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Preface

This report should be cited as follows:

Downer, C. W., Nelson, E. J., and Byrd, A. (2002). "Primer: Using Watershed Modeling System (WMS) for Gridded Surface Subsurface Hydrologic Analysis (GSSHA) Data Development—WMS 6.1 and GSSHA 1.43C," ERDC/CHL TR-02-XX, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

1 *OVERVIEW*

Introduction

This document is a primer for use of the Watershed Modeling System (*WMS*) interface with the physically based, distributed-parameter hydrologic model Gridded Surface Subsurface Hydrologic Analysis (*GSSHA*). The primary purpose of this primer is to describe how the *WMS* interface is used to develop inputs and analyze output from the *GSSHA* model. This primer also provides a brief description of the *GSSHA* model, including the overall model formulation, processes that can be simulated, and input formats for files not supported by *WMS*.

Along with the *WMS* 'how-to' information, the primer provides hints on appropriate values to use in a *GSSHA* simulation, potential problem areas, and trouble shooting suggestions. However, this primer is not meant to be a substitute for the *GSSHA User's Manual* (Downer and Ogden in preparation), which should be consulted for specific information on the *GSSHA* model. Many of the concepts used in the *GSSHA* model are complex, and an in-depth knowledge of the processes involved and the solution methods available are critical for successful application of the model. It is highly recommended that users obtain and read the *GSSHA User's Manual* before attempting to use the *GSSHA* model. In addition, many of the procedures outlined in this primer are described in greater detail in the *WMS Help File* (Nelson 2001).

Users should be aware that the *GSSHA* model is always in development and is constantly being improved, refined, and updated with new ideas. Typically, linkage with the *WMS* interface is the last task completed in new model developments, after development, implementation, and testing of the new feature in *GSSHA* are complete. Therefore, *WMS* may not support new developments in the *GSSHA* model. Some files that the *GSSHA* model uses, such as the rainfall and hydrometeorological data files for long-term simulations, are not supported by the *WMS* interface. Files that *WMS* does not support are pointed out in the primer and also in the user's manual. This primer is meant to be used with *WMS 6.1* (Nelson 2001) and *GSSHA 1.43c* (Downer and Ogden in preparation).

History

The *GSSHA* model is a significant reformulation and enhancement of the *CASC2D* model (Ogden and Julien 2002). The *CASC2D* runoff model originally began with a two-dimensional (2-D) overland flow routing algorithm developed and written in a programming language (APL) by Prof. P. Y. Julien, 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 & Ampt infiltration and explicit diffusive-wave channel routing (Julien and Saghafian 1991; Saghafian 1992; and Julien, Saghafian, and Ogden 1995). The FORTRAN code was reformulated, significantly enhanced, and rewritten in the C programming language by Dr. Saghafian at the U.S. Army Construction Engineering Research Laboratories. This version, named r.hydro.casc2d, was part of the Geographic Resources Analysis Support

System/Geographic Information System (*GRASS*)/(GIS) for hydrologic simulations (Saghafian 1993). Work began in 1995 to reformulate *CASC2D* with the addition of continuous simulation capabilities and ability to interface with the Watershed Modeling System graphical user interface developed by the Environmental Modeling Research Laboratory (EMRL) at 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. Johnson (1997) added overland sediment transport. Development of the *CASC2D* model for *WMS* by the Department of Defense (DoD) ended with version 1.18b, which has been the working distributed hydrologic model for the DoD (Downer et al. 2002a). *CASC2D Ver. 1.18b* is linked with *WMS 5.1* as described by (BYU 1997a and 1997b).

While developed from the *CASC2D* model, the *GSSHA* model is inherently different in that it extends the capability of the model to simulate runoff mechanisms other than infiltration excess. Also, input of parameters for the *GSSHA* model is significantly different from the methods employed for *CASC2D*. The *GSSHA* model is backwards compatible with *CASC2D Ver. 1.18b* data sets. *CASC2D Ver. 1.18b*, and thus *GSSHA*, is not necessarily compatible with prior versions of *CASC2D* data sets. Also, *WMS* no longer supports the *CASC2D* input format, which is based on providing parameter values for every grid cell through a number of floating point *GRASS* ASCII format maps. When trying to utilize old *CASC2D* data sets, make sure they conform to the standards described in the *GSSHA User's Manual*.

Description

GSSHA is a physically based, distributed-parameter, structured grid, hydrologic model that simulates the hydrologic response of a watershed subject to given hydrometeorological inputs. Major components of the model include spatially and temporally varying precipitation, snowfall accumulation and melting, precipitation interception, infiltration, evapotranspiration, surface runoff routing, unsaturated zone soil moisture accounting, saturated groundwater flow, overland sediment erosion, transport and deposition, and in-stream sediment transport. 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. This formulation permits the efficient simultaneous simulation of processes that have dissimilar response times, such as overland flow, evapotranspiration (ET), and lateral groundwater flow. This scheme also allows an integrated solution of processes coupled through boundary conditions and flux exchanges.

Process 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. For several processes, there are multiple solution methods. A brief description of the processes and solution methods is presented. To obtain detailed information about the processes and methods, please refer to the *GSSHA User's Manual* (Downer and Ogden in preparation).

Process	Description
Precipitation distribution	Thiessen, Inverse distance square weighted
Snowfall accumulation and melting	Energy balance
Precipitation interception	Two-parameter emphirical
Overland water retention	Specified depth
Infiltration	Green & Ampt (G&A), Multi-layered Green & Ampt, Green & Ampt with Redistribution (GAR), One-dimensional (1-D) vertical Richards' equation (RE)
Overland flow routing	2-D lateral diffusive wave Explicit, Alternating Direction Explicit (ADE), Alternating Direction Explicit with Prediction-Correction (ADE-PC)
Channel routing	1-D longitudinal, explicit, up-gradient, diffusive wave
Evapotranspiration	Deardorff (1977) Penman-Monteith with seasonal canopy resistance
Soil moisture in the Vadose zone	Bucket, 1-D vertical Richards' equation (RE)
Lateral saturated groundwater flow	2-D vertically averaged
Stream/groundwater interaction	Darcy's law
Exfiltration	Darcy's law
Overland sediment erosion	Kilinc and Richardson (1973) equation
Channel sediment routing	Yang's method

Table 1. Process and Approximations Techniques in the GSSHA Model. (G&A – Green and Ampt (1911), GAR – Green and Ampt with Redistribution (Ogden and Saghafian 1997), RE – Richards' equation (Richards 1931), ADE – alternating direction explicit, ADE-PC – alternating direction explicit with prediction-correction *(Downer et al. 2002b)*

Precipitation distribution

In *GSSHA*, precipitation may be spatially distributed over the watershed by specifying a number of rain gages in the rainfall input file. Precipitation is distributed between the gages using either Thiessen polygons or an inverse distance square weighted method. Precipitation at each gage may vary in time, and nonuniform time increments may be used.

Snowfall accumulation and melting

Precipitation will automatically be treated as snowfall any time long-term simulations are conducted and the dry bulb temperature is below 0 °C. Any accumulated snowfall is treated as a one-layer snowpack that melts as a result of heat sources including: nonfrozen precipitation, net radiation, heat transferred by sublimation and evaporation, and sensible heat transfer as the result of turbulence.

Precipitation interception

Interception is the process of vegetation capturing precipitation and preventing it from reaching the land surface. Interception is modeled in *GSSHA* using an empirical two-parameter model that accounts for an initial volume of water that vegetation can hold plus the fraction of precipitation captured after the initial volume of water has been satisfied. The fate of intercepted water is not accounted for in *GSSHA*. The rainfall intercepted by vegetation is assumed to evaporate.

Infiltration

Infiltration is the process whereby rainfall and ponded surface water seep into the soil because of gravity and capillary suction. In *GSSHA* there are two general methods used to simulate infiltration. These are the Green and Ampt (1911) model and the Richards' equation (1931) models. There are also two extended Green and Ampt models, making a total of four infiltration options to chose from.

Green and Ampt

The use of all the Green and Ampt based methods is limited to conditions where infiltration excess, or Hortonian runoff (Horton 1933), is the dominant stream flow producing mechanism. In the Green and Ampt model of infiltration, water is assumed to enter the soil as a sharp wetting front. Precipitation on initially dry soil is quickly infiltrated because of capillary pressure. As rainfall continues to fall and the ground becomes saturated, the infiltration rate will decrease until it approaches the saturated hydraulic conductivity of the soil.

Multi-layer Green and Ampt

The Green and Ampt model described assumes an infinitely deep, homogeneous, soil column. The *GSSHA* model also allows the user to specify Green and Ampt infiltration into soils with three defined layers. Changes in the hydraulic properties resulting from layering in the soil column always results in reduced infiltration capacity.

Green and Ampt with redistribution

When conducting long-term simulations, the Green and Ampt infiltration with redistribution (GAR) can be used (Ogden and Saghafian 1997). With GAR, multiple sharp wetting fronts can be simulated, and the water is redistributed in the soil column during nonprecipitation periods.

Richards' equation

Richards' equation is currently the most complete method to compute soil water movement including hydrologic fluxes such as infiltration, actual evapotranspiration (AET), and groundwater recharge. The use of Richards' equation is not limited to Hortonian runoff calculations. Richards' equation is a partial differential equation (PDE) that is solved using finite difference techniques. In *GSSHA* three soil layers, each with independent parameters for each soil type and layer, are specified. Because the Richards' equation is highly nonlinear, finding a solution can be difficult and time-consuming when Richards' equation is used to simulate the highly transient conditions often found in hydrology, such as sharp wetting fronts and fluctuating water table. The *GSSHA* model employs powerful, mass conserving methods of solving the Richards' equation and has been capable of simulating both soil moistures and associated hydrologic fluxes when the proper spatial discretization is employed (Downer 2002).

Overland flow routing

Water on the soil surface that neither infiltrates nor evaporates will pond on the surface. It can also move from one grid cell to the next as overland flow. The overland flow routing formulation is based on a 2-D explicit finite volume solution to the diffusive wave equation. Three different solution methods are available: point explicit, alternating direction explicit (ADE), and ADE with prediction-correction (ADE-PC). Through a step function, a depression depth may be specified. No water is routed as overland flow until the depth of water in the cell exceeds the depression depth. This depression depth represents retention storage resulting from microtopography.

Channel routing

When channel routing is specified, overland flow that reaches a user-defined stream section enters the stream and is routed through a 1-D channel network until it reaches the watershed outlet. Channel routing in *GSSHA* is simulated using an explicit solution of the diffusive wave equation. This simple method has several internal stability checks that result in a robust solution that can be used for subcritical, supercritical, and transcritical flows.

Evapotranspiration

Evapotranspiration (ET) is the combined effect of evaporation of water ponded on the soil surface and contained in the soil pores, as well as the transpiration of water from plants. *GSSHA* uses evapotranspiration to track soil moisture conditions for long-term simulations. Evapotranspiration can be modeled using two different techniques, the Deardorff (1977) and Penman-Monteith (Monteith 1965 and 1981). The Deardorff method is a simplified method used for formulations involving only bare soil. The Penman-Monteith method is a more sophisticated method used for vegetated areas.

Soil moisture in the vadose zone

During long-term simulations, the soil moisture in the unsaturated, or vadose, zone can be simulated with one of two methods: a simple fixed soil volume accounting method (Senarath et al. 2000) (bucket method), or simulation of soil moisture movement and hydrologic fluxes using Richards' equation (Downer 2002). Evaporative demand is supplied to either method by the ET calculations.

Lateral saturated groundwater flow

Where groundwater significantly affects the surface water hydrology, saturated groundwater flow may be simulated with a finite difference representation of the 2-D, lateral, saturated groundwater flow equations. The saturated groundwater finite difference grid maps directly to the overland flow grid. The saturated groundwater zone resides below the unsaturated zone, which may be represented with either the GAR model or the Richards' equation model. When simulating saturated groundwater flow, the additional processes of stream/channel interaction and exfiltration may occur.

Stream/groundwater interaction.

When both saturated groundwater flow and channel routing are being simulated, water flux between the stream and the saturated groundwater can be simulated. By specifying that both overland flow and saturated groundwater flow grid cells containing stream network nodes be considered as river flux cells, water will move between the channel and the groundwater domain based upon Darcy's law.

Exfiltration.

Exfiltration is the flux of water from the saturated zone onto the overland flow plane. You may have seen a seep at a change in slope on a hillside. This seepage is exfiltration. Exfiltration occurs when the water table elevation exceeds that of the land surface. Fluxes to the land surface are computed using Darcy's law.

Overland sediment erosion

Sediments on the overland flow plane can be eroded, transported, and deposited using the soil erosion model developed by Kilinc and Richardson (1973), modified by Julien (1995) and implemented in *CASC2D* by Johnson (1997). Cell to cell sediment discharge by means of overland flow is a function of the hydraulic properties of the flow, the physical properties of the soil, and surface characteristics. Sediment transport is computed for three grain sizes: sand, silt, and clay. Conservation of sediment mass is used to determine what portion of sediment in a grid cell is deposited and what portion stays in suspension. The suspended sediment may be transported from one cell to another. If there is insufficient sediment in suspension, previously deposited sediment is used to satisfy the erosion demand. Insufficient previous deposition results in the erosion of the surface.

Channel sediment routing

When both channel routing and overland-flow sediment routing are simulated, sediment routing in the channel can also be simulated. The present version of *GSSHA* employs Yang's (1973) method for routing of sand-size total load in stream channels. The routing formulation works

only with trapezoidal cross sections. Silt and clay size fractions are transported with the flow as wash load. Any gains or losses of wash load, such as deposition or erosion of silts and clays within the channels, are neglected.

Applications

GSSHA accounts for the following conditions that may be encountered when simulating watershed hydrology:

1. Spatial variability of soil textures, land use, and vegetation that may affect parameter values needed to simulate important hydrologic processes.

2. Spatial and temporal variability of precipitation.

3. Snowfall accumulation and melting.

4. Drainage network of arbitrary shape and cross sections.

5. Effect of soil moisture on infiltration and runoff.

6. Effect of water table on soil moisture, infiltration, and runoff.

7. Gaining and losing streams.

8. Hortonian runoff.

9. Saturated source areas.

10. Exfiltration.

11. Overland sediment movement.

12. In-stream sediment movement.

It has been verified that *GSSHA*, and/or the methods taken from *CASC2D* and employed in *GSSHA*, can be used to simulate the following types of hydrologic variables:

1. *Stream discharge in Hortonian basins (Doe and Saghafian 1992; Ogden et al. 2000; Senarath et al. 2000; Downer et al. 2002a)*

2. *Stream discharge in non-Hortonian and mixed runoff basins. (Downer 2002; Downer et al. 2002b)*

3. *Soil moistures in Hortonian basins. (Downer 2002).*

4. *Sediment discharge in Hortonian basins (Johnson 1997)*

Modeling Process

Application of *GSSHA* requires the creation of a variety of input files and grid data (or maps). *GSSHA* has been coupled with *WMS* in an attempt to minimize the time required to create the needed inputs. *WMS* is also intended to aid in model conceptualization and analysis of results. The basic parts of the modeling process are watershed delineation and grid construction, selection of processes to model, parameter assignment, channel routing assignment, running the model, and postprocessing. The *GSSHA User's Manual* (Downer and Ogden in preparation) provides detailed information on the modeling process.

Grid construction

GSSHA is a finite difference based model and requires a 2-D grid representation of the watershed being modeled. Construction of this grid is the first step in the development of a *GSSHA* model. *WMS* has a variety of tools that can be used for watershed delineation and grid generation from digital elevation data as well as data exported from the *GRASS* or *Arc/Info* GISs.

Process selection

Once the grid is constructed, the processes to be simulated must be selected based on the needs of the study. The processes to be simulated are selected. It is best to start with a simple model with few processes and proceed to build more complicated models with several processes. The *GSSHA User's Manual* (Downer and Ogden in preparation) should be consulted for more information on which processes are appropriate for which studies.

Model parameter assignment

Once the grid has been created and processes selected, model parameters governing the execution of *GSSHA* must be assigned. Model parameters include global variables such as simulation time and time-step, as well as the distributed parameters needed to simulate processes such as interception, infiltration, and overland flow routing. *WMS* facilitates global parameter assignment with dialog boxes and distributed-parameter assignment with the use of index maps and the mapping tables.

Channel routing

Larger watersheds normally require that the 1-D channel routing option in *GSSHA* be used. The channel routing method is an explicit diffusive-wave approximation. The channel network is described with a series of channel links and computational nodes. A link is a channel segment, or other internal boundary condition, such as a weir, comprised of two or more computational nodes. *WMS* feature arcs are used to create the channel links and assign cross-sectional parameters to the links. In order to couple the channel routing with surface runoff, *GSSHA* must know which grid cells "contain" stream nodes. When *WMS* creates the appropriate input files, grid cells beneath the stream arcs are identified as stream cells and their connectivity is written to link and node map files. *WMS* has several tools for creating, numbering, and assigning parameters to the channel links and nodes.

Running GSSHA

Once all necessary input for a *GSSHA* simulation has been prepared, the *GSSHA* model is run. *GSSHA* is a stand-alone program that can be executed from the command line or through the *WMS* interface.

Postprocessing

Results from successful *GSSHA* simulations may be viewed in *WMS*. The optional output created by *GSSHA* can include time series of maps of a number of variables including: surface water depth, infiltration rate, cumulative infiltrated depth, spatially varied rainfall, soil moistures, groundwater heads, and others. Time series data of several variables, such as soil moisture or groundwater head, may be output at selected points in the grid. Time series output of discharge,

depth, and sediment concentration can be produced at selected nodes in the channel network. *WMS* has capabilities to contour, shade, and animate the results for the entire 2-D grid. Additionally, 2-D plots of any result variable versus time can be generated for any location in the grid. Postprocessing techniques are used to help the user determine if a solution is reasonable or if further model modification is necessary.

2   *WATERSHED DELINEATION AND GRID CONSTRUCTION*

Introduction

The primary input files for a *GSSHA* rainfall/runoff simulation are the 2-D finite difference grid and its' accompanying surface elevations. The grid is a rectangular area that covers the extents of the watershed. Individual cells whose centroid are within the watershed boundary are flagged as "active" (a value of "1" in the watershed mask), and cells outside the boundary are flagged as "inactive" (a value of "0" in the watershed mask). *WMS* can be used to automatically delineate a watershed boundary from digital elevation data and then construct a finite difference grid with the appropriate active and inactive flags set for individual cells.

In this chapter you will learn where to locate digital elevation data that can be used for automated basin delineation and assignment of surface elevations for the finite difference grid. You will also learn the basic processes used by *WMS* to delineate the watershed boundary and construct a grid.

Obtaining DEM Data for Watershed Delineation

The United States Geological Survey (USGS) has converted their topographic maps into digital elevation model (DEM) files. These files represent the land surface as a matrix (grid) of elevation values at a given space (resolution) apart. The most commonly used maps are the 1:24,000 series that are commonly found in a 30-m resolution, with many areas now being converted to a 10-m resolution. In addition, the 1:250,000 map series has also been converted into 3 arc-second (approximately 90 m) resolution DEMs. Both DEM classes have been distributed by the USGS for a number of years. More recently free downloads are available from the World Wide Web (www). Many other local, state, and Federal agencies warehouse and deliver these DEM products. The EMRL at BYU has developed a single website that contains links to some of the most common and easy to use websites for free downloading of DEM data. This website is hosted at:

http://www.emrl.byu.edu/gsda

In addition to DEM data, this site also contains resources for locating, downloading, and preparing land use, soil textural classification, and image data. Each topic contains basic information, frequently asked questions, and detailed instructions for obtaining and preparing the data to be used in *WMS*.

DEM File Formats

The USGS has two different file formats. Historically, quadrangle map DEMs have been stored in a single file using what is often referred to as the "USGS Format." In recent years, the Federal Geographic Data Committee (FGDC) has developed standards for sharing spatial data and most DEMs have been converted to this format, referred to as the "SDTS Format." *WMS* can import either format, but the old-style USGS format is a little easier to work with. The SDTS is a format defined for vector as well as raster (grid) data. Multiple files are required to define the elevation grid with the STDS format. In the case of DEMs, many of these required files are blank or small. The USGS DEMs often are named with a ". dem" extension while the SDTS DEM files will contain a ". ddf" extension. When reading the SDTS DEM, any of the ".ddf" files may be specified for the file. *WMS* will automatically extract the needed information from the various files.

Besides the two USGS file formats, the Arc/Info ASCII grid is another commonly used format by many GIS systems. If you are trying to obtain data stored in Arc/Info grid files, you must have the grid converted to ASCII, as the binary file format is proprietary to Environmental Systems Research Incorporated (ESRI) and unreadable by *WMS*. *WMS* also supports the DTED and *GRASS* grid file formats.

