RECLAMATION
Managing Water in the West

Improved Flood Frequency Extrapolation Procedures

Using a Physically-Based, Distributed Watershed Model

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Water Resources Services Division
Flood Hydrology Group
Denver, Colorado

January 2005

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Cover Photo: Flow depth map from CASC2D rainfall-runoff model for Arkansas River watershed upstream from Pueblo, Colorado.

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Using a Physically-Based, Distributed Watershed Model

by

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1.0 INTRODUCTION

Estimates of extreme floods and probabilities are needed for hydrologic engineering and dam safety risk analysis. Extreme flood estimates are needed for situations where the reservoir inflow peak discharge is greater than the maximum spillway capacity, the reservoir has a large, carry-over storage, and/or the reservoir has dedicated flood control space. In addition, flood estimates are required in order to evaluate spillway issues and potential seepage from high reservoir levels. Typical extreme flood estimates include peak flow, volume, timing, flood hydrographs, and reservoir levels. Flood hydrographs include peak, volume and timing, and integrate the drainage basin and channel response to precipitation, given some initial, variable state of moisture throughout the watershed. To conduct risk analyses and dam safety evaluations, extreme floods and probability estimates are required (Reclamation, 1999, 2003). In contrast to widely used deterministic design procedures for large dams, such as the Probable Maximum Flood (PMF), methods to estimate extreme floods and their probabilities are not mature (NRC, 1988), and flood frequencies are not well understood (Pielke, 1999). Burges (1998) notes that assessing the adequacy of existing spillways for extreme floods is a major hydrometeorological issue and that critical factors include the complete spatial and temporal descriptions of extreme storms and the associated flood hydrograph.

This research focuses on new methods to estimate extreme floods for dam safety and hydrologic engineering. Physically-based, distributed watershed models are used as an avenue to estimate extreme floods, and as a basis to extrapolate frequency curves. The main elements of this research include improving and using a physically-based rainfall-runoff model to estimate extreme floods and probabilities for dam safety on a large watershed. The test watershed is the Arkansas River above Pueblo, Colorado.

1.1 BACKGROUND

This research project focuses on two areas in flood hydrology to develop tools needed to solve hydrologic problems for the Dam Safety Office. The two areas are extrapolation of flood frequency curves and rainfall-runoff modeling to produce extreme flood hydrographs for reservoir routing. There have been recent attempts to extrapolate frequency curves, such as using the paleoflood and streamflow data/distribution, or rainfall distributions. However, there are no general, reliable methods for extrapolating frequency curves.

Extreme flood hydrographs are needed to estimate floods at most high-risk Reclamation dams. The prescriptive extreme flood hydrograph methods that have been developed to date are based on scaling observed or modeled hydrographs, and do not properly partition snowmelt and rainfall contributions. Storage in channels and reservoirs are not accounted for with these hydrographs. This research is designed to address these problems and provide improved methods for Reclamation Dam Safety risk analysis process.

Extrapolation and hydrograph methods have been investigated under several Dam Safety research projects. Progress has been made to develop interim techniques, and these techniques have been applied to several projects such as Pineview/Deer Creek, Red Willow, North Platte, and Folsom Dams. Internal and external reviewers have pointed out several shortcomings of that work. Extrapolation of frequency curves at Pineview and Deer Creek Dams was based on very simplified assumptions. Other shortcomings include: assumptions of linear runoff and extrapolation, use of observed hydrographs, failure to separate rainfall and snowmelt, and the challenges of using the techniques at larger basins (greater than about 500 mi^2). This research proposal attempts to address some of these concerns.

For Reclamation dam safety risk assessments, flood estimates are needed for AEPs of 1 in 10,000 (1×10^{-4}) and ranging down to 1 in 100,000,000 (1×10^{-8}). Current procedures used by Reclamation to estimate these floods and associated probabilities are described in Swain et al. (2004). The initial approach is to extrapolate a peak-flow frequency curve assuming a two-parameter log Normal distribution fit through the 100-year peak flow and paleoflood data (Figure 1-1). The PMF is currently recognized as a practical upper physical limit to flood frequency extrapolations (Reclamation, 2002). Reclamation uses the PMF as the upper limit of flood potential at a site for storm durations defined by the PMP (Swain et al., 2004).

One of the problems with the current approach is the distribution assumption used for peak-flow extrapolation. The peak discharge estimate for a given probability may be substantially underestimated or overestimated; the results may potentially impact a risk analysis that uses the flood frequency information. Hypothetical examples for these situations are shown on Figure 1-1. Instead of using a simplified method and statistical function for extrapolation, this research focuses on the use of a physically-based, distributed approach to derive the peak-flow frequency curve. Ramirez et al. (1994) state that the distributed approach provides a better insight of flood processes within the catchment. The CASC2D model (Julien and Saghafian, 1991; Julien et al., 1995; Ogden and Julien, 2002; Rojas-Sanchez, 2002) is used in this research. Cotton et al. (2003, p. 131) recognized the potential of CASC2D to simulate runoff from extreme storms: "Our simulations of extreme precipitation events conclude with rainfall on the ground. But the destructive power of those events is dependent upon the local topography, land-use, soil wetness, and vegetation. Thus it would be desirable to interface RAMS with a runoff/routing model such as CASC2D to explicitly represent runoff and streamflow associated with extreme precipitation events."

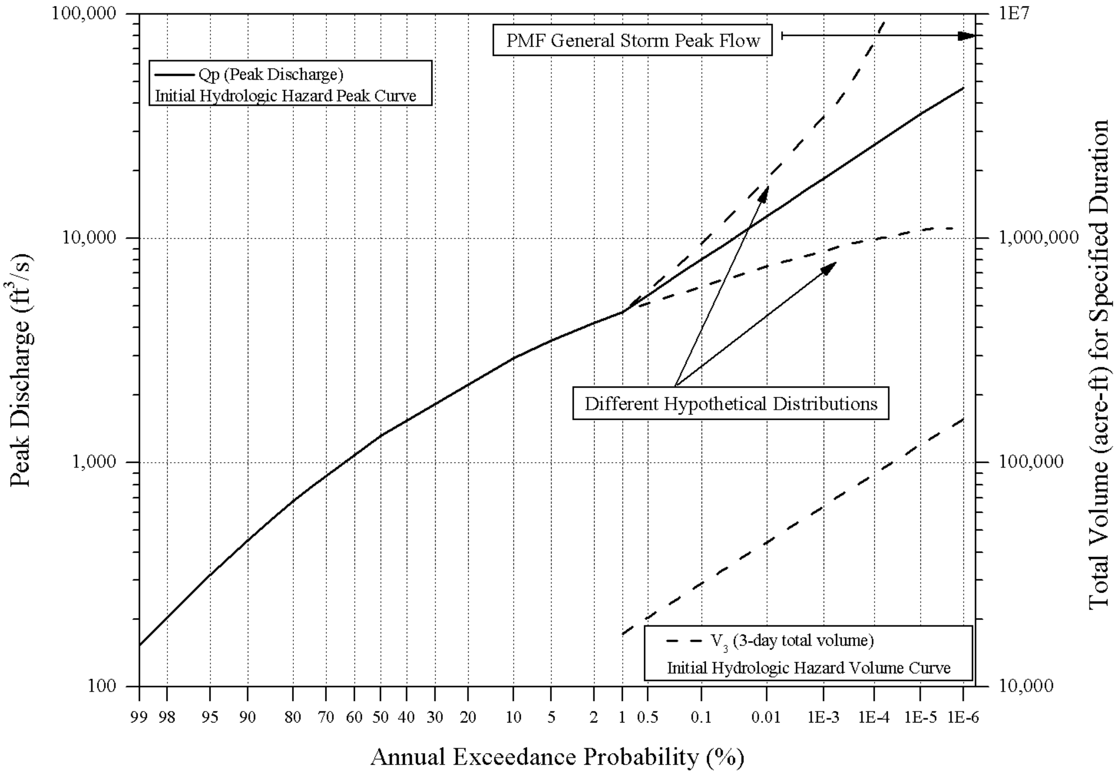


Figure 1-1. Example hydrologic hazard curve (after Swain et al. 2004). Different hypothetical extrapolation assumptions are shown.

1.2 OBJECTIVES

The purpose of this research project is to develop improved methods to extrapolate flood frequency curves and develop extreme flood hydrographs. The major approach to flood frequency extrapolation will be based on a combination of rainfall extrapolation and derivation from physically-based runoff mechanisms. Rainfall-runoff models will be used to derive the peak discharge frequency distribution from input basin characteristics and precipitation, and be used as the basis for frequency curve extrapolation. The CASC2D rainfall-runoff model will be evaluated and tested for application at Reclamation sites. CASC2D is a 2-dimensional, distributed rainfall-runoff model that has successfully reproduced the 1997 Fort Collins flood (Ogden et al., 2000). The main precipitation, snowmelt and stochastic components that have been recently developed will be added to CASC2D. It is anticipated that model selection and extrapolation functions can be derived from the watershed topography, hydraulic routing characteristics, and precipitation characteristics at specific sites. Input rainfall will be derived from frequency analysis or from stochastic storm generation. Flood frequency and hydrograph uncertainty bounds will be approximated by simulation. The model will be demonstrated for Pueblo Dam, Colorado, a large (4,600 mi^2) basin where paleoflood data are available.

1.3 DELIVERABLES

The major deliverables include this report and computer software. Software deliverables include CASC2D and ancillary support programs/macros, with modifications.

2.0 DERIVED FLOOD FREQUENCY FRAMEWORK

The idea and basis for using CASC2D for extreme flood modeling and prediction is centered on two concepts: (1) a derived distribution approach (e.g., Eagleson, 1972) can be used to estimate the extreme flood peak and volume probability distributions; and (2) physically-based methods for flood runoff and routing provide a suitable and improved physical basis for the extrapolations of derived flood probability distributions. Ramirez (2000) summarizes the theory behind the derived distribution approach. In the disciplines of science and engineering, relationships that predict the value of a dependent variable in terms of one or many basic (independent) variables are commonly developed. Physical systems are naturally complex. The functional form of the relationship between independent and dependent quantities, or values of the independent variables (or both) is not usually known with certainty. Techniques based on probabilistic assumptions can be used to account for this uncertainty. When the uncertainty derives from uncertainty in the independent variables, but not from uncertainty in the functional dependence, a derived distribution approach leads to the probability density function (PDF) of the dependent variable. In this case, the functional form relating independent and dependent variables is assumed known with certainty. In such instances, it is possible to derive the PDF of the dependent variable(s) from that of the independent variable(s) (Ang and Tang, 1975).

There are several research applications using the derived distribution approach to estimate flood frequency curves; these show much promise. The pioneering study for flood frequency is Eagleson (1972). Bras (1990) discusses some of the potential applications of derived distributions in hydrology. There has been a resurgence in derived flood frequency methods over the past several years, as shown by some recent publications. Gottschalk and Weingartner (1998) derived peak flows from rainfall and unit hydrographs. Hashemi et al. (2000), using a monte carlo derived distribution approach, show some major factors, such as the probability distribution of initial soil moisture at the storm arrival time, affect flood frequency curves. Menabde and Sivapalan (2001) explored scaling issues and the flood frequency curve, and showed that storm duration, time of concentration, rainfall spatial variability and relative contribution of direct runoff were important. Rulli and Rosso (2002) used a space-time stochastic rainfall model and a distributed runoff model to predict flood frequency curves. Loukas (2002) described recent research on derived distributions and flood frequency, and demonstrated a method to estimate flood frequency curves for ungaged small to medium watersheds in British Columbia. Jothityangkoon and Sivapalan (2003) demonstrated the importance of channels and floodplain processes when deriving flood frequency curves.

In order to model extreme floods on a large watershed, it is hypothesized that the basin response is dominated by the following major factors:

- infiltration excess (Hortonian) overland flow;
- storm precipitation: spatial and temporal distribution, duration, movement/direction;
- drainage and channel network;
- snowmelt during storm; and
- antecedent conditions/wetness.

The framework to estimate flood frequency with CASC2D for large watersheds is based on four main criteria:

1. the CASC2D model will be used to compute runoff;
2. the Annual Exceedance Probabilities (AEPs) of interest range from about 1/1,000 to 1/10,000, and may extend perhaps even to 1/500,000;
3. storm characteristics, including duration, timing and areal distribution can be included; and
4. mixed-population effects are simulated.

These considerations are based on identified large watershed research issues and practical questions. As CASC2D is an event model, initial conditions are also included in the criteria.

The proposed procedure that will be used is a hydrologic simulation using monte-carlo (MC) methods (e.g., Bocchiola et al., 2003) coupled with the stochastic storm transposition (SST) technique (Foufoula-Georgiou, 1989) to estimate extreme rainfall probabilities. The procedure is based on the stochastic storm transposition and runoff approach used by Franchini et al. (1996) with some modifications. This approach is outlined by NRC (1988, p. 5), in their "Method III":

1. construct a stochastic mathematical model of extreme rainfall (in space and time);
2. generate several large synthetic storms from model;
3. model deterministic rainfall-runoff transformation; and
4. produce approximate probability statements for resultant large flood hydrographs.

One major input to a derived distribution approach is the method to generate extreme storms and associated probabilities. Stochastic storm transposition (SST) is an alternative method to station-based rainfall analyses. NRC (1994) reviewed approaches to estimating Probable Maximum Precipitation (PMP) in the United States. They noted the conflict between storm-based and station-based analyses, and that current PMP techniques are based on storm analyses. In looking at alternatives to PMP, NRC (1994) recommended pursuing the stochastic storm transposition procedures (e.g., Fontaine and Potter, 1989; Foufoula-Georgiou, 1989). They noted that these techniques are not mature. There has been some limited progress and applications in this area over the past 10 years. Bradley and Potter (1992) utilized the technique to expand storm samples for flood frequency simulation in the Midwest. Franchini et al. (1996) extended the technique to focus on design flood estimation, by including stochastic descriptions of antecedent moisture and storm temporal distributions. Agho et al. (2000) focused on the problem of regional homogeneity for SST, and developed a nondimensionalized approach to overcome statistical nonhomogeneity of depth exceedance probabilities. However, there are many unresolved questions with developing SST concepts and applying the method. Little research and virtually no practical work has been done with SST since the recommendations made by NRC (1994). There has not been a published case of using SST to estimate extreme storms and resultant floods for a real watershed, and demonstrating the subsequent impacts to dam safety. The only storm data that have been analyzed and probability estimates made are for a 9-state Midwest U.S. region (Foufoula-Georgiou and Wilson, 1990; Wilson and Foufoula-Georgiou, 1990). Fontaine (1989) and Fontaine and Potter (1993) did briefly demonstrate the task of computing flood probabilities for a 570 km^2 site in Wisconsin, and note there is much work to be done prior to routine application.

Stedinger et al. (1993, p. 18.52) noted that the SST methodology has been developed for very low frequency rainfall (exceedance probabilities less than 1/1,000). Wilson and Foufoula-Georgiou (1990) demonstrate average catchment depth probability curves with AEPs that range from 10^{-3} to 10^{-9}.

The essential elements of the approach that will be implemented here are as follows. The stochastic model of extreme rainfall is the SST method described in Foufoula-Georgiou (1989) and Wilson and Foufoula-Georgiou (1990). The maximum areally averaged depth that can occur over a catchment of area A_c during a time period Δt is estimated via:

$$\bar{d}_c(\Delta t)=\frac{1}{|A_c|}\int_{Ac}\int\left[d(x,y,t_s+\Delta t)-d(x,y,t_s)\right]dxdy \quad \text{(2-1)}$$

where d_c is the maximum areally-averaged depth, (x,y) are spatial coordinates and t_s is related to the storm duration. The annual probability of exceedance of the maximum average depth is:

$$G^a(d)=1-\sum_{\nu=0}^{\infty}\left[F_{d\bar{c}(\Delta t)}(d)\right]^{\nu}\cdot pr\left[Z(1)=\nu\right] \quad \text{(2-2)}$$

where $Z(1)$ is the random number of extreme storms per year. The exceedance probability of peak flow Q_p can be derived numerically via (Franchini et al., 1996):

$$\begin{aligned} G(q)=1-\int_{\Omega}\int_{Wo}\int_{\Psi}\int_{T(t)} pr\left[Q_p\leq q|\omega,w_o,\psi,\tau(t)\right] \\ \times f_{\Omega}(\omega)f_{Wo}(wo)f_{\Psi}(\psi)f_{T(t)}(\tau(t))\,d\omega\,d\omega_o\,d\psi\,d\tau(t) \end{aligned} \quad \text{(2-3)}$$

where Ω is the vector of storm characteristics and locations, W_o is the initial storage condition, Ψ is the vector of runoff model properties, and $T(t)$ is the temporal distribution of storm depths. The random parameters for each vector, as well as fixed parameters, will be determined based on data analysis following Foufoula-Georgiou and Wilson (1990), Wilson and Foufoula-Georgiou (1990) and Franchini et al. (1996).

3.0 A PHYSICALLY-BASED DISTRIBUTED WATERSHED MODEL

3.1 CASC2D OVERVIEW

CASC2D is a fully-unsteady, physically-based, distributed-parameter, raster (square-grid), two-dimensional, infiltration-excess (Hortonian) hydrologic model for simulating the runoff response of a watershed subject to an input rainfall field for a particular storm event (Julien and Saghafian, 1991; Julien et al., 1995; Ogden and Julien, 2002). Major components of the model include: rainfall interception, infiltration, surface and channel runoff routing using the diffusive wave method, soil erosion and sediment transport. The Green and Ampt (1911) equation is used to represent infiltration:

$$f = K_s\left(1 + \frac{\Psi_f M_d}{F}\right) \quad \text{(3-1)}$$

where f is the infiltration rate, K_s is the hydraulic conductivity at normal saturation, Ψ_f is the capillary pressure head at the wetting front, M_d is the soil moisture deficit equal to $(\theta_e - \theta_i)$, θ_e is the effective porosity equal to $(\phi - \theta_r)$, ϕ is the total soil porosity, θ_r is the residual saturation, θ_i is the soil initial moisture content, and F is the total infiltration depth.

Overland flow is estimated in two dimensions via the continuity equation:

$$\frac{\partial h}{dt} + \frac{\partial q_x}{dx} + \frac{\partial q_y}{dy} = i \quad \text{(3-2)}$$

where h is the surface flow depth, q_x and q_y are unit flows in the x- and y-directions, and i is the net rainfall intensity. The momentum equation for the x-direction, using the diffusive wave approximation, is:

$$S_{fx} = S_{ox} - \frac{\partial h}{\partial x} \quad \text{(3-3)}$$

where S_{fx} and S_{ox} are the friction and bed slopes, respectively. A general depth-discharge relationship is used, assuming Manning equation holds:

$$q_x = \alpha_x h^{\beta} \quad ; \quad \alpha_x = \frac{S_{fx}^{1/2}}{n} \quad ; \quad \beta = 5/3 \quad \text{(3-4)}$$

where n is the Manning coefficient.

Channel flow is estimated in one dimension using the diffusive wave approximation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l \quad \text{(3-5)}$$

where A is the channel flow cross-sectional area, Q is the total channel discharge, and q_l is the lateral inflow rate to the channel. Q is estimated using the Manning equation with the friction slope S_f.

CASC2D is appropriate for simulating extreme floods and physically-based extrapolations of frequency relationships, combined with a derived distribution approach. CASC2D is a fully distributed model and uses hydraulic principles for runoff generation and routing precipitation excess. CASC2D is also a somewhat experimental model that has not been used in extreme flood applications for dam safety, or for many applications outside academic research. Ogden and Julien (2002, p. 108) note that the appropriate and acceptable range of application of the model has not been established.

The basic components of CASC2D are described in Julien and Saghafian (1991), Julien et al. (1995) and Ogden and Julien (2002). The major model components of interest for this research are rainfall, infiltration, overland flow routing, and channel flow routing, and are summarized in Table 3-1. The model requires four main parameters for each grid cell, and one parameter for each channel segment (Table 3-1). The CSU version of CASC2D, recently updated by Rojas-Sanchez (2002), is used here. It is classified as an event model as it simulates the Hortonian (overland flow) surface watershed response from a single storm with no soil infiltration capacity recovery between events.

Table 3-1: A Summary of Major CASC2D Model Processes Considered

Process Name	Process Description/Mechanism	Parameters
Rainfall	Single or multiple rain gages; constant temporal interpolation; spatially uniform or inverse-distance squared spatial interpolation	none
Infiltration (Overland Plane)	Green and Ampt (1911) equation, explicit formulation (Li et al., 1976)	soil saturated hydraulic conductivity *Ks* capillary pressure head at wetting front *Hf* soil moisture deficit *Md*
Overland Flow Routing	Diffusive wave equation (Julien, 2002) in two dimensions (x,y) for each grid cell, explicit finite difference formulation	Manning n_{ov} (geometry estimate includes cell size *W* and depression storage depth)
Channel Flow Routing	Diffusive wave equation (Julien, 2002) in one dimension (defined along channel segment path), explicit finite difference formulation	Manning n_{ch} (geometry estimates includes width, bank height, slope, length, sinuosity, and dead storage depth)

As part of this research, the CASC2D model has been completely rewritten. A listing of the computer code functions for the program and a basic input description is attached as Appendix A. A procedure to estimate model inputs via a Geographic Information System is described in Appendix B.

3.2 CASC2D ENHANCEMENTS

This section describes enhancements to particular model features. As noted above, CASC2D is primarily a research model. The applications have been limited to relatively “small” watersheds and have been completed by researchers at universities. It has not been used outside these environs except for limited small-watershed research applications by the U.S. Army. The proposed enhancements are intended to expand the capabilities of the model to simulate extreme floods and flood frequency. The goal is to have a practical and tested alternative to the current watershed models used to simulate extreme floods in the western United States.

The CASC2D components that have been modified, tested and enhanced as part of this research are summarized in Table 3-2. Each component is then discussed in detail below. Data pre-processing tools that have been developed as part of this research are listed in Appendix C.

Table 3-2: New Features and Improvements to Existing CASC2D Model Processes

Process/Model Component	Existing CASC2D Model	New Features, Improvements and Testing
Rainