blackbody, with an emissivity of 1.0. The long-wave radiation from clear skies is strongly related to the atmospheric water content. The following formulation is used to evaluate the atmospheric emissivity (Idso 1981):

$$E_a = 0.740 + 0.0049e \tag{73}$$

where e is the vapor pressure (mb), and can be obtained from the following relationship:

$$e = rhe_s \tag{74}$$

where: rh is the relative humidity (dimensionless, expressed as a decimal number between 0 and 1), and e_s is the saturated vapor pressure (mb). Using the Teten's formula (Teten 1930) the saturated vapor pressure can be approximately evaluated as:

$$e_s = 0.6108\, e^{\left(\frac{17.27\, T_a}{237.3 + T_a}\right)} \tag{75}$$

The presence of clouds gives rise to an increase in long-wave radiation. The following relationship, suggested by the TVA (1972), is used to evaluate K^*:

$$K^* = (1 + 0.17N^2) \tag{76}$$

where N is the fraction of sky covered by clouds.

Heat conduction into soil

Many models neglect the soil heat flux (Manabe et al. 1974; Gates 1975), however, Deardorff (1978) has found the assumption of an insulated soil surface to be especially poor under random atmospheric forcing-conditions. Following Kasahara and Washington (1971), in *GSSHA* the soil heat flux at the surface (positive when directed into the soil) is represented as a function of sensible heat flux. Deardorff (1978) found the following relationship to be of "intermediate but surprisingly acceptable accuracy" in determining the sum of energy fluxes into the soil (W m^{-2}) for short time-steps:

$$G = \frac{1}{3} H_s \tag{77}$$

where H_s is the sensible heat flux (W m^{-2}) (positive when directed upward), represented mathematically as:

$$H_s = \rho_a c_p c_H u_a (T_g - T_a) \tag{78}$$

where: c_p is the specific heat at constant pressure, equal to 1.013 kJ kg^{-1} °C^{-1}, u_a is the wind speed (m s^{-1}) at the reference level, z, and

c_H is the dimensionless heat or moisture transfer coefficient applicable to bare soil. Following Deardorff (1978) a value of 0.0025 is selected for c_H. The air density ρ_a is calculated as (kg m^3):

$$\rho_a = 3.486 \frac{P_a}{275 + T_a} \tag{79}$$

where: P_a is the atmospheric pressure in kPa, and T_a is the air temperature in ^{o}C.

Estimation of ground temperature

Because ground temperature appears explicitly in the outgoing long-wave energy flux-term, and implicitly in the Deardorff (1978) and Penman-Monteith evaporation formulae, it is important for radiation and evaporation calculations. Ground temperature varies considerably during the diurnal cycle and is not generally measured or provided by meteorological or weather stations. In *GSSHA* the ground temperature is obtained numerically by solving the surface energy balance equation with the Newton-Raphson iterative method as described by Deardorff (1978).

Assuming that the energy lost due to temporary storage, advection and biochemical usage are negligible for nonvegetated surfaces, the surface energy balance formulation can be written as:

$$f(T_g) \equiv H_s + E - R_l - R_s + G = 0 \tag{80}$$

where: the terms H_s, R_l, Rs and G have been previously defined, and E is the evaporation latent heat flux (W m^{-2}) from bare soil, as described in the next section.

The saturation specific humidity (kg kg^{-1}), a function of ground temperature, q_{sat} (T_g) (mb) can be calculated from:

$$q_{sat}(T_g) = \varepsilon \frac{e_s}{P - (1 - \varepsilon) e_s} \tag{81}$$

where: ε is the ratio of molecular weight of water vapor to that for dry air (0.622), and q_a is the specific humidity, estimated by substituting $e = rhe_s$ for e_s, where rh is the relative humidity.

The Clausius-Clapeyron equation is used to calculate the derivative of q_s with respect to T_g as:

$$\frac{dq_s(T_g)}{dT_g} = \left[\frac{P}{P - (1 - \varepsilon)\, e_s} \right] \frac{L}{R_{water}\, T_g^2}\, q_s(T_g) \tag{82}$$

where: R_{water} is the gas constant for water vapor (461 J kg^{-1} °K^{-1}) and L is the latent heat of evaporation (2.50036 MJ kg^{-1}). Following Williamson et al. (1987), the latent heat of evaporation, known to vary with ground temperature, is a constant. The ground temperature can be obtained iteratively using the following relationship:

$$T_g^{K+1} = T_g^{K} - \frac{f(T_g^{K})}{f'(T_g^{K})} \tag{83}$$

where: K indicates the iteration count, $f(T_g)$ is obtained from Equation 80 and $f'(T_g)$ is obtained from Equation 82. The initial value for the iterative procedure is the surface temperature from the previous time-step, T_g^{n-1}. The procedure is repeated until the following condition is satisfied:

$$\left| T_g^{k+1} - T_g^{k} \right| \le \delta_\varepsilon \tag{84}$$

A convergence criterion, δ_ε of 0.001 °K is utilized in this analysis. When the convergence criterion is satisfied the Clausius-Clapeyron equation is solved, and $T_g^n = T_g^{k+1}$.

Bare ground evaporation

The **ET_CALC_DEARDORFF** card is used to specify bare ground evaporation with the Deardorff method. For areas without vegetation the evaporation rate from the ground, E, (kg m^{-2} s^{-1}) can be calculated based on the saturation specific humidity and soil wetness mathematically as:

$$E = \rho_a\, c_H\, u_a\, \alpha^* \left[q_{sat}(T_g) - q_a \right] \tag{85}$$

The wetness factor, α^* is a function of soil moisture. Following Budyko (1948) and Manabe (1969) the wetness factor is estimated by using the following two relationships

$$\alpha^* = \begin{cases} 1.0 & W \geq W_c \\ \dfrac{W}{W_c} & W \prec W_c \end{cases} \quad (86)$$

where W is the moisture available at the beginning of the time-step in the surface layer of soil, defined with the **SOIL_MOIST_DEPTH** project card (m), and W_c represents the fraction of soil field capacity at which potential evaporation ceases. The latter is represented mathematically as follows:

$$W_c = 0.75 W_{fc} = 0.75 n_e d_{soil} \quad (87)$$

where: W_{fc} is the soil field capacity, n_e is the effective porosity and d_{soil} is the depth of the upper soil layer (cm). It is assumed that evaporation ceases when soil water content reaches the wilting point. This correction is only applied when using the GAR method for infiltration. Calculation of AET from PET for the Richards' equation solution was described in Chapter 7, "Evapotranspiration source term."

When using the GAR method of computing infiltration, wilting point water contents may be entered in the mapping table file, Chapter 11, or with a GRASS ASCII map specified with the **WILTING_POINT** project card. When using Richards' equation, the wilting point is entered in the mapping table along with the other RE parameters, Chapter 11.

Evapotranspiration

The **ET_CALC_PENMAN** project card is used to select the Penman-Monteith method for evapo-transpiration. The Penman-Monteith equation is one of the most advanced resistance-based models available for the prediction of evapo-transpiration from a vegetated land-surface (Shuttleworth 1993). Although Monteith (1965) points out several simplifying assumptions utilized to derive the Penman-Monteith evaporation formula, Lemeur and Zhang (1990) have found that for arid watershed the performance of the Penman-Monteith is better than both the CRAE (Morton 1983) and the Advection-Aridity (Brutsaert and Stricker 1979) models. In the Penman-Monteith model, the actual evapo-transpiration estimates are obtained by using the following relationship:

$$E^* = \frac{1}{\lambda}\left[\frac{\Delta A^* + \frac{\rho_a c_p}{r_a}(e_s - e)}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)}\right] \tag{88}$$

where:

Δ = the slope of the specific humidity/temperature curve between the air temperature and the surface temperature of the vegetation (kPa °C^{-1})

λ = the latent heat of vaporization of water (2.50036 MJ kg^{-1})

c_p = the specific heat of air at constant pressure (1.013 kJ kg^{-1} °C^{-1})

γ = the psychrometric constant (kPa °C^{-1})

r_a = the aerodynamic resistance to the transport of water vapor from the surface to the reference level z (s m^{-1})

r_c = the (Monteith) canopy resistance (s m^{-1}) to the transport of water from some region within or below the evaporating surface to the surface itself. The canopy resistance is expected to be a function of the stomatal resistance of individual leaves. Under wet-canopy conditions r_c = 0.

A^* = the available energy given by $A^* = (R_l + R_s) - G$ (W m^{-2})

R_s = the net incoming short-wave radiation at the reference level z, (W m^{-2})

R_l = the net long-wave radiation at the reference level z (W m^{-2})

G = the sum of energy fluxes into the ground, to adsorption by photosynthesis and respiration and to storage between ground level and z (in W m^{-2})

The standard reference level, z, is taken as 2 m. The current formulation does not explicitly calculate the leaf temperature of the vegetation canopy, and the ground temperature is substituted for the leaf temperature when calculating Δ. The psychrometric constant, γ, is defined as:

$$\gamma = \frac{c_p P}{\varepsilon\lambda} 10^{-3} \tag{89}$$

where: P is the atmospheric pressure (kPa). The gradient of the saturation vapor pressure curve with respect to temperature, Δ, is given by:

$$\Delta = \frac{4098 e_s}{(237.3 + T_g)^2} \tag{90}$$

The rate of water diffusion from the ground surface due to turbulence is controlled by the aerodynamic resistance term, r_a. This term is a function of wind speed and the height of the vegetation cover. Mathematically, r_a is represented as:

$$r_a = \frac{\ln\left[\frac{(z_u - d)}{z_{om}}\right] \ln\left[\frac{(z_e - d)}{z_{ov}}\right]}{(0.41)^2 U_z} \tag{91}$$

where: z_u and z_e are the heights of the wind speed and humidity measurements (m), respectively, and U_z is the wind speed (m s^{-1}). Following Brutsaert (1975), z_{om} is assumed to be $0.123 h_c$ and z_{ov} is assumed to equal $0.0123 h_c$, where h_c is the mean height of the crop (m). According to Monteith (1981) $d = 0.67\ h_c$.

Parameter values

Calculation of evapo-transpiration requires additional parameter values be assigned to every active grid cell. These parameters may be assigned with either the mapping table file, Chapter 11, or GRASS ASCII maps specified with project cards described in Chapter 3, "Continuous Simulations-Optional." ET parameters are typically assigned with a combination soil texture/land use (STLU) index map. The Deardorff method requires values of land surface albedo. For the Penman-Monteith method, values of land surface albedo, vegetation height, vegetation canopy resistance, and vegetation transmission coefficient are needed.

Land surface albedo.

Ground surface temperature calculations, discussed previously, require values of land surface albedo, which describe the fraction of long-wave radiation reflected back to the atmosphere. Values range from 0.0 to 1.0. Literature values for a variety of land covers compiled from a number of sources are listed in Table 12.

Table 12. Land Surface Albedo Values.

Ground Cover	Albedo
Fresh snow	0.75 - 0.95[b], 0.70 - 0.95[c], 0.80-0.95[d]
Fresh snow (low density)	0.85[f]
Fresh snow (high density)	0.65[f]
Fresh dry snow	0.80 - 0.95[g]
Pure white snow	0.60 - 0.70[g]
Polluted snow	0.40 - 0.50[g]
Snow several days old	0.40 - 0.70[b], 0.70[c], 0.42 - 0.70[d]
Clean old snow	0.55[f]
Dirty old snow	0.45[f]
Clean glacier ice	0.35[f]
Dirty glacier ice	0.25[f]
Dark soil	0.05 - 0.15[b], 0.05 - 0.15[g]
Dry clay or gray soil	0.20 - 0.35[b], 0.20 - 0.35[g]
Dark organic soils	0.10[f]
Dry black soil	0.14[i]
Moist black soil	0.08[i]
Dry gray soils	0.25 - 0.30[i]
Moist gray soils	0.10 - 0.20[g], 0.10 - 0.12[i]
Dry blue loam	0.23[i]
Moist blue loam	0.16[i]
Desert loam	0.29 - 0.31[i]
Clay	0.20[f]
Dry clay soils	0.20 - 0.35[d]
Dry light sand	0.25 - 0.45[b]
Dry, light sandy soils	0.25 - 0.45[g]
Dry, sandy soils	0.25 - 0.45[a]
Light sandy soils	0.35f
Dry sand dune	0.35 - 0.45[b], 0.37[c]
Wet sand dune	0.20 - 0.30[b], 0.24[c]
Dry light sand, high sun	0.35[f]
Dry light sand, low sun	0.60[f]
Wet gray sand	0.10[f]
Dry gray sand	0.20[f]
Wet white sand	0.25[f]
Dry gray sand	0.35[f]
Yellow sand	0.35[i]
White sand	0.34 - 0.40[i]
River sand	0.43[i]

Ground Cover	Albedo
Bright, fine sand	0.37[i]
Rock	0.12 - 0.15[i]
Peat soils	0.05 - 0.15[d]
Dry black coal spoil, high sun	0.05[f]
Dry concrete	0.17 - 0.27[b]
Road black top	0.05 - 0.10[b]
Densely urbanized areas	0.15 - 0.25[i]
Wet dead grass	0.20[f]
Dry dead grass	0.30[f]
High, dense grass	0.18 - 0.20[i]
Green grass	0.26[i]
Grass dried in sun	0.19[i]
Typical fields	0.20[f]
Dry steppe	0.25[f], 0.20 - 0.30[g]
Tundra and heather	0.15[f]
Tundra	0.15 - 0.20[g]
Heather	0.10[i]
Meadows	0.15 - 0.25[g]
Cereal and tobacco crops	0.25[f]
Cotton, potatoes and tomato crops	0.20[f]
Cotton	0.20 - 0.22[i]
Cotton plantations	0.20 - 0.25[g]
Potatoes	0.19[i]
Potato plantations	0.15 - 0.25[g]
Lettuce	0.22[i]
Beets	0.18[i]
Sugar cane	0.15[f]
Agricultural crops	0.20 - 0.30[d]
Rice field	0.12[i]
Rye and wheat fields	0.10 - 0.25[g]
Spring wheat	0.10 - 0.25[i]
Winter wheat	0.16 - 0.23[i]
Winter rye	0.18 - 0.23[i]
Deciduous forests	0.15 - 0.20[g]
Deciduous forests - bare with snow on the ground	0.20[d]
Mixed hardwoods in leaf	0.18[f]
Rain forest	0.15[f]
Eucalyptus	0.20[f]

Ground Cover	Albedo
Forest - pine, fir, oak	0.10 - 0.18[c]
Forest - coniferous forests	0.10 - 0.15[g], 0.10 - 0.15[d]
Forest - red pine forests	0.10[f]
Tops of oak	0.18[i]
Tops of pine	0.14[i]
Tops of fir	0.10[i]
Water	-0.0139 + 0.0467 tan Z, 1 >= A >= 0.03[h]

Notes: [a]The smaller value is for high zenith angles; the larger value is for low zenith angles.
From [b]Sellers (1965); [c]Munn (1966); [d]Rosenburg (1974); [f]Lee (1978); [g]de Jong (1973); [h]Atwater and Ball (1981); and [i]Eagleson (1970).

Canopy stomatal resistance

Plants lose water through their leaves through a process called transpiration. This water is lost through small opening in the leaves called stomata. Inside the leaf the air is near saturation, and the difference between air saturation and leaf saturation causes the plant to lose moisture due to diffusion. The plant can control the loss of water by opening and closing the stomata. The loss of water vapor from plants can be calculated from a resistance law, where the difference in saturation between the interior of the leaf and the atmosphere is the forcing term, and the canopy stomatal resistance is the resisting term.

The canopy stomatal resistance values entered in *GSSHA* must represent the resistance of the canopy for an entire grid cell. The canopy resistance is affected by coverage, time of day, and the type and condition of plants in the cell. Greater leaf coverage means lower resistance values. In *GSSHA*, noontime canopy resistance values are entered. Canopy resistance has a strong diurnal variation and the *GSSHA* model corrects the noontime canopy resistance for the time of day. Although stomatal resistances are not commonly available for mixed-vegetation types, data are available for a variety of single vegetation types (e.g., Sceicz and Long (1969) for grass; Stewart and Thom (1973) for pine forest; Allen et al. (1989) for clipped grass and alfalfa). Noontime values of canopy resistance (s m^{-1}) for different types of plant under different conditions are listed in Table 13.

Table 13. Canopy Stomatal Resistance.

Vegetation Type	Canopy Resistance at Noon (s m^{-1})
Cotton field[1]	~ 17
Coniferous forest (Spruce)[1]	~ 100
Coniferous forest (Hemlock)[1]	~ 150
Coniferous forest (Pine, March)[2]	~ 140
Coniferous forest (Pine, June)[2]	~ 120
Coniferous forest (Pine, September/October)[2]	~ 123
Prairie grasslands (late July)[3]	~ 100
Prairie grasslands (mid September)[3]	~ 500
Irrigated short grass crop[4]	~ 86
Unirrigated barley[4]	~ 43

Notes: [1]Pielke (1984); [2]Gash and Stewart (1975), [3]Monteith (1975); and [4]Sceicz and Long (1969).

The Penman-Monteith equation has been found to be very sensitive to the value of canopy resistance. As pointed out by Lemeur and Zhang (1990), a 10 percent error in canopy resistance will result in a 10 percent error in the estimated evapo-transpiration. Senarath et al (2000) found that the discharges calculated during long-term simulations with *CASC2D* were also sensitive to the canopy resistance.

In the northern hemisphere temperate zone ET is subject to strong seasonal variations. ET is dependent on both climatic conditions and the vegetative cover. The seasonal variability of climatic conditions is reflected in the model with the hourly hydrometeorological inputs (Senarath et al. 2000). Vegetative cover is represented with simple land use/land cover indexes, such as forest, pasture, etc. Seasonal changes in vegetation cover are best simulated with plant growth models. Comprehensive plant growth models, such as *SWAT* (Arnold et al. 1999), and hydrologic models that include comprehensive plant growth models, *TOPOG_IRM* (Dawes et al. 1997) require extensive information on plant communities and growing conditions. Such detailed data are not routinely available.

Senarath et al. (2000) determined that of the ET parameters used in the Penman-Monteith equation, evapo-transpiration is most sensitive to the value of canopy resistance, and is quite insensitive to the other ET parameters. Leaf area and canopy resistance can vary by as much as several hundred percent during the year for crops, grasses, and deciduous forest in

temperate regions (Monteith 1975; Doorenbos and Pruitt 1977; Federer and Lash 1978). Based on this information, the canopy resistance was chosen as the vehicle to incorporate seasonal variability of ET in the *GSSHA* model.

Midgrowing season values of canopy resistance are input as the starting point. For each month an amplification factor is used to represent the change in the canopy resistance related to plant growth. This midseason value is then applied directly for the months of May through September. Thus, the amplification factor for May-September is 1.0. For the months November through February, the amplification factor is 4.0. This high factor relates to the death of crops, the browning of grasses and loss of leaves in deciduous trees. The months of March and October are considered transition months, and an amplification factor of 2.5 is used during these months. The timing of these events corresponds to values used for the transpirational leaf area of deciduous forest in North Carolina (Federer and Lash 1978), though similar timing in conductance and ET is seen in other areas of the continental U.S. (Nixon et al. 1972 for example). The implied assumptions of this simplistic approach, depicted in Figure 13, are then:

a. At the end of March grasses begin to green, crops to sprout and trees leaf
b. By the first of May crops are near mature, and trees have full foliage
c. By the beginning of October crops begin to die, grasses to brown and trees lose leaves
d. For the period November through February, plants are dormant and transpire little water to the atmosphere

Use of this simple method at the Goodwin Creek Experimental Watershed (GCEW) in north Mississippi resulted in improved predictions of soil moistures and outlet discharge for periods outside the summer growing season (Downer 2002a). The timing of seasonal changes should be adjusted to make the method applicable to climates different from that of southeast region of North America.

Seasonal variability of canopy resistance is selected by placing the **SEASONAL_RS** card in the project file along with the **LONG_TERM** card.

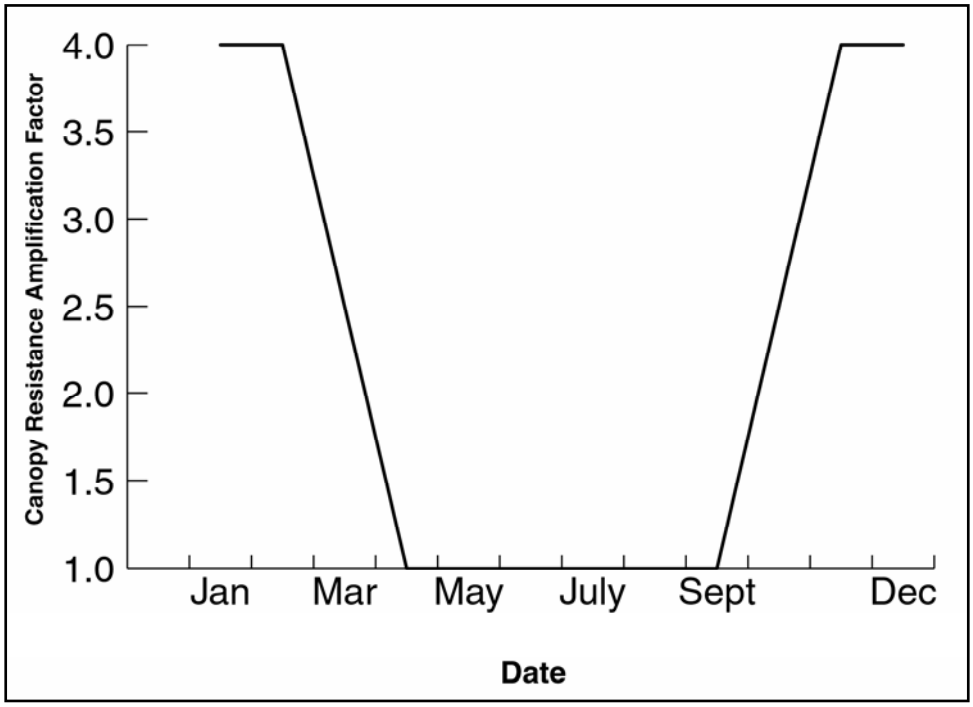


Figure 13. Seasonal variation of canopy resistance in GSSHA.

Vegetation height

The vegetation height is required to compute the aerodynamic resistance term in the calculation of turbulent diffusion. Vegetation heights are entered in meters. Sample values are listed in Table 14 (see Eagleson 1970) from Table 12. The values may not be the representative, expected vegetation height-values of these vegetation/forest types.

Table 14. Sample Values of Vegetation Height.

Vegetation / Forest Types	Sample Vegetation Height (cm)
Mown grass	1.5 - 4.5
Alfalfa	20 - 40
Long grass	60 - 70
Maize	90 - 300
Sugar cane	100 - 400
Brush	135
Orange orchard	350
Pine forest	500 - 2700
Deciduous forest	1,700

Vegetation transmission coefficient

The plant canopy can prevent radiation from reaching the ground surface, reducing the amount of radiation available to heat the ground surface and produce evaporation. The vegetation transmission coefficient describes the fraction of light that penetrates the vegetation canopy and reaches the ground. Values can range between 0.0, total canopy blocking of sunlight, to 1.0, total light penetration on bare soil. Table 15 lists measured values of canopy resistance for grass.

Table 15. Vegetation Transmission Coefficient Values for Grass.

Grass Height (cm)	K_t
100	0.18
50	0.18
10	0.68
Notes: Data from Sutton (1953)	

Hydrometeorological data

In order to perform continuous simulation in *GSSHA* hydrometeorological data are required for the entire period of the continuous simulation. The required data are hourly values of:

a. Barometric pressure
b. Relative humidity
c. Total sky cover
d. Wind speed
e. Dry bulb temperature
f. Direct radiation
g. Global radiation

These data are available from a wide variety of sources and three different input file formats can be used. The *GSSHA* model also contains provisions to synthetically produce solar radiation estimates and fill in short-term data gaps.

Hydrometeorological input file formats

The three file formats that *GSSHA* supports are discussed in the following paragraphs in order of preference. Simple file formats are preferred

because the likelihood of a data format error is reduced. The WES format is the simplest because it uses no alphabetical characters. Users are encouraged to produce and use hydrometeorological data files in the WES format for continuous simulations. The other formats contain data quality flags, extraneous data, and occasionally errors. Such errors can be difficult to locate. Reducing data down to the WES format through independent software (such as a spreadsheet) ensures that the data are properly formatted and contains no extraneous values.

HMET_WES (Recommended format).

This file contains only hourly values of the required hydrometeorological parameters: barometric pressure, relative humidity, total sky cover, wind speed, temperature, direct radiation, and global radiation. The **HMET_WES** format contains the following numbers in columns 1-11 (Table 16):

Table 16. HMET_WES File Format.

Col.	Variable	Units	No Data Flags	Type
1	Year (4 digit)			integer
2	Month			integer
3	Day			integer
4	Hour			integer
5	Barometric Pressure	in Hg	No Data (ND) = 99.999	real
6	Relative Humidity	%	ND=999	integer
7	Total Sky Cover	%	ND=999	integer
8	Wind Speed	kts	ND=999	integer
9	Dry Bulb Temperature	^{o}F	ND=999	integer
10	Direct Radiation	W h m^{-2}	ND=9999.99	real
11	Global Radiation	W h m^{-2}	ND=9999.99	real

Data format is important; the year is stored as a four-digit number; the hour varies between 0 and 23. The data in columns 1-4, 6-9 are stored as integers, while the data in columns 5, 10, and 11 are stored as real numbers. The data in this file should be space delimited. The number of spaces between columns does not matter, provided that the total width of the line is less than 256 characters. There must be one hourly record for each hour of the intended duration of the continuous simulation, even if there are no

data available for that hour. Gaps in the hourly record will cause the *GSSHA* simulation to terminate prematurely.

The following are three example lines from a **HMET_WES** formatted hydrometeorological data file (note the distinct presence of both real and integer numbers):

```
1995 4 14 23 29.625 86 100 000 53 9999.9 9999.9
1995 4 15  0 29.625 83 100 003 53 9999.9 9999.9
1995 4 15  1 29.615 90  80 003 52 9999.9 9999.9
```

This data input format is strongly recommended because it is compact, easy to read and write and contains no extraneous information. The no data flags are important. *GSSHA* has a set procedure for dealing with missing data.

HMET_SAMSON (Recommended over surface airways format).

In 1993 the National Climatic Data Center (NCDC) published a CD-ROM containing surface meteorological observations from 1961-1990. This CD-ROM is the result of collaboration between the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Energy, National Renewable Energy Laboratory. The SAMSON CD-ROM represents an excellent nationwide data set for the 1961-1990 period. Unfortunately, this CD-ROM is not being updated as new data become available.

The following is an example of data from the SAMSON CD-ROM. A reader program provided with the SAMSON data produces this data format. The ASCII Samson data format includes a one line station header (in this case the data are from the Memphis, Tennessee station), and a one line descriptive header with column ID's. These two header lines are followed by a user selectable number of hourly data points (in this example two hourly lines are shown).

```
~13893 MEMPHIS TN -6 N35 03 W089 59 87
~YR MO DA HR I 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
21
 82 4 1 1 0 0 0 0 ?0 0 ?0 0 ?0 0 0 12.8 6.1 64 1011 100 2.1 24.1
77777 999999999 16 99999. 0 26
 82 4 1 2 0 0 0 0 ?0 0 ?0 0 ?0 0 0 12.2 6.1 67 1011 80 2.1 24.1
77777 999999999 16 99999. 0 26
```

The first header line consist of the Weather Bureau Army Navy (WBAN) number for the station (13893), followed by 26 character descriptive string

(MEMPHIS), the state name where the station is located (TN), the time difference between local standard and UTC in hours (-6), degrees and minutes of latitude, N|S, (N35 03), degrees and minutes of longitude, E|W, (W089 59) and the station elevation in meters above sea level (87). The first header record containing the station information was written by NCDC with the following FORTRAN format statement:

```
(1X,A5,1X,A22,1X,A2,1X,I3,2X,A1,I2,1X,I2,2X,A1,I3,1X,I2,2X,I4)
```

The second line is for the identifier record, which shows the numerical identifier for the data elements in the National Solar Radiation Data Base (NSRDB) synoptic format (see: *http://rredc.nrel.gov/solar/pubs/NSRDB/*).

The observed data occupy the third record and all ensuing records (lines) in the file until a new year of data occurs. When a new year of data is encountered the header record and identifier record are repeated, followed by more data records. The data records include year, month, day, hour (1-24) in local standard time. The number below the "I" column is an "observation indicator" for which 0 means the weather observation was made, and a 9 indicates that the observation is missing. The following table describes the contents of each data record (Table 17):

Table 17. HMET_SAMPSON File Format.

No.	Name	Value Range	Description and Notes:
YR	Year	(61-90)	Year of observation
MO	Month	(1-12)	Month of observation
DA	Day	(1-31)	Day of month
HR	Hour	(1-24)	Hour of the day, local standard time
I	Observation indicator	0 9	0= weather observation made 9= no observation made NOTE: if this field=9 OR if field 13 (wind speed) = missing (9999. or 99.0) then fields 6,7,8,10,11,17, and 18 were all modeled and not actually observed
1	Extraterrestrial horizontal radiation	0-1415	Amount of solar radiation in W-h m^{-2} on a horizontal surface at the top of the atmosphere during the 60 min preceding the hour indicated
2	Extraterrestrial direct normal radiation	0-1415	Amount of solar radiation in W-h m^{-2} received on a surface normal to the sun at the top of the atmosphere during the 60 min preceding the hour indicated

No.	Name	Value Range	Description and Notes:
3	Global horizontal radiation	0-1415 flag for data 0-9 9999=missing data	Total amount of direct and diffuse solar radiation in W-h m^{-2} on a horizontal surface during the 60 min preceding the hour indicated
4	Direct normal radiation	0-1415 flag for data 0-9 9999=missing data	Amount of solar radiation in W-h m^{-2} received within 5.7 deg field of view centered on the sun during the 60 min preceding the hour indicated
5	Diffuse horizontal radiation	0-1415 flag for data 0-9 9999=missing data	Amount of solar radiation in W-h m^{-2} received from the sky (excluding the solar disk) on a horizontal surface, during the 60 min preceding the hour indicated
6	Total sky cover	1-10 99=missing data	Amount of sky dome (in tenths) covered by clouds
7	Opaque sky cover	1-10 99=missing data	Amount of sky dome (in tenths) covered by clouds that prevent observing the sky or higher cloud layers
8	Dry bulb temperature	-70.0 to +60.0 9999.=missing data	Dry bulb air temperature in degrees C
9	Dew point	-70.0 to +60.0 9999.=missing data	Dew point temperature in degrees C
10	Relative humidity	0-100 999=missing data	Relative humidity in percent
11	Station pressure	700-1100 9999=missing data	Station barometric pressure in mb
12	Wind direction	0-360 999=missing data	Wind direction in degrees. N=0 or 360, E=90, S=180, W=270
13	Wind speed	0.0-99.0 9999. or 99.0= missing data	Wind speed in m s^{-1}
14	Visibility	0.0-160.9 777.7=unlimited 99999.=missing data	Horizontal visibility in kilometers
15	Ceiling height	0-30450 77777=unlimited 88888=cirroform 999999=missing data	Ceiling height in meters
16	Present weather	Table denoted by 9 indicators	Present weather conditions (See NOAA document for codes)
17	Precipitable water	0-100 9999=missing data	Precipitable water in millimeters
18	Broadband aerosol optical depth	0.0-0.900 99999.=missing data	Broadband aerosol optical depth (broadband turbidity) on the day indicated
19	Snow depth	1-100 9999=missing data	Snow depth in centimeters on the day indicated

No.	Name	Value Range	Description and Notes:
20	Days since last snow-fall	0-88 88=88 or > days 999=missing data	Number of days since last snowfall
21	Hourly precipitation	000000-099999	In inches and hundredths

HMET_SUFAWAYS - NOAA/NCDC Surface Airways format (Not recommended).

The Surface Airways data format is included in the list of supported formats because surface meteorological data ordered from NCDC are delivered in this format. In the Surface Airways data format each data element (wind, temperature, radiation, etc.) is written on a separate line in the file. Each line contains 24 hourly values. Missing data are not flagged.

The details of this data format are discussed in "TD-3280, Hourly Surface Airways Observations," published by the National Oceanic and Atmospheric Administration, National Climatic Data Center. *GSSHA* users are strongly encouraged to reformat Surface Airways observations into the WES data format. There is a strong likelihood that data in the Surface Airways format will produce problems during the *GSSHA* simulation. This occurs not as consequence of faulty data, but because of the large number of data flags in the Surface Airways output format make the Surface Airways data format difficult to read in a robust fashion.

Missing hydrometeorological data

Frequently, hydrometeorological records have periods of missing data because observational instruments are inoperative, the data are not reliable, or certain observations (e.g., direct radiation, global radiation) are not available for a given station. Because hourly hydrometeorological inputs are required for the entire simulation period, missing data are synthetically produced within the *GSSHA* model.

Radiation data.

Many hydrometeorological stations do not record solar radiation measurements. Missing solar radiation data are simulated in *GSSHA* based on the location of the watershed, day of the year, and time of day, as previously described in "Computation of Evaporation and Evapo-transpiration."

When only a portion of the solar radiation data is missing, it is replaced as described in the next section.

Short duration gaps in hydrometeorological measurements.

When required data are missing, *GSSHA* creates the needed data by either persistence or persistence adjusted for the time of day. Missing variables without strong diurnal variability are filled in by "persistence" estimates. These variables include:

a. Barometric pressure
b. Wind speed
c. Dew point temperature
d. Percent cloud cover

Persistence means that the value is held constant until a new observation becomes available. Missing variables with strong diurnal components include:

a. Air temperature
b. Global radiation
c. Direct radiation

They are replaced with the last good reading from the same time of day. It is the responsibility of the user to check for missing data. Extended periods of missing record (many days) will cause *GSSHA* to simulate conditions for the last day of good record over and over again. This scheme requires that the hydrometeorological data file begin with at least one day of good observations of all required variables.

Snowfall Accumulation and Melting

When *GSSHA* is run in the **LONG_TERM** simulation mode, snowfall accumulation and melting is simulated. Because the *CASC2D* model has no explicit way to account for the seasonal variability in hydrologic response of watersheds, its appropriate use has been limited to periods where seasonal effects can largely be ignored, and has most typically been applied during the summer growing season (Senarath et al. 2000; Downer et al. 2002). An energy balance method of estimating snowfall accumulation and melting has been added to the *GSSHA* model to increase its utility in regions with significant snowfall. This method is admittedly simple and

other factors, soil freezing, change in overland roughness, etc., are not yet considered. This is an area of active research and model development at ERDC.

Snowfall has a large impact on hydrologic fluxes because snowfall is normally stored for a significant period of time in the snowpack and is later released as melt water. In many parts of the world melt of the snow cover is the single most important event of the water year (Gray and Prowse 1993). Because snowfall accumulation and subsequent melting can have such a large influence in hydrologic response of a watershed, it is important to simulate these processes. The purpose of the snowfall accumulation and melting routine is to allow an accounting of these processes with the intent to differentiate between precipitation that is rainfall that will immediately infiltrate, pond and run off or evaporate, and snow and ice that accumulates and significantly alters the timing of hydrologic fluxes. Precipitation freezing and snowpack melting can be modeled during long-term simulations when hourly hydrometeorological data values of air temperature (T_a), relative humidity (rh), wind speed (U), barometric pressure (P_a) and cloud cover, are required inputs.

Any time the air temperature is below 0^{o} C during precipitation, the precipitation is assumed to be snow or ice that will accumulate on the land surface. At air temperatures below 0^{o} C, precipitation is nearly always snowfall (Gray and Prowse 1993). If snow is already present in a cell, the new snow accumulation is added to the existing accumulated snow. While precipitation in the *GSSHA* model is distributed over the land surface, the effects of vegetation, elevation, and wind on the spatial distribution of snowfall are ignored.

Snowmelt models use either an energy balance or a temperature-index method. Physically-based systems are recommended for short-term forecasts (Gray and Prowse 1993), which are needed for hydrologic modeling. In the energy budget model the amount of heat available is applied to the snowpack and the amount of meltwater is calculated. The simplest representation of the snowpack is used; each 80 calories of heat added to the snowpack results in the release of 1 cm^3 of meltwater (Linsley et al. 1982; Gray and Prowse 1993). This method ignores complex snowpack behavior, such as ripening of the snowpack and refreezing of meltwater. Hourly values of hydrometeorological variables allow both seasonal and diurnal variations in climatic conditions to be included in the heat balance.

The amount of heat, Q (cal cm^{-2} hr^{-1}) available is computed from the components of the energy balance. In *GSSHA* the following components are accounted for:

a. Q^* - net radiation (in - out)
b. Q_v - heat in precipitation
c. Q_e - heat transferred by sublimation and evaporation
d. Q_h - sensible heat transfer due to turbulence

For nonprecipitation periods the net radiation is typically the dominant source of energy for melting of the snowpack (Gray and Prowse 1993). The net radiation is computed using Stephan-Boltzman's law, with the assumptions that incoming radiation can be computed from the ambient temperature, T_a (C), and outgoing radiation is computed assuming the snowpack is at 0^o C (Bras 1990):

$$Q^* = 49.56 \times 10^{-10}(T_a + 273)^4 - 27 \quad (92)$$

Precipitation falling on the snowpack at temperatures above 0^o transmits the difference in heat between the raindrop and the snowpack. Assuming the snowpack is at 0^o C and the rainfall is a ambient temperature the difference in heat energy is:

$$Q_v = IT_a \quad (93)$$

where: I is the precipitation intensity (cm hr^{-1}). Heats transferred from evaporation, sublimation, and turbulent energy are usually much smaller parts of the heat balance and are ignored in many computations (Gray and Prowse 1993). However, convective exchange can be significant (Linsley et al. 1982). If the dew point is below the temperature of the snowpack, assumed to be 0^o C, then condensation occurs and heat is transferred (Linsley et al. 1982; Gray and Prowse 1993). Estimates of turbulent and latent heat exchange are usually based on measurements of air temperature, humidity, and wind speed (Gray and Prowse 1993). During periods of melt, the temperature of the snowpack is 0^o C and the saturated vapor pressure (e_s) is 6.11 mb (Linsley et al. 1982). The latent heat exchange is computed assuming the latent heat of evaporation/condensation is 600 cal g^{-1} (Anderson 1968) and a water density of 1 g cm^{-3} as:

$$Q_e = 600\left(f(V)\frac{rh}{100}e_s - 6.11 \right) \tag{94}$$

where: rh is the relative humidity (%), $f(V) = 0.0002\ U$ (km hr^{-1}) (Anderson 1978), where U is the wind speed (m s^{-1}). Employing the Bowen ratio (Bowen 1926) the sensible heat transfer is computed assuming the snowpack temperature is at 0^{o} C, latent heat of evaporation is 600 cal g^{-1}, density of water is 1 g cm^{-3}, and the Bowen ratio coefficient is 0.61 x 10^{-3} C^{-1} (Bras 1990) as:

$$Q_h = 0.366 T_a P_a f(V) \tag{95}$$

where: P_a is the atmospheric pressure (mb).

For nonprecipitation periods, the energy budget is calculated at an hourly time-step (same as the standard hydrometeorological data), so diurnal changes in energy inputs are included in the model formulation. During precipitation periods the energy budget is updated each overland flow routing time-step (generally less than 5 min).

The described snowfall accumulation and melting calculations proceed any time the **LONG_TERM** simulation option is chosen and hourly air temperatures are provided. If snowfall occurs, a warning will be printed to the screen and to the summary file. When snow accumulation occurs the amount of snow in the watershed is reported at the beginning and end of each event summary in the summary file.

Sequence of Events During Long-Term Simulations

a. At the beginning of a long-term simulation, *GSSHA* opens the hydrometeorology data file, and determines the date/time of the beginning and end of the hydrometeorology data. *GSSHA* begins at the date/time specified as the beginning of the hydrometeorology data file.
b. If the first rainfall event in the rainfall input file does not begin during the period of hydrometeorology data, then *GSSHA* aborts with a warning.
c. What the model does next depends on which infiltration option is chosen.
   (1) If **INF_REDIST** is specified as the infiltration option, then the following sequence transpires.
   BEFORE AN EVENT: *GSSHA* performs evapo-transpiration and

soil moisture accounting calculations each hour until the date/time of the beginning of the first event specified in the rainfall data file.
DURING AN EVENT: Overland flow, infiltration and channel routing are performed at the overall model time-step, typically 60 sec, until two conditions are met: a) the rainfall data for the current event is over; b) the outflow has fallen below the value specified in the project file as **EVENT_MIN_Q**.
AFTER AN EVENT: *GSSHA* writes an event summary to the **SUMMARY** file and resumes hourly ET and soil moisture accounting until the date/time of the beginning of the next event in the rainfall data file. If water remains on the overland flow plane at the end of the event, overland flow and infiltration calculations continue. Channel routing can also continue. These calculations do not affect the soil moisture accounting routine calculations, which proceed as though ET is the only process that changes the soil moisture in the root zone. If there are no more events in the rainfall data file, the simulation is terminated. This process continues until the end of the last rainfall event in the precipitation input file, or the end of the hydrometeorology data, at which time the *GSSHA* simulation terminates.

(2) If **INF_RICHARDS** is chosen, control of process activation switches from rainfall events to the physical conditions in the watershed. When there is no moving water on the overland flow plane or in the channels, ET demand and unsaturated water movement are updated at an hourly basis.
When water appears on the overland flow plane due to rainfall, exfiltration or channel overbank flow, overland flow routing and unsaturated zone calculations begin at the overall model time-step, typically around 60 sec. Channel routing begins as water in the channel accumulates, also at the overall model time-step. Overland flow calculations continue until all water on the overland flow plane runs off, infiltrates, evaporates, or stops moving. Channel routing continues as long as a minimum amount of water is in the channel and the water is moving. If groundwater/channel interactions are specified, these fluxes continue to be computed and the volume in the channel is updated each groundwater time-step. If exchange with the groundwater results in the minimum amount of water required for channel routing to begin, then channel routing will resume, but at the larger groundwater time-step. Any time rainfall is occurring, overland flow, ET, channel flow, unsaturated zone

water movement, and saturated groundwater flow are updated each overall model time-step. Events are still recognized, but are only used for accounting purposes.

10 Soil Erosion and Sediment Routing

Overland Erosion Formulation

In order to estimate overland erosion, *GSSHA* employs an equation based on the work of Kilinc and Richardson (1973). Kilinc and Richardson studied the mechanics of overland soil erosion in at Colorado State University Engineering Research Center in a flume that is 1.2 m deep, 1.5 m wide, and 4.9 m in length. Their investigation resulted in a sediment transport equation of uniform flow sheet and rill erosion on bare sandy soil. The original one-dimensional Kilinc-Richardson (1973) equation is:

$$q_s = 25500 q^{2.035} S_o^{1.664} \tag{96}$$

where: the factor 25,500 is an empirical constant, q_s is the sediment unit discharge (ton m^{-1} s^{-1}) and q and S_o have previously defined. The form of Equation 96 is consistent with many sediment transport predictors, as reviewed by Julien and Simons (1985).

Julien (1995) modified the original Kilinc-Richardson equation to expand the applicability of the equation to non-uniform flow with consideration of soil and land-use specific factors:

$$q_s = 25500 q^{2.035} S_f^{1.664} \frac{K * C * P}{0.15} \tag{97}$$

where:

K = soil erodibility factor, with values ranging from 0 to 1
C = soil cropping factor (0-1)
P = conservation factor (0-1)

The K, C and P factors are empirical coefficients with the same conceptual meaning as those used in the Universal Soil Loss Equation (Renard et al. 1991). The factor 0.15 in the denominator represents the maximum erosivity of the sand used in the original flume experiments. Equation 97 is applied within each model grid cell in two dimensions, which allows separate calculations of the potential sediment transport rate in the x- and y-directions:

$$q_{sx} = 25500 p^{2.035} S_{fx}^{1.664} \frac{K * C * P}{0.15} \tag{98}$$

$$q_{sy} = 25500 q^{2.035} S_{fy}^{1.664} \frac{K * C * P}{0.15} \tag{99}$$

with S_{fx} and S_{fy} defined using Equation 2, and p and q calculated using Equations 6 and 7, respectively.

The numerical approach in the current version of *GSSHA* is to apply the modified Kilinc and Richardson equations, 98 and 99, to determine potential transport of sediment within each grid cell. The methodology is explained in detail in Johnson (1997) and Johnson et al. (2000), and is summarized here.

The potential sediment discharge in each of the two flow directions in each grid cell is calculated using the following two equations:

$$q_{sx_{ij}} = 25500 p_{ij}^{2.035} \left| S_{fx_{ij}} \right|^{1.644} \frac{S_{fx_{ij}}}{\left| S_{fx_{ij}} \right|} \frac{K * C * P}{0.15} \tag{100}$$

and,

$$q_{sy_{ij}} = 25500 q_{ij}^{2.035} \left| S_{fy_{ij}} \right|^{1.644} \frac{S_{fy_{ij}}}{\left| S_{fy_{ij}} \right|} \frac{K * C * P}{0.15} \tag{101}$$

The potential sediment discharges calculated using equations 100 and 101 are assumed to be satisfied at all times. This assumption results in the sediment transport being transport limited, as opposed to supply or detachment limited.

The surface of each grid cell is either eroded or aggraded depending upon the quantity of sediment in suspension and the potential sediment transport rates. This determination is made for three grain sizes, sand, silt, and clay. Conservation of mass of sediment determines what amount of sediment entering each grid cell stays in suspension, and what amount is deposited. The sediment transport capacity, equations 100 and 101, is satisfied by sediments already in suspension, previously deposited sediments, and then sediments in the parent material, respectively. If sedi-

ments in suspension are unable to satisfy the potential transport rate, the previously deposited sediment is used to satisfy the demand. If there is insufficient previous deposition, then the surface is eroded to meet the demand.

If the potential sediment transport rates calculated using Equations 100 and 101 are insufficient to transport the sediment already in suspension within a grid cell, sediment is deposited on the surface. Sediment deposition in each grid cell is calculated for each of the three size fractions using a trap efficiency relation (Johnson et al. 2000):

$$TE_i = 1 - e^{\frac{\Delta x \omega_i}{dV}} \tag{102}$$

where:

TE_i = trap efficiency for the i^{th} size fraction
ΔX = length of the grid cell (m)
ω_i = fall velocity of the i^{th} size fraction (m s^{-1})
d = overland flow depth (m)
V = overland flow velocity (m s^{-1})

The trap efficiency is a number between 0 and 1, assumed equal to the fraction of suspended sediment in each size fraction that is deposited in the receiving grid cell. The use of the trap efficiency forces larger particles to deposit before smaller particles.

Channel Sediment Transport Formulation

The present version of *GSSHA* employs the unit stream power method of Yang's (1973) for routing sand-size total-load in stream channels. Unit stream power is defined as the product of the average flow velocity, U, and the channel slope S_o. The rate of work done per unit weight of water in transporting sediment is assumed directly related to the rate of work available per unit weight of water. Thus, the total sediment concentration or total bed-material load must be directly related to the unit stream power. The following relation gives the basic concept of Yang's (1973) method:

$$\phi(C_s, US_o, U^*, \nu, w, d) = 0 \tag{103}$$

where: C_s is the total concentration of sand-size sediment particles in motion, US_o is unit stream power (L T^{-1}), U_* is the shear velocity (L T^{-1}), ν = kinematic viscosity of the sediment-water mixture (L T^{-2}), w = fall velocity of the sediment (L T^{-1}), d = particle diameter (L). With some mathematical and statistical manipulations with Buckingham's π theorem, Yang (1973) derived an energy-based equation to estimate the total sand-size sediment concentration in the channel.

The routing formulation for sand-size sediments is limited to trapezoidal channels, link type 30 or 31, with a user-specified a maximum allowable depth of degradation in the channel (Figure 14). The bed is assumed to be mobile, and the banks are fixed. Channels degrade vertically into the crosshatched area in the Figure 14. Degradation continues and bed load is transported at the rate calculated with the Yang (1973) method until the maximum degradation is reached. During degradation the initial bed width is maintained and degradation is uniform across the width of the bed. If the channel aggrades, the trapezoidal cross section is filled. If a channel link has aggraded, and then degrades, the degradation will occur uniformly over the bottom of the trapezoid until the original bed elevation is restored. Further degradation occurs vertically downward from the initial trapezoid bottom-width. If a channel, degraded below the original bed elevation begins to aggrade, sediment will accumulate uniformly in the rectangular degraded area below the original bed elevation. Once the bed aggrades beyond the original bed elevation, the entire width of the trapezoid is filled.

In the channels, silt and clay size particles are assumed to be in suspension, and are transported as wash load. This treatment implies that the flow is turbulent, and the travel time to the outlet of the catchment is short compared to the settling time, such that particles do not settle in the channel network. This assumption, combined with no bank erosion, results in the channels being neither a source nor sink of fines. Routing of suspended fines is a natural extension of the explicit diffusive-wave channel routing method. Suspended fine sediments are routed as concentrations. The concentration changes as a function of gradients in both concentration and velocity.

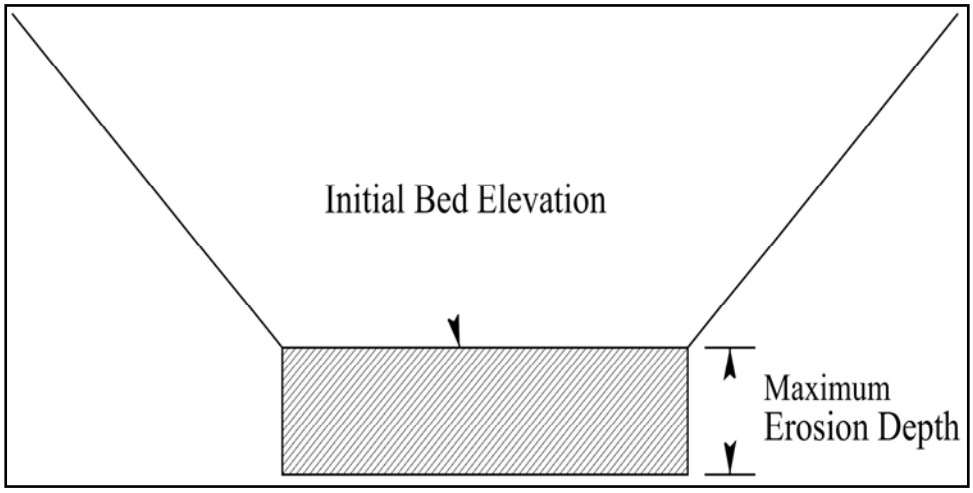


Figure 14. Channel bed erosion.

Applicability of Sediment Routing Methods

The Kilinc and Richardson (1973) soil erosion model as modified by Julien (1995) is a highly empirical formulation. The soil, cropping, and land use factors (*K*, *C*, and *P*) from the USLE are not related to specific physical processes, but instead are intended to capture the behavior of a number of complex and interrelated phenomena. Caution should be exercised in applying this method. As with all empirical models, careful calibration to extended observed data is necessary to determine coefficients that provide reasonable answers for the particular study. Verification of the calibrated parameters by simulating events not during the calibration period is important to ensure that the calibrated parameters indeed can be used for predictive purposes. The current overland erosion and sediment transport scheme is the same as that used in *CASC2D* Version 1.18. Ogden and Heilig (2001) performed a detailed study of the performance of the scheme and highlighted a number of serious limitations of the approach.

a. The factors *K*, *C*, and *P* are linearly dependent. Without significant apriori information, parameter assignment is difficult. Using an automated calibration technique, Ogden and Heilig (2001) found that these three linearly dependent factors require heavy emphasis on calibration constraints, and concluded that the current formulation by Julien (1995) essentially cannot be calibrated.
b. The current formulation does not consider raindrop impact, known to play an important role in overland erosion.
c. The current formulation implicitly includes rill and gully erosion without any specific parameters governing their formation or propagation.

d. As pointed out by Julien and Simons (1985) almost any bed-load predictor can be cast in the form of an overland erosion predictor. However, such equations are always assumed applicable when the sediment source is unlimited. Limits on detachment are not considered in the current erosion formulation.
e. Ogden and Heilig (2001) determined that the combined effect of the formulation deficiencies reduces the range of applicability of the approach in terms of event magnitude. Despite a significant calibration effort, the current overland erosion formulation considerably overestimates overland erosion rates during runoff events that are considerably larger than the calibration events. Research is underway to attempt to address these limitations and improve the overland erosion routines in a future version of *GSSHA*.

Simulations with Soil Erosion

General

Soil erosion simulations are specified with the SOIL_EROSION project card. The user must also provide soil percent sand, percent silt, and erodibility, crop management, and conservation practice parameters for each cell in the watershed. As described in "Soil Erosion-Optional" in Chapter 3, these may be provided with either a series of *GRASS* ASCII maps or with the use of the mapping table. Additional optional inputs and outputs are also available. These are also described in detail in Chapter 3. If channel routing is not specified in the project file only overland soil erosion calculations are performed.

Assignment of overland routing parameter values

Combined, the factors *K*, *C*, and *P*, describe the overall erodability of the soil, including the effects of soil texture, vegetation coverage, and management practices. As can be seen in Equations 100 and 101, lower values indicate less erodability. The general erodability, *K*, is based on the composition of the soil in each cell. This erodability can be reduced by vegetative or other coverage with the *C* factor, and can be further reduced, or increased, by the management practice factor, *P*.

Soil erosion parameters and soil erosion factors may be estimated from land use, vegetation, and soil texture indices. These values may be entered

with either the mapping table file, Chapter 11, or with *GRASS* ASCII maps (see Chapter 3).

Soil erodability (K).

Soil erodability describes the susceptibility of the soil to detachment and transport by rainfall impact and overland flow. Soil erodability is generally a function of soil texture, soil structure, organic content, and permeability. In general, larger particles are harder to erode, as are undisturbed soils. Organic soils are less susceptible to erosion, and have lower *K* values. The values in Table 18, from Wanielista (1978), are for undisturbed, inorganic soils.

Table 18. Soil Erodability Factor (*K*), Wanielista (1978).

Soil Texture	Erodability Factor *K*
Sand	0.05
Loamy sand	0.12
Sandy loam	0.27
Loam	0.38
Silt loam	0.48
Sandy clay loam	0.27
Silt	0.60
Clay loam	0.28
Silty clay loam	0.37

Cropping management factor (C).

The cropping management factor (*C*) describes the effect of land coverage on reducing the erodability of bare soils. In general, covered lands are less susceptible to erosion, and have lower *C* values. With no cover on the soil, the full erodability (*K*) can be achieved, and C=1.0. Table 19 lists values for general land coverage types.

Table 19. Cropping Management Factors (*C*), Wanielista (1978) and Goldman et al. (1986).

Cover	*Cropping Factor C*
None (fallow)	1.00
Native vegetation	0.01
Crops	0.08
Pasture	0.01
Forest	0.005
Urban	0.01
Other	1.0

Conservation practice factor (P).

The conservation practice factor reflects efforts specifically intended to reduce erodability of the soil. This factor is generally associated with practices used by farmers to conserve the soil, such as no-till and contour farming. This factor may also be important for certain types of construction practices, such as coverage with geotextiles, which tend to reduce erodability. Other construction practices, such as smoothing and compacting the soil, actually increase erodability and can result in the value of *P* being greater than 1.0. Table 20 lists recommended values of *P* for general land use.

Table 20. General Land Use Erosion Control Factors (*P*), Wanielista (1978).

General land use	*Control Practice Factor, P*
Crop	0.5
Pasture	1.0
Forest	1.0
Urban	1.0
Other	1.3

Channel routing of sediments

If explicit channel routing is specified in the project file with the **CHAN_EXPLIC** project card along with the **SOIL_EROSION** project card, sediment routing in channels will also be performed. In the **CHAN_INPUT** file, the user specifies the initial cross section of an "erodable trapezoidal", channel link type 30 or 31, Chapter 5, "Sediment Transport in Channels." If there are no type 30 or 31 links in the channel input data file, then the *GSSHA* simulation will terminate and print a

message to the screen that there must be type 30 or 31 links in the channel input file to perform sediment channel routing. The fluvial link type 30 has a trapezoidal channel cross section and so the channel input file specification of link type 30 is the same as a trapezoidal link type (link type 1, Chapter 5, “Breakpoint cross section (link type 1”)) with the addition of an additional parameter- the maximum depth of erosion (m). Link type 31 is the same as link type 30, with the addition of stream loss parameters. Proper construction of a channel input file is given in Chapter 5.

11 Mapping Table File

The mapping table file has been designed for easy assignment of most of the parameters needed to model different processes in *GSSHA*. The mapping table consists of a short series of data tables, linked to a small number of integer-based index maps. The data tables are associated with different processes that can be simulated in *GSSHA* that require parameter values in every cell in the watershed, i.e. overland flow, infiltration, etc. From these inputs, *GSSHA* is able to internally create over two dozen floating-point *GRASS* ASCII maps, which would otherwise have to be created by the user and specified with project cards. Consolidating the parameters into a series of tables and index maps reduces model construction time, organizes information, makes calibration easier, and allows easy parameter assignment for project alternatives and future scenarios. By using index maps as the patterns for assigning parameters, many different input parameters for a single cell can be assigned by changing the number in the index map.

Parameter values in the mapping table file are linked to the index maps through the identification numbers (IDs) used in the index maps. Data in the tables are arranged according to ID. The index maps contain the spatial distribution of the IDs over the watershed. To build the required input *GRASS* maps, *GSSHA* reads in the specified index maps, and replaces the index map ID values with the data corresponding to the ID from the appropriate table. This information is stored internally as an input floating-point map. Most watersheds can be simplified into a small set of parameters and a few index maps, but even large and complex watershed models can be quickly constructed using the mapping table file. The program *WMS* V6.1 and later releases, is designed to work with the mapping table file and parameters are assigned with the mapping table file when using *WMS* V6.1. When using *WMS* 6.1 and higher, *WMS* will place the **MAPPING_TABLE** card in the project file when one or more processes requiring distributed parameter values are chosen to be modeled. The **MAPPING_TABLE** project card, followed by the name of the mapping table file, informs *GSSHA* to obtain parameters needed for process simulations from the mapping table file, and that detailed ASCII maps or uniform values of parameters will not be used.

The following is a description of the overall structure of the mapping table file, followed by a detailed description of the structure of the index maps, the structure and organization of the various tables in the mapping table file, and a description of how to link the index maps to the tables in the mapping table file. Finally, a summary of the different sections of the mapping table file is given, as well an example of the mapping table file.

File Description

The mapping table file has three main sections: header, index map declaration lines, and data tables. These three sections of the file are arranged in the following order:

a. Header
b. Index map declaration lines
c. Data tables

The header is a line that specifies the type of file being read in, in this case a mapping table file. The index map declaration lines specify the index maps to use with the following data tables. The index map names are then referenced by the data tables that follow. The data tables link a set of input parameters to a named index map.

Header

The first section of the mapping table file is a header line, or a line that specifies the type of file being read by *GSSHA*. This must be the first line in the file. The line has the following identifier:
GEISSHA_INDEX_MAP_TABLES, which appears alone on the first line of the mapping table, i.e.

GSSHA_INDEX_MAP_TABLES

This line indicates that the data that follows has been arranged into the mapping table format, as described in this document. This header is used to verify that the file being read in by *GSSHA* has been set up as a mapping table file. *WMS* v6.1 and higher automatically places this line in the mapping table file when *WMS* is used to describe the processes in the *GSSHA* model.

Index map declaration lines

The second section of the mapping table file is a series of index map declaration lines. These lines are used to specify index maps that will be linked to the tables in the mapping table file. An index map consists of an *index map name* and an index map *filename*. The index map declaration lines associate the *filename* of a file in the format of an index map with an *index map name*. The index map is then referenced throughout the mapping table file by its name, not by the *filename*. Each *index map name* must be unique, though the index map *filename* do not necessarily have to be unique. That is, a single map could be assigned multiple names in the mapping table. *WMS* automatically adds the suffix *idx* to the *filename* of all index maps. The index map declaration lines follow the format:

INDEX_MAP *filename "Index map name"*

For example:

INDEX_MAP soil1.idx "Soils map of North Fork"

The amount of spacing between the three specifiers (i.e. INDEX_MAP, *filename*, "*Index map name*") is not important; but at least one white-space character (i.e., tab, space) must appear between inputs. The index map name must be in quotes. There is no limit to the number of index maps that may be specified. Index maps named in the index map declaration lines need not be referenced by any tables in the mapping table file. An index map *filename* may be associated with multiple index map names, but each *Index map name* must be unique. All index map names referenced in the mapping table file must have an index map declaration line that has the exact same index map name.

Data tables

Following the index map declaration lines come a series of tables. For each process to be simulated, data tables are used to assign the distributed parameters needed to model the process. The tables are identified by a unique name, TABLE_NAME, followed by the associated *Index map name*, in quotes. The next line must start with the identifier NUM_IDS followed by the number of IDs defined for the table. For the Richards Havercamp and Richards Brooks tables, the next line must start with the identifier MAX_NUMBER_CELLS followed by an integer number. For all

tables, the next line is a header or descriptive line. This line is ignored by *GSSHA*. Following the descriptive line comes the listing of the IDs. The IDs must be an integer value greater than zero. The first six spaces of the line are allotted for the ID number. The IDs need not be in numerical order, or even numerically sequential. Each ID is followed by an 80-character description and the appropriate number of floating point values for the table. The following is a basic format for the data tables (the descriptions are truncated for display purposes):

```
TABLE_NAME "Index map name"
NUM_IDS ##
MAX_NUMBER_CELLS ### (only if table is of a Richards' equation
type)
ID DESCRIPTION VALUE DESCRIPTORS …
## ID description ##### ##### … #####
## ID description ##### ##### … #####
…
## ID description ##### ##### … #####
```

For example, a data table for overland roughness might look like (the descriptions have been shortened for display purposes):

```
ROUGHNESS "roughness map"
NUM_IDS 4
ID DESCRIPTION ROUGHNESS
1 Corn Fields 0.3000
2 Soybean Fields 0.3300
3 Empty Fields 0.2500
7 Natural Vegetation 0.2700
```

The first line is the table is the table identifier, ROUGHNESS. *GSSHA* then expects that the table contains the values needed to create the internal map of overland roughness floating-point values. Following the table identifier is the name of the index map associated with the table. In this example, "roughness map" is the index map associated with the table. The next line contains the identifier NUM_IDS that declares how many IDs are in the table. In this example, four IDs are declared, numbered 1, 2, 3 and 7. ID 1 corresponds to a roughness of 0.3000, ID 2 corresponds to a roughness of 0.3300, etc. The descriptions following the IDs must be present, and must be 80 characters, but are purely for user identification. The descriptions are not used by *GSSHA*. The line following the NUM_IDS line, or the line following MAX_NUMBER_CELLS in the Richards' equations tables, is discarded by *GSSHA*. It may contain any sort of text desired but it is usually used to describe the parameters set up in the data table.

The name of the index map associated with the table is “roughness map.” There must be a line for this map in the index map declaration lines, i.e.

INDEX_MAP roughness.idx “roughness map”

The file roughness.idx cannot contain integer values, IDs, other than 1, 2, 3, or 7, and 0, which is used for the inactive regions of the grid. See MASK_FILE. The index map file does not have to refer to all of these IDs. If the index map file roughness.idx only references IDs 1 and 7, then only roughness values of 0.3000 and 0.2700 will be in the final roughness map internal to *GSSHA*.

File format

The mapping table file follows the following basic format:

```
GEISSHA_INDEX_MAP_TABLES
INDEX_MAP filename.idx “Index map name”
INDEX_MAP filename.idx “Index map name”
etc.
INDEX_MAP filename.idx “Index map name”
TABLE_NAME “Index map name”
NUM_IDS ##
ID DESCRIPTION VALUE DESCRIPTORS …
## ID description ##### ##### … #####
## ID description ##### ##### … #####
etc.
## ID description ##### ##### … #####
TABLE_NAME “Index map name”
NUM_IDS ##
ID DESCRIPTION VALUE DESCRIPTORS …
## ID description ##### ##### … #####
## ID description ##### ##### … #####
etc.
## ID description ##### ##### … #####
…
TABLE_NAME “Index map name”
NUM_IDS ##
ID DESCRIPTION VALUE DESCRIPTORS …
## ID description ##### ##### … #####
## ID description ##### ##### … #####
etc.
## ID description ##### ##### … #####
```

An example file can be found later in this chapter in “Example Mapping Table File.” Note that there may not be blank lines between the tables, between the index map declaration lines, between the header and the index map declaration lines or even between the index map declaration lines and the data tables. Text and blank lines after the data table section are permitted.

Index Maps

An index map is a *GRASS* ASCII file that contains integer values in each grid cell. The data should follow the same shape or pattern as the **WATERSHED_MASK** file because each cell of the index map will be used to supply data for the corresponding watershed cell. The data cells outside of the watershed should contain the value 0. All data cells inside the watershed should be of integer value greater than or equal to 1. These values are ID numbers, and will correspond to IDs from a table in the mapping table file. It is from the index maps that the final structure and mapping of the data in the tables takes place. Developing good index maps is a key part in building a model that is easy to work with and modify.

The following is an example of a watershed mask and an index map file:

Watershed Mask File

```
north: 150.00
south: 50.00
east: 150.00
west: 50.00
rows: 10
cols: 10
0 0 0 1 0 0 0 0 0 0
1 1 1 1 0 0 0 0 0 0
0 0 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 0 0 0
0 0 1 1 1 1 1 0 0 0
0 0 0 1 1 1 1 0 0 0
0 0 0 1 1 1 1 0 0 0
0 0 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 1 1 0
0 0 0 0 0 0 0 1 1 0
```

Index Map File

```
north: 150.00
south: 50.00
east: 150.00
west: 50.00
rows: 10
cols: 10
0 0 0 1 0 0 0 0 0 0
1 1 1 1 0 0 0 0 0 0
0 0 1 1 1 1 1 1 0 0
0 0 0 2 2 2 1 0 0 0
0 0 1 2 2 1 1 0 0 0
0 0 0 1 2 1 1 0 0 0
0 0 0 1 1 1 1 0 0 0
0 0 1 1 3 3 3 1 0 0
0 0 0 1 1 3 3 3 1 0
0 0 0 0 0 0 0 1 1 0
```

This index map has three IDs, 1, 2, and 3. Any table in the mapping table file that uses this index map should at least have the IDs 1, 2, and 3. The table may have other IDs, but the associated values will not be in the final floating-point map generated internally by *GSSHA*. A table may refer to more IDs than an index map references, but an index map cannot contain the IDs that are not listed in the associated table. Allowing IDs in the tables not associated with the index maps is useful in running different scenarios; for example, pre- and post-project conditions. To change the model scenario, only the name of a different index map need be assigned to the table in the mapping table file.

Each index map used in the mapping table file is identified by its *index map name*, which is different than the index map *filename*. The index map

filename is the name of the file on disk, referenced by the operating system. The *index map name* is an internal descriptive name used in the mapping table file to identify which index map is assigned to which tables. The index map *filenames* and the associated *index map names* are associated with each other at the beginning of the file in the index map declaration lines. These index map declaration lines follow the first line of the file, which identifies the file as a mapping table file.

Mapping Tables

The mapping tables consist of an index map name, and a set of IDs, each ID having an associated set of parameter values. *GSSHA* reads in the integer-based index map, and then builds the floating-point-based map by looking up the ID for each cell and inserting the associated floating-point value from the table. *GSSHA* expects each ID to have the correct number of values, in the correct order. The number of values and the order of them are given in the following table. The mapping table file does not need to contain all of the tables listed in Table 21.

Table 21. Mapping Tables.

Table Name	# Values	Parameter	Units
ROUGHNESS	1	Roughness (n)	none
INTERCEPTION	2	Storage capacity (a)	mm
		Interception coefficient (b)	none
RETENTION	1	Retention depth (d_{ret})	mm
GREEN_AMPT_INFILTRATION	5	Saturated hydraulic conductivity (K_s)	cm hr^{-1}
		Wetting front suction head (ψ_f)	cm
		Porosity (θ_s)	none
		Pore distribution index (λ	none
		Residual water content (θ_r)	none
GREEN_AMPT_INITIAL_SOIL_MOISTURE	1	Initial soil moisture (θ_i)	none
RICHARDS_EQN_INFILTRATION_BROOKS 3 sets of values for each ID 1 set per line	9 x 3	K_s	cm hr^{-1}
		θ_s	none
		θ_r	none
		θ_i	none
		Wilting point (θ_{wp})	none
		Layer thickness (t_L)	cm
		λ	none
		Bubbling pressure (ψ_b)	cm
		Cell size (Δz)	cm

Table Name	# Values	Parameter	Units
RICHARDS_EQN_INFILTRATION_HAVERCAMP 3 sets of values for each ID 1 set per line	11 x 3	K_s	cm hr^{-1}
		θ_s	none
		θ_r	none
		θ_i	none
		θ_{wp}	none
		Layer depth	cm
		Havercamp factor α	none
		Havercamp factor B	none
		Havercamp factor A	none
		Havercamp factor B	none
		Δz	cm
EVAPO-TRANSPIRATION	5	Albedo	none
		θ_{wp}	none
		Vegetation height	m
		Transmission coefficient	none
		Canopy resistance	s m^{-1}
SOIL_EROSION_PROPS	3	Erodability factor	none
		Fraction sand	none
		Fraction silt	none
SOIL_EROSION_FACTORS	2	Crop management factor	none
		Conservation practice factor	none

The following sections outline the table names, number of parameters, order and type of the parameters, and the table format. Also included is an example table. In the example tables the descriptions have been shortened for display purposes. In all fields of the table, except the ID and descriptions fields, the amount of spacing between the identifiers does not matter. The format of the ID lines is given after the soil erosion factors table is described.

Roughness

See also ID Line Format

Table Name	# Values	Parameter	Units	Typical Range
ROUGHNESS	1	Surface Roughness (n)	none	0.02 – 0.5

Table Format							
ROUGHNESS			*"Index Map Name"*				
NUM_IDS			####				
Text Line							
ID #1	*Description*	###.###					
ID #2	*Description*	###.###					
etc.							
ID #N	*Description*	###.###					

Example Table

```
ROUGHNESS "roughness map"
NUM_IDS 2
ID Description                SURF_ROUGH
1 Fields                      0.1000
2 Forest                      0.2000
```

Interception

See also ID Line Format

Table Name	# Values	Parameter	Units	Typical Range
INTERCEPTION	2	Storage capacity	mm	0.0 - ?
		Interception Coefficient	fraction	0.0 – 1.0

Table Format							
INTERCEPTION			*"Index Map Name"*				
NUM_IDS			####				
Text Line							
ID #1	*Description*	###.###	###.###				
ID #2	*Description*	###.###	###.###				
…							
ID #N	*Description*	###.###	###.###				

Example Table

```
INTERCEPTION "interception map"
NUM_IDS 2
ID Description          STOR_CAPY INTER_COEF
1 Fields     0.1000 0.1000
2 Forest          0.2000       0.2000
```

Retention

See also ID Line Format

Table Name	# Values	Parameter	Units	Typical Range
RETENTION	1	Retention depth (d_{ret})	mm	1.0 – 5.0

Table Format							
RETENTION			*"Index Map Name"*				
NUM_IDS			####				
Text Line							
ID #1	*Description*	###.###					
ID #2	*Description*	###.###					
…							
ID #N	*Description*	###.###					

Example Table

```
RETENTION "retention map"
NUM_IDS 2
ID Description    RETENTION_DEPTH
1 Fields                    0.5000
2 Forest                    1.0
```

Green and Ampt infiltration

See also ID Line Format

Table Name	# Values	Parameter	Units	Typical Range
GREEN_AMPT_INFILTRATION	5	K_s	cm hr^{-1}	0.01 – 2.0
		ψ_f	cm	10.0 – 100.0
		θ_s	none	0.25 – 0.60
		λ	none	1.0 – 4.0
		θ_r	none	0.01 – 0.1

Table Format							
GREEN_AMPT_INFILTRAION		*"Index Map Name"*					
NUM_IDS		####					
Text Line							
ID #1	*Description*	###.###	###.###	###.###	###.###	###.###	###.###
ID #2	*Description*	###.###	###.###	###.###	###.###	###.###	###.###
…							
ID #N	*Description*	###.###	###.###	###.###	###.###	###.###	###.###

Example Table

```
GREEN_AMPT_INFILTRATION "green and ampt infil map"
NUM_IDS 2
ID Description HY_COND CAP_HEAD POR POR_IDX RES_SAT A_R_DEPTH
1 Clay       0.10 50.0 0.45 3.0 0.10 0.1
2 Sand       1.0 7.0 0.55 1.0 0.05 0.1
```

Initial soil moisture

See also ID Line Format

Table Name	# Values	Parameter	Units	Range
GREEN_AMPT_INITIAL_SOIL_MOISTURE	1	θ_i	none	θ_r - θ_s

Table Format							
GREEN_AMPT_INITIAL_SOIL_MOISTURE					*"Index Map Name"*		
NUM_IDS					####		
Text Line							
ID #1	*Description*	###.###					
ID #2	*Description*	###.###					
…							
ID #N	*Description*	###.###					

Example Table

```
GREEN_AMPT_INITIAL_SOIL_MOISTURE "green and ampt moisture map"
NUM_IDS 2
ID Description               SOIL_MOISTURE
1 Fields                     0.25
2 Forest                     0.30
```

Richards' equation, Brooks option

See also ID Line Format

Table Name	# Values	Parameter	Units	Typical Range
RICHARDS_EQN_INFILTRATION_BROOKS 3 sets of values for each ID, one set of values per line for each soil layer	9 x 3	K_s	cm hr^{-1}	0.05 – 23.5
		θ_s	none	0.4 – 0.55
		θ_r	none	0.01 – 0.1
		θ_i	none	θ_r - θ_s
		θ_{wp}	none	0.03 – 0.25
		d	cm	NA
		λ	none	1.0 – 4.0
		ψ_b	cm	5.0 – 100.0
		Δz	cm	0.1 – 10.0

Table Format										
RICHARDS_EQN_INFILTRATION_BROOKS							*"Index Map Name"*			
NUM_IDS							####			
MAX_NUMBER_CELLS							####			
Text Line										
ID #1	*Description*	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###
ID #2	*Description*	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###
…										
ID #N	*Description*	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###

Example Table

RICHARDS_EQN_INFILTRATION_BROOKS "richards brooks map"									
NUM_IDS 2									
MAX_NUMBER_CELLS 65									
ID	Descript	K_s	θ_s	θ_r	θ_i	θ_{wp}	d	θ	θ_b	θz
1	Clay	0.1	0.5	0.1	0.25	0.15	10.0	3.0	-50.0	1.0
		0.1	0.5	0.1	0.35	0.15	50.0	3.0	-50.0	2.0
		0.1	0.5	0.1	0.45	0.15	100.0	3.0	-50.0	5.0
2	Sand	1.0	0.45	0.1	0.25	0.05	10.0	1.5	-10.0	2.0
		1.0	0.45	0.1	0.35	0.05	10.0	1.5	-10.0	5.0
		1.0	0.45	0.1	0.35	0.05	10.0	1.5	-10.0	10.0

Richards' equation, Havercamp option

See also ID Line Format

Table Name	# Values	Parameter	Units	Range
RICHARDS_EQN_INFILTRATION_HAVERCAMP 3 sets of values for each ID One set of values per line for each soil layer	11 x 3	K_s	cm hr^{-1}	0.05 – 23.5
		θ_s	none	0.4 – 0.55
		θ_r	none	0.01 – 0.1
		θ_i	none	θ_r - □s
		θ_{wp}	none	0.03 – 0.25
		d_L	cm	NA
		α	none	fit to curve
		B	none	fit to curve
		A	none	fit to curve
		B	none	fit to curve
		Δz	cm	0.1 – 10.0

Table Format												
RICHARDS_EQN_INFILTRATION_HAVERCAMP							*"Index Map Name"*					
NUM_IDS							####					
MAX_NUMBER_CELLS							####					
Text Line												
ID #1	*Description*	###	###	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###	###	###
ID #2	*Description*	###	###	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###	###	###
…												
ID #N	*Description*	###	###	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###	###	###
		###	###	###	###	###	###	###	###	###	###	###

Example Table

RICHARDS_EQN_INFILTRATION_HAVERCAMP "richards havercamp map"												
NUM_IDS 2												
MAX_NUMBER_CELLS 45												
ID	Descript	K_s	θ_s	θ_r	θ_i	θ_{wp}	*d*	α	B	*A*	*B*	ΔZ
1	Clay	0.1	0.5	0.09	0.25	0.25	20	80	1.3	125	1.8	1.0
		0.1	0.5	0.09	0.35	0.25	30	80	1.3	125	1.8	2.0
		0.1	0.5	0.09	0.45	0.25	50	80	1.3	125	1.8	5.0
2	Sand	1.0	0.4	0.01	0.25	0.03	10	35	4.0	1175	4.7	1.0
		1.0	0.4	0.01	0.35	0.03	40	35	4.0	1175	4.7	2.0
		1.0	0.4	0.01	0.35	0.03	50	35	4.0	1175	4.7	5.0

Evapotranspiration

See also ID Line Format

Table Name	# Values	Parameter	Units	Typical Range
EVAPO-TRANSPIRATION	5	Albedo	none	0.0 – 1.0
		Wilting Point	none	0.03 – 0.25
		Vegetation Height	m	0.1 – 10.0
		Vertical Radiation Coefficient	none	0.0 – 1.0
		Canopy Resistance	s m^{-1}	0.0 – 500.0

Table Format							
EVAPO-TRANSPIRATION			*"Index Map Name"*				
NUM_IDS			####				
Text Line							
ID #1	*Description*	###.###	###.###	###.###	###.###	###.###	
ID #2	*Description*	###.###	###.###	###.###	###.###	###.###	
…							
ID #N	*Description*	###.###	###.###	###.###	###.###	###.###	

Example Table

```
EVAPO-TRANSPIRATION "evapo-transpiration map"
NUM_IDS 2
ID Description                Alb Wilt VegH VRadC CanRes
1 Fields                  0.100 0.100 0.10 0.100 30.0
2 Forest                  0.200 0.200 10.0 0.200 200.0
```

Soil erosion properties

See also ID Line Format

Table Name	# Values	Parameter	Units	Range
SOIL_EROSION_PROPS	3	Erodability	none	0.0-1.0
		Sand	none	0.0-1.0
		Silt	none	0.0-1.0

Table Format							
SOIL_EROSION_PROPS			*"Index Map Name"*				
NUM_IDS			####				
Text Line							
ID #1	*Description*	###.###	###.###	###.###			
ID #2	*Description*	###.###	###.###	###.###			
…							
ID #N	*Description*	###.###	###.###	###.###			

Example Table

```
SOIL_EROSION_PROPS "soil erosion properties map"
NUM_IDS 2
ID Description                Erode Sand Silt
1 Fields                  0.100 0.100 0.100
2 Forest                  0.200 0.200 0.200
```

Soil erosion factors

See also ID Line Format

Table Name	# Values	Parameter	Units	Range
SOIL_EROSION_FACTORS	2	Crop Management	none	0.0 – 1.0
		Conservation Practices	none	0.0 – 1.0

Table Format							
SOIL_EROSION_FACTORS			*"Index Map Name"*				
NUM_IDS			####				
Text Line							
ID #1	*Description*	###.###	###.###				
ID #2	*Description*	###.###	###.###				
…							
ID #N	*Description*	###.###	###.###				

Example Table

```
SOIL_EROSION_FACTORS "soil erosion factors map"
NUM_IDS 2
ID Description           C Mngt. Cons P
1 Fields                      0.100 0.100
2 Forest                      0.000 0.000
```

ID Line Format

The ID lines consist of three parts, the ID number, the description, and the parameter values. The main difference between the ID lines for the non-Richards' equation tables and the ID lines for the Richards' equation tables is that the Richards equations tables assign parameters for three different soil layers, each layer having its' own parameter set. In the ID lines for the Richards' equations, the two lines that do not begin with the ID and the description can have up to 86 characters. For each ID line, the ID must fill the first six spaces. There may be, and usually is, white space after the ID number, to fill the remaining six spaces. Likewise, the description must be 80 characters long. There may be as much white space in the 80 characters as needed. The 80 characters following the ID are only for the description of the ID and are not read by *GSSHA*. The 80-character length is mainly for the program *WMS*, which outputs two 40-character descriptions. The ID and description are followed by a number of parameter values dependent on the table type. All values for a table must be present, even if they are not used in a particular model. When unused values must be assigned, any valid floating point number, including 0.0, may be input. The amount of spacing between the values is not important, but it is usually visually helpful to align the parameters.

Format of ID lines (non-Richards equation tables)					
Number of Characters					
<- 6 ->	<------ 80 ------->	<-Parameter->	<-Parameter->	...	<-Parameter->
ID #1	Description	####.######	####.######	...	####.######
ID #2	Description	####.######	####.######	...	####.######
...					
ID #N	Description	####.######	####.######	...	####.######

Format of ID lines (Richards equation tables)					
Number of Characters					
<- 6 ->	<------ 80 ------>	<-Parameter->	<-Parameter->	...	<-Parameter->
ID #1	Description	####.######	####.######	...	####.######
		####.######	####.######	...	####.######
		####.######	####.######	...	####.######
ID #2	Description	####.######	####.######	...	####.######
		####.######	####.######	...	####.######
		####.######	####.######	...	####.######
...				...	
ID #N	Description	####.######	####.######	...	####.######
		####.######	####.######	...	####.######
		####.######	####.######	...	####.######

Example Mapping Table File

The following example mapping table file is for the North Fork watershed. Index maps of land use and soil texture are used to assign all the parameter values. The land use index map can contain three values, 1, 2, and 3. The soil texture index map can contain only the values 1 and 2. Tables for processes not used and multiple methods of solving different processes, such as Green and Ampt infiltration and Richards' equation can be created. Which method is used will be determined by the card in the project file, i.e. **GREEN_AMPT**, **INF_REDIST**, **INF_RICHARDS**.

```
GEISSHA_INDEX_MAP_TABLES
INDEX_MAP soil1.idx "Soils map of North Fork"
INDEX_MAP landuse.idx    "Land use map of North Fork"
INDEX_MAP landuse.idx "This map not used"
ROUGHNESS "Land use map of North Fork"
NUM_IDS 3
ID Description                      Roughness
1 Urban                             0.05
2 Fields                 0.2000
3 Fields                      0.1000
INTERCEPTION "Land use map of North Fork"
NUM_IDS 3
ID Description                StorCap IntrCoeff
1 Urban 0.1000 0.1000
2 Fields                0.1000       0.1000
3 Forest           0.2000      0.2000
RETENTION "Land use map of North Fork"
NUM_IDS 3
ID Description                Retention
1 Urban 0.5
1 Fields                1.0
2 Forest                2.0
```

```
GREEN_AMPT_INFILTRATION "Soils map of North Fork"
NUM_IDS 2
ID Description HY_COND CAP_HEAD POR POR_IDX RES_SAT
1 Clay       0.10 50.0 0.45 3.0 0.10
2 Sand       1.0 7.0 0.55 1.0 0.05
GREEN_AMPT_INITIAL_SOIL_MOISTURE "Soils map of North Fork"
NUM_IDS 2
ID Description                Moisture
1 Clay                        0.40
2 Sand                        0.10
RICHARDS_EQN_INFILTRATION_BROOKS "Soils map of North Fork"
NUM_IDS 2
MAX_NUMBER_CELLS 65
ID  Descript  Ks     •s     •r     •i     •wp     d       •     •b       •z
1   Clay      0.1   0.5    0.1   0.25   0.15   10.0    3.0   -50.0    1.0
              0.1   0.5    0.1   0.35   0.15   50.0    3.0   -50.0    2.0
              0.1   0.5    0.1   0.45   0.15   100.0   3.0   -50.0    5.0
2   Sand      1.0   0.45   0.1   0.25   0.05   10.0    1.5   -10.0    2.0
              1.0   0.45   0.1   0.35   0.05   10.0    1.5   -10.0    5.0
              1.0   0.45   0.1   0.35   0.05   10.0    1.5   -10.0    10.0
EVAPO-TRANSPIRATION "Land use of North Fork"
NUM_IDS 2
ID Description          Alb Wilt VegH VRadC CanRes
1 Urban                 0.100 0.100 0.100 0.100 0.100
2 Fields          0.200 0.200 10.0 0.200 0.200
3 Forest          0.300 0.300 0.15 0.300 0.300
SOIL_EROSION_PROPS "Soils map of North Fork"
NUM_IDS 2
ID Description                Erode Sand Silt
1 Clay                        0.100 0.100 0.900
2 Sand                        0.200 0.900 0.100
SOIL_EROSION_FACTORS "Land use map of North Fork"
NUM_IDS 3
ID Description                C Mng Cons P
1 Urban 0.100 0.100
1 Fields           0.100 0.100
2 Forest                0.500 0.500
```

12 Additional Table Inputs Not Supported by WMS

GSSHA will accept many types of data in table formats that *WMS* does not currently support. Some of these tables are too large to be effectively input with *WMS*, such as the rainfall input table. Others are either formats that are available in addition to the formats supported by *WMS*, or haven't yet been incorporated into the *WMS* system.

Spatially and Temporally Varied Rainfall

This file, described in Chapter 6, is used to describe the rainfall distribution, both spatially and temporally. This file is the only method to describe temporally or spatially varied rainfall.

Soil Layer Input File

The soil layer input file can be specified by inserting the SOIL_LAYER_INPUT_FILE card in the project file and providing the name of the file that contains the soil layer table. The soil layer input file is used to assign parameter values for use with the three-layer Green and Ampt model (INF_LAYERED_SOIL) and can be used to assign parameters for the Richards' equation with long-term simulations. The SOIL_LAYER_INPUT_FILE, as described in Chapter 7, must be used to provide inputs for the three layers Green and Ampt model (INF_LAYERED_SOIL). The soil layer input file can also be used to create a condensed form of the information that is provided when the mapping table file is used to assign parameter values for the Richards' equation (INF_RICHARDS). It is useful for automated calibrations when the input files must be repeatedly written out for multiple simulations. The format is not supported by *WMS*, so the table must be constructed with other software outside of *WMS* and the project file annotated. An index map must be specified with the SOIL_TYPE_MAP project card. This card names a *GRASS* ASCII map with integer values related to the IDs in the SOIL_LAYER_INPUT_FILE table. For use with RE, the file has the following two formats depending on whether the RICHARD_C_OPTION is *BROOKS* or *HAVERCAMP*.

Soils in the table (*N*)
Maximum number of cells of any soil in table
For each Soils from 1 to *N*:
Soil ID# albedo vegetation ht (m) transmission coefficient canopy resistance (m s^{-1})

Then for **RICHARDS_C_OPTION** *HAVERCAMP*:

Ks_{11}	$\theta_{s\,11}$	$\theta\ r_{11}$	$\theta\ i_{11}$	$\theta\ _{WP11}$	d_{11}	A_{11}	B_{11}	A_{11}	B_{11}	Δz_{11}
Ks_{12}	$\theta_{s\,12}$	$\theta\ r_{12}$	$\theta\ i_{12}$	$\theta\ _{WP12}$	d_{12}	A_{12}	B_{11}	A_{12}	B_{12}	Δz_{12}
Ks_{13}	$\theta_{s\,13}$	$\theta\ r_{13}$	$\theta\ i_{13}$	$\theta\ _{WP13}$	d_{13}	A_{13}	B_{13}	A_{13}	B_{13}	Δz_{13}

where:

Ks = saturated hydraulic conductivity (cm hr^{-1})
θ_s = porosity (fraction)
$\theta\ r$ = residual saturation (fraction)
$\theta\ i$ = initial water content (fraction)
$\theta\ _{WP}$ = wilting point water content (fraction)
d = depth of layer (cm)
A and B = Parameters used to fit water content/head curve
A and *B* = parameters used to fit hydraulic conductivity/head curve
Δz = vertical increment space step (cm)

The subscripts refer to the soil number and layer number, respectively, so that Ks_{12} is the hydraulic conductivity of soil 1 layer 2.

For RICHARDS_C_OPTION *BROOKS*:

Ks_{11}	$\theta_{s\,11}$	$\theta\ r_{11}$	$\theta\ i_{11}$	$\theta\ _{WP11}$	d_{11}	λ_{11}	ψ_{b11}	Δz_{11}
Ks_{12}	$\theta_{s\,12}$	$\theta\ r_{12}$	$\theta\ i_{12}$	$\theta\ _{WP12}$	d_{12}	λ_{12}	ψ_{b12}	Δz_{12}
Ks_{13}	$\theta_{s\,13}$	$\theta\ r_{13}$	$\theta\ i_{13}$	$\theta\ _{WP13}$	d_{13}	λ_{12}	ψ_{b13}	Δz_{13}

where: λ is the pore distribution index (dimensionless), and ψ_b – bubbling pressure (cm) (ψ_b values must be negative).

Example data set for sand: 1 Soil with uniform layers, 70 cm deep, Brooks and Corey parameters, 1.0 cm vertical discretization for all layers. For the ET parameters: land surface albedo - 0.1, vegetation height - 0.2 m, transmission coefficient - 0.8, and canopy resistance – 100 m s^{-1}.

```
1
70
1 0.1 0.2 0.8 100.0
 34.16 0.287 0.000 0.100 0.08 5.0 0.84 -19.60 1.0
 34.16 0.287 0.000 0.100 0.08 35.0 0.84 -19.60 1.0
 34.16 0.287 0.000 0.100 0.08 30.0 0.84 -19.60 1.0
```

Example data - Same Soil, Havercamp Parameters, same ET variables

```
1
70
1 0.1 0.2 0.8 100.0
34.00 0.287 0.075 0.100 0.075 5.0 35.5 3.96 1175000 4.74 1.0
34.00 0.287 0.075 0.100 0.075 35.0 35.5 3.96 1175000 4.74 1.0
34.00 0.287 0.075 0.100 0.075 30.0 35.5 3.96 1175000 4.74 1.0
```

Example data set - 7 soils with varying layer properties, each 1 meter deep, Brooks and Corey parameters, 7 different ET parameter sets

```
7
100
1 0.1 0.2 0.8 100.0
 34.16 0.287 0.000 0.100 0.08 10.0 0.84 -19.60 1.0
 34.16 0.287 0.000 0.100 0.08 40.0 0.84 -19.60 1.0
 34.16 0.287 0.000 0.100 0.08 50.0 0.84 -19.60 1.0
2 0.2 0.2 0.8 100.0
 0.0428 0.495 0.055 0.4950 0.055 1.0 0.25 -18.1 1.0
 0.0428 0.495 0.055 0.2376 0.055 49.0 0.25 -18.1 1.0
 0.0428 0.495 0.055 0.2376 0.055 50.0 0.25 -18.1 1.0
3 0.2 0.1 0.6 100.0
 3.9000 0.420 0.130 0.200 0.13 10.0 0.51 -141 1.0
 3.9000 0.420 0.130 0.200 0.13 40.0 0.51 -141 1.0
 3.9000 0.420 0.130 0.200 0.13 50.0 0.51 -141 1.0
4 0.1 0.2 0.6 150.0
 0.0428 0.495 0.055 0.495 0.055 1.0 0.25 -18.1 1.0
 0.0428 0.495 0.055 0.2376 0.055 4.0 0.25 -18.1 1.0
 3.9000 0.420 0.130 0.200 0.13 50.0 0.51 -141 1.0
5 0.15 0.2 0.4 25.0
 0.0428 0.495 0.055 0.495 0.055 1.0 0.25 -18.1 1.0
 0.0428 0.495 0.055 0.2376 0.055 4.0 0.25 -18.1 1.0
 34.16 0.287 0.000 0.100 0.08 50.0 0.84 -19.60 1.0
6 0.17 0.25 0.15 200.0
 34.16 0.287 0.000 0.100 0.08 45.0 0.84 -19.60 1.0
 0.0428 0.495 0.055 0.2376 0.055 10.0 0.25 -18.1 1.0
 34.16 0.287 0.000 0.100 0.08 45.0 0.84 -19.60 1.0
7 0.22 0.3 0.25 75.0
 0.0428 0.495 0.055 0.4 0.055 5.0 0.25 -18.1 1.0
 34.16 0.287 0.000 0.100 0.08 90.0 0.84 -19.60 1.0
 0.0428 0.495 0.055 0.4 0.055 5.0 0.25 -18.1 1.0
```

Static Pumping Wells

Static pumping well data for groundwater simulations must be input using the **GW_FLUX_BOUNDTABLE** as described in Chapter 8.

Hydrometeorological Input File

For continuous, **LONG_TERM**, simulations, hourly hydrometeorological variables must be input using the **HMET_WES**, **HMET_SAMPSON**, or **HMET_SURFAWAY** project cards. The formats of these files are described in Chapter 9.

13 Output

There are two required output files for each *GSSHA* simulation. These two files are specified with the **OUTLET_HYDRO** and **SUMMARY** project file cards, and contain the hydrograph at the catchment outlet and a summary of model performance, respectively (Table 22).

Required Flags and Files

Table 22. Required Output Cards.

CARD NAME	ARGUMENT	DESCRIPTION
SUMMARY	*file name*	Output file written during and after a simulation containing information on options selected, inputs read, mass conservation, and warnings generated during the simulation. REQUIRED
HYD_FREQ	*integer*	The frequency at which hydrograph ordinates are written, in time-steps. REQUIRED.
OUTLET_HYDRO	*file name*	Output file containing the outflow at the catchment outlet. REQUIRED

The outlet hydrograph file has no header, and contains two columns of real values. The first column contains the time in minutes since the beginning of the simulation for event simulations, the time in decimal years for continuous simulations, or the strict Julian date if the **STRICT_JULIAN_DATE** card is used in the project file. The second column contains the discharge, m^3s^{-1} default, or ft^3s^{-1} if the **QOUT_CFS** project card is present.

Run Summary File

The run summary contains a summary for each event simulated and simulation totals after the last event summary. For each event the run summary file contains a number of sections: title, start-up inputs, mass-conservation, warnings, and outputs. If Richards' equation is used to simulate the unsaturated zone a separate mass-conservation section is included in each event summary. If saturated groundwater is simulated then a separate mass-conservation is included in each event summary. The following is an example of the run summary file output for a continuous simulation with a single event. In this example Richards' equation is used to simulate the unsaturated zone and lateral groundwater flow is calculated, along with interaction with the stream network.

```
_________GSSHA start-up information_________
Run parameters read from WMS project file: 10gw.prj
reading watershed mask from file: test.mask
number of grid cells in watershed: 110
reading elevation map from file: elev_file
reading soil map from file: test.mask
reading water table map from file: test.wt
reading aquifer bottom map from file: test.gwb
Inital volume of water in root zone= 4989.621857

Inital volume of water in soil column= 574165.748622

reading groundwater boundary file: test.bound
reading hyd. cond. map from file: hycond_file
reading link map from file: test2.link
reading node map from file: test2.node
reading channel input data from file test.chan1
Initial soil water volume= 24948.109285
writing output for optimization to file
using precipitation data from file: one_event.gag
Running....

 GSSHA LONG-TERM RUNOFF SIMULATION SUMMARY- EVENT 1
Event began on strict Julian date: 2445113.04166667
Event ended on strict Julian date: 2445113.66111111
Event began on 05/23/1982 at 13:00 GMT -6.0 hours.

GSSHA used NCDC/SAMSON hydrometeorological data from the MEMPHIS
station
Hydrometeorology data began on: 05/24/1982 at 3:00
and ended on: 07/01/1982 at 0:00
The following number of hydromet. data points were repaired:0
Penman-Monteith evapo-transpiration was calculated.

With raingage data using Thiessen polygon interpolation.

time-step 60.0 seconds
elevation and gridsize are in meters
initial basin-averaged soil water content:16.21 percent
number of time-steps with rain: 630
elapsed time when rain began: 2204.00

peak occured on strict Julian date: 2445113.45486111
date/time of peak discharge: 5/23/1982 22:55:00
peak discharge (cms): 4.22

initial volume on overland (cu. m): 0.0
initial volume in channels (cu. m): 0.0
inital volume of snow (cu. m): 0.0

volume of rainfall (cubic meters): 225500.0
volume of discharge (cu. m): 122219.5
volume of infiltrated water (cu. m): 99579.3
volume of water exfiltrated (cu. m): 0.0
volume of lateral inflow (cu. m): 122652.2
volume of gw to chan (cu. m): -402.6
volume from overland point sources 0.0

volume remaining on surface (cu. m): 2005.3
final volume in channels (cu. m): 29.9
final volume of snow (cu. m): 0.0
```

```
mass conservation error: 0.0001 percent

 Richard's EQ. Computations

volume lost due to dir. evap (cu. m): 1263.3
net vol infiltrated to soil (cu. m.): 99354.7
volume to deep ground water (cu. m): 1025.9
Initial volume in soils (cu. m.): 574198.2
Final volume in soils (cu. m.): 670524.7
Richard equation mass balance error -0.1902 percent
Number of cells at start of event 9595
Number of cells at end of event 9589
net volume of infiltration is infiltration minus evaporation

 GROUNDWATER CALCULATION SUMMARIES FOR EVENT

volume of water directly to surface from groundwater (cu. m): 0.0
beginning vol of water exfiltrated this event (cu. m): 0.0
total vol of water exfiltrated this run (cu. m): 0.0
vol from gw to unsat this event (cu. m): -910.1
vol from gw to chan this event (cu. m): -402.6

final basin-averaged soil water content:74.69 percent

 THE FOLLOWING WARNINGS ARE GIVEN:
No Warnings.

 THE FOLLOWING INPUTS WERE READ:
A WMS Project File was used.
Floating point GRASS maps were read.

 THE FOLLOWING PROCESSES WERE SIMULATED:
Explicit diffusive-wave channel routing.
Uniform overland roughness.
Infiltration by Richards Eq.

 THE FOLLOWING OUTPUT MAPS WERE WRITTEN EVERY 60 TIME-STEP(S):
ASCII WMS maps of:
 overland flow depth.

 THE FOLLOWING ASCII OUTPUT FILES WERE WRITTEN TO EVERY 1 TIME-
STEP(S):
 hydrograph at the catchment outlet.


SIMULATION TOTALS

GROUNDWATER CALCULATIONS

GW volume start = 58878050.00
GW volume end = 58880266.51
Sat/unsat. trickery = 0.00
Exfiltration back on overland = 0.00
Infiltration to groundwater = 900.98
Total inputs to groundwater= 2212.47
Mass Balance error = -0.00

GLOBAL MASS BALANCE CALCULATIONS
All volumes are in cubic meters

Initial volume on surface= 0.00
```

```
Initial volume in channels= 0.00
Initial volume in soils= 574165.75
Initial volume in groundwater= 58878050.00

Final volume on surface= 2005.27
Final volume in channels= 29.94
Final volume in soils= 670524.67
Final volume in groundwater= 58880266.51
Final volume of snow= 0.00

Total amount of precip= 225500.00
Total amount of infiltration= 99579.28
Total amount of evaporation= 1576.53
Total direct evaporation= 1263.26
Total flux from unsat to gw= 900.98
Total amount of discharge= 122219.46
Total flux of gw across bounds= 0.00
Total flux from gw to river= -402.57
Total amount of exfiltration= 0.00
Total overland point sources= 0.00

Mass balance error of inputs= 0.000094 percent

Overall mass balance error = -0.001836 percent
```

Optional Flags

The optional flags are listed in Table 23.

Table 23. Optional Output Cards.

CARD NAME	ARGUMENT	DESCRIPTION
QOUT_CFS	*none*	Flag instructs *GSSHA* to write outflow hydrograph ordinates in cubic feet per second. The default is cubic meters per second. OPTIONAL
QUIET	*none*	Flag instructing *GSSHA* to suppress printing of information to the screen each time-step. OPTIONAL
STRICT_JULIAN_DATE	*none*	All time series data are written with strict Julian date.

Time Series Data at Internal Locations

GSSHA has the capability to save time series data of a number of parameters at internal locations in the channel network and within cells in the 2-D grid.

Time series data at internal stream network locations

GSSHA can save time series of discharge, depth, concentration and sediment flux at any link-node pair in the channel network by specifying the cards listed in Table 24. If internal time series data are desired then the

IN_HYD_LOCATION and **OUT_HYD_LOCATION** files must be specified in the project file.

Table 24. Internal Stream Network Output Cards.

CARD NAME	ARGUMENT	DESCRIPTION
IN_HYD_LOCATION	*table name*	Name of input ASCII file containing the link/node pairs to write out hydrograph ordinates to the file specified by OUT_HYD_LOCATION.
OUT_HYD_LOCATION	*file name*	Filename to output discharge ($m^3 s^{-1}$ or $ft^3 s^{-1}$) every HYD_FREQ time-steps, at internal channel locations specified in IN_HYD_LOCATION. REQUIRED if IN_HYD_LOCATION was specified.
OUT_DEP_LOCATION	*filename*	Filename to output time channel depths (m) every HYD_FREQ time-steps at internal channel locations specified in the IN_HYD_LOCATION file.
IN_SED_LOC	*filename*	Name of input ASCII file containing the link/node pairs to write out sediment discharge ordinates to the file specified by OUT_SED_LOC.
OUT_SED_LOC	*filename*	Filename to output sediment flux every HYD_FREQ time-steps at internal channel locations specified in the IN_SED_LOC file. REQUIRED if SOIL_EROSION and IN_SED_LOC card are specified.

The file specified by the **IN_HYD_LOCATION** card has a fixed format, which consists of an integer number equal to the number of points where hydrographs are to be saved (*N*), followed by *N* pairs of link and node numbers. For instance, if one wished to write out the hydrographs at 2 locations (link 8, node 18) and (link 6 node 113), the contents of **IN_HYD_LOCATION** file would be:

```
2
8 18
6 113
```

During the simulation, hydrograph ordinates would be written to the file specified with the **OUT_HYD_LOCATION** project file. The **OUT_HYD_LOCATION** file has (*N+1*) columns of data, where the first column contains the time in minutes since the beginning of the simulation for single events, the time in decimal years for continuous simulations, or the strict Julian date if the **STRICT_JULIAN_DATE** project card is used, and *N* columns of hydrograph ordinates. The hydrograph ordinates are written in the order they appear in the **IN_HYD_LOCATION** file. So, for example, an **OUT_HYD_LOCATION** file for the above example might appear as:

```
0.000 0.000 0.000
15.0 2.678 1.184
30.0 5.988 3.714
```

• • •
• • •
• • •

If depths are desired at the same locations specified in the **IN_HYD_LOCATION** file, then the **OUT_DEP_LOCATION** project card is used to specify the filename where depths (m default, ft if **OUT_CFS** is used) will be output.

If sediment flux at internal link-node locations is desired, the **OUT_SED_LOC** card is used to specify the filename where the sediment flux ($m^3\ s^{-1}$) will be output. For sediment flux the link-node locations must be specified in a file identified with the **IN_SED_LOC** project card. To get time series data of in-stream sediment flux, the **SOIL_EROSION** project card must be specified along with the appropriate sediment erosion inputs.

Strictly, there are no limits on the number of link-node pairs at which time series ordinates can be saved. Practically, however, there may be limits due to the number of columns of data that may be imported into your data analysis/plotting software. Hydrograph ordinates are written every **HYD_FREQ** time-steps.

Time series output at internal 2-D grid cell locations

Time series data of soil moisture and groundwater level may be output at any cell in the 2-D grid network. This capability is provided to be able to compare to measured soil moisture and groundwater level data.

When saturated groundwater is being simulated observation, wells at any row (*i*) and column (*j*) in the 2-D grid can be specified in the **OUT_WELL_LOCATION** file. The **OUT_WELL_LOCATION** file contains the number of locations where groundwater levels are desired, followed by the *ij* location of each desired observation well. The file has the following format.

observation wells (*N*)
i location of well 1 (i_1) j location of well 1 (j_1)
i_2 j_2
i_3 j_3
etc.

i_{N-1} j_{N-1}
i_N j_N

Time series values of groundwater elevation (m) at every well location will be output every **HYD_FREQ** time-steps to the file specified in the **GW_WELL_LEVEL** project card. This file will have one column for time and one column of groundwater surface elevation (m) for each well (*N* wells) listed in the **OUT_WELL_LOCATION**. The order of the output is the same as the order of the input.

Any time infiltration is being calculated, soil moistures may be output at any cell in the soil column of any cell in the 2-D grid. To get time series data of soil moistures the **IN_THETA_LOCATION** card is used to provide the name of a file that contains the locations of cells where soil moisture output is desired. When any Green and Ampt approximation is used the location 2-D grid location, *i* row, *j* column, is specified in the **IN_THETA_LOCATION** file. For the various Green and Ampt approximations, soil moistures at the soil surface will be output. For Green and Ampt approximations the **IN_THETA_LOCATION** file has the following format.

The first line contains the number of 2-D grid locations where output is desired. Then for each 2-D grid cell where soil moisture output is desired the *i* location and *j* location are specified. This sequence is repeated for each 2-D grid location. This file has the following format:

2-D Grid Locations (*N*)
i_1 j_1
i_2 j_2
...
...
....
i_{N-1} j_{N-1}
i_N j_N

To get output from a given cell in the Richards' equation solution, the location in the 2-D grid, *i* row, *j* column, and the location within that *ij* location, k^{th} cell, must be specified. The **IN_THETA_LOCATION** file has the following format. The first line contains the number of 2-D grid locations where output is desired and the maximum number of cells desired at

any 2-D grid point. Then for each 2-D grid location desired, the *i* location, *j* location, and the number of vertical cells at that *ij* location are specified. This is followed by the vertical cell numbers (*k*) of each of the cells at the ij location. This sequence is repeated for each 2-D grid location. This file has the following format:

2-D Grid Locations (*N*) Maximum number of cells at any location (*M*)
i_1 j_1 M_1
vertical cell # 1 (k_1)
k_2
k_3
etc.
k_{M1-1}
k_{M1}
i_2 j_2 M_2
k_1
etc.
k_{M2-1}
k_{M2}
etc.
i_N j_N M_N
k_1
etc.
k_{MN-1}
k_{MN}

For example, soil moistures are desired at two locations in the 2-D grid, at cell *i* = 40, *j* = 13 and at cell *i* = 24, *j* = 32. Soil moistures are desired at five depths at each of these *ij* locations, corresponding to vertical cell # (*k*) 25, 50, 71, 111, 170 at both sites. The required file would look like

```
2 5
40 13 5
25
50
71
111
170
24 32 5
25
50
71
111
170
```

The soil moistures are then output to the file specified in the **OUT_THETA_LOCATION** file whose format is identical to that of the **OUT_HYD_LOCATION** file. For the preceding Richards' equation example, the **OUT_THETA_LOCATION** file would contain 11 columns of data, one for the time and 10 for soil moistures at the specified locations, which will appear in the order requested in the **IN_THETA_LOCATION** file. For all Green and Ampt approximations each line will contain the time followed by one value of soil moisture, soil moisture at the surface, for each 2-D grid cell selected in the **IN_THETA_LOCATION** file, in the order requested in the **IN_THETA_LOCATION** file.

WMS Hydrograph File

GSSHA has the capability to write the outlet and the internal location hydrographs to a file format readable by *WMS* v7.0 and higher. This is specified by including the **WMS_HYDRO** project card and the name of the file to be written to. The *WMS* hydrograph file is generated post-process, at the end of a *GSSHA* run. The file has the following format:

```
GEISSHA_WMS_HYDROGRAPH_FILE
[Number of internal hydrographs {N}]
[start date (YYYYMMDD)]
[start time (2400)]
[time-step interval, in seconds]
[number of hydrograph ordinates {M}]
[first node/link pair]
[second node/link pair]
…
[Nth node/link pair]
[outlet hydr. ord.–1] [outlet hydr. ord.–2] … [outlet hydr. ord.–10]
[outlet hydr. ord.–11] [outlet hydr. ord.–12] … [outlet hydr. ord.–20]
[outlet hydr. ord.–21] [outlet hydr. ord.–22] … [outlet hydr. ord.–30]
…
[outlet hydr. ord.–M–9] [outlet hydr. ord.–M–8] … [outlet hydr. ord.–M]
[internal hydr1 – 1] [internal hydr1 – 2] … [internal hydr1 – 10]
[internal hydr1 – 11] [internal hydr1 – 12] … [internal hydr1 – 20]
[internal hydr1 – 21] [internal hydr1 – 22] … [internal hydr1 – 30]
…
[internal hydr1 – M–9] [internal hydr1 – M–8] … [internal hydr1 – M]
[internal hydr2 – 1] [internal hydr2 – 2] … [internal hydr2 – 10]
[internal hydr2 – 11] [internal hydr2 – 12] … [internal hydr2 – 20]
[internal hydr2 – 21] [internal hydr2 – 22] … [internal hydr2 – 30]
…
[internal hydr2 – M–9] [internal hydr2 – M–8] … [internal hydr2 – M]
…
[internal hydrN – 1] [internal hydrN – 2] … [internal hydrN – 10]
[internal hydrN – 11] [internal hydrN – 12] … [internal hydrN – 20]
[internal hydrN – 21] [internal hydrN – 22] … [internal hydrN – 30]
…
[internal hydrN – M–9] [internal hydrN – M–8] … [internal hydrN – M]
```

The hydrograph ordinates are arranged 10 to a row, with each new hydrograph starting on a new line. If the number of hydrograph ordinates is not evenly divisible by 10 then the rest of the last line of ordinates for the hydrograph is left blank. The node-link pairs are arranged in the same order as the input and output hydrograph location files. The hydrograph data follow the same order, with the hydrograph data for the outlet being first and the internal location hydrographs following in order.

Time Series Maps

GSSHA can produce time series maps of most spatially varied model output. In particular, *GSSHA* can write time series maps of spatially distributed rainfall, overland flow discharge, flow depths on the watershed, depths in the channel network, discharges in the channel network, cumulative infiltrated depth, infiltration rate, soil surface water content, groundwater head, contaminant concentration, volume of suspended sediment, maximum sediment flux, and net sediment flux. The project file cards required to write output time series maps are listed in Chapter 3, "Optional Output Maps."

The **MAP_TYPE** project file card described in the preceding table determines the format of the output map. If the argument of **MAP_TYPE** is 0, then a series of *GRASS* ASCII maps are written, each with a different extension (e.g., depth.0, depth.1, depth.2 ...). These maps may be imported back into *GRASS* using the *r.in.ascii* command. Maps of types 1 and 2 are written in a generic *WMS* format. Maps of type 1 are written as ASCII files that may be read and processed by the user. All ASCII maps have the disadvantage of being up to twice the size of binary maps. Map type 3 is binary *WMS* format, which is the most compact, but cannot be directly read or edited. All maps are written every **MAP_FREQ** time-steps.

Output time series maps are very useful for obtaining an intuitive feel as to what is happening in the watershed at a given time. Using *WMS* to animate a series of maps provides the user with a moving time series of the output of concern. This allows the user to see how the variable's spatial distribution progresses with time. Besides providing a means of visually analyzing the output, the output maps can be helpful in spotting problems with the model. If fact, many years ago, the spatially varied maps of rainfall made obvious a problem in the inverse weighted distance rainfall distribution routine that may have otherwise gone by unnoticed.

In particular, the overland depth map is useful for getting *GSSHA* to run properly. This map contains overland flow depths (m). If the **INCLUDE_CHANNEL_DEPTH** card is included, the channel depth (m) is written in place of the overland flow depth in grid cells that contain channel links. The first map always corresponds to the initial condition and shows the water-surface profile corresponding to the base flow discharge within the channel network. Similarly, the last depth map corresponds to the end-of-simulation time, or to the time at which the program finished abnormally. Abnormal program termination caused by oscillating depths may show negative depths in the overland plane, typically in a checkerboard fashion. This map output can be informative to illustrate the location of flow problems such as pits, dams, or flat regions in the overland flow plane.

After calibration of *GSSHA*, depth and discharge maps are useful for floodplain determination, flow velocity estimation, and a host of other purposes. The spatially-varied output maps of soil surface water content and cumulative infiltrated depth are useful for analyzing the spatial variability of infiltration, and may be used as input for other surficial process models. The spatially varied rainfall map is illustrative for demonstrating storm and rainfall dynamics. These maps can be imported into *GRASS* and displayed as a film loop using the *GRASS* `xganim` program. *WMS* can be used to animate the time series of maps and build standard AVI files that can be played back by any type of animation software. Such animations can make a lasting image when inserted into otherwise vanilla PowerPoint presentations.

14 Creating Project Files

The following sections provide examples to illustrate the typical form of project files for three situations. The first project file represents the bare minimum input requirements for running *GSSHA* for a single event with spatially uniform surface roughness and rainfall, without infiltration or channel routing. The second project file shows the required cards for an event simulation with spatially varied rainfall, surface roughness, infiltration and channel routing. The third example shows a project file for *GSSHA* running in the continuous simulation mode with fully spatially varied inputs.

Simple Project File

For this project file example, we use an invented watershed data set. The topography of the watershed is shown in the Figure 15 with a 50-m resolution *GSSHA* grid overlay:

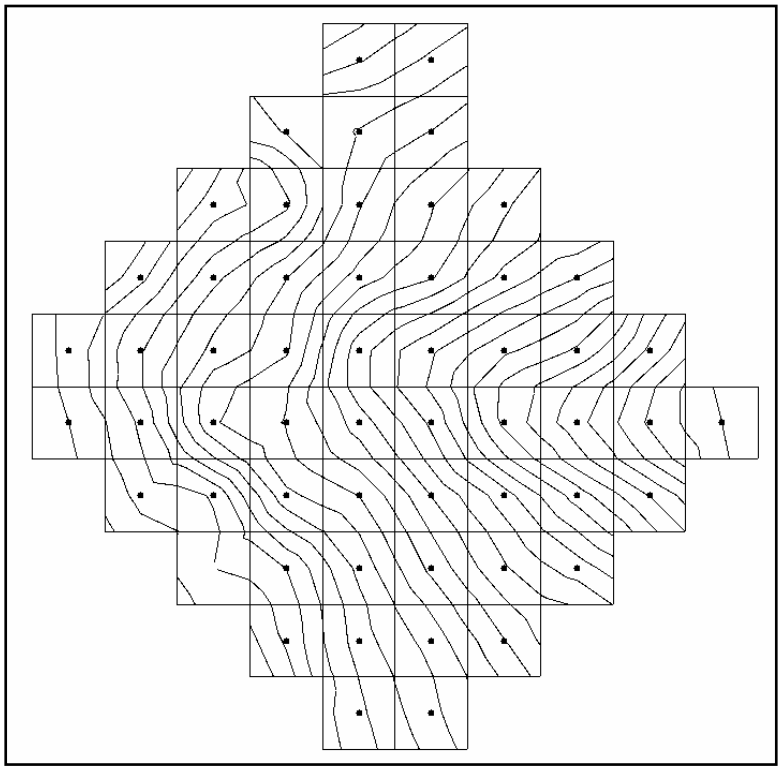


Figure 15. Example watershed grid with elevation topography.

This watershed has a mask map which is appears as (with contrived coordinates):

```
north: 11000.0
south: 10500.0
east: 2000.0
west: 1500.0
rows: 10
cols: 10
0 0 0 0 1 1 0 0 0 0
0 0 0 1 1 1 0 0 0 0
0 0 1 1 1 1 1 0 0 0
0 1 1 1 1 1 1 1 0 0
1 1 1 1 1 1 1 1 1 0
1 1 1 1 1 1 1 1 1 1
0 1 1 1 1 1 1 1 1 0
0 0 1 1 1 1 1 1 0 0
0 0 0 1 1 1 1 0 0 0
0 0 0 0 1 1 0 0 0 0
```

In addition, the watershed digital elevation model from which the Figure 15 was derived (using *WMS*) appears as:

```
north: 11000.0
south: 10500.0
east: 2000.0
west: 1500.0
rows: 10
cols: 10
 0.0 0.0 0.0 0.0 89.6 85.7 0.0 0.0 0.0 0.0
 0.0 0.0 0.0 86.1 83.1 80.3 0.0 0.0 0.0 0.0
 0.0 0.0 96.7 92.8 80.7 74.8 69.2 0.0 0.0 0.0
 0.0 98.9 90.1 83.5 76.2 71.9 64.8 59.8 0.0 0.0
100.0 92.5 85.5 80.9 66.9 60.3 54.6 50.5 41.5 0.0
101.1 94.6 80.8 77.3 70.2 62.1 50.2 43.2 35.6 30.3
 0.0 97.2 94.8 81.2 77.4 68.6 61.1 52.6 44.9 0.0
 0.0 0.0 95.2 92.2 82.5 73.8 66.1 61.4 0.0 0.0
 0.0 0.0 0.0 94.7 84.9 79.3 71.7 0.0 0.0 0.0
 0.0 0.0 0.0 0.0 87.0 81.3 0.0 0.0 0.0 0.0
```

The mask and elevation maps were saved in files name “mask.map” and “elev.map,” respectively. Notice that the outlet of the catchment is in row 6 and column 10 of the DEM. This is the lowest point on the perimeter of the watershed. Also notice that the headers for the two maps are identical, and that the grids are square, and 50 m in size.

The following represents the simplest possible project file to run *GSSHA*. This project file will run *GSSHA* with a spatially uniform Manning roughness coefficient equal to 0.036 and with spatially uniform rainfall at a rate of 80.0 mm/hr for a duration of 2 hr (120 min). Notice that lines that

begin with the pound sign are comments, which are allowed in the project file.

```
CASC2DPROJECT
#The only 2 required maps.
WATERSHED_MASK          mask.map
ELEVATION               elev.map
#Required watershed geometrical information.
UNITS                   0
GRIDSIZE                50.0
ROWS                    10
COLS                    10
#Run duration information.
TOT_TIME                2000
TIME-STEP               20.0
#The next 3 lines req'd because no channel routing.
OUTROW                  6
OUTCOL                  10
OUTSLOPE                0.106
#Spatially-uniform overland flow roughness.
MANNING_N               0.036
#Rainfall input.
PRECIP_UNIF
RAIN_INTENSITY          80.0
RAIN_DURATION           120
#Following two lines required only for spatially-unif. rainfall.
START_DATE              1997  7 17
START_TIME              22 20
#Required output files.
SUMMARY                 simple.sum
HYD_FREQ                6
OUTLET_HYDRO            simple.hyd
```

Without the comments, the project file is more readable:

```
CASC2DPROJECT
WATERSHED_MASK mask.map
ELEVATION elev.map
UNITS 0
QUIET
GRIDSIZE 50.0
ROWS 10
COLS 10
TOT_TIME 2000
TIME-STEP 20.0
OUTROW 6
OUTCOL 10
OUTSLOPE 0.106
MANNING_N 0.036
PRECIP_UNIF
RAIN_INTENSITY 80.0
RAIN_DURATION 120
START_DATE 1997 7 17
START_TIME 22 20
SUMMARY simple.sum
HYD_FREQ 6
OUTLET_HYDRO simple.hyd
```

This project file is saved under the name “simple.prj”. *GSSHA* is run by typing the command “*GSSHA* simple.prj.” For this example, the following outflow hydrograph is the result:

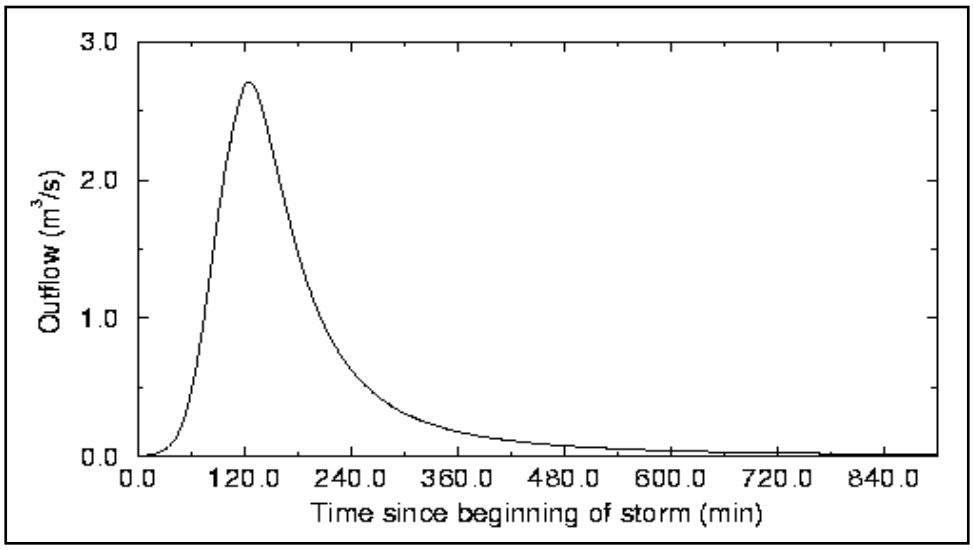


Figure 16. Hydrograph output from simple project example.

Involved Project File

Infiltration can be included in the simulations using one of the optional methods. For the sake of this example, Green & Ampt infiltration will be simulated, which requires additional inputs of porosity, saturated hydraulic conductivity, capillary head parameter, and initial water content as maps or as mapping table inputs related to index maps. Assume that these data are saved in maps named “simple.por,” “simple.sat,” “simple.cap,” and “simple.moi,” respectively. Spatially distributed rainfall will also be input, with two rain gages using inverse distance squared interpolation. The rainfall data are stored in a file called “simple.gag.” A single channel, which consists of two links, will also be simulated. The channel input data file will be called “simple.chn,” with link and node maps name “simple.lnk,” and “simple.nod,” respectively. The format of the channel input files is described in the Appendix on channel routing.

The resulting project file for this simulation appears as:

```
CASC2DPROJECT
WATERSHED_MASK mask.map
ELEVATION elev.map
UNITS 0
QUIET
GRIDSIZE 50.0
```

```
ROWS 10
COLS 10
TOT_TIME 2000
TIME-STEP 20.0
MANNING_N 0.036
PRECIP_FILE             simple.gag
RAIN_INV_DISTANCE
GREEN_AMPT
POROSITY                simple.por
CONDUCTIVITY            simple.sat
CAPILLARY               simple.cap
MOISTURE                simple.moi
CHAN_EXPLIC
CHANNEL_INPUT simple.cip
LINKS                   simple.lnk
NODES                   simple.nod
SUMMARY simple.sum
HYD_FREQ 6
OUTLET_HYDRO simple.hyd
```

Notice that the START_DATE and START_TIME project file cards have been removed. These two cards are required only for spatially- and temporally-uniform precipitation, because this information is contained in the precipitation input data file. Also note that the OUTCOL, OUTROW, and OUTSLOPE project file cards have been removed, because they are not required when channel routing is enabled. The outlet of the catchment is determined from the overland flow/channel flow connectivity information provided by the link and node maps.

The four maps simple.por, simple.sat, simple.cap, and simple.moi can also be replaced with tabled values related to an index map, such as a soil texture map. This is the standard way processes are assigned parameter values in *WMS* 6.1 and higher. In this case the project file would look like.

```
CASC2DPROJECT
WATERSHED_MASK mask.map
ELEVATION elev.map
UNITS 0
QUIET
GRIDSIZE 50.0
ROWS 10
COLS 10
TOT_TIME 2000
TIME-STEP 20.0
MANNING_N 0.036
PRECIP_FILE             simple.gag
RAIN_INV_DISTANCE
GREEN_AMPT
MAPPING_TABLE green_ampt.tbl
CHAN_EXPLIC
CHANNEL_INPUT simple.cip
LINKS                   simple.lnk
NODES                   simple.nod
```

```
SUMMARY simple.sum
HYD_FREQ 6
OUTLET_HYDRO simple.hyd
```

And the mapping table file named *green_ampt.tbl* would contain the values of hydraulic conductivity, porosity, suction head, and initial moisture, which would be indexed to integer based index maps, such as a soil-texture map, as described in Chapter 11.

Continuous Simulation Project File

The following example project file will instruct *GSSHA* to perform a continuous simulation with the Penman-Monteith evapotranspiration scheme, Green and Ampt infiltration with redistribution (Ogden and Saghafian 1997), surface retention storage, spatially distributed surface roughness, and rainfall interception. Furthermore, ASCII *GRASS* maps of spatially distributed depth on the watershed will be written every 30 time-steps.

```
CASC2DPROJECT
WATERSHED_MASK mask.map
ELEVATION elev.map
UNITS 0
QUIET
GRIDSIZE 50.0
ROWS 10
COLS 10
TOT_TIME 2000
TIME-STEP 20.0
ROUGHNESS simple.man
PRECIP_FILE        simple.gag
RAIN_INV_DISTANCE
RETENTION               simple.ret
STORAGE_CAPACITY   simple.sto
INTERCEPTION_COEFF      simple.ico
LONG_TERM
LATITUDE                37.15
LONGITUDE               99.34
GMT                     -7
ET_CALC_PENMAN
ALBEDO                  simple.alb
WILTING_POINT           simple.wlp
TCOEFF                  simple.tco
VHEIGHT                 simple.vht
CANOPY                  simple.can
SOIL_MOIST_DEPTH   0.85
EVENT_MIN_Q        0.01
HMET_WES                hmet.dat
INF_REDIST
POROSITY                simple.por
CONDUCTIVITY            simple.sat
CAPILLARY               simple.cap
MOISTURE                simple.moi
```

```
PORE_INDEX              simple.lam
RESIDUAL_SAT            simple.res
CHAN_EXPLIC
CHANNEL_INPUT           simple.cip
LINKS               simple.lnk
NODES               simple.nod
SUMMARY simple.sum
HYD_FREQ 6
OUTLET_HYDR simple.hyd
MAP_FREQ                30
MAP_TYPE                0
DEPTH                   simple.dep
```

Again, in using *WMS* to construct the project file all the spatially varied maps would be replaced with mapping table entries linked to appropriate index maps, such as land use, soil-texture, and combination land-use/soil-texture maps. In this case the project file would look like

```
CASC2DPROJECT
WATERSHED_MASK mask.map
ELEVATION elev.map
UNITS 0
QUIET
GRIDSIZE 50.0
ROWS 10
COLS 10
TOT_TIME 2000
TIME-STEP 20.0
PRECIP_FILE         simple.gag
RAIN_INV_DISTANCE
LONG_TERM
LATITUDE 37.15
LONGITUDE           99.34
GMT                 -7
ET_CALC_PENMAN
SOIL_MOIST_DEPTH    0.85
EVENT_MIN_Q         0.01
HMET_WES            hmet.dat
INF_REDIST
MAPPING_TABLE simple.tbl
CHAN_EXPLIC
CHANNEL_INPUT       simple.cip
LINKS               simple.lnk
NODES               simple.nod
SUMMARY simple.sum
HYD_FREQ 6
OUTLET_HYDRO simple.hyd
MAP_FREQ            30
MAP_TYPE            0
DEPTH               simple.dep
```

The mapping table file *simple.tbl* would supply all the needed parameters for overland flow, ET, infiltration, and soil moisture accounting.

As these examples indicate, the complexity of *GSSHA* simulations is determined by the contents of the project file (and the availability of data, of course). Project files can be built which incorporate every nonexclusive option of *GSSHA* to perform continuous simulations with complete spatial variability in rainfall, interception, retention storage, evapo-transpiration, overland flow, channel flow, unsaturated zone calculation for infiltration and soil moisture accounting, and lateral saturated groundwater flow with feedback to the unsaturated zone, stream network, and overland flow-plane. In the construction of project files, the user must provide all required data for a given option, and avoid specifying mutually exclusive options.

15 Building GSSHA Model

To this point this manual has described the theory, processes, solutions, and various inputs and outputs that can be used in the *GSSHA* model. This section is intended to provide the user with a step-by-step instruction on how to build a model beginning with a blinking curser. While there are many ways to construct a model with *GSSHA*, significant experience by the authors suggest that the following methodology is a prudent, if not the best way, to construct a *GSSHA* model.

While *CASC2D* models were routinely built using a variety of software, including spreadsheets, *GRASS*, and other GIS and GUIs in addition to *WMS* v5.1, *GSSHA* has been closely linked to the *WMS* v6.1 and higher, and it is strongly recommended that this software be used to develop the needed inputs for the model. As listed in Chapter 12, tables not supported by *WMS*, many required and optional plain vanilla tables must be created outside the *WMS* framework, and these can be created with a simple spreadsheet or word processing software. Unlike *CASC2D*, which obtains distributed inputs exclusively from *GRASS* ASCII maps, *GSSHA* is intended to be used with the mapping table and the related index maps described in Chapter 11. This is the method *WMS* 6.1 and higher will employ. Experience with the *CASC2D* model indicates that this method of assigning parameters is superior for the typical case where parameters must be assigned based on reclassification of common index maps, such as land use, soil-texture, and vegetation (Downer et al. 2002a). In addition to the *WMS* and a spreadsheet to build table inputs, a GIS is usually needed, or at least helpful, in developing many of the data layers that the *GSSHA* model requires. While the steps required to build a *GSSHA* model will be presented here, *WMS* how-to information is contained in the *WMS* User Manual (Nelson 2001) and the *WMS* for *GSSHA* Primer (Downer et al. 2003).

An essential element in successfully developing a complex *GSSHA* model is to start simple, get parts or processes of the model to run, and then build upon success. It is important to follow the methodology described here. *WMS* can be used to build a complex model all at one time. Such a model could have millions of cells, a complex stream network, unsaturated zone calculations, saturated groundwater flow, etc. Such a model would also

have little chance of ever working properly because the amount of information and possible problems is overwhelming.

Delineating Watershed

The first step in building a *GSSHA* model is to delineate the watershed. The watershed is delineated from the DEM. DEM data of various resolutions can be obtained from the USGS and EPA Basins data bases, accessable through links provided by the EMRL geospatial data access Web site at BYU, *http://www.emrl.byu.edu/gsda*. 90-m resolution data are available for all of the United States; 30-m resolution data are available for most areas, and 10-m data are becoming available. While models are not routinely run with grid sizes finer than 90 m, the 10-m data have a much better vertical resolution, typically 0.1 m as opposed to 1.0 m for the 90-m resolution data. Unless the GIS or GUI cannot digest the large number of data points, the 30-m data will provide better watershed and stream delineations. These data are typically available as 7.5-min quad sheets. When the watershed overlaps two or more maps, then the overlapping sheets need to be put together and any discrepancies between the different maps resolved. The *WMS* software has tools available to accomplish these tasks. With the DEM covering the watershed in hand, *WMS* can be used to delineate the watershed above any give point in the basin, basin outlet, based on calculations from *TOPAZ* (Martz and Garbrecht 1992). The *TOPAZ* model also determines the stream network from the DEM data. This may or may not be useful. If a watershed boundary has been predetermined, the watershed polygon can be used to “cut out” the appropriate DEM data, or can be imported for use as the watershed boundary in *WMS*. If a watershed boundary is imposed on the DEM then it is likely that the DEM or resulting grid will have to be edited to force the cells in the predefined watershed to all drain toward the basin outlet.

Selecting Grid Size

Selection of an appropriate grid size is important in successful modeling of a watershed and was discussed in Chapter 4. Key to successful modeling of processes at the cell level is that the cell size be smaller than the size of the essential feature of the landscape involved in the model. For example, Ogden et al. (2000) used a 30-m grid size to model the Fort Collins, CO, flash flood of July 28, 1997. This small grid size was used because the urbanized Spring Creek catchment in Fort Collins has a number of small-scale landscape features such as: roads, parking lots, buildings. Con-

versely, Doe and Saghafian (1992) successfully modeled the Taylor Arroyo watershed near Trinidad Colorado with a 300-m grid. While the climates are similar, the Taylor Arroyo watershed is essentially completely undeveloped. Three hundred-m grid cells are not large compared to soil texture and vegetation complexes in the watershed. It is possible that even larger grid cells could be used. The grid size also has an effect on slopes, which may be important for overland sediment transport calculations as discussed by Sanchez (2002).

Overland Flow Routing

The simplest *GSSHA* model consists of a grid with elevations from the DEM and roughness values assigned, allowing overland flow routing to be simulated. Overland flow routing should first be attempted with uniform values of rainfall and overland roughness and a small time-step, on the order of 10 sec. Spatially varied maps of depth should be output every few time-steps. As described in Chapter 13, these maps are useful for locating problem areas in the watershed, and comparing areas that water ponds to independent topographic data. If the overland flow module will not run with a small time-step and the very stable *ADEPC* overland flow routine, the depth maps should be consulted to identify potential problems in the watershed. The elevations in the watershed may be smoothed using algorithms in the *WMS* software, or the elevations may also be manually edited. If water is ponding along the edge of the watershed, these cells will either have to be removed from the grid or raised in elevation. Another potential solution to making the overland flow module run is to increase the grid size, which will reduce the Courant number, and smooth the elevations in the model.

Once the overland flow routine will run with uniform roughness parameters, initial roughness parameters and retention depths can be spatially distributed according to index maps of land use and vegetation.

Infiltration

With a working overland flow model in hand, the next step is to select an infiltration routine and assign the needed initial parameters. In selection of an infiltration routine, the source of runoff and streamflow should be a major consideration. The GA, multilayer GA, and GAR models are only valid selections if the primary mechanism generating streamflow is Hortonian (Horton 1933) infiltration excess runoff. Downer et al. (2002a)

explain the pitfalls of trying to apply the GA based methods to watersheds where the Hortonian runoff mechanisms is not dominant. In this case, the more general RE solution should be used to calculate infiltration. If a shallow water table is present, then the effects of the water table will also have to be included in the model. This will be discussed later. Conversely, if Hortonian flow is the dominate stream flow producing mechanism, solving RE will likely yield only small benefits over solving a less general GA approximation (Downer and Ogden 2003).

For single events the GA model or multilayer GA model will suffice. For continuous simulations the GAR method is used. A single event model using GA may later be changed to GAR by changing the infiltration option and supplying the additional needed parameters. With a method of calculating infiltration selected, the appropriate initial parameters are assigned using the mapping table and a combination index map of soil-texture, land use, and vegetation. When using RE the appropriate vertical grid size is important (Downer 2002) and the effect of the grid size on runoff should be investigated to determine an adequate resolution. This model should also be run with the uniform rainfall event. As infiltration will tend to reduce the amount of runoff, the model with infiltration will likely run on the first attempt, and the time-step can likely be increased without changing the shape of the predicted outlet hydrograph.

Channel Routing

While small watersheds with no well defined channel may be simulated without channel routing, large basins or basins with a defined channel almost always need channel routing to accurately reproduce the outlet flow. There are many possible ways to locate the stream. The location of the stream network may be surveyed, come from USGS .dlg files or other sources of digital stream network, or the stream delineation provided by *TOPAZ* may be used. In any case, as with the overland flow, it is best to start with a simple channel network and add complexity. As a first approximation, the main stem and only major tributaries should be included in the stream network. Once the simple network is running, additional stream segments can be added. As the stream segments begin to represent smaller and smaller tributaries, the effect of adding additional streams will begin to diminish.

As discussed in Chapter 5, ideally the stream network comes with surveyed cross sections and thalweg elevations. Also discussed in Chapter 5 is a

procedure for taking stream bottom elevations from the DEM. As discussed in "Longitudinal channel profile smoothing," it will be important to smooth the thalweg elevations to create a realistic channel profile and perhaps edit the grid elevations to ensure that overland flow can enter the stream. Whether to use breakpoint cross sections or trapezoidal approximations generally depends on the availability of surveyed cross sections. However, if in-stream sediment transport is to be simulated, trapezoidal cross sections must be used.

Single Event Calibration

A *GSSHA* model with overland flow, infiltration, and channel routing represents a fairly complete model, and this model can be used to determine appropriate time-steps, RE cell sizes, and channel routing parameters, i.e. channel roughness. While this step is not essential, it is useful. For the single event calibration the user should select one storm event from the observed data that provides a reasonably well-defined outlet hydrograph. Overland flow and infiltration parameters can be adjusted to produce the approximately correct volume of flow at the watershed outlet. The in-stream channel roughness is tuned to match the hydrograph peak and shape. This initial single event calibration can either be done manually, or with an automated calibration process, such as the SCE method. With a single event the SCE method will converge in a short period of time, likely overnight. While the overland flow and infiltration parameters from this effort are of limited value (Senarath et al. 2000), the values of in-stream roughness should be approximately correct. Also, this calibrated model can be used to determine what model time-step can be used and the appropriate cell size for RE solutions.

Assuming the model has been calibrated at some small time-step, say 10 sec, the calibrated simulation can be repeated with increasingly larger time-steps until either a) the model crashes , b) the outlet hydrograph begins to oscillate, or c) the shape of the outlet hydrograph begins to significantly change in shape. When any of these occur, the time-step is too large and should be reduced until the problem disappears. It is possible that very large time-steps, several minutes, can be used in the simulation without significantly affecting the results. This will significantly reduce execution times and may be especially important when using an automated calibration process over an extended simulation period. As this exercise will demonstrate, the model will produce almost exactly the same results for time-steps below some critical value, so that using time-steps

much smaller than this critical value will not result in improved results, only longer simulation times. This optimal time-step is then used in subsequent calibrations and simulations.

The same procedure can be used to determine the appropriate cell size to use in the RE solution (Downer 2002). Starting with very small cell sizes in the top 10 cm of the soil column, 1 – 10 mm, the cell size is increased until the volume of runoff begins to significantly deviate from the original results. This theshold cell size is used in subsequent calibrations and simulations.

Long-term Simulations

Long-term simulations with ET calculations, as described in Chapter 9, are needed to model longer periods with multiple storm events. Long-term simulations must also be performed to properly simulate soil moistures in the unsaturated zone, saturated groundwater movement and stream interaction. As described by Senarath et al. (2000) long-term simulations are also necessary to properly calibrate any *GSSHA* model, even if it to be used only to simulate single events. ET parameters are assigned with the mapping table, and related to the combination land use/soil-texture/vegetation index map. The selection of appropriate root depths for such crude indexes can be difficult (Downer and Ogden 2003) and these values are most properly thought of as effective values that are determined through calibration. Although the method to simulate the seasonal effects in *GSSHA* is crude, it has been shown to be effective (Downer and Ogden 2003) and the SEASONAL_RS card should be included in the project file if simulations are to be conducted outside the summer growing season, May-September.

The rainfall file and hourly hydro-met data file should be constructed to cover the calibration, verification, and simulation scenarios period. This period may be weeks to years, depending on the available record. To properly calibrate a model, a period with overlapping rainfall and streamflow measurements from several storm events that produce stream flow should be selected. The hydro-met data should start just after the last rainfall event before the simulation or calibration period, and saturated or near saturated initial moistures are assumed. The model should be run in continuous mode with the entire calibration period to locate and fix problems in the input files and assure the model will run for the entire period with the initial parameters, time-step and grid size.

Saturated Groundwater Modeling

Whether to simulate saturated groundwater depends on the properties of the watershed to be simulated and the availability of subsurface information. For intermittent streams, lateral groundwater flow is not likely an important consideration. For streams with significant baseflow, and for streams where there is an obvious contribution of groundwater flow or known or suspected saturated source areas during rainfall events, groundwater simulations will likely be required to capture the shape and volume of discharge hydrographs (Downer et. al. 2002a; Downer et al. 2002b).

When saturated groundwater is to be simulated the information on the bedrock elevations and properties of the saturated groundwater media are required. In addition, boundaries must be supplied along the watershed boundary. Unlike in surface-water flow, where the boundary condition is obvious and simple, assignment of groundwater boundaries can be difficult and the boundary conditions can dominate the groundwater flow solution. If there is a known groundwater divide along all (unlikely) or part (more likely) of the watershed boundary then a no flow boundary can be used on this part of the watershed boundary. Otherwise, head boundaries must be imposed. Imposition of improper head boundaries will lead to bad simulations despite an otherwise good model. Head boundaries along the edge of the watershed should come from measured well data or from a good regional groundwater model that includes the watershed of interest.

If channel routing is being performed, the streams should be defined as RIVER_FLUX boundaries and the flux between the stream and the groundwater will be computed every stream routing time-step. For this calculation to be meaningful, the thalweg elevation and the grid land surface elevation must be correct, or at least the difference in thalweg elevation and land surface elevation must be correct. For this reason, land surface elevations in the cells corresponding to stream nodes may need to be adjusted. This is almost a requirement if smoothing of the thalweg elevations has occurred. If groundwater/stream interactions are to be simulated, it is best to begin by editing the land surface grid elevations to produce a smooth channel profile, and then subtract the incision of the channel in the grid cell to determine the thalweg elevations to be used in the channel input file.

Initial water-surface elevations may be interpolated from well data or may be some assumed elevations. In either case it is usually necessary to run

the groundwater simulations for an extended period to produce realistic initial values of groundwater elevation to be used in simulations. For instance, if the simulation period of interest is May though September, the model should be run from January to May to produce a starting WATER_TABLE file. Depending on the outcome, this procedure may have to be repeated multiple times, where the ending water-surface elevation becomes the starting water-surface elevation for the next attempt. A proper initial water surface has been established once the baseflow is on the correct order of magnitude, and maps of groundwater elevation are both smooth and agree reasonably well with well observations.

Calibration and Verification

The complete model should be calibrated and verified to an extended period of data while operating in the LONG_TERM mode. For flow models, the model should be calibrated to observed discharges at the outlet and any interior points. The OPTIMIZE project card can be used to provide peak discharge and discharge volume for individual events and the entire simulation at the watershed outlet and at any desired internal locations. These can be used to calculate a cost function, and parameter sets that produce the smallest cost function, minimum error as defined by the cost function, can be determined either manually or preferably with an automated method, such as the SCE method. Typical calibration parameters listed in order of importance for each process include:

Overland Flow
Surface roughness
Retention depth
Infiltration
Saturated hydraulic conductivity (all methods)
Suction head (GA, multilayer GA, GAR) or bubbling pressure (RE)
Initial moisture
Porosity
Channel Flow
Roughness coefficient
Evapo-transpiration
Root depth
Canopy resistance
Soil Moisture
Pore distribution index
Wilting-point soil moisture
Groundwater Flow
Saturated hydraulic conductivity

Porosity

To use the SCE method, the number of parameters to be calibrated should be kept to a minimum, typically less than 16 (Senarath et al. 2000). To reduce the number of parameters, the proportions of initial estimates of parameters for different index types can be adjusted as a set, i.e. adjust all values of some parameter, saturated hydraulic conductivity for example, by the same fractional amount.

The model with the calibrated parameter set should be tested against independent verification period, such as a split-sample test (Klemes 1986). Once the model demonstrates the ability to predict discharge, or other variables of interest, for the verification period, it can be used with confidence to analyze model scenarios and make predictions under varying hydrologic conditions.

Sediment Transport

Once a working hydrology/hydraulics model has been calibrated and verified, sediment transport can be added to the model. Overland sediment transport parameters are derived from the soil-texture/land-use index maps. Users should consult the manual and sediment transport textbooks (such as Yang 1996) to learn about using Yang's method (Yang 1973) to assign appropriate parameters for the in-stream sediment routing. As with the hydrology/hydraulics portion of the code, the sediment model should also be calibrated and verified to observed data.

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14. ABSTRACT

The need to simulate surface water flows in watersheds with diverse runoff production mechanisms has led to the development of the physically-based hydrologic model Gridded Surface Subsurface Hydrologic Analysis (GSSHA). GSSHA is a reformulation and enhancement of the two-dimensional, physically based model CASC2D. The GSSHA model is capable of simulating stream flow generated by a variety of sources, including runoff due to infiltration excess and saturated sources areas and seeps, as well as direct interaction between streams and the saturated groundwater. The model employs mass-conserving solutions of partial differential equations. The hydrologic components are closely linked, assuring an overall mass balance. The model has been applied to a diverse variety of projects and has been proven useful for analysis of hydrologic and sedimentation processes, and can provide information needed for designed systems and the potential effects of projects, land-use change, environmental restoration, best management practices, climate change, and related issues. This manual describes the model formulation, model input, and provides information on the practice of hydrologic modeling with GSSHA, and hydrologic modeling in general.

15. SUBJECT TERMS

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