Watershed Delineation

While it is possible to manually create a grid and set the active and inactive regions, it is not recommended. Since the DEM (or other elevation data) will be used to assign elevations to the grid cells, it is good practice to use the elevation data to automatically create a watershed boundary. You can then use that boundary (a polygon, as shown in Figure 1) to construct a grid that covers the watershed extents and automatically assigns cells within the boundary as active, and cells beyond as inactive.
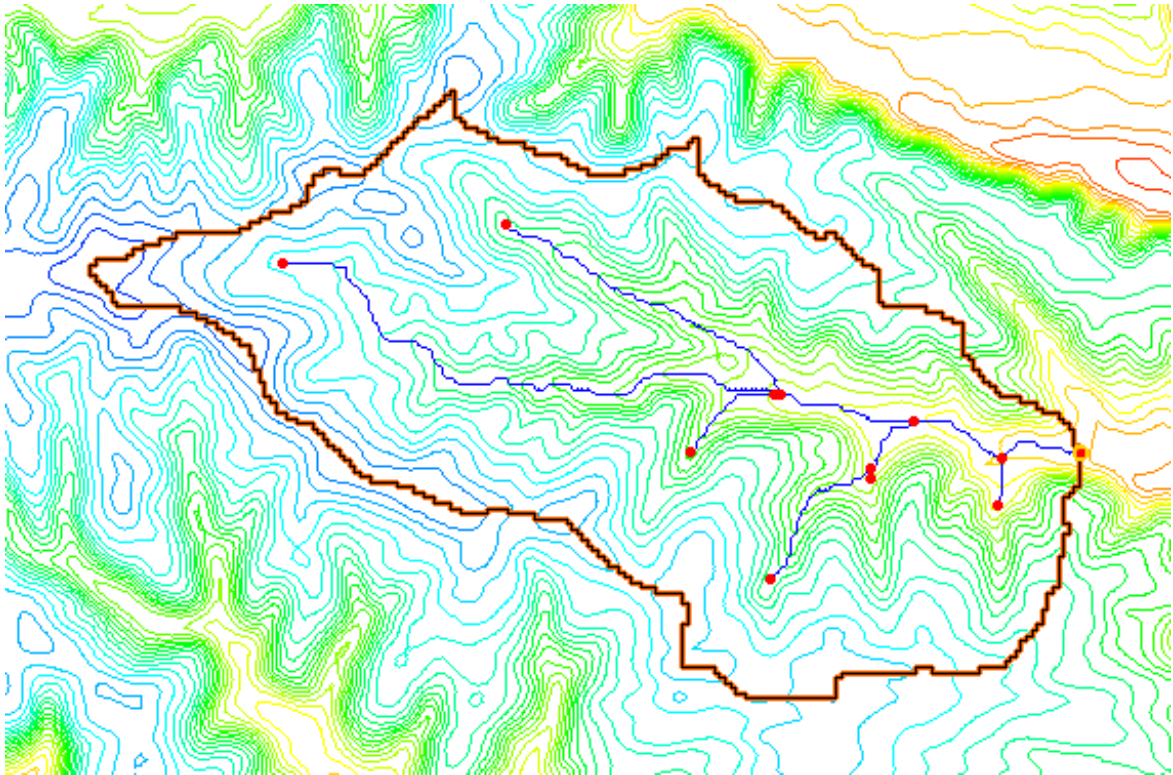
Figure 1. An automatically delineated watershed boundary through the use of a digital elevation file and the program TOPAZ. The streams shown were also automatically created by WMS

WMS provides three methods of automated watershed delineation. An overview of each is given here. A broader overview can be found in the *WMS* reference file under the Introduction chapter, with more detailed instructions in the individual chapters. The simplest and best way to create the watershed boundary from the DEM. Additional methods can be employed if you do not have access to the required DEM data.

Basin delineation with DEMs

DEM data can be used in *WMS* to automatically delineate basin boundaries and define stream networks. Typically a USGS DEM (multiple quadrangles can be tiled together) is imported. Any gridded elevation data set can be used providing it is in one of the formats readable by *WMS*. The United States Department of Agriculture (USDA) program *TOPAZ* (Martz and Garbrecht 1992) is launched from *WMS* to define flow directions and flow accumulations for each DEM cell. This information is used to trace and convert the stream networks and basin boundaries to lines and polygons of the *WMS* drainage coverage. The polygon and stream network shown in the Figure 1 were delineated in *WMS* using this method. More details about basin delineation with DEMs can be found in the *WMS* help file (Nelson 2001).

Basin delineation with TINs

Triangulated Irregular Networks (TINs) can also be used to delineate a watershed boundary that will be used for *GSSHA* models. A TIN is another form of elevation data, but rather than be organized as a grid, rows and columns of elevations with equal spacing between, it is a network of triangles formed from scattered elevation points. TIN data are much less common than DEM data and slightly more complicated to work with. When using the TIN method for watershed delineation in *WMS,* you should convert the resulting boundaries and stream network to feature objects using the "Drainage Data-> Feature Objects command. Details on the use of TINs for automated watershed delineation can be found in the *WMS* help file.

Basin delineation with feature objects

If you have an existing watershed boundary and stream network already defined in a GIS or CAD environment, then it is possible to import these data in *WMS* as a drainage coverage and use the imported feature arcs directly to create the *GSSHA* grid and channel data. However, elevation data are still required to interpolate surface elevations to the resulting *GSSHA* grid. When using an existing watershed boundary, you should use caution because, unlike the DEM method where the boundaries and streams are defined directly from the elevations, the streams and boundary of the imported data may not coincide with the interpolated elevation data. This can result in elevation errors in overland flow grid cells and channel nodes, leading to numerical instability in the *GSSHA* model. The elevations in the resulting grid may need to be edited on a cell by cell basis. Further details on the use of feature objects are provided in the *WMS* Help File.

Grid Sizes

In general, the higher the resolution (smaller grid cells), the more accurate the solution will be. While theoretically the number of grid cells that can be used for *GSSHA* modeling is unlimited, there are some practical limitations. In order to define all model parameters, approximately 3,500 bytes of memory are required for each grid cell. This means that one megabyte of RAM is required for each 300 grid cells of a *GSSHA* simulation. In addition to the amount of memory, the time to display and work with the model inside of *WMS* and the time required for the *GSSHA* simulation to run will increase.

The issue of appropriate grid sizes has not been adequately answered to date. Several research papers address the range of applicability of the diffusive wave form of the equations of motion that are used for overland flow routing in *GSSHA*. However, the picture is complicated by the difficulty in including the effects of microtopography on runoff routing. Given this fact, the use of any physically based routing technique is merely an approximation of reality. *GSSHA* has been successfully used with grid sizes ranging from 30 to 1,000 m (~100 ft to 3,280 ft). However, experience by the *GSSHA* developers has shown that grid sizes smaller than 200 m (660 ft) produce more robust calibrations. Downer et al. (2002b) discuss how grid size should be sufficiently small to capture the essential features in the study watershed. In general, the philosophy of distributed hydrology is that "smaller is better" provided that the problem remains computationally feasible and the quality of the data warrants the use of small grid sizes.

Constructing a Grid

Once a boundary feature polygon has been defined by one of the methods described above, a 2-D grid can be created in *WMS* using the *Create Grid* command in the *Feature Objects* menu. *WMS* will then prompt you for the grid size and fill the interior of the rectangle that just bounds the watershed. Each grid cell is flagged as being inside the watershed (active) or outside the watershed (inactive) according to the location of the centroid of each grid cell. The results of a typical grid generation are shown in Figure 2.
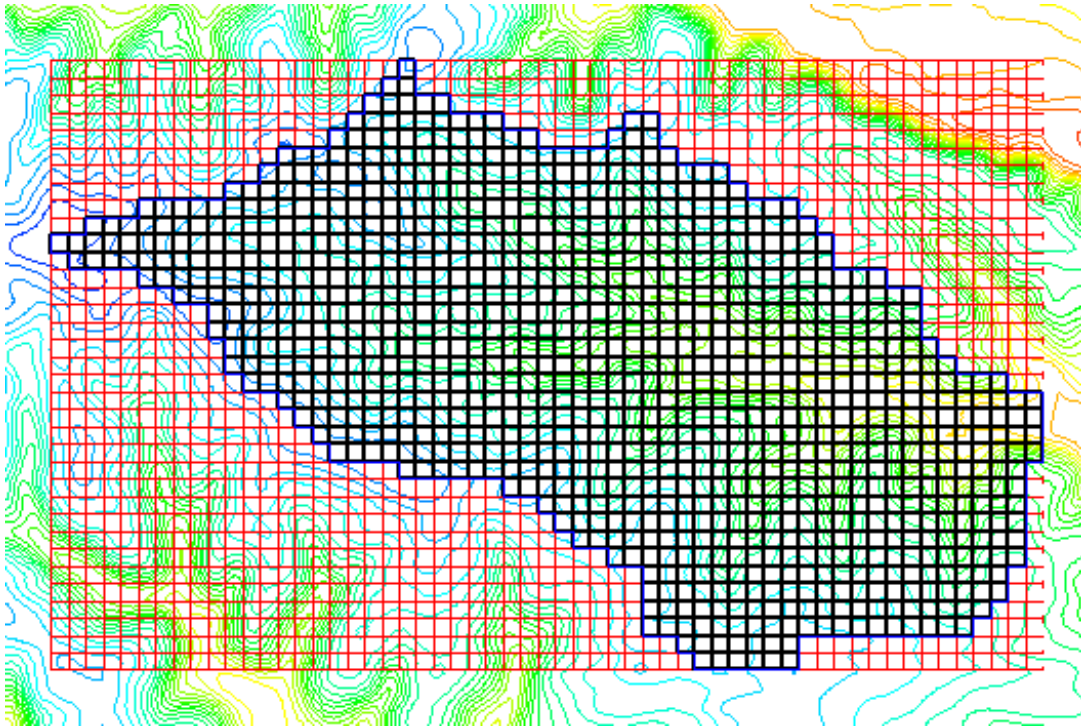
Figure 2. The finite difference grid covers the extents of the watershed. Each grid cell is flagged to indicate whether it is inside or outside the watershed. Elevations for the cells inside the watershed are then interpolated from the background DEM

For more information on how to use this command, please see the *WMS Help File*. This grid is the heart of the *GSSHA* model and defines the watershed mask (grid cells within the watershed) and elevation map required to run *GSSHA*.

Editing the Grid to Correct Elevation Errors

The quality of the DEM plays a major role in the success of distributed hydrologic simulations. Unfortunately, DEMs almost always contain errors. Large flat areas in the DEM may be the result of the limited vertical resolution of elevation data. Routing over such flat areas can create problems for the numerical techniques used in *GSSHA*. Artificial pits in the DEM may be artifacts of the interpolation scheme used to rasterize digitized contours, or may be the result of coarse resolution in areas of concave topography. As a rule of thumb, the user must cross check the DEM with topographic maps of the area. Interpolating elevations from the DEM at one resolution to a grid with cells of coarser resolution induces additional error.

One way to discover potential errors in the grid elevations is to run *GSSHA* with a relatively short time-step, uniform rainfall, and simulating just the overland flow. Infiltration, channel routing and all other model options are turned off. If the simulation terminates normally, overland depth maps can be examined to determine where water accumulates on the overland flow plane and whether the topographic map of the area justifies such accumulation. Alternatively, if the model crashes at a certain location (whose address is printed on the screen as well as at the bottom of discharge file) the user must double-check the grid elevations for problems. This process is described in detail in the next chapter. Some manual editing of the grid elevations is almost always necessary to impose actual drainage trends and correct obvious errors in the elevations. Manual editing is done in *WMS* by selecting individual grid cells and manually typing in a new elevation in the edit window.

Nonsmoothed grid elevations result in the need for short computational time-steps and can lead to numerical instability problems when running *GSSHA*. Properly smoothed grid elevations, particularly those with coarser grid space resolution, allow use of longer time-steps while maintaining the stability of the model. Once overland flow is working satisfactorily, other processes such as infiltration and channel routing can be incrementally added to the simulation.

Conclusions

The basic process used in *WMS* to create a grid is to first delineate the watershed boundary and streams from a DEM and convert the results to a bounding polygon for the watershed. This bounding polygon is then "filled" with grid elements of the appropriate size for the planned simulation, and elevations for grid cell centers are interpolated from the original DEM. *WMS* provides multiple options or creating the bounding polygon, but the recommended method is to use a DEM. *WMS* supports both USGS file formats as well as Arc/Info ASCII grid files.

The size of grid cells used for a *GSSHA* simulation will vary depending on the area of the watershed and objectives of the simulation, as well as computing resources. Inevitably some of the grid cells will need to have elevations adjusted to create more "natural" and numerically stable overland flow. The need to edit grid cells is most easily identified by running a basic simulation to examine areas on the grid that pond excessively. Setting up and running a basic simulation is the content of the next chapter.

3   *Building a Basic GSSHA Simulation*

Introduction

A complete *GSSHA* simulation may include temporally and spatially varying rainfall for multiple events over an extended period, distributed roughness parameters, infiltration modeling with distributed parameters, channel routing, and saturated groundwater flow with stream interaction. However, such a simulation is built in pieces, not all at once. A simple simulation is constructed, problems are corrected, and then additional processes or inputs are added, one at time. The key is to successfully build a simple simulation, and then build upon your success.

The most basic simulation is built through four steps:

1.   Assigning elevations to each cell, as described in Chapter 2.

2.   Assigning the values of a limited number of global parameters.

3.   Describing the uniform rainfall event.

4.   Assigning uniform value of overland flow roughness.

Once this simple simulation works, processes or complexities, as described in the following chapters, are added. The information in this primer is presented in the order that complexities should be added. The new simulation, with added complexity, should be tested before adding more complexity to the simulation. This process of building a simulation is described in detail in the *GSSHA User's Manual*.

Basic Model Inputs

Global parameters

The global parameters of a simulation refer to the input control and other parameters not assigned on a cell-by-cell basis; e.g., the numerical method for computing overland flow, the computational time-step and total simulation time, and whether to activate certain model options such as channel routing, long-term simulations, infiltration, evapotranspiration, groundwater interaction, etc.

To have *WMS* allocate the memory required for development and storage of *GSSHA* model parameters, you must first initialize a simulation. This is usually done when creating a grid, because *WMS* prompts the user whether or not to do so. However, the simulation parameters can be initialized or deleted using the identified buttons in the *GSSHA Job Control Parameters* dialog. Data necessary to run a *GSSHA* simulation are determined based on the settings in the *GSSHA Job Control Parameters* dialog (Figure 3). A better description of the various options is provided in the next several sections.
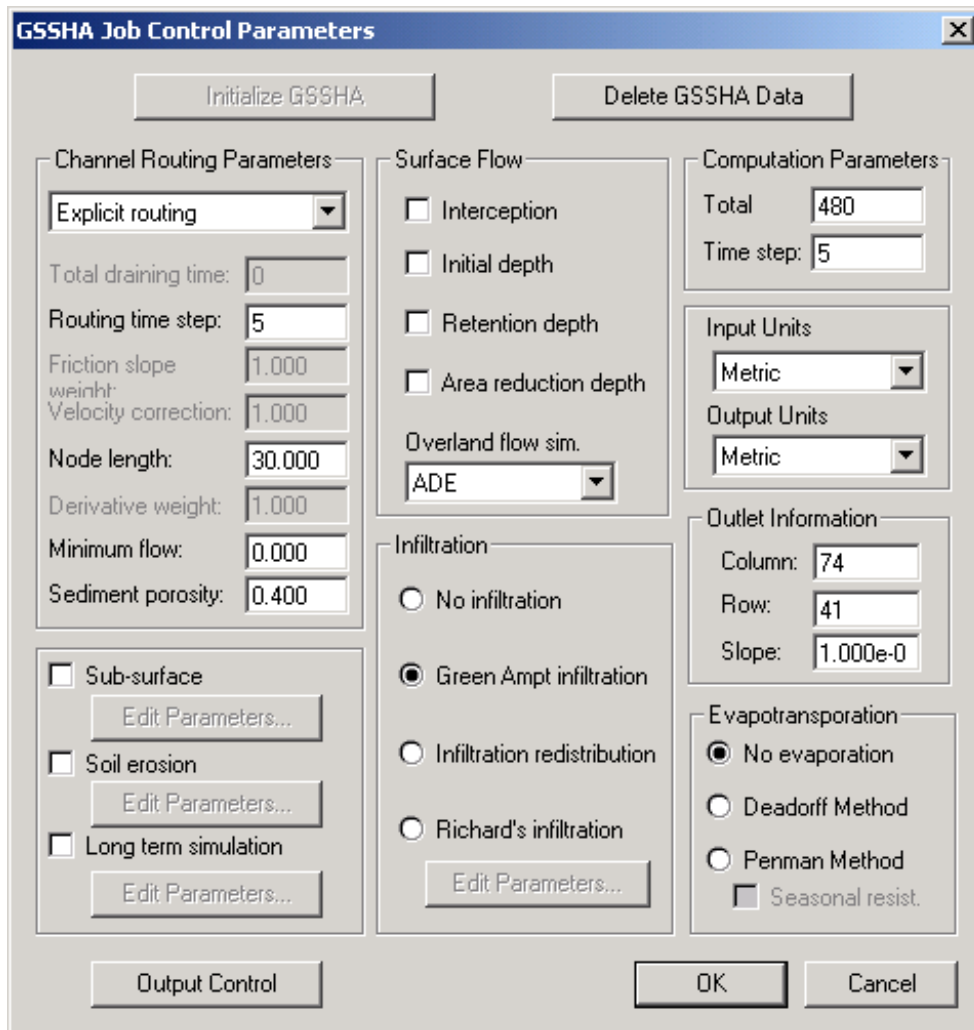
Figure 3. GSSHA Job Control dialog in WMS. This dialog is used to select model options and global parameters needed by GSSHA. The Output Control dialog, accessible from the Output Control button in the lower left-hand corner, is used to indicate the desired time-series maps that GSSHA can output, such as the depth of water on the overland flow plane.

Total time

The *total time* parameter sets the total simulation time for a model in minutes. If the falling limb of the discharge hydrograph is of particular interest, the total simulation time must be set to a value greater than total rainfall duration plus the expected recession time. The total time is used

only for single-event simulations. During long-term simulations, the total time is not used because the simulation time is determined from the rainfall and hydrometeorological input files.

Time-step

The *time-step* (Δt) is the duration of the computational time-step, in seconds. The time-step is a critical variable in determining the wall clock execution time for a simulation. Typical time-steps for *GSSHA* simulations range from 20 sec up to 5 min. For particularly hard problems, the time-step may need to be very short, 10 sec, 5 sec, or even less. One second (1 sec) is the smallest permissible time-step. The overall model time-step must be less than, and integer divisible into the smallest increment of time in the rainfall file. For example, for 1-min rainfall data the maximum time-step is also 1 min. Other permissible values would be 30, 20, 10, 5, 2, and 1 sec. If saturated groundwater flow is being simulated, then the overall model time-step must also be equal to or less than, and integer divisible into, the groundwater time-step.

The general rule for overland routing is that shorter time-steps must be used for higher intensity storms, finer horizontal grid resolution (grid spacing, Δx), steeper watershed slopes, larger watershed areas, and smoother surfaces. Stability of the explicit routing routines depends in part upon the Courant number. The Courant number is a dimensionless number that expresses the wave celerity, water velocity for steady flows, over the model celerity, $\Delta t/\Delta x$. For model stability, the Courant number must be less than 1.0; that is, water should not move more than one grid cell during a single time-step.

Shorter time-steps must be used when backwater effects are significant, which occurs mainly in flat areas. If the time-step is too long, the surface water depth in flat areas may show a checkerboard pattern, i.e., oscillations are observed in the water surface level. In such cases, the time-step should be decreased and the simulation repeated. Alternately the flat areas can be removed by editing the elevations.

Outlet information

When channel routing is not specified, information about which cell represents the watershed outlet and the slope of the land surface at the outlet must be defined. The outlet location is input as the row and column (*I* and *J* indices). The user must ensure that the outlet described by its row and column is within the active area of the watershed mask. The bed slope is equal to the tangent of the angle that is made between the bed profile at the outlet and the horizontal plane. This slope is used to calculate the outflow overland discharge at the outlet based on a normal depth boundary condition. When channel routing is specified, the outlet of the catchment is defined by the location of the stream network, and the grid cell that contains the outlet need not be specified.

Units

The units flag in *WMS* is used to identify whether the grid dimensions and elevations are in feet or meters. *GSSHA* is entirely formulated in metric units. When English units are specified, the grid dimensions and elevations are converted to metric inside of *GSSHA*. For instance, the UTM coordinate system uses meters for the *X,Y* coordinates. The user should verify that the elevation (*Z*) coordinates are also in meters. It is not possible to use a mixed unit system in *GSSHA*. The grid size and elevation data <u>must</u> be in the same unit system. When using UTM coordinates, the units flag should be set to metric. The State-Plane coordinate system, on the other hand, uses feet for the *X,Y* dimensions. The elevation values in State-Plane maps should also be in feet, and the units flag should be set to English to inform *GSSHA* that the conversion from feet to meters is

required. To avoid problems, it is recommended that metric units be used to run *GSSHA*. Output units of either Metric or English can be specified.

Defining a uniform precipitation event

Rainfall can input in one of three formats:

- Uniform constant rainfall over the entire watershed.
- Single temporally varying rain gage.
- Multiple, temporally varying rain gages.

All rainfall types in *GSSHA* must be tied to a specific point in time by specifying the year, month, day, hour, and minute of each rainfall data point. The *GSSHA Precipitation* dialog in *WMS* allows you to specify the type of rainfall and enter the necessary data associated with the rainfall type (Figure 4).

Figure 4. GSSHA Precipitation dialog. Accessible from the GSSHA menu in the 2-D grid module, this dialog is used to define precipitation events. WMS currently supports only the capability to simulate a single-gage event or uniform precipitation. Precipitation patterns that include multiple gages and/or multiple events must be developed in a text editor external to WMS. See the GSSHA User's Manual for more information on the format of the precipitation input file

For a spatially uniform constant rainfall, the specified rainfall covers the entire basin for the specified period. The input parameters are:

- Rainfall Intensity - (mm·h^{-1}).
- Rainfall Duration - (minutes).
- Start Time.

1. *Year*

2. *Month*

3. *Day*

4. *Hour*

5. *Minute*

Temporally and spatially varied precipitation is discussed in Chapter 7.

Describing overland flow

The computational method used to compute overland flow is selected in the *GSSHA Job Control Parameters* dialog from *Overland flow sim*. Three methods are available.

- Explicit – original point explicit method developed for *CASC2D*, as described by Julien and Saghafian (1991).

- ADE – alternating direction explicit (Downer 2002).

- ADE-PC – alternating direction explicit with prediction-correction (Downer 2002).

The default value is Explicit. The ADE and ADE-PC methods are described in the *GSSHA User's Manual*. Generally, the ADE method is recommended. The ADE method will usually out perform the original Explicit method, and a larger time-step may be used without affecting the hydrograph shape. The ADE-PC method is the most robust and may be employed when particularly difficult conditions are encountered. The ADE-PC method will often work when the other two methods will not. The additional computations in the ADE-PC method make it significantly slower than the other two methods, which require about the same wall clock time. Some experimentation may be required to determine which method will work best for a particular problem.

The following inputs are required in overland flow simulations in *GSSHA*.

- Land surface elevation.

- Land surface roughness.

The grid cell land surface elevations (determined from the DEM, as discussed in Chapter 2) and the surface roughness comprise the minimum input parameters that must be defined for a *GSSHA* surface runoff simulation.

The surface roughness represents the overland Manning's roughness coefficient *n*. These values can be spatially distributed using an index map defined from vegetation cover and/or land use. Values of overland roughness coefficients based on vegetation coverage are presented by Engman (1986) and Ree, Wimberly, and Crow (1977), and summarized in the *GSSHA* User's Manual (Downer and Odgen in preparation).

By using Manning's resistance equation, it is assumed that the overland flow is turbulent flow over rough surfaces. Manning's roughness coefficients are dimensionless. Assignment of parameter values to every grid cell is discussed in Chapter 5.

Verifying the basic model

For every new *GSSHA* model a basic simulation with uniform roughness should be run to determine the overall quality of overland flow. The minimum parameters that must be defined to run a basic simulation are surface roughness and rainfall. As described above, the time-step, total time, and outlet information must also be defined. The required steps are described below.

1. In the *GSSHA Job Control Parameters* dialog, make sure that all optional processes (routing, sediment, infiltration, etc.) are turned off. Enter a value for total simulation time in minutes (a few hours) and a small time-step in seconds (5 to 10 sec). In the *GSSHA Job Control Parameters* dialog, select *Output Control*, toggle on *Surface depth* under the *Data Set Map Options*. Toggle on the *ASCII* map *Type*. Input a *Write Frequency (time-steps)* such that maps of surface depth are written out every 15 to 30 min, about 90 to 180 time-steps.

2. For the uniform rainfall event, enter an intensity of 10 to 50 mm·hr^{-1} and a duration of 1 to 2 hr (60 to 120 min).

3. Assign a uniform overland roughness coefficient, as described in Chapter 4, with a value of 0.05.

4. Save the project and run *GSSHA*.

The model should run to completion and produce a hydrograph at the outlet. If the model runs but does not produce flow at the outlet, then either increase the *total time* of your simulation, your rainfall duration, or your rainfall intensity and rerun the model. Do this until there is output. The model may or may not run to completion as flow is produced.

If the model does run to completion, use the methods described in Chapter 13, Postprocessing, to view the outlet hydrograph and the overland flow depth maps. These maps are useful for locating problem areas in the watershed and comparing areas of ponded water to independent topographic data. If water is ponded on the watershed at the end of the simulation (ponded water shows up as blue areas on the overland flow depth maps), compare these locations to topological maps and ensure that the ponded areas correspond to real depressions. If these areas should drain, you may have to go back and do more smoothing on the DEM or manually edit the values of elevation in the affected grid cells, as discussed in Chapter 2. Even if the ponding areas correspond to natural depressions, you may still wish to smooth the DEM or edit the grid elevations to drain these areas, as computation of overland flow with significant backwater effects requires a small time-step. Experience has shown that DEM smoothing has minimal effect on streamflow predictions.

If the overland flow routine crashes, information on problem areas will be printed to the screen and also to the run summary file. If the overland flow module will not run you can try to change the overland flow routing method to ADE-PC, reduce the time-step, or decrease the uniform rainfall intensity or duration. If the model will not run with a small time-step and the very stable ADE-PC overland flow routine, the depth maps should be consulted to identify potential problems in the watershed. The DEM may be smoothed using algorithms in the *WMS* software, or the elevations in the grid may also be manually edited. The information provided by *GSSHA* will tell you where to target editing of grid cell elevations. Zoom in on these identified problem areas; turn on the color fill contours, and display the grid cell elevations. You may have to remove flat spots, dams, or depressions that are causing the overland flow model to crash. 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.

Determining an appropriate time-step

A good way to determine the appropriate time-step for a given problem is to conduct a temporal convergence study. Select from the study period a rainfall event of the highest rainfall intensity, or the one that produces the maximum discharge. Select a short time-step, 5 to 20 sec, and simulate the event. Write out the discharge hydrograph at small intervals, equal to the time-step. Increase the time-step and repeat. Continue increasing the time-step until the program crashes during execution. At this point, the upper limit of the time-step for your problem has been reached. Look at the hydrographs produced using the various time-steps. If the hydrograph begins to oscillate, normally near the peak, the time-step is too large. Eliminate any simulations that produce oscillations in the hydrograph.

There should now be a set of hydrographs produced by various time-steps. As the time-step is increased, the hydrograph shape may begin to change. A primary theory of the finite difference method is that the model results converge on the solution as the time-step decreases. Therefore, the hydrograph with the smallest time should be treated as the "correct" answer, and the other hydrographs should be judged against it. A simple visual comparison of the hydrographs is usually sufficient. Figure 5 shows the hydrographs produced from a test case with time-steps of 10, 150, 180, and 210 sec. At 150 sec, the hydrograph is significantly shifted from the 10-sec simulation. At 180 sec, oscillations appear. At 210 sec, the oscillations cause the model to crash. All these time-steps are too large. The simulation time-step may also be judged by the peak discharge, time of peak, and discharge volume information from the summary file. To decrease wall clock execution time, select the largest time-step that produces results equal to, within an acceptable error level, the results with the smallest time-step.
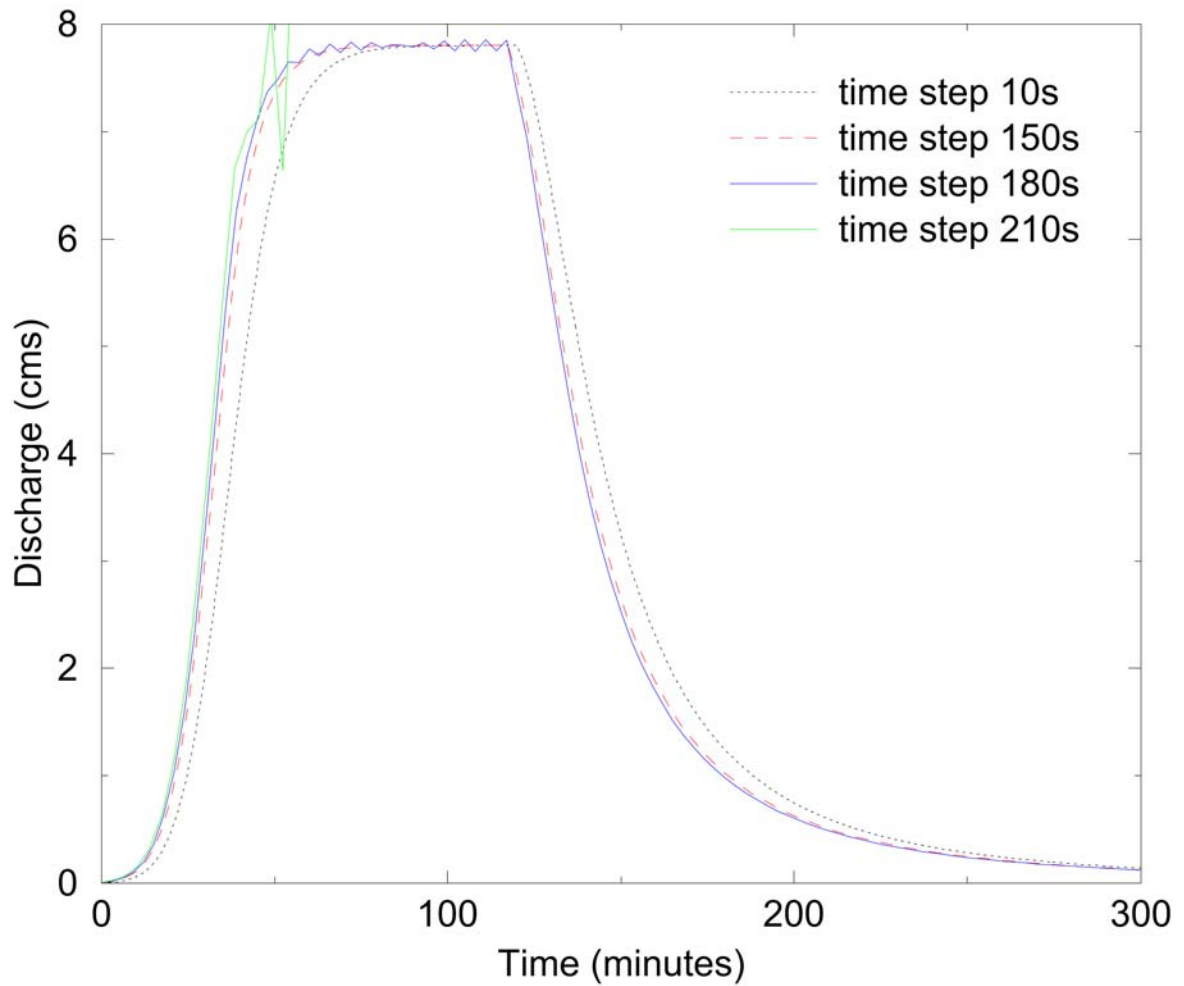
Figure 5. Example of a temporal convergence study. The hydrograph produced by the 10-sec time-step can be considered the most correct because it has the shortest time-step. The 210-sec time-step hydrograph crashed partway through the run. The 180-sec time-step, shows the oscillations that will be produced by a time-step too close to the limiting or crashing time-step. The 150-sec time-step appears normal, but when judged against the 10-sec time-step, the significant difference in peak time is observed, making the 150-sec time-step also inappropriate

4   ADDITIONAL MODELING CAPABILITIES

Introduction

As described in Chapter 1, there are many modeling options in *GSSHA* beyond the basic overland flow model described in Chapter 3.   This chapter summarizes and describes the additional modeling options in *GSSHA*. More detailed descriptions of some modeling options are offered in following chapters, as needed.   The processes *GSSHA* simulates to predict streamflow may include overland flow, spatially and temporally varied rainfall, infiltration, and channel routing. It is typical to use the long-term model to conduct simulation calibration or to simulate extended events. Modeling of the unsaturated zone with Richards' equation and saturated groundwater modeling may be required in areas where infiltration-excess runoff is not the predominate stream-flow producing mechanism.   Sediment routing is an additional capability used in studies specifically designed to compute sediment loads.

Overland Flow Routing Options

GSSHA offers several optional processes that can be selected along with the basic overland flow routing described in Chapter 3. These optional processes are selected in the *GSSHA Job Control Parameters* dialog box under *Surface Flow*. Toggle on the desired options and then supply the needed inputs as described below. The optional processes are:

- Interception.

- Initial Depth.

- Area Retention.

- Retention Depth.

Interception

Interception is defined in *GSSHA* using two distributed parameters: an interception coefficient (b) and a storage capacity (a). The interception rate (i) is expressed as:

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

where:

>   *r(t)*   denotes rainfall intensity at time *t*
>
>   *a*   is the storage capacity, m
>
>   *b*   is the interception coefficient, m·s^{-1}
>
>   *I*   is the cumulative interception depth

The interception storage capacity, *a*, must be specified in units of meters, and the interception coefficient, *b*, must be in units of meters·seconds^{-1}. For a table of storage capacity and interception coefficient values, see Gray (1970), section 4.6, or Bras (1990), p 233.

These two parameters may vary in space, depending on vegetation and land use distributions. The storage capacity parameter, as well as interception coefficient parameter, is usually created from an index map of the vegetation cover. Typically, interception is not simulated in *GSSHA*; the effects of interception are included in the surface retention and infiltration parameters.

Initial depth

This value represents the beginning overland depth value in the grid cells. This feature is rarely used, since the overland flow plane is usually dry prior to the first storm event. Initial depths are specified in units of meters.

Area reduction

This dimensionless fraction is used to reduce the area over which there is infiltration opportunity after the end of rainfall because of flow concentration in micro-topography.

Retention

This feature allows the simulation of storage as a result of micro-topography. If the depth of water in a grid cell is less than the retention depth, no overland flow is routed. This feature has the effect of increasing the amount of infiltration. The retention depth is specified with the Mapping Table tied to index maps of land use or vegetation. Retention depth is specified in units of millimeters.

Infiltration

GSSHA provides two basic methods and four different options for simulating infiltration. The two basic methods are the Richards' equation, described in Chapter 9, and the Green and Ampt method (1911), as described below. Selection of Richards' equation over one of the Green and Ampt methods actually results in the model operating quite differently, most notably during long-term simulations (Chapter 8). There are three Green and Ampt methods; basic Green and Ampt (1911), Green and Ampt with Redistribution (GAR) (Ogden and Saghafian 1997), and multi-layer Green and Ampt (Downer and Odgen in preparation). The multi-layer Green and Ampt model is not currently supported by *WMS*, and the user is referred to the *GSSHA User's Manual* for more information on this option.

In the *Job Control* dialog, one of four choices can be specified:

- *No infiltration.*

- *Green & Ampt.*

- *Infiltration redistribution.*

- *Richard's infiltration.*

If no infiltration method is specified, then no parameters need be defined. If *Green & Ampt* is chosen, then grid parameters of soil hydraulic conductivity, porosity, wetting front suction head (capillary head), and initial moisture content must be defined.   If the infiltration with redistribution option is chosen, the pore distribution index and residual saturation must also be defined. Selection of Richards' equation requires the user to specify both global parameters and distributed grid cell parameters, as described in Chapter 9.

Green & Ampt infiltration

In the Green and Ampt model of infiltration, water on an overland flow grid cell resulting from precipitation, overland flow, or other sources is assumed to enter the soil as a sharp wetting front. The soil behind the front is assumed to be saturated. The soil ahead of the front is assumed to be at some uniform initial moisture. The wetting front is drawn into the soil because of gravity and soil capillary pressure. As the front moves into the soil column, the effect of the soil capillary head is reduced and infiltration slows, approaching the value of the saturated hydraulic conductivity.

Four soil property parameters are required for each cell:

- Saturated hydraulic conductivity ($cm \cdot hr^{-1}$).

- Wetting front suction head or capillary head (cm).

- Porosity - fraction of voids in the soil (dimensionless).

- Initial moisture content - initial fraction of water in the soil (dimensionless).

The first three parameters may be assigned based on an index map of soil textures. As the land use may also affect these parameters, it is typical to create a composite land use/soil texture index map to assign these parameters. In the absence of measured field data, the parameters may be estimated based on the soil textural classification. Tables of parameters can be found in Rawls, Brakensek, and Saxton (1982) and are summarized in the *GSSHA* User's Manual (Downer and Ogden in preparation).   Assignment of these parameters based on soil textural classification typically requires that one, some, or all of these parameters be adjusted during calibration.

The initial moisture content must be less than or equal to the porosity and should be greater than the residual water content. Estimation of the initial soil moisture is based on antecedent conditions in the watershed. The Green and Ampt method is highly sensitive to the value of initial moisture. Accurate initial moisture estimates are required. Initial moisture estimates may be determined from field measurements, satellite measurements, or may be provided by the *GSSHA* model when long-term simulations are conducted (Chapter 8). Senarath et al. (2000) demonstrate the dangers of using initial moisture as a calibration parameter in single event calibrations.

Redistribution

When GAR is selected for modeling infiltration, soil pore water is redistributed during periods of no or low-intensity rainfall, and infiltration capacity recovers for the next burst of storm intensity.

The technique used for hiatus and posthiatus stages is based on the method by Smith, Corradine, and Melone (1993) with minor modifications (Ogden and Saghafian 1997). In this model, the Green & Ampt equation is used for posthiatus stage, so the four Green & Ampt parameters must be specified. In addition, the pore size distribution index (dimensionless) and residual saturation (dimensionless) are required. Without field measurements, values for these parameters may also be estimated bases on soil textural classifications and assigned from literature values, e.g. Rawls, Brakensek, and Saxton (1982) and summarized in the *GSSHA* User's Manual (Downer and Ogden in preparation).

Richards' infiltration

When Richards' equation is specified for simulation of infiltration, the movement of water in the soil is explicitly solved using Richards' equation (Richards 1931). Detailed soil moisture profiles are calculated in each overland grid cell with infiltration calculated as a by-product of the solution. Richards' equation requires many of the same parameters described above, in addition to global parameters related to the solution techniques used in the model. Richards' equation and the proper assignment of parameters are described in detail in Chapter 9.

Channel routing options

One-dimensional channel routing can be coupled with overland flow routing by turning on the channel routing option. A channel network, complete with geometric cross sections and other parameters, must be defined. Details of defining channel routing parameters for *GSSHA* using *WMS* are discussed in Chapter 6.

Long-term simulations

Long-term simulations can be used to simulate multiple rainfall events that occur over an extended time period. The effects of wetting and drying of the soils in the watershed are simulated. Long-term simulations require many additional inputs as detailed in Chapter 8.

Subsurface

Subsurface simulations can be performed to simulate the lateral flow of saturated groundwater movement and interactions with surface water. The 2-D free surface equation (Pinder and Bredehoeft 1968) is solved using finite difference techniques (Trescott and Larson 1977; Downer 2002). Selecting this option requires the assignment of appropriate boundary conditions and parameters to define the groundwater media. Details of simulating saturated groundwater are discussed in Chapter 10.

Soil erosion

Soil erosion and sediment transport can be simulated on the overland flow plane using the Kilinc Richardson equation (Kilinc and Richardson 1973). Selecting overland soil erosion requires that appropriate soil parameters be defined for each grid cell. Channel sediment routing can also be simulated if both the overland flow sediment routing option and channel routing options are specified. Yangs' method (Yang 1973) is used to route sand as bed load. Silt and clay are routed as wash load (Ogden 2000). Details for setting up soil erosion and sediment transport simulations are discussed in Chapter 11.

5   *ASSIGNING PARAMETER VALUES TO INDIVIDUAL GRID CELLS*

Introduction

As described in the preceding chapters, the simulation of many processes requires that parameter values be assigned to every cell in the active watershed grid. *GSSHA* can accept parameter values for every cell as a specified uniform value, as a *GRASS* ASCII map with a different value for every cell, or as tabled values referenced to index maps. In *WMS,* parameters are assigned to cells by using the mapping tables and index maps. Index maps are maps that assign integer ID values to every cell in the active watershed area. Index maps for distributed parameters are usually based on soil texture, land use, and vegetation classifications. Parameter values are assigned to each cell based on its index number. A table of parameter values is created for each process and assigned an index map.

Index Maps

An index map is an array of integer values (one for each grid cell) that represent unique IDs for the different spatially distributed properties being defined. The typical maps (although not restricted to) are derived from:

- A land use (land cover or vegetation cover) coverage.

- A soil texture coverage.

- A combination of land use and soil type coverages where all the combinations of land use and soil texture are determined with an ID created for each unique pair of overlapping polygons.

The *Index Maps* dialog is used to create and manage different index maps used in *WMS*. This dialog is shown in Figure 6.
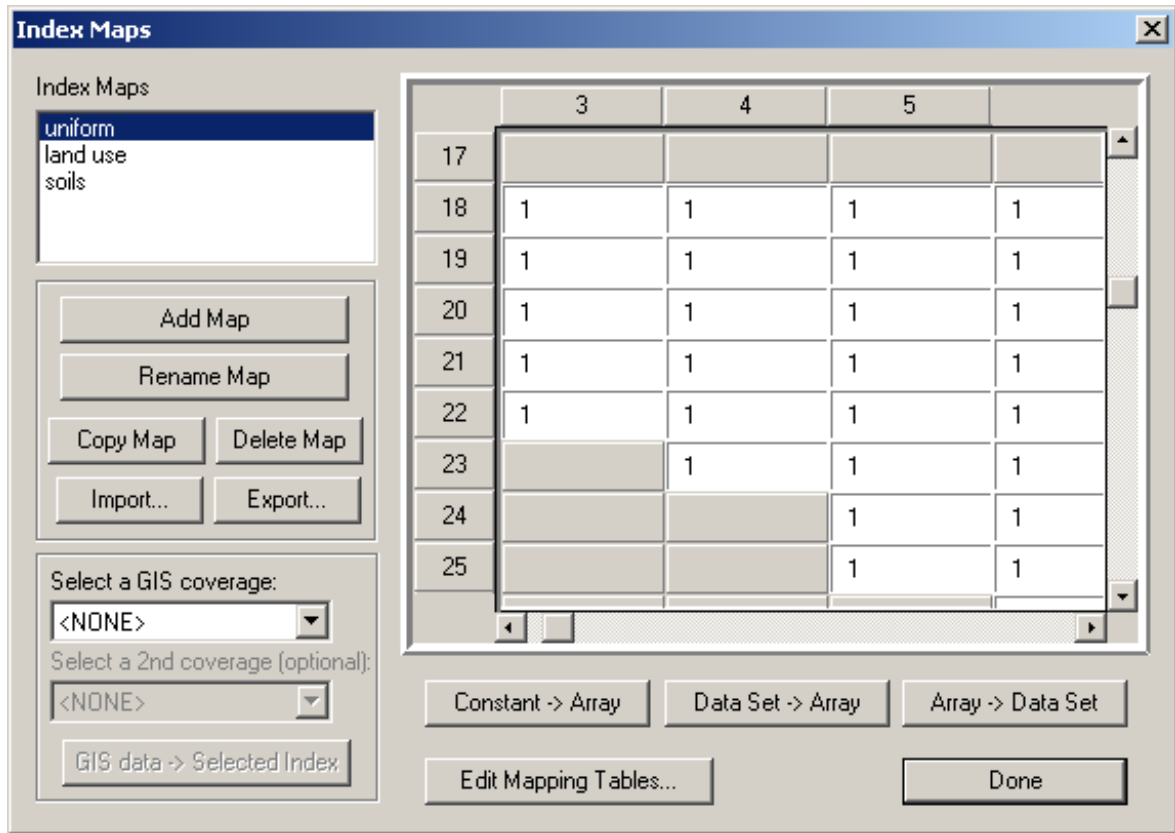
Figure 6. The Index Map dialog. Index maps can be created through generating unique IDs from a GIS coverage or coverages, such as land use, or the entire map may be assigned a single ID through the Constant->Array button. Also, individual cell IDs may be manually modified

Several options exist for creating index maps including:

- Importing an existing grid file.

- Mapping a GIS coverage.

- Setting a constant value for all grid cells.

- Interpolating from a data set.

The following sections describe the key elements of the *Index Maps* dialog.

The Index Maps window contains a list of maps created for the *GSSHA* project. A new map can be created using the *Add Map* button, and the *Rename Map* button can be used to give it a more meaningful name. The *Copy Map* and *Delete Map* buttons can also be used to add or delete maps from the list. The *Import* button allows a *GRASS* ASCII grid to be imported and used as an index map. The *Import* command is primarily used when the *GRASS* GIS is used as a companion to *WMS* for *GSSHA* model development. The imported grid must be of the same resolution as the *GSSHA* grid already created in *WMS*. Unless both of these grids are created in *GRASS,* this is unlikely to be the case. The *Export* command can be used to save an ASCII grid of the selected index map. This function is most useful if you wish to view the grid with *ArcView* or other GIS software.

Mapping Tables

Mapping tables are used to relate index map IDs to parameter values. The required values depend on which simulation options are selected. The most basic value is surface roughness, but if infiltration, evapotranspiration, or other options are defined then the parameters for each of those options will also need to be defined. The mapping table editor, shown in Figure 7, is accessible by selecting the *Mapping Tables…* command from the *GSSHA* menu, or by using the *Edit Mapping Tables…* button in the index map dialog.
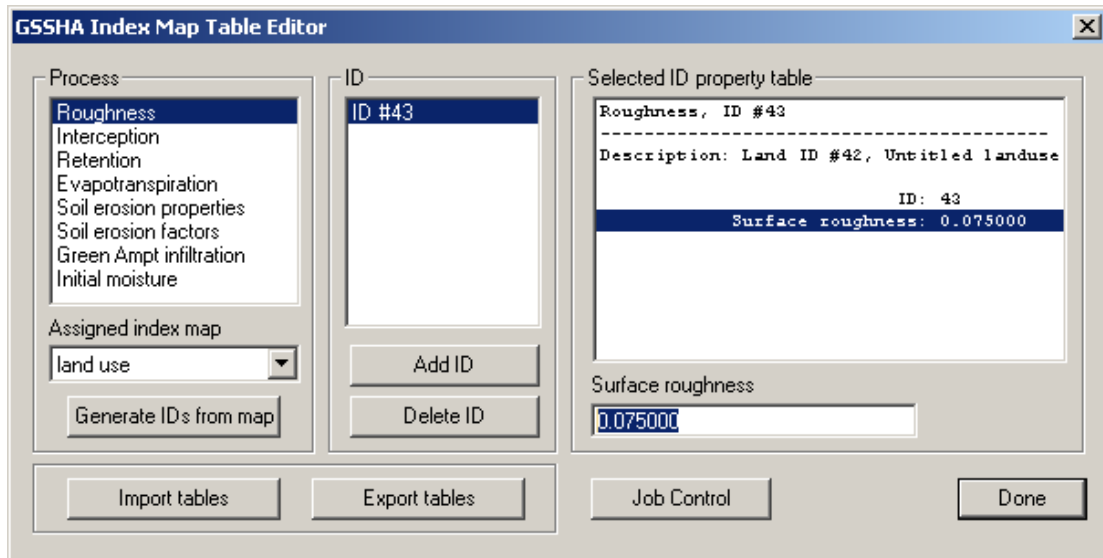
Figure 7. The GSSHA Index Map Table Editor. Each active process should be assigned an index map, and parameter values assigned to the generated IDs. The index maps along with the mapping tables provide the means to quickly and easily distribute the spatially varied parameters across the 2-D finite difference grid

The *GSSHA Index Map Table Editor*, shown in Figure 7, allows you to select a process, generate table IDs for that process, and define the parameter values for the IDs of the table. If you try to select a process (evapotranspiration, for example) that has not been enabled in the *Job Control* dialog, you will be prompted to turn on that option if you wish to define parameter values for the IDs. Each active process must be associated with an index map, assigned from the *Assigned index map* drop-down combo box.

The *Generate IDs from map* button will generate a new table ID from each unique ID in the map. You can also *Add* or *Delete* a given ID using the appropriate buttons. To define parameter values for a given ID, you should select that ID from the ID window. Edit the corresponding values for that process by selecting the appropriate line in the *Selected ID Property* window and change the value in the edit field just below it.

You can export a table for later use if you have a certain set of parameter values that correspond to a standard classification system of soils or land use. This table can then be imported for use in the development of other GSSHA models.

Assigning Uniform Parameters

Uniform values are assigned from the *Index Maps* command in the *GSSHA* menu. Using this dialog, a new index map can be created, and then the *Constant to Array* button used to assign a single ID number to every cell in the active grid. This uniform index map may then be assigned to any given process. The uniform index map could be assigned for overland roughness in the following manner. Select the *Edit Mapping* table button. Select Roughness from the process list and the uniform index map from *Assigned index map.* ID numbers may be automatically generated from the index map by selecting the *Generate IDs from map* button. Alternatively, hitting the *Add ID* button will also generate IDs, but in a numerically sequential order. Parameter values for each ID are entered by selecting the ID number under *ID* and then filling in the information in the *Selected ID property table*, which will be *Surface roughness* in this example. Select *Done* when finished.

Assigning Spatially Distributed Parameters

One of the greatest assets of distributed hydrologic models like *GSSHA* is the ability to spatially distribute the parameters for processes, such as overland flow and infiltration, over the watershed. Assigning values, grid cell by grid cell, is tedious and makes all but the simplest and smallest models impossible. Using *WMS*, GIS coverages (layers) representing land use and soil texture can be used to assign model parameter values to groups of grid cells sharing the same characteristics.

The basic process of assigning spatially distributed parameters consists of the following steps:

1. Import a GIS coverage for land use, soil texture, or vegetation type (generally this should be in the *ArcView* shapefile format).

2. Map the land use, soil texture, or vegetation ID to the grid cells using a spatial overlay operation.

3. Define parameter values (e.g., surface roughness, hydraulic conductivity, etc.) for the unique ID numbers.

A given soil texture/land use (STLU) index map can be used to assign multiple parameters. Since most of the grid cell parameters can be referenced to either land use or soil properties, a given simulation generally requires only a single index map of each. A combination land use and soil texture index map makes it possible to relate a parameter value to the combination of land use and soil texture (for example infiltration or erosion). Once the index maps are defined, parameter values are assigned to the IDs of the index maps. The combination of the index maps, with ID numbers, and the mapping tables, with the parameter values, are used by *GSSHA* to internally assign parameter values to each grid cell.

Locating GIS data

The ability to locate and obtain relevant land use and soil texture data is an important part of assigning parameter values to a *GSSHA* simulation. The World Wide Web is an excellent resource for obtaining data and the *WMS* developers have created a web site summarizing the key nation-wide (US) data available for download. This web site, maintained at http://www.emrl.byu.edu/gsda, is updated on a periodic basis. It should be noted that the gsda web site references data sources are maintained and distributed on a nation-wide basis. More

accurate (higher resolution and more recent) data are often available from local government agencies and universities, so it is wise to check for alternative data sources. Elevation data in either USGS Format or Arc/Info ASCII grid, as described in Chapter 2, should be requested. Vector coverages representing land use and soil texture should be requested in *ArcView* shapefile format.

Elevation

Elevation data are essential for delineating the watershed and establishing the initial elevations in the finite difference grid. The gsda web site contains many excellent sources of elevation data throughout the United States and related territories. The *WMS* reference manual contains more detailed information on importing, displaying, and manipulating DEM data. Chapter 2 of this primer discusses the use of a DEM to delineate a watershed and establish the numerical grid.

Land use

The USGS provides land use classifications for the entire United States at 1:250,000 scale. These data are available from the USGS directly, but in a format called GIRAS, not directly readable by *WMS*. Arc/Info is required to convert the GIRAS data to a form useable by *WMS*. The Environmental Protection Agency (EPA), as part of the BASINS program, has converted the GIRAS files to *ArcView* shapefiles. These data can be downloaded from the EPA, as directed on the gsda web site, and used directly in *WMS*. A list of land use code descriptions can be read from the Appendix at the following USGS site:

http://edcwww.cr.usgs.gov/glis/hyper/guide/1_250_lulc

A link to this location can also be found in the gsda web site.

The land use maps downloaded from the EPA site are organized by the USGS 1:250,000 maps. These maps are generally large relative to the size of the watershed being modeled and can tax *WMS*'s memory resources. It is suggested that you use *ArcView* or other GIS software to clip out the region of interest. For example: after delineating the basin as described in Chapter 2, export the basin boundary polygon as a shape file. You can then use the GeoProcessing extension within *ArcView* to clip out the land use that covers the area of interest. You can also simply make a bounding box that is bigger than the watershed and use it to clip out the desired data. The following lists some details for using *ArcView* to do this.

- Follow the links on the EMRL gsda website to the EPA basins data and download the required data for your watershed. These data will include both the USGS Land Use/Land Cover data on the 1:250,000 map scale and the Natural Resources Construction Service (NRCS) Statsgo soil data clipped by watershed Hydrologic Unit Classification (HUC).

- From your delineated watershed in WMS, export the basin boundary as a shapefile.

- Load the basin boundary shapefile into *ArcView*.

- Load the land use data downloaded for your watershed (often there are multiple 1:250,000 map sheets for a given HUC) into *ArcView*.

- The land use data are in geographic (lat/lon) coordinates, while your boundary is likely in Universal Transverse Mercator (UTM) or some other planimetric coordinate system. You will need to "project" one or the other data sets so that they are consistent. The following is recommended.

- o *ArcView* contains tools for projecting shapefiles. The latest version 8.0 has a projection wizard, but there is also a simple tool in the sample extensions called the "projector." This extension will add a little button to your macros.

- o Using the *ArcView* projection tools, change the land use data from geographic coordinates to the coordinate system of your watershed.

- o If your watershed overlaps multiple land use maps, you will need to project all of them.

- o While it is possible to use the *WMS* coordinate conversion (projection) tools, this method requires two conversions. First, the boundary must be converted to geographic coordinates before exporting. The land use and soil data must also be converted from geographic to your working coordinate system after importing. In *ArcView* only one conversion is required.

- Make sure the geoprocessing wizard extension is on in *ArcView*.

- Using the Clip command in the geoprocessing wizard, clip the land use data using the watershed boundary polygon.

- If you have multiple land use maps, you will need to clip both and then merge the results (or merge the maps before clipping).

- The clipped land use file can now be imported to *WMS* as a *Land Use* type coverage where the *LU_CODE* attribute is mapped as the *WMS Land Use data*.

- Make an index table with matching attributes for the *GSSHA* model based on the *LU_CODE* parameters. The EMRL gsda website includes a link to the USGS land use information describing the different land use codes. That index table is reproduced here:

Classification codes

1 Urban or Built-Up Land

      11 Residential

      12 Commercial Services

      13 Industrial

      14 Transportation, Communications

      15 Industrial and Commercial

      16 Mixed Urban or Built-Up Land

      17 Other Urban or Built-Up Land

2 Agricultural Land

      21 Cropland and Pasture

      22 Orchards, Groves, Vineyards, Nurseries

      23 Confined Feeding Operations

      24 Other Agricultural Land

3 Rangeland

> 31 Herbaceous Rangeland
>
> 32 Shrub and Brush Rangeland
>
> 33 Mixed Rangeland

4 Forest Land

> 41 Deciduous Forest Land
>
> 42 Evergreen Forest Land
>
> 43 Mixed Forest Land

5 Water

> 51 Streams and Canals
>
> 52 Lakes
>
> 53 Reservoirs
>
> 54 Bays and Estuaries

6 Wetland

> 61 Forested Wetlands
>
> 62 Nonforested Wetlands

7 Barren Land

> 71 Dry Salt Flats
>
> 72 Beaches
>
> 73 Sandy Areas other than Beaches
>
> 74 Bare Exposed Rock
>
> 75 Strip Mines, Quarries, and Gravel Pits
>
> 76 Transitional Areas
>
> 77 Mixed Barren Land

8 Tundra

> 81 Shrub and Brush Tundra
>
> 82 Herbaceous Tundra
>
> 83 Bare Ground
>
> 84 Wet Tundra
>
> 85 Mixed Tundra

9 Perennial Snow and Ice

> 91 Perennial Snowfields
>
> 92 Glaciers

Soils

The Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), has created a comprehensive set of soil coverages. These can be found at three different scales. From least detailed to most detailed they are:

- NATSGO - nation
- STATSGO - state
- SSURGO - county

The STATSGO data have been compiled in *ArcView* shapefile format by watershed units (large basins) for distribution as part of the EPA BASINS program. Detailed information for downloading STASGO data is provided on the gsda web site.

The NRCS also distributes the files on a state-by-state basis. The state files are very large. For many states the files are too big to read into *WMS* without clipping, as suggested in the Land Use section above. A secondary table containing various soil classification information must be joined to the polygons using *ArcView* prior to using in *WMS*. The name of this table is "comp.dbf" and should be joined with the polygons based on the MUID field name (present in both the feature attribute table of the polygons and the "comp.dbf" file).

The necessary details for using *ArcView* to process the soils data follows:

- From your delineated watershed in *WMS,* export the basin boundary as a shapefile.
- Load the basin boundary shapefile into *ArcView*.
- Load the soils data downloaded for your watershed into *ArcView*.
- The soils data are in geographic (lat/lon) coordinates, while your boundary is likely in UTM or some other planimetric coordinate system. You will need to "project" one or the other data sets so that the two types of data are in consistent coordinates. Follow the instructions above in the land use section to do this for the soils as well.
- You must now link the attribute table for soils to the features.
    - o Open the table "statsgoc.dbf" (included with the Basins data).
    - o Select the MUID field from this table.
    - o Open the feature attribute table for your soils.
    - o Select the MUID field and choose the Join command (this will append the attributes in "statsgoc.dbf" to the soils feature attributes).
    - o Do this before clipping so that the clipped soils file will contain all of the attributes describing the soils.
- Make sure the geoprocessing wizard extension is on in *ArcView*.
- Using the Clip command in the geoprocessing wizard, clip the soils data using the watershed boundary polygon.
- Unlike the land use data, there is not a single Soils Code. You now need to "reclassify" based on a soil attribute. The best attribute for "linking" soil properties is probably the Surftex value. This will have values like SIL (silt) LSIL (loamy silt), etc.

- Create a new field for soil attributes that is of type number and name it something like SOILID.

- Examine the set of different soil values and then for each one do the following:
    - Run a query to select all soil polygons of the given type.
    - Select the new field (SOILID).
    - Use the calculator to set an integer ID value (you can go 1, 2, 3, or 10, 20, 30, etc.)

- Save your table with edits.

- Import this clipped, reclassified soil table into *WMS*. Make sure to import the soil as a *NEW* coverage that is of type *Soil Type*.
    - Manually map the new field (*SOILID*) to be the *SCS Soil attribute* in *WMS*.
    - Make an Index map based on your soil types with the appropriate *GSSHA* parameters.

Always check for the availability of SSURGO data from local NRCS offices or other local agencies that disseminate GIS data. These data are often available near regions of higher population and land development and provide greater resolution of soil texture data.

Consistent Coordinate Systems

In order to accurately overlay your land use and soil data with the grid, all of these data must be in the same coordinate system. The data coordinate system depends on the standard of the agency that disseminates data. Some data are in geographic coordinates (latitude-longitude), some in UTM, and a few others in different coordinate systems. Areas and distances cannot be computed directly from geographic coordinates. Although any planimetric (*X,Y*) coordinate system can be used, it is recommended that you convert all data to the UTM coordinate system. Converting coordinates can be done using *ArcView* or other GIS software, or using *WMS*. If using *WMS* first complete the *WMS* tutorial to learn how to convert data to different coordinate systems. Information about coordinate systems is also available in the on-line *WMS* help.

Mapping to the Grid

GIS coverages are used to assign spatially varying grid parameters by mapping the points, arcs, and polygons of a GIS coverage to an index map of unique land use, soil texture, or land use/soil texture IDs. A series of mapping tables that relate the parameter values of the IDs can then be developed. Assigning the GIS coverage IDs to the grid cells is accomplished by selecting the GIS coverage you wish to generate the index map from and then choosing the *GIS data -> Selected Index* button. Figures 8 and 9 illustrate how the IDs from a land use (or soil texture) coverage are mapped to the finite difference grid.

Once an index map has been created, the individual parameters are assigned for each ID (five in the example shown in Figures 8 and 9) through a mapping table, as described above.
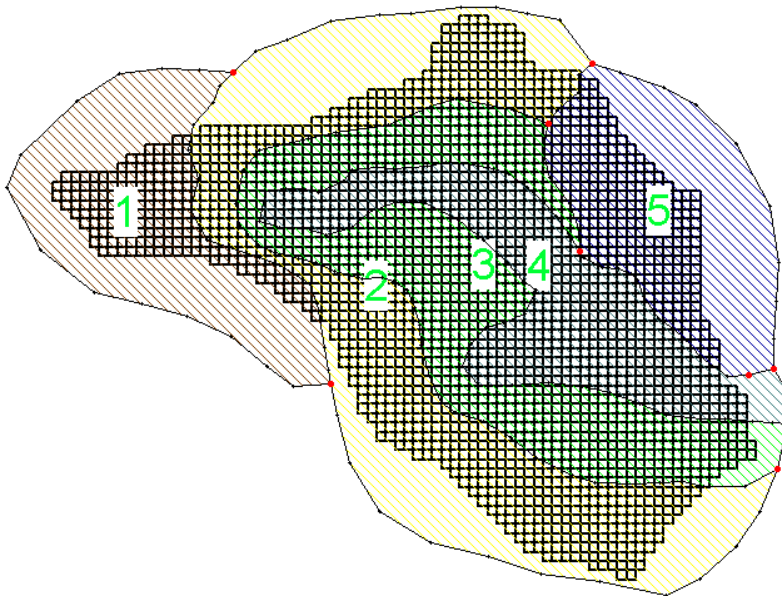
Figure 8. Polygon coverage overlaid on a finite difference grid. Five different polygons are shown, as classified by their ID numbers. These ID numbers can be mapped to an index map. Also, combinations of coverages, such as soil type and land use coverages, may be mapped to an index map, with a unique ID being created for each combination of polygons that cover a grid cell
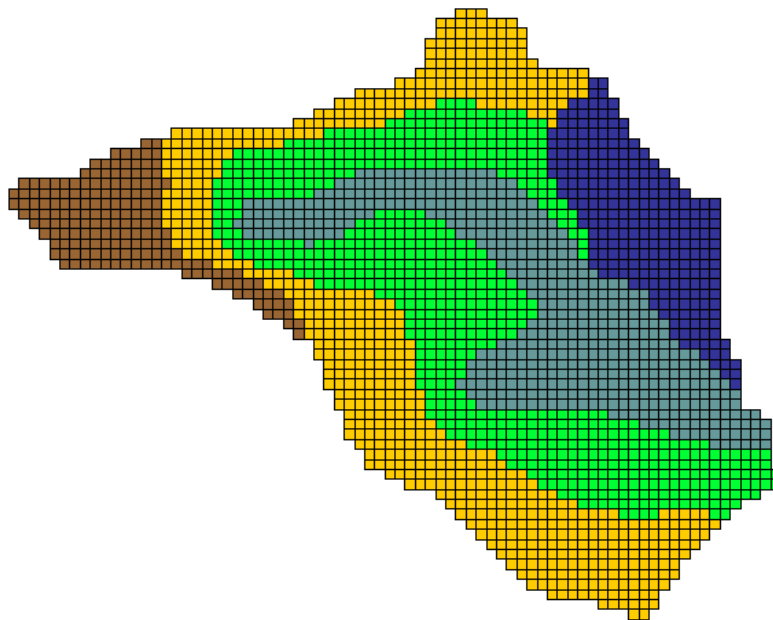
Figure 9. Polygon IDs from a coverage that has been mapped to the grid cells; the grid has been cell-fill colored according to the index map ID for each cell

6   *CHANNEL ROUTING*

Introduction

A strength of the *GSSHA* model is the capability to couple surface runoff with channel hydraulics. Channel flow is simulated as a 1-D finite volume system of links and nodes. Channel networks are defined in *WMS* using feature arcs to create the channel links. *WMS* automatically maps the vector streams to the grid cells in order to prepare the input necessary for *GSSHA* to simulate the interaction between overland and channel flow. Each segment of the channel network must be assigned cross-sectional parameters, and hydraulic structures may be placed at any point in the network.

WMS has several tools for creating, assigning attributes, and numbering the links and nodes. How these tools can be used to easily create the necessary data for channel routing is the focus of this chapter. The next section discusses the "nuts and bolts" of the input parameters required by *GSSHA*. This is followed by a detailed discussion on how to build the proper channel files using *WMS*.

Besides the identification of grid cells containing the stream channels and the definition of their cross-sectional parameters, several physical constants and simulation parameters for the channel routing algorithms must be defined. All of these parameters are defined in the *GSSHA Job Control* dialog of *WMS* as discussed in Chapter 3.

Channel routing is defined by selecting the *Explicit* routing method. If no channel routing is defined, only surface runoff calculations are performed. If the *Explicit* method is defined, then the following parameters must also be set:

- **Node length** - the distance between computational stream channel nodes. This value is typically equal to the grid cell dimension, but may be increased to the distance from one corner to the opposite corner of a cell, since channels often move diagonally across the grid. The value of the node length specified will be applied to all links in the network. One valid option is to specify the node length as the product of the average channel sinuosity in the network and the overland flow grid size.

- **Routing time-step** - the computational time-step in seconds. At present this value <u>must</u> be equal to the time-step used for overland flow routing.

Links and Nodes

Channels in *GSSHA* are represented with a series of links and nodes. A node is the basic computational element in channel routing. A link is a channel segment comprised of two or more computational nodes. Any internal boundary condition, such as a weir, is also considered a link with only two nodes, one node upstream of the internal link and one downstream. All internal boundary conditions contain two nodes, while fluvial (natural or man-made channels) reaches

may contain two or more nodes. The possible link types are presented in Table 2. Currently *WMS* does not support a fluvial link with dual side slope trapezoidal cross section.

Description	# Parameters per cross section	# Nodes
Fluvial link, trapezoidal cross section	5	>= 2
Fluvial link, trapezoidal cross section, sediment transport	6	>= 2
Fluvial link, trapezoidal cross section, subsurface parameters	7	>= 2
Fluvial link, dual side slopes trapezoidal cross section	6	>= 2
Look-up table (break point) cross sections	2	>= 2
Look-up table (break point) cross sections, subsurface parameters	4	>= 2
Overflow Weir	8	2

Table 2. Different link types that can be used in GSSHA. WMS supports all but the fluvial, dual-sided trapezoidal cross section link

Information on the links and nodes is contained in three files, a text file referred to as the channel input file, and two *GRASS* ASCII maps, the link and nodes maps. The link and nodes maps are used to relate the position of channel links and nodes to overland flow and saturated groundwater cells. *WMS* creates these three files from the information entered as the feature arc attributes. The details of these three files are contained in Appendix A of the *GSSHA User's Manual* (Downer and Ogden in preparation). In the link map, each node in a link is numbered with same link number. In the nodes map, each node in the different links is numbered 1 through the total number of nodes. General properties of links and nodes maps are:

- Looped reaches cannot be simulated.

- Streams may run only in orthogonal directions from cell to cell, not diagonally.

- Link types cannot be mixed within a link.

Defining Stream Networks with Feature Lines

Link and node maps are set up and automatically numbered in *WMS* using feature objects. Rather than specify which grid cell is part of the stream, a feature arc representing the stream is created. Stream feature arcs can be defined using any combination of the tools and import options available in *WMS*, but typically they will be defined from the results of the stream runoff characteristics computed by TOPAZ and generated during the initial delineation of the watershed from the digital elevations. When using the arcs computed by TOPAZ, make sure that the stream network created does not violate the following rules:

- Stream arcs should not pass through cell corners (Figure 10).
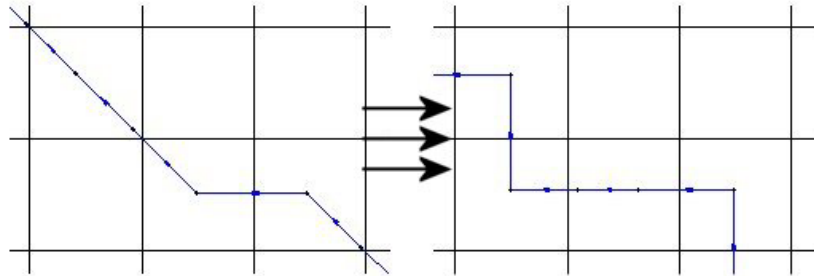
Figure 10. Changing diagonal stream arcs to orthogonal stream arcs

- Stream arcs should not exit and then re-enter the same cell (Figure 11).
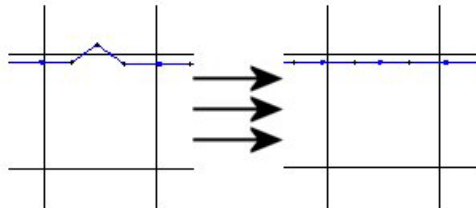
Figure 11. Straightening small bends in the stream arcs

- Two stream arcs should not exist in the same grid cell. The only exception is where there is a channel junction (Figure 12).
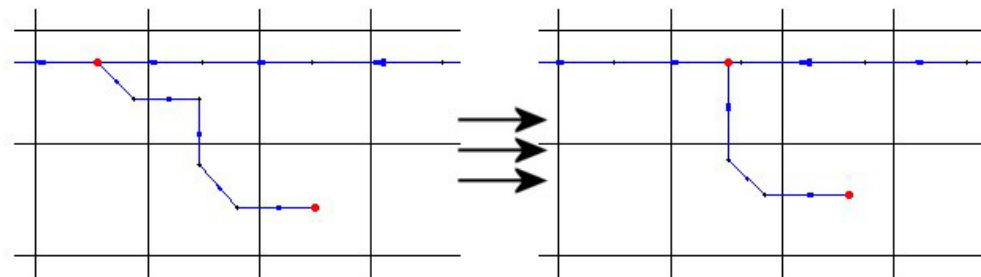
Figure 12. Modifying the junction location of a stream arc

- Stream spurs smaller than a cell width cannot be simulated in *GSSHA*. Usually, they are inconsequential to the overall watershed response and should be deleted. If they are necessary, reduce the grid size so that they pass through more than one cell (Figure 13).
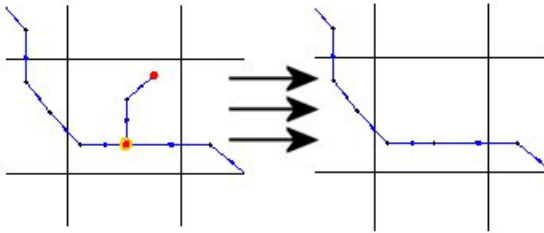
Figure 13. Deleting small stream spurs

- Stream arcs cannot pass along the edges of cells. They must be moved to one side or the other. Otherwise, *WMS* is likely to incorrectly define the cells that make up the channel (Figure 14).
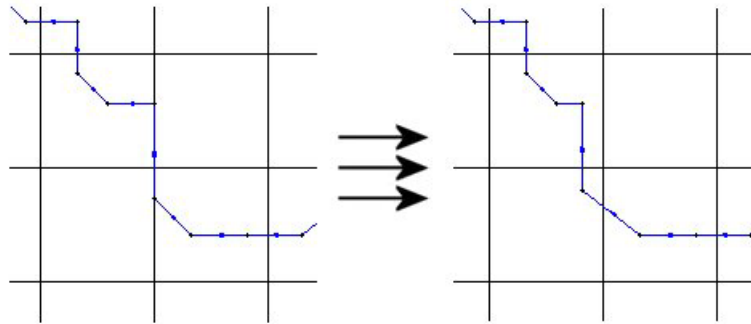
Figure 14. Adjusting stream arcs along cell edges

- A link may have only two upstream links, not three. The third stream can usually be adjusted to connect one cell up or down to the downstream link with negligible consequences (Figure 15).
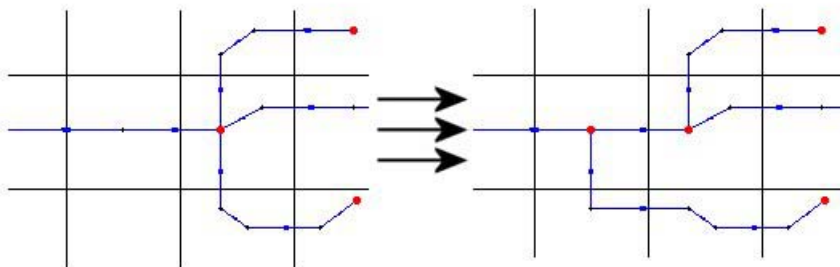
Figure 15. Reassigning stream connections at an invalid junction

Often, dlg files showing the stream location are available. These can be imported into *WMS* and converted to feature objects or displayed in the background and used as a template for manually constructing the stream arcs. When manually creating stream arcs, all feature lines should be constructed from *downstream* to *upstream*.

Link Types

Once the arcs are defined, the link types and their associated parameters are assigned to the feature arcs and nodes. *WMS* will automatically assign nodes at the junction of stream sections as *Link Breaks* when the *Renumber Links* option is chosen. Since the stream network is generated using feature arcs and a *GSSHA* coverage, the *Renumber Links* option is located under the *GSSHA* menu in the Map Module. *Link Breaks* desired at other locations must be assigned manually by selecting a feature node (you may have to convert a feature vertex to a node if a node does not exist in a location where you wish to add a link break) and defining that node as a link break using the *Attributes* command in the *Feature Objects* menu. If there is no vertex at the desired location, then you must create one. Arcs can be assigned as streams by selecting the arc and then defining it as a stream under the *Attributes* menu. Two general types of streams can be created, *Trapezoidal* and *Break Point Cross Section,* as shown in the *Feature Arc Attributes* dialog in Figure 16.
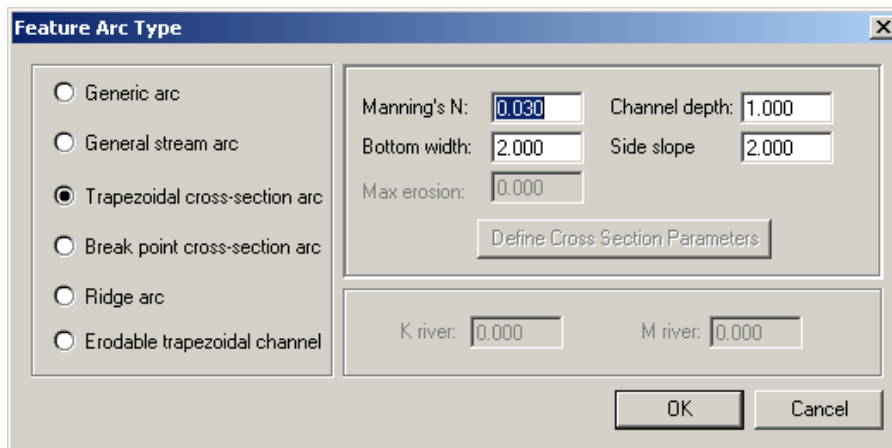
Figure 16. The Feature Arc Attributes dialog is used to assign both the type and physical parameters of the stream channel

Once the stream network is complete, the *Renumber Links* command can be used to automatically renumber the stream arcs according to the rules required by *GSSHA*. Each time a new branch is created, or the stream network is edited in any way, the links should be renumbered. Link and node maps are created when a *GSSHA* project is saved. Cells inherit the link number, type, and associated parameters of the overlying stream arc. An example of a stream arc, and how grid stream cells are located with it, is shown in Figures 17 and 18.
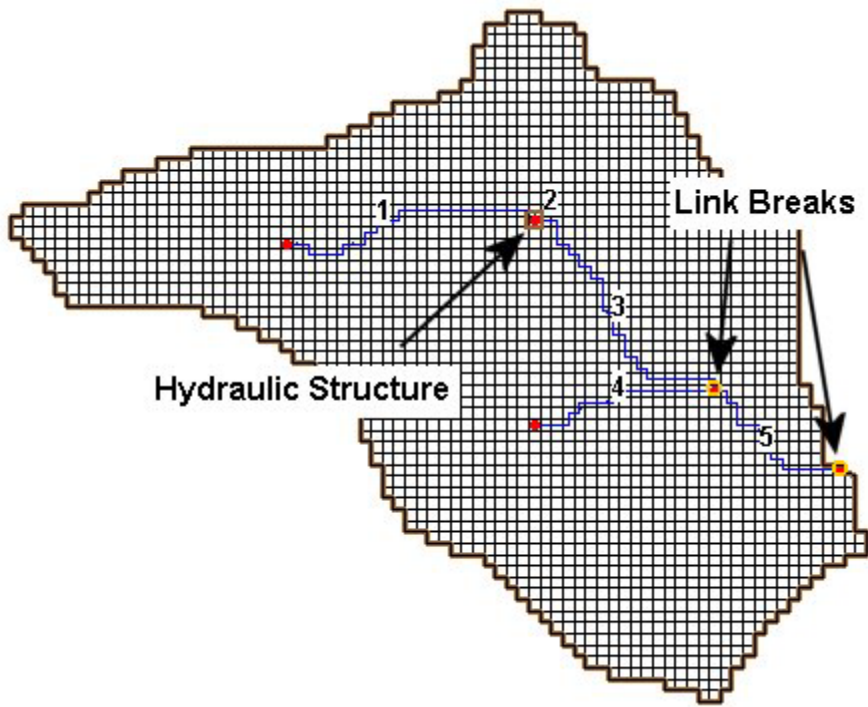
Figure 17. The stream network as a set of feature objects in WMS
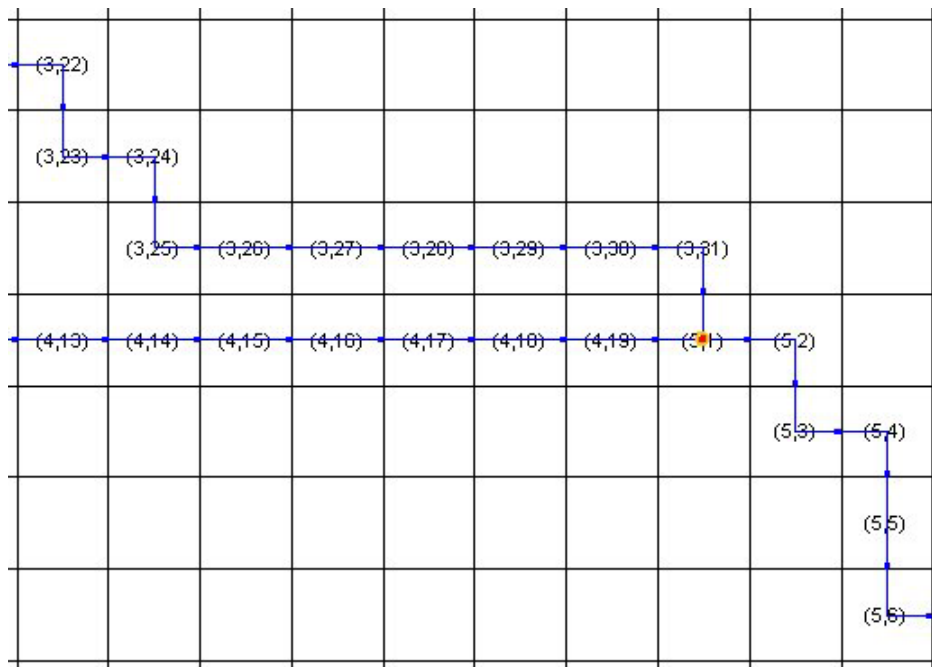
Figure 18. The (Link, Node) numbers from the stream network being mapped to the finite difference grid

Fluvial streams

There are two basic types of stream cross sections that can be defined under the feature line *Attributes* menu, *Trapezoidal* and *Break Point*. Cross sections are defined by selecting feature arcs using the select feature arc tool while in the Feature Line Module. While in the Map Module, and with the links or links selected, select *Attributes* under the *Feature Object* menu. Trapezoidal and break point cross sections can then be defined in *Feature Arc Type* dialog box.

Trapezoidal cross sections.

Trapezoidal cross sections are defined by:

- **Bottom width** (m).

- **Channel depth** (m).

- **Side slope** (change in *X* with a change in *Y* of 1).

- **Manning's N** - Manning's roughness coefficient, *n* (dimensionless).

Break point cross sections.

Look-up tables or break point cross sections are used when actual field surveyed cross-sectional data are available. After selecting *Break point cross section arc*, click on *Define Cross section parameters*. From here you can import, create, or edit values in the look up table, and then assign look up tables to stream sections.

The parameters in the look-up table are:

Depth (m)   Area (m^2)   Top width (m)   Conveyance ($AR^{2/3}/n$)

These values may be entered directly into the table, imported from a separate program, or computed from the cross section. To create a new table, select *New*; a dialog box will appear asking for the number of increments in the table. The default value is 8. Any number of segments in the table can be specified. The number of segments should be commensurate with the size of the cross section. Too large a change in the look up table values may cause *GSSHA* to crash. If in doubt, increase the number of values in the table.

To construct a table from measured points from the cross section, select *Compute Parameters from Cross section…* at the bottom of the dialog box. Another dialog box appears asking for the type of units to use, English or Metric, and the value for Manning's *n*. This value is used to compute the conveyance. The default value is 0.01. After selecting a unit system and assigning a Manning's n, an *X,Y* series editor appears. Surveyed points are entered with this editor. Surveyed *X,Y* points may be imported using the *Import* button on the right-hand side of the editor, or values may be entered manually for each point under *X* and *Y* at the left-hand side of the screen. Values of *X* must increase with successive points. Values of *X* and *Y* may be positive or negative. As values are typed into the editor, points appear on the screen to the right. The location of these points may be adjusted by selecting the Select Data Point tool (three dots with an arrow in the center) and then clicking and dragging the point to the desired location. Additional points may be added by selecting the Add Data Points tool (the three dots below the Select Data Point tool) and clicking on a point inside the *X,Y* Screen. Additional cross sections may be created by clicking on *New* and defining the points as described above. You will want to provide a meaningful name for each channel cross section and corresponding table. Once all the points are entered select *OK*, and the *Table Parameters* will automatically be computed.

Once all the tables are created, tables can be assigned to a link by selecting the link, selecting *Attributes* under *Feature Objects*, toggling on *Break point cross section arc*, selecting *Define Cross section Parameters*, and then selecting the name of the table from the list that appears on the left-hand side of the dialog box.

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 break point 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. In *WMS* this can be done by breaking a single link in to two or more links and assigning different cross sections to each of these links. Sometimes it is necessary to provide a different cross section for every node in a link or along the entire channel. To do this, the channel input file will have to be manually edited. Users should consult the *GSSHA User's Manual* for more information on the format of the channel input file.

Hydraulic structures

Internal boundary conditions, such as weirs, are defined at nodes along the feature arc network. Internal boundaries are given a unique link number and parameters are defined for these nodes in the same way as they are defined for the feature arcs. These internal boundary conditions represent point features of the channel network. To add an internal boundary condition, select the feature point at the proper location. You may need to add a new feature node or convert a feature vertex to a feature node by selecting the feature vertex, and then selecting *vertex<->node* under the *Feature Objects* menu. Under the *Feature Objects* menu select *Attributes* and then toggle on weir. The input values required for a weir are:

- *Free flowing discharge coefficient* - typical 0.9
- *Flooded coefficient* - typical 0.8
- *Crest width* (m)
- *Crest elevation* (m)

The crest elevation of the weir must be greater than the elevation of the upstream node. You may request a discharge hydrograph at this location by toggling on *GSSHA hydrograph location*. Select *OK* when done.

Smoothing the Profile

The channel input file contains the channel bed elevation at each node, which constructs the longitudinal profile of the deepest portion of each channel (thalweg) in the drainage network.

Ideally, you will use surveyed cross sections and thalweg profiles of the channel network. However, extensive surveys are often impossible for the entire drainage networks of large watersheds. In lieu of an extensive survey, there are existing tools for extracting channel topology from digital elevation data. If the channel network is extracted from the digital terrain data, smoothing of the channel thalweg must be performed to produce physically realistic longitudinal profiles because of errors inherent in any digital data. The algorithm developed by Ogden (Ogden, Saghafian, and Krajewski 1994) has been embedded in *WMS* so that the

streambed elevations along the channel network can be smoothed. The following guidelines should be followed when smoothing channels:

- Streambed elevations should always be lower than adjacent surface elevations. *WMS* recognizes both the streambed elevation and a surface elevation at each grid cell. When smoothing of channels is done, only the streambed elevation is changed.

- Abrupt transitions in streambed elevation should be avoided. If abrupt transitions occur naturally in the stream (e.g., a headcut), a weir internal boundary condition can be inserted to simulate this feature.

- Topographical maps of the watershed can be very useful in detecting obvious errors in the DEM that cause unusual features in the stream profile. Unusual profile features extracted from the DEM can usually be removed without significant effects on the simulation results.

Smoothing of the streambed profile and inputting or adjusting the streambed elevation of individual nodes is done under the *GSSHA* menu, while in the Map Module. First, select the stream segment you wish to smooth using the Select Feature Arc tool. Hold down the shift key to select multiple segment; select from downstream to upstream. You cannot select multiple branches along a stream. Next, under the *GSSHA* menu, select *Smooth Stream Cells*. The *Streambed Elevation Smoothing* dialog will appear, showing the stream bottom elevation in blue and the ground elevation in red (Figure 19). If the stream has not already been edited, the two lines may fall on top of each other and appear as one red line. Clicking the *Smooth* button will automatically smooth the channel, but with varied success. Continued clicking on this button results in successive smoothing of the streambed.
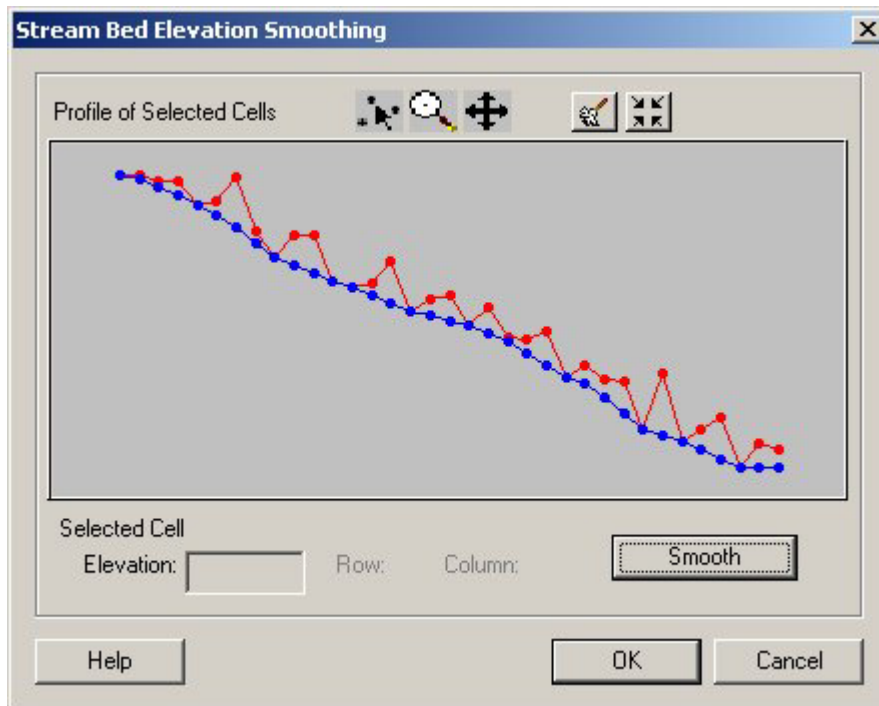

Figure 19. The Streambed Elevation smoothing editor allows you to adjust the streambed profile by manually entering the elevation, through a click-and-drag operation on a node, or through the automated Smooth function

In addition to using the *Smooth* option, the elevation of individual nodes can be adjusted by selecting the node with the Select Feature Point tool. The selected node can be moved by holding down the mouse button and dragging and dropping the node at the desired elevation. The exact elevation for the node can also be typed in at the bottom of the display in the *Elevation* box. Typically, it is necessary to manually move points into an approximate shape and then use the *Smooth* feature to smooth out remaining irregularities.

Even when the thalweg of the stream is surveyed, it is unlikely that the elevation of every computational node in the stream will be known. In this case, you may wish to continue using the smoothing algorithm, yet fix the known points. If the known points fall at the end of arc lengths, select the arcs between known points, then select the *Smooth Stream Cells*. You may then input the elevations of the end points and *Smooth* between these points. Alternatively, if there are no nodes at the known locations, then you may wish to create another generic feature line whose endpoints correspond to the known locations. You can then use this arc to smooth the stream cells and then discard the generic arc after smoothing is completed.

Trouble Shooting Channel Routing Problems

The explicit diffusive wave scheme employed in *GSSHA* naturally diffuses, or smoothes, the water surface profile between sharp transitions. The scheme also contains a number of internal stability checks and will typically run on a properly prepared channel network. As discussed above, essential to a properly prepared channel network are smooth transitions between channel cross sections and thalweg elevations.

Problems typically arise when cross sections change abruptly, the thalweg elevation changes abruptly, there are regions of adverse slope in the channel section, or the channel thalweg is above the overland cell elevation. These situations should be eliminated from the beginning. If regions of adverse slope (slope is in the general upstream direction) really exist in the channel network, then it may be possible to include them in the channel network.

Once a problem occurs during channel routing, the task of the user then is to identify the location of the problem. When channel instability occurs, usually because of negative depths caused by oscillations, the model ceases execution and prints warning statements identifing the problem cells. The user should look at the node/link pairs involved and try to identify the problem. The problem can typically be corrected by smoothing the channel thalweg and/or increasing the number of channel cross sections, or reducing the depth increment in look-up tables. If a surveyed longitudinal profile is causing the trouble, it may be necessary to reduce the channel time-step or do some minimal smoothing of the profile.

7   SPATIALLY AND TEMPORALLY VARYING RAINFALL

Introduction

The ability to assign uniform rainfall over the entire watershed is maintained largely as a trouble-shooting feature and is mostly used in initial model development. Real watersheds are modeled with temporally and spatially varying rainfall. As briefly described in Chapter 3, all precipitation inputs are created in *WMS* by selecting *Precipitation* from the *GSSHA* Menu while in the 2-D Grid module. This will bring up the *GSSHA Precipitation* dialog box. How to assign temporally varying rainfall for one or more gages is described below.

Temporally Varying, Spatially Uniform Rainfall

Temporally varying, spatially uniform rainfall can be assigned by toggling on the *Single Gage Rainfall* button. A single-gage rainfall produces a time series of rainfall for the entire watershed. The time series is specified by clicking *Define Event* and entering the time series with the *X,Y* data series editor. A single rain gage event can also be constructed in the same manner as described below, where spatially and temporally varying rainfall simulations are discussed in more detail. For a single temporally varying rain gage, the maximum number of rainfall data points in the time series is limited to 1,500. Larger rainfall events can be modeled by *GSSHA* but cannot be brought into *WMS* for manipulation. These rainfall files, as well as multiple rain gage files, can be constructed with an editor outside of *WMS,* and then this file can be named as the rainfall file when saving the *GSSHA* project file.

Temporally Varying Multiple-Gage Rainfall

To assign rainfall data from recorded gages, toggle on *Multiple-Gage Rainfall*, and select a method of distributing the rainfall, by either *Thiessen polygons* or *Inverse distance weighted*. *WMS* does not currently support the file *GSSHA* required for temporally varying multiple rain gage input. If you select *View Event File, WMS* will automatically put you in an editor to create or edit the necessary file. The default editor is Microsoft Notepad. The file may also be created separately from *WMS* with any appropriate software.

The rainfall file consists of storm event header information, a description of each rain gage, and then cards with a time and value for each rainfall data point. For long-term simulations with multiple rain events, the single-event format is repeated for each additional event.

At the top of the file is a description of the event. This is followed by the number of rain data points in the rain time series. The next line specifies the number of rain gages. This is followed

by a series of four-column lines containing the easting, northing, gage name, and the time series name for each rain gage. Rain gages need not be located within the watershed of study. If a gage falls in a different UTM zone to the left of the zone the watershed is in, then negative values can be entered.

Rain gages located well outside the watershed under analysis generally provide poor rainfall estimates. The instantaneous correlation distance for convective rainfall is typically on the order of a few kilometers. Use caution when using data from rain gages further than a few kilometers from the catchment.

The remaining lines at the bottom of the rain gage file reflect the temporal variation of rainfall intensity. The number of columns per line equals the number of rain gages, each being separated by space. The number of lines in this lower portion is equal to number of rainfall periods (NRPDS).

Each rainfall file must have the following cards:

- EVENT – simple description string of the event, must be set in double quotations.

- NRGAG - number of rainfall gages to follow (integer value).

- NRPDS - number of rainfall data points to follow (integer value).

- COORD - coordinate, easting and northing of gage, one card for each gage (NRGAG), must have an identifying string in double quotations, and need not have the same number or locations of gages for different storm events when multiple events are simulated.

- GAGES, RADAR, RATES, ACCUM - rainfall data point. The number of these cards must be NRPDS. Each card specifier should be followed by Year, Month, Day, Hour, Minute, and then one value of rainfall (decimal format) for each NRGAG. The proper card name depends on the type of rainfall entered. The four types are:

  1. *GAGES - rainfall accumulation (mm) over the last time period.*

  2. *RADAR -rainfall rate (mm·hr^{-1}) for the last time interval.*

  3. *RATES - rainfall rate (mm·hr^{-1}) for the next time interval.*

  4. *ACCUM - cumulative amount of rainfall up until that time period (mm).*

  Some guidelines for use are:

  1. *Specified rainfall types cannot change within a storm event.*

  2. *The time interval can be any value, but there must be a rainfall value for each NRGAG.*

  3. *Separate values with spaces or tabs.*

  4. *Names of events and gages are NOT optional and must be in double quotation marks, as shown below.*

The proper format is shown below. For this example there are three gages and five rainfall data points. The *GSSHA User's Manual* should be consulted for additional information on constructing rainfall files.

EVENT "Event of 30 June 1995- rainfall stops on July 1st"

NRGAG   3

NRPDS   5

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 20 22 56   0.00   0.00   0.00

RADAR 1995 06 20 23 18   10.75   2.25   5.80

RADAR 1995 06 20 23 39   21.16   1.80   41.50

RADAR 1995 06 20 23 57   12.13   20.90   20.70

RADAR 1995 07 01 00 09   11.71   16.50   2.30

Within *GSSHA,* the values of rainfall at the gages are interpolated to the grid cells. Either Thiessen polygons or inverse distance-squared interpolation are used. For RADAR type rainfall inputs, Thiessen polygons should be selected.

8 *LONG-TERM SIMULATIONS*

Introduction

The *GSSHA* predecessor, *CASC2D*, was originally developed as an episodic model, and *GSSHA* can still be used to simulate single events with a specified simulation time. However, Senarath et al. (2000) showed the pitfalls of calibrating distributed parameter models like *CASC2D* to single events. *CASC2D* was subsequently modified to be able to simulate multiple rainfall events over an extended period. Typically, *GSSHA* is run in the long-term simulation mode.

There are no restrictions on the duration of the simulation or the number of rainfall events that can be simulated. Annual simulations have been successfully performed for a variety of watersheds. The only requirement is that hydrometeorological and rainfall data be available for the simulation period.

How *GSSHA* operates during a long-term simulation depends on the model options selected. When GAR is used to calculate infiltration, *GSSHA* operates in a dual mode. During rainfall events, *GSSHA* performs in the normal episodic rainfall/runoff mode. Once a user specified minimum discharge is reached on the recession limb of the hydrograph, the rainfall/runoff model is stopped and soil moisture calculations begin. At this point, *GSSHA* performs hourly evapotranspiration and soil moisture calculations until another precipitation event begins. If saturated groundwater calculations are chosen, then saturated groundwater and infiltration are calculated on a continual basis. See the *GSSHA User's Manual* for more information.

When Richards' equation is chosen as the infiltration option, Richards' equation is continually solved so that infiltration, evapotranspiration, soil moisture accounting, and groundwater recharge are calculated whether or not rainfall events are occurring. When a rainfall event does occur, precipitation distribution, interception, retention, overland flow, and channel routing are initiated, assuming these processes have been selected for simulation. These processes continue as long as there is rainfall. After rainfall ceases, overland and channel flow continue until water on the overland flow plane and channels ceases to flow. As the decision is based on process conditions, any process may begin or end at any time. The minimum flow criteria discussed above is still used to describe events, but it is used for accounting purposes only and is not used to stop the execution of any processes.

Global Parameters

Global parameters for long-term simulations are defined by selecting *Job Control* from the *GSSHA* menu, while in the 2-D Grid module. This produces the *GSSHA Job Control Parameter* dialog box. Check *Long-term Simulation* and press the *Edit Parameters...* button and assign the following values in the *Continuous Simulation* dialog box.

- *Latitude* – used in radiation calculations for missing data, decimal format (degrees).

- *Longitude* – used in radiation calculations for missing data, decimal format (degrees).

- *GMT* – deviation from Greenwich Mean Time (GMT) (+/- h), e.g.

    1. *Pacific Standard Time is -8.*

    2. *Mountain Standard Time is -7.*

    3. *Central Standard Time is -6.*

    4. *Eastern Standard Time is -5*

- *Minimum event discharge* –discharge on the recession limb to stop event simulations when using GAR and to stop event accounting when using Richards' equation to calculate infiltration ($m^3 \cdot s^{-1}$).

- *Soil moisture depth* – depth of soil column over which evapotranspiration is distributed (m). For GAR, this is the total depth of the soil column from which ET can occur. For Richards' equation, this is the maximum depth for distributing potential ET demand. See Chapter 9.

- *Hydrometeorological (HMET) Data File* - name of hydrometeorological data file.

- *HMET Format* - format of hydrometeorological data file. Toggle on either.

    1. *Samson.*

    2. *Surface Airways.*

    3. *WES.*

    See the following discussion of Hydrometeorological Data.

Infiltration Model

When long-term simulations are conducted, the infiltration type, selected in the *GSSHA Job Control Parameters* dialog box, must be either *Infiltration redistribution* (GAR) or *Richards' infiltration*. The necessary parameters for modeling infiltration with GAR are discussed in Chapter 4. A discussion of Richards' equation is presented in Chapter 9.

Evapotranspiration Model

When performing long-term simulations, a method to model evapotranspiration is also selected in the *GSSHA Job Control Parameter* dialog box. The two methods available are *Deardorff Method* and *Penman Method*. The Deardorff method is a bare-soil evaporation model. The Penman Monteith method calculates the combined effect of evaporation and plant transpiration, and requires additional information on the plant community in each grid cell. When the Penman method is selected, the option to vary the entered values of vegetation canopy resistance according to the season is available. When this option is selected, by toggling on the *Seasonal Resist* button, midgrowing season values of canopy resistance are entered and are automatically varied throughout the year as described in the *GSSHA* Users Manual. The canopy resistance varies as shown in Figure 20.
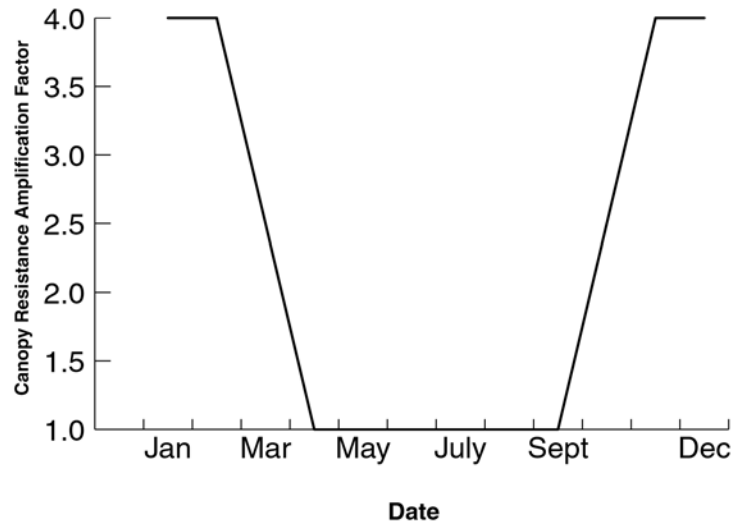
Figure 20. Annual variation in canopy resistance when seasonal resistance is selected

Depending on the method of ET selected, the following distributed parameters are input through the mapping tables as described in Chapter 5. Values may be assigned based on field measurements, or from land use and vegetation information. Literature values based on land use, snow cover, and vegetation characteristics are compiled in the *GSSHA User's Manual*.

Deardorff

- Land surface albedo – fraction of radiation reflected back to the atmosphere, range 0.0 to 1.0.

- Wilting point water content – water content below which plants can no longer transpire (dimensionless). The value varies between the residual water content and the porosity.

Penman-Monteith

- Land surface albedo - fraction of radiation reflected back to the atmosphere (dimensionless), range 0.0 to 1.0.

- Wilting point water content – water content below which plants can no longer transpire (dimensionless). The value varies between the residual water content and the porosity.

- Vegetation height (m).

- Vegetation transmission coefficient – direct solar radiation penetrating the vegetation canopy and reaching the ground, range 0.0 - 1.0.

- Canopy stomatal resistance– resistance of the canopy to transpiration at noon $(\text{s} \cdot \text{m}^{-1})$.

Hydrometeorological Data

Hourly values of the following hydrometeorological data must be specified for the long-term simulation period:

- Barometric Pressure (in Hg)

- Relative Humidity (%)

- Total Sky Cover (%)

- Wind Speed (kts)

- Dry Bulb Temperature (^{o}F)

- Direct Radiation (W·h·m^{-2})

- Global Radiation (W·h·m^{-2})

The needed data can be obtained from a variety of sources including the National Climatic Data Center (NCDC) and commercial vendors (such as Earth Info). All seven parameters are contained in data sets referred to as Surface Airways data by most sources. These data are used to perform evapotranspiration calculations.

Because of the variety of data sources, *GSSHA* will read the data in a variety of formats. These are:

- *SAMSON*, *Surface Airways,* and U.S. Army Engineer Research and Development Center/*WES*. The *SAMSON* format is developed for the NCDC historical database of Surface Airways data called *SAMSON*. These data files may be purchased from the NCDC in the form of a CD, which contains all historical data from 1961-1990.

- If more recent data are required, they can also be purchased from the NCDC in the *Surface Airways* format. These file formats contain numerous data parameters in addition to the seven required inputs above.

- All sources of data can be transferred to the *WES* format containing only the data required by the model. A sample of the ERDC/*WES* format is shown below. Examples of the other formats can be found in the *GSSHA User's Manual*.

WES formatted data

The HMET_WES format contains the following numbers in columns 1 through 11:

1. Year (4 digit)

2. Month

3. Day

4. Hour

5. Barometric pressure   (inches Hg)   No Data (ND) = 99.999

6. Relative humidity   percent   ND=999

7. Total sky cover   percent   ND=999

8. Wind speed	knots	ND=999
9. Dry bulb temperature	degrees F	ND=999
10. Direct radiation	Watt hour per meter squared	ND=9999.99
11. Global radiation	Watt hour per meter squared	ND=9999.99

and appears in the following format.

```
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
```

The type of hydrometeorological data and the name of the hydrometeorological data file are selected in the *Continuous Simulation* dialog box. *WMS* supports none of the hydrometeorological input data formats, and the hydrometeorological data must be assembled in software external to *WMS*. It is highly recommended that hydrometeorological data be converted to the WES format before use in the *GSSHA* model.

Missing data

In the case of missing data, the ND code, as described above, should be entered in the data set. One line of data is required for each hour of the simulation. Do not skip hours or leave blank values in a line. If no data are present, enter the Year, Month, Day, Hour, and the appropriate ND code for each missing variable for each missing hour. Upon encountering the ND codes, *GSSHA* fills in missing data in the following way:

- In the case of missing pressure, total sky cover, wind speed, and dry bulb temperature, the last recorded readings are used until actual data resumes.

- For parameters with a strong diurnal pattern, such as air temperature, relative humidity, and global and direct radiation, missing hourly values are replaced with the last good value at the same time of day. For extended no data periods, the last values from the last good day of measurements are repeated until actual data resumes.

It is important that the hydrometeorological data set begin with at least one full day of complete data; no ND codes may be present.

Many stations have no radiation data. If no radiation data are available, *GSSHA* will calculate radiation based on the latitude and longitude of the watershed and the time of day. The latitude/longitude and time deviation from GMT is specified in the *Continuous Simulation* dialog box.

Rainfall Data

The Rainfall data file for long-term simulations is comprised of a series of single storm events, as described in Chapter 7. An example of a two-storm long-term rainfall file is shown below. The *GSSHA User's Manual* (Downer and Ogden in preparation) should be consulted for additional information on constructing rainfall files.

EVENT "Event of 30 June 1995- rainfall stops on July 1st"

NRGAG   3

NRPDS   5

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 20 22 56   0.00   0.00   0.00

RADAR 1995 06 20 23 18   10.75   2.25   5.80

RADAR 1995 06 20 23 39   21.16   1.80   41.50

RADAR 1995 06 20 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"

NRGAG   4

NRPDS   7

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

GAGES 1995 07 04 10 49   14.0   0.0   26.0   16.0

GAGES 1995 07 04 11 01   8.0   42.0   21.0   22.0

GAGES 1995 07 04 11 13   0.0   19.0   9.0   9.0

As shown in this example, it is possible to change the location and number of gages among storm events, as well as the type of rainfall. However, rainfall types cannot be mixed within a rainfall event.

9   *MODELING THE UNSATURATED ZONE WITH RICHARDS' EQUATION*

Introduction

Modeling of the unsaturated zone is a key addition of the *GSSHA* model. Richards' equation is currently the most complete method to simulate soil water movement in the unsaturated zone. When Richards' equation is solved in *GSSHA* to calculate soil moistures and soil water movement, infiltration, actual evapotranspiration, and groundwater recharge are also calculated as part of an integrated solution. Because most soil water movement is in the vertical direction, a 1-D representation of the soil column is employed to simulate the unsaturated zone. The *GSSHA* representation of the soil column is shown in Figure 21. As shown in this figure, when using Richards' equation to represent the unsaturated zone, the soil column is subdivided in to three layers: A, B, and C horizons. Parameters must be specified for each of these three layers. Unlike the Green and Ampt based models of infiltration, Richards' equation is a partial differential equation that must be solved numerically. Therefore, each of the soil layers must be subdivided into cells. The user must specify the cell size of each layer, along with the hydraulic properties of the soil.

To use Richards' equation, several global and distributed parameters must be set. The global parameters are related to the numerical solution of Richards' equation.   The distributed parameters describe the soil and are similar to the parameters used in the Green and Ampt approaches.

Richards' equation is selected from the *GSSHA Job Control Parameters* dialog under the *Infiltration* options.

Global Parameters

The global parameters for Richards' equation are set from the *GSSHA Job Control Parameters* dialog under the *Infiltration* options.   With *Richard's infiltration* toggled on, hit the *Edit Parameters...* button to access the global parameter list. The global parameters are:

- *Weight* – Fraction between 0.0 and 1.0 (dimensionless). This is the weighting factor used to calculate inter-cell hydraulic conductivities when using an *arithmetic* mean to calculate the inter-cell hydraulic conductivities. Use 1.0 for forward weighting, 0.0 for backwards, and 0.5 for central. The default value is 1.0
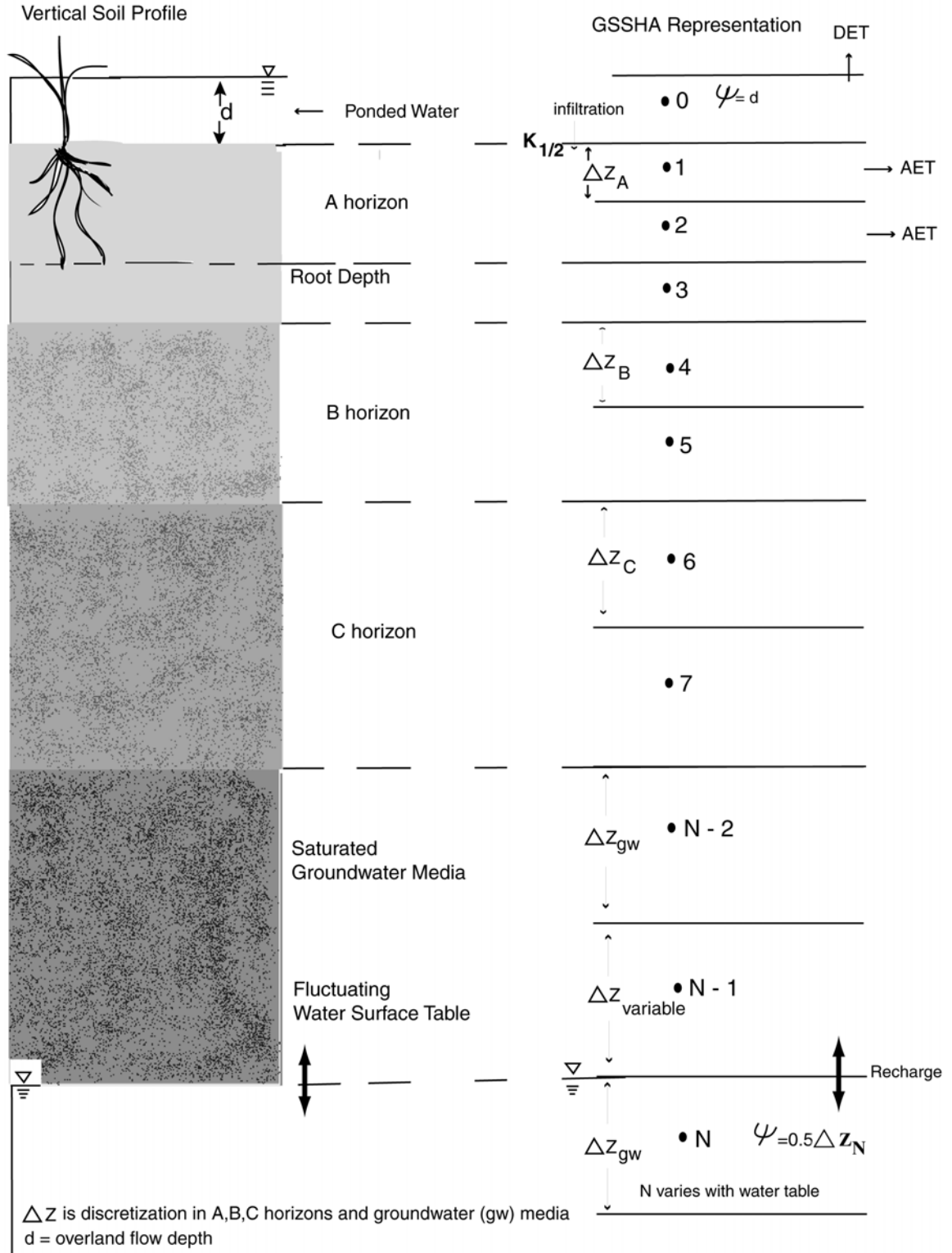
Figure 21. GSSHA representation of the unsaturated zone

- *DTHETA Max* – Fraction between 0.0 and the porosity of the soil (dimensionless), the maximum allowable water content change in any finite difference cell during a single time-step. Typical range is between 0.002 and 0.030 (Belmans, Wesseling, and Feddes 1983). The default value is 0.025.

- *C Option* – *Brooks* or *Havercamp* sets the curves used to define the relationships between water content and soil suction, pressure, and water content and hydraulic conductivity. An example of the curves for a typical clay and sand are shown in Figure 22. The user is referred to the *GSSHA User's Manual* for more detailed information on this topic. The default value is *Brooks*.

- *K Option* – (*Arithmetic* or *Geometric*) method used to calculate inter-cell hydraulic conductivities.

- *Upper Option* – method used to determine the hydraulic conductivity at the soil surface during ponded water conditions; the options are *Normal*, *Green Ampt*, and *Average*. *Normal* specifies that the normal cell-centered value of hydraulic conductivity be used, *Green Ampt* specifies that the saturated hydraulic conductivity of the soil in the cell be used, and *Average* specifies that an average of the two be used. The default value is *Normal*. For more information, see the *GSSHA User's Manual*.

- *Max Iteration* – the maximum number of iterations each time-step to determine water capacity and hydraulic conductivity. The typical range is 1 to 10 iterations. The default value is 1.

- *Max Num* – integer value, maximum number of cells in any unsaturated soil column.

Distributed Parameters

As with all distributed parameters, the distributed parameters for the Richards' equation are assigned using index maps and the mapping tables as described in Chapter 5. Assignment of parameters with Richards' equations differs from the other processes in that for each different soil type in the index map, three soil layers must be defined. Parameters and discretization must also be assigned for all three layers. The parameters that must be defined depends on which option is used to define the PCS curves, *Brooks* or *Havercamp*. The Havercamp formulation is best if laboratory data are available to fit the needed parameters as detailed below (Figure 22). Testing by Downer (2002) showed that the Havercamp equations could best define the soil behavior. If no detailed data exist, as is typical, then the Brooks and Corey (1964) method may be used and the parameters needed for the Brooks and Corey model can either be measured or estimated from soil textures and literature sources such as Rawls, Brakensiek, and Saxton (1982).

Parameters for the Richards' equation are assigned in the *GSSHA Mapping Table Editor*. For the Brooks and Corey method, the following parameters are assigned for each of the three layers.

- *Hydraulic Conductivity* –saturated hydraulic conductivity of the soil (cm·hr^{-1}) describes the rate water will enter the soil under unit head and saturated conditions.

- *Porosity* - volume of voids/total volume of soil, fraction between 0.0 to 1.0 (dimensionless).

- *Residual saturation* –water content of air dry soil, fraction between 0.0 to 1.0 (dimensionless).

Water Retention Curves

Figure 22. Water retention curves, water content vs. negative pressure head, for both sand and clay. The Havercam, Brooks & Corey and extended Brooks and Corey equations are shown. (BC – after Brooks & Corey 1964)

- *Wilting point* – fraction between residual saturation and porosity, water content below which plants cannot uptake water from the soil (dimensionless).

- *Depth* – thickness of the soil layer (cm). Should be rounded up or down to nearest centimeter.

- *Lambda* – pore distribution index (dimensionless). Describes the straight line length to the soil water path length.

- *Bubbling pressure* – pressure at which air enters the soil column (cm). Must be negative.

- *Delta Z* – vertical cell size of the layer (cm). Should be evenly divisible into the *depth* of the layer.

For the Havercamp method, the following parameters must be specified for each of the three layers. Parameters from the Havercamp method must be determined from field or laboratory testing.

- *Hydraulic Conductivity* –saturated hydraulic conductivity of the soil (cm·hr^{-1}) describes the rate water will enter the soil under unit head and saturated conditions.

- *Porosity*   - volume of voids/total volume of soil, fraction between 0.0 to 1.0 (dimensionless).

- *Residual saturation* –water content of air dry soil, fraction between 0.0 to 1.0 (dimensionless).

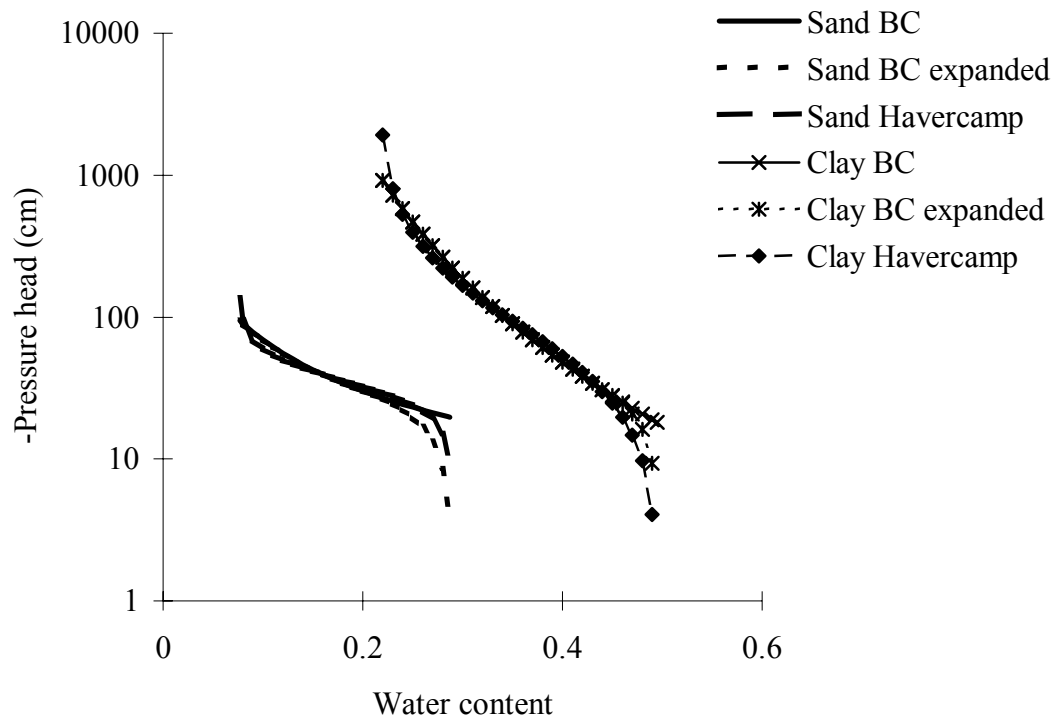- *Wilting point* – fraction between residual saturation and porosity, water content below which plants cannot uptake water from the soil (dimensionless).

- *Depth* – thickness of the soil layer (cm). Should be rounded up or down to nearest centimeter.

- *Alpha* – factor fitted from field or laboratory data.

- *Beta* – factor fitted from field for laboratory data.

- *AHAV* – factor fitted from field for laboratory data.

- *BHAV* - factor fitted from field for laboratory data.

- *Delta Z* – vertical cell size of the layer (cm). Should be evenly divisible into the *depth* of the layer.

Soil Depth and Discretization

The soils in the unsaturated zone need to be defined down to a depth that includes the active region of the soil, where the water content experiences large changes in value. This should include the root zone. Typically, soil surveys describe the A, B, and C soil horizons of soils in the study region. In lieu of field measurements, these surveys provide information on the appropriate thicknesses of each of the soil layers for the Richards' equation model. While Downer (2002) showed that the *GSSHA* model is not sensitive to the depth of the soil layer, it is best to err on the conservative side and make the soil columns deeper than necessary. As this will increase the computation time, it may be useful to experiment with the soil layer depths to reduce the amount of soil being simulated, if possible. When the saturated zone is the lower boundary, the area between the defined soil column and the water table will be assigned the parameters used in the third, C, layer, and the cells will be the size specified in the *WMS* subsurface parameters dialog found in the job control options.

The other big consideration in application of Richards' equation is the cell discretization. Essentially, the smaller the cells the better the answer, but the longer the simulation time. Very small cells, 1 cm or less, will typically be required in the top 10 cm of the soil column (van Dam and Feddes 2000; Downer 2002). Much larger cells may be used at depth in the soil column. Increases in the cell size between layers should be gradual.

10 MODELING TWO-DIMENSIONAL, SATURATED, LATERAL GROUNDWATER FLOW

Description

Two-dimensional, saturated, lateral groundwater movement may be simulated in *GSSHA*. The purpose of simulating 2-D, lateral groundwater movement is to provide the effects of saturated groundwater on surface water processes, such as influences on soil moisture, infiltration, and ET, location of saturated source areas and seeps, and stream/groundwater interactions. The saturated groundwater modeling option is intended to be used in conjunction with Richards' equation modeling of the unsaturated zone. When 2-D saturated groundwater is coupled to the Richards' equation, the 1-D unsaturated model sits on top of the moving water table, which becomes the lower boundary condition for the unsaturated zone solver (Figure 21). The unsaturated model provides recharge (positive or negative) to the unsaturated zone.

When conducting long-term simulations (Chapter 8), it is also possible to use the GAR model of infiltration to provide estimates of groundwater recharge for the 2-D lateral groundwater solution. However, this option does not provide many of the advantages of coupling Richards' equation to the 2-D lateral groundwater model, such as the effect of groundwater on soil moistures in the unsaturated zone. This approach is intended for simple problems and where a more qualitative result is acceptable, and has been applied as such. Downer et al. (2002b).

Global Parameters

Global parameters for 2-D saturated flow modeling are specified by toggling on *Subsurface* in the *GSSHA Job Control Parameters* dialog. This produces the *Subsurface Parameters* dialog box where the following parameters may be specified.

- *Time-step* – groundwater model time-step (s). Typically the groundwater time-step may be much larger than the overall model time-step, typical values are 300 - 1,200 sec. The groundwater time-step must be equal to or larger than the overall model time-step, and the overall model time-step must be integer divisible into the groundwater model time-step. During rainfall events, the groundwater model time-step is temporarily changed to the overall model time-step, and then changed back at the end of channel routing and overland flow routing. This switching is handled internally.

- *LSOR direction* – The solution technique currently used to solve the 2-D groundwater free surface flow equations is line successive over relaxation (LSOR) (for example Tannehill, Anderson, and Pletcher 1997). When LSOR is applied, the solution is either

by rows or by columns. The solution should be aligned with the principal direction of saturated groundwater flow. The options are either *Vertical* or *Horizontal*, which indicates that your principal direction of flow is in the vertical direction, along the *y* axis, or in the horizontal direction, along the *x* axis.

- *LSOR convergence* – LSOR is an iterative method. The user must supply a convergence criteria. The criterion is in meters of groundwater head or depth. The default value, 10^{-5}, is typically sufficient for a good solution. Stricter criteria may lead to slower solutions, or nonconvergence.

- *Relaxation* – The relaxation coefficient is used to project the current solution out into the future in an attempt to speed up convergence. A value of 1.0, the default, indicates no projection. Values greater than 1.0 indicate that projections into the future are desired. Values up to 1.5 may speed the groundwater model solution. Typically, a value of about 1.2 provides the fastest solution. Increasing the relaxation coefficient to greater than 1.0 can result in nonconvergence of the solution. If this happens, the relaxation coefficient should be reduced. It is sometimes necessary to reduce the relaxation coefficient to less than 1.0 to obtain convergence of the solution.

- *Leakage rate* – this is the leakage rate ($cm \cdot hr^{-1}$) through the bottom of the aquifer. This is a uniform value that is applied to every cell in the grid. The default value is 0.0.

- *Define initial moisture* – when this option is toggled on, it means you wish to use the values of initial moisture of cells in the unsaturated zone as entered in the mapping table. Otherwise, the default, initial soil moistures in the unsaturated zone are assumed to be the water contents that correspond to soil pressures in equilibrium with the saturated groundwater elevation.

Distributed Parameters

Unlike many of the other distributed parameters assigned to each cell, distributed groundwater modeling parameters are not assigned using the mapping tables and index maps. All distributed parameters for the groundwater model are assigned with the *Continuous Maps...* dialog, selected in the *GSSHA* menu. The values for the continuous maps may be imported as *GRASS* or *Arc/Info* gridded data, may be assigned a constant value, may be assigned from an index map, or may be manually entered using the spreadsheet in the *Continuous Maps* dialog box.

To import any required data, select *Import*, toggle on the gridded data type, *GRASS ASCII grid file* or *Arc/Info grid file*, and then select the name of the file to be imported. To assign values using an index map, select *Index Map -> Array*, and select the name of the index map you wish to use. The *Reclassify Options* may then be used to assign all the necessary groundwater parameters from the assigned Index map or maps. The *Constant -> Array* option may also be used to assign a uniform value of any parameter. Finally, any and all of the values of parameters may be entered or edited manually in the spreadsheet. The distributed parameters that must be entered are:

- *Aquifer bottom* – elevation of the aquifer bottom (m).

- *Water table* – initial values of groundwater elevation (m).

- *GW hydraulic conductivity* – value of horizontal hydraulic conductivity in the saturated zone ($cm \cdot hr^{-1}$).

- *GW porosity* – value of porosity of the saturated media, fraction of voids (dimensionless).

Boundary Conditions

Solution of the 2-D, lateral flow, saturated groundwater equations requires that boundary conditions be assigned to every cell in the grid. A boundary condition map must be created that assigns an integer value representing the boundary condition to every cell.

Boundary conditions are assigned from the Map Module. The coverage is set to *GSSHA Boundary Condition* from the *Coverages* dialog box under the *Feature Objects* menu. Boundary conditions are established from feature points or arcs. The points or arcs are created over the grid cells to assign a boundary, and the type of boundary condition is selected from *Attributes ...* under *Feature Objects* menu. The option of which type of boundary conditions can be assigned as *Attributes...* depends on whether a feature node or arc is selected.

The following boundary conditions can be assigned:

- No-flow
- Regular infiltration cell (no special boundary condition)
- Specified head
- Dynamic flux, well (not currently active in *GSSHA*)
- Stream cell with calculated flux between stream node and groundwater cell
- Stream cell with a specified head
- Static flux (well)

No-flow

This boundary type is typically assigned along the watershed boundary or along portions of the watershed boundary. This boundary condition represents a region where no lateral groundwater flow is permitted. When no-flow arcs are located along the watershed boundary, this is referred to as a groundwater divide. All cells not within the active watershed are no-flow boundary cells. No-flow boundaries are assigned with feature arcs.

General

The general type specifies that the cell is a regular infiltration cell, indicating no special boundary is desired. The general boundary condition is the default option. General boundaries can be assigned with either feature nodes or arcs.

Constant head

A constant head boundary indicates that the groundwater level in that cell remains constant for the duration of the simulation. The value for the head boundary is taken from the initial values assigned with the water table map (See above). Specified heads are normally applied along the watershed boundary where known values of head exist. They may be assigned with either a feature node or arc.

Dynamic well

This boundary indicates that a dynamic, temporally varying, pumping well exists in the cell. They may be assigned with feature nodes. This option is not currently supported by *GSSHA*.

Flux river

This boundary condition indicates that the cell contains a stream node and the flux between the stream node and saturated groundwater below the stream node be calculated based on Darcy's law, as described by McDonald and Harbaugh (1988), allowing an exchange of water between the stream and groundwater during every groundwater update. These boundaries are assigned with feature arcs.

When assigning flux river boundaries to a cell, the thickness of the bed material, *M river* (m), and the hydraulic conductivity of the bed material, *K river* ($cm \cdot hr^{-1}$), must be assigned to the stream network as *Attributes...* to the *GSSHA* coverage. Only trapezoidal stream sections may be specified as flux river boundaries.

Head river

Another possible boundary condition for cells containing stream nodes is a head boundary condition, head river. This boundary condition indicates that for the purposes of the saturated groundwater simulations, the cell will behave as a constant head cell and will not be updated during the saturated groundwater calculations. The value of the head in the cell is set to be the elevation of the water surface in the stream node above the cell. In this case, the stream cell influences the groundwater calculations, but the groundwater calculation does not influence the stream calculations.

Static well

A static well boundary means that the cell will have a source/sink term of constant rate, $m^3 \cdot d^{-1}$. These boundaries are assigned with feature nodes. Select, or create and select, the node where the static pumping well is to be located. Select *Feature Objects -> Attributes*. Select static well from the drop down list and type in the pumping rate in the box labeled *Pumping rate*. Groundwater extractions have a positive sign; injections have a negative sign.

11 SEDIMENT EROSION AND TRANSPORT

Introduction

In *GSSHA* soil erosion, transport and deposition may be simulated on the overland flow plane, and within the stream network, sediment transport may also be simulated if the channel routing option has been selected.

Overland Sediment Routing

Description

Currently, *GSSHA* uses the soil erosion model developed by Kilinc and Richardson (1973), modified by Julien (1995), as implemented in *CASC2D* by Johnson (1997). Sediment discharge by means of overland flow is a function of the hydraulic properties of the flow, the physical properties of the soil, and surface characteristics. The modified Kilinc and Richardson equation is used to determine the sediment transport from one overland flow grid cell to the next. Sediment transport is computed for three grain sizes: sand, silt, and clay. Conservation of mass of sediment is used to determine what portion of sediment in a grid cell is deposited and what portion stays in suspension. The suspended sediment may be exported from one cell to the next. If there is insufficient sediment in suspension, previously deposited sediment is used to satisfy the erosion demand. If there is insufficient previous deposition, then the surface is eroded. See Johnson (1997) for details related to the numerical formulation. Sediment transport as a result of erosion under simulated rainfall is assumed to be related to a number of different variables, which can generally be assigned from index maps related to land use and soil textural classification.

Parameters

To model overland sediment erosion, toggle on *Soil erosion* in the *GSSHA Job Control Parameters* dialog box. If desired, select *Edit Parameters* to assign optional global parameters as described below.

- *Sand size* – average size of sand particles (mm); default value is 0.25 mm

- *Silt size* – average size of silt particles (mm); default value is 0.016 mm

- *Clay size* – average size of clay particles (mm); default value is 0.001 mm

- *Water temp.* – temperature of water on the overland flow plane (°C); default value is 20 °C

Use the index maps and mapping table, as described in Chapter 5, to define the following required distributed parameters.

<u>*Soil erosion properties*</u>

The soil erosion properties are dimensionless fractional factors with values between 0.0 and 1.0.

- *Soil erodibility* – universal soil loss equation (USLE) soil erodibility index

- *Sand percentage* – fraction of the soil that is sand for that cell

- *Silt percentage* – fraction of the soil that is silt for that cell

<u>*Soil erosion factors*</u>

The soil erosion factors are dimensionless fractional factors with values between 0.0 and 1.0

- *Crop management* – USLE crop management factor

- *Conservation practice* – USLE conservation practice factor

Channel Sediment Routing

Description

The present version of *GSSHA* employs Yang's (1973) method for routing of sand-size total load in stream channels. The bed is allowed to erode, but the banks do not. The routing formulation works only with trapezoidal cross sections. Wash load (silt and clay size fractions) is transported with the flow. Any gains or losses of wash load, such as deposition or erosion of silts and clays within the channels, are neglected.

Parameters

Parameters for channel sediment routing are assigned to the stream arcs in the *GSSHA* map coverage by selecting the stream arcs and then *Attributes ....* In the Feature Arc Type dialog box, toggle on *Erodable trapezoidal channel*. In addition to the normal parameters required for stream routing with trapezoidal channels, as defined in Chapter 6, you must define the *Max. Erosion* value. The maximum erosion is the maximum depth of erosion (m) of the channel section assigned to the arc.

12 RUNNING GSSHA

Introduction

GSSHA can be executed from *WMS*, or from the command line, once all of the necessary data to run a *GSSHA* simulation have been defined and a project file saved. The project file, which specifies all parameters, mapping files, and other input and output files, is the only direct input required to run *GSSHA*.

Running GSSHA from WMS

You can launch the *GSSHA* model directly from *WMS* by choosing the Run *GSSHA* command from the *GSSHA* menu. *WMS* will expect that the current executable for *GSSHA* is named *GSSHA*.exe and that it resides in the same directory as the *WMS* executable. If *WMS* cannot find the *GSSHA*.exe file, then you will be prompted to locate the file separately using a file browser.

WMS passes the current project file to *GSSHA,* and you have the opportunity to let *WMS* write the project file prior to launching *GSSHA*. If you have already saved the project file and no changes have been made since saving, it is not necessary to write the project file again. If you have made modifications to your simulation since last saving the project file, you should turn on the toggle box to write the project file before running *GSSHA* so that all changes are saved to the project file.

Running GSSHA from Command Line

GSSHA can also be run from the command line using the project file as the sole command-line argument. For example, from a command prompt window you would type:

> **gssha simulate.prj**

where simulate.prj is the name of the project file saved from *WMS* and resides in the same directory as *GSSHA*.exe. You may also use the Start -> Run command from Windows.

If the project file is not in the same directory as *GSSHA*.exe, you must enter the full path name to the project file (i.e., C:\mysimulations\simulate.prj) in order for *GSSHA* to run successfully. Often it is best to copy the *GSSHA*.exe file to the directory where the project has been saved.

Project File

The project file definition is made up of a series of cards followed by parameter(s) (usually a file name) related to that card. For example, the watershed mask is defined on a single line using the card WATERSHED_MASK followed by the name of the file containing the watershed mask.   The project file informs *GSSHA* which simulation options (e.g., overland flow, infiltration, long-term, etc.) to perform along with all of the necessary parameters required for the desired options. An example project file is shown below:

```
CASC2DPROJECT
WMS 6.1
WATERSHED_MASK          bear2.msk
FLINE                   bear2.map
METRIC
GRIDSIZE                30.000000
ROWS                    61
COLS                    76
TOT_TIME                480
TIMESTEP                5
OUTROW                  41
OUTCOL                  74
OUTSLOPE                0.001000
MAP_FREQ                360
HYD_FREQ                180
MAP_TYPE                2
CHAN_EXPLIC
SED_POROSITY            0.400000
ELEVATION               bear2.ele
DEPTH                   bear2.dep
CHANNEL_INPUT           bear2.cip
LINKS                   bear2.lks
NODES                   bear2.nod
DIS_PROFILE             bear2.qpf
WAT_SURF_PROFILE        bear2.wpf
OVERTYPE                ADE
GREEN_AMPT
MAPPING_TABLE           bear2.cmt
MATERIALS               bear2.mat
SUMMARY                 bear2.sum
OUTLET_HYDRO            bear2.hyd
OUTLET_SED_FLUX         bear2.sed
PRECIP_UNIF
RAIN_INTENSITY          20.000000
RAIN_DURATION           120
START_DATE              1994 1 1
START_TIME              12 0
```

For a complete description of all the cards and their related parameter(s), see the *GSSHA User's Manual* (Downer and Ogden in preparation).

13 POSTPROCESSING

Introduction

GSSHA can produce a variety of outputs for the user. *GSSHA* automatically outputs a run summary file, which has the extension *.sum*, and an outlet hydrograph file, which has the extension *.hyd*. *GSSHA* can also output time series data for a number of variables at any point in the channel network and in the 2-D grid. *GSSHA* can produce a series of maps that can be displayed in *WMS* containing surface depth and/or other results. Once the simulation has been completed, results can be read back into *WMS* for postprocessing. This chapter discusses the different output options available from *GSSHA* and a few of the methods available in *WMS* for viewing these computed results.

Output Control

In *WMS* the output map choices are specified from the *Output Control* dialog accessible only from within the *Job Control* dialog. Since the computational time-step is generally small compared to the overall simulation time, a value representing the time between saving of results data may be defined. This time parameter determines the frequency of writing output raster maps or data sets. The time is measured in units of time-steps. For example: for a computational time-step of 10 sec to output maps every 15 min (900 sec), the *Write Frequency* for maps (and time-steps) would be set to 90. For a total simulation time of 200 min, a data set of 15 maps, each 15 min apart, would be created. There are 15 maps instead of 13, because the values at both the beginning and ending of the simulation are always saved.

Data set map options

The data set map output options are selected, along with the output frequency, with *Write Frequency,* and the type of map to output, with *Type*. The output maps can be a *WMS* data set in binary or ASCII format, or a series of *GRASS* ASCII maps. Since this primer accompanies *WMS*, it will be assumed that the data set option is turned on throughout the rest of the primer.

The different data set maps supported by *WMS* that may be saved for a given simulation include:

- Distributed rainfall intensity ($mm \cdot h^{-1}$)

- Surface depth (m) - displays channel depth in channel cells if channel routing is performed

- Cumulative infiltration depth (m) – (infiltration must be turned on for the simulation)

- Surface soil moisture - soil volumetric water content

- Infiltration rate ($cm \cdot h^{-1}$) - infiltration must be turned on for the simulation

- Channel depth (m)

- Channel discharge ($m^3 \cdot s^{-1}$)

- Volume of suspended sediments (m^3)

- Maximum sediment flux ($m^3 \cdot s^{-1}$)

- Net sediment volume (m^3)

- Groundwater head (m)

Additional maps may be created by specifying the appropriate cards in the project file, as described in the *GSSHA User's Manual*.

Time series data

Time series data from a single channel node or grid cell can be output for a variety of model results.

Channel results at nodes.

Output from individual channel nodes can be requested anytime channel routing is specified. In the *Output Control* dialog, check the set the *Hydrograph write frequency* in time-steps. You may also choose to output the data using the *Strict Julian date,* and you may choose to *Suppress printing* output *to the screen*. Choosing not to output your hydrograph to the screen can significantly reduce run times.

To select the nodes to output time series data, select the grid cells containing the nodes of interest with the Select a Grid Cell tool. This is done while in the 2-D grid module. Under the *GSSHA* menu, select *Cell properties* and assign the cell as either a *Hydrograph cell* or *Sediment location* by checking the appropriate box.

Time series data of depth at any specific node, not currently supported by *WMS*, can also be output as described in the *GSSHA User's Manual* (Downer and Ogden in preparation).

Results at grid cells.

While *WMS* does not currently support output of time series data at individual grid cells, *GSSHA* does have the ability to output the following information at any cell in the 2-D grid. See the *GSSHA User's Manual* for more information.

- Soil moisture

- Groundwater head (m)

- Overland discharge ($m^3\ s^{-1}$)

Visualizing Results

WMS has several different ways to view resulting data sets of a *GSSHA* simulation. These data sets can be read back into *WMS* via the *Import* command from the *Data Browser*. The data browser is accessed from the *Data* menu of the 2-D grid module. After a data set has been imported, individual time-steps may be contoured, animation sequences of the entire (or part) simulation created, and/or a 2-D plot of the data created at any grid location.

Data sets

The *Data Browser*, shown in Figure 23, is used to control which data set and time-step are currently active for contouring. It is also used for importing and exporting of data sets and to view key information about data sets. The data calculator (in the same menu as the browser) may be used to perform numerical operations on data sets. For example, a new data set can be generated as the difference of two computed data sets. This new data set can then be contoured/animated to visualize the difference between two simulations with differing parameters, etc.
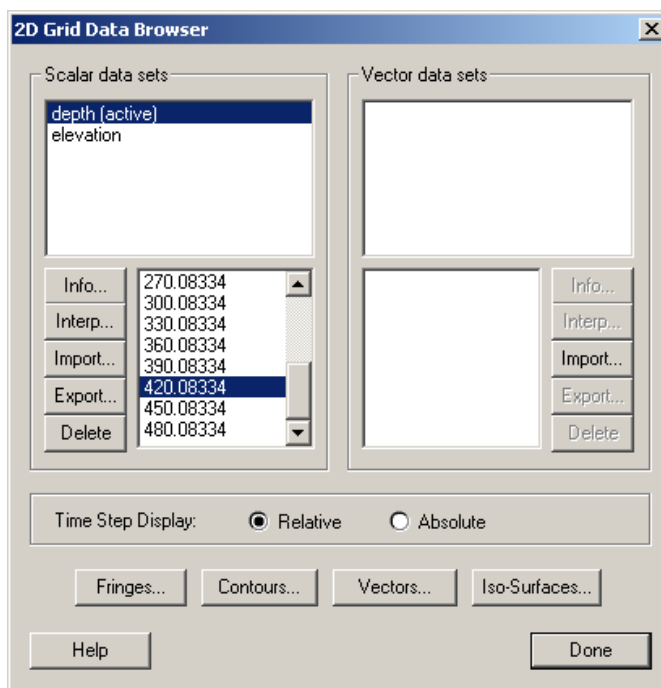

Figure 23. The WMS Data Browser. The data set time series files, the index maps, and continuous maps can be read in and mapped as the current data set through this dialog

Contouring

Turning on the contour option allows any data set to be contoured. Contours can be:

- Single colored isolines

- Variations from dark to full intensity of a specified color (based on magnitude) as isolines or color-filled

- Variations from a blue-to-red color ramp (based on magnitude) as either isolines or color filled

Also, cell fill contouring fills the entire grid cell with the same color according to its computed function value. The *Contour Options* dialog can be used to control all of the different available options. The *Color Ramp Options* is used to specify the coloring scheme of contours and whether or not a legend of values is drawn in the upper left portion of the graphics window. More information on contouring can be found in the *WMS* Reference Manual (Nelson 2001).

Animations

Animation sequences are created in *WMS*'s *Film Loop* dialog using a series of saved images. Prior to running an animation, the *Setup* dialog should be brought up so that the size of images, number of time-steps, and other display parameters can be set. Upon exiting the *Setup* dialog, an image for each time-step of the animation is created. After all images have been created, they can be played back using the VCR-like controls of the *Film Loop* dialog. Animation files may be saved as AVI files so that subsequent runs do not require the setup process but can simply be read into the *Film Loop* dialog or run in any movie playing software.

Gage plots

A virtual gage can be placed at any location of the grid and a 2-D plot of the current output data vs. time created. Data for selected gages are plotted in the hydrograph window. Several different options exist for defining and displaying these plots and are accessible from the *Gage Plot Manager* dialog. An example of gage plotting is shown in Figure 24; as shown, it is possible to plot more than one gage at a time.

Mapping to elevations

An effective way to view any resulting data is to map the result as the grid cell elevations. The results can then be viewed in three dimensions with the "higher" grid cells representing large magnitude results of the mapped data set. Obviously, the grid must be viewed from an oblique projection in order to see variations in elevation. The rotate tool can be used to locate the best viewing position. Typically the magnification factor must be increased in order to exaggerate the function value differences as elevations, as shown in Figure 25.
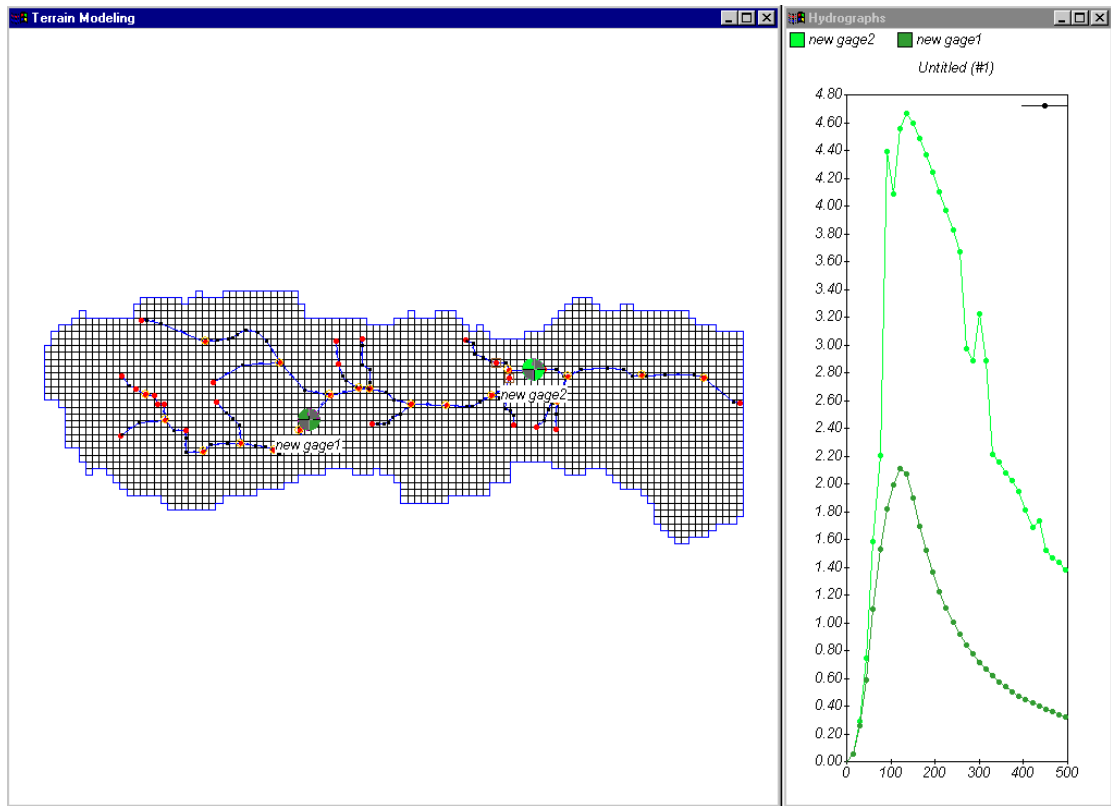
Figure 24. Multiple gage plots. The gages should be placed over the cell(s) for which a data value vs. time plot is to be drawn. When multiple gages are selected they are plotted together
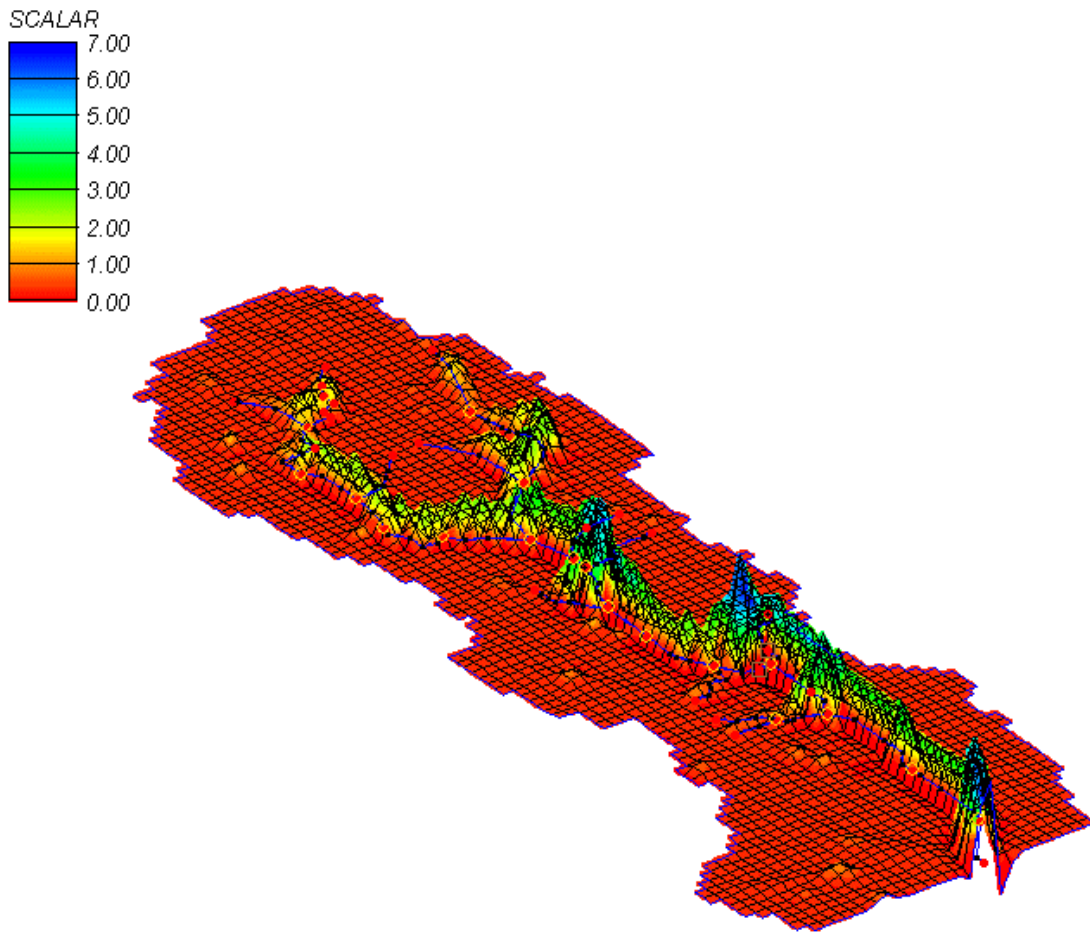
Figure 25. Flow depth mapped and magnified on the 2-D grid

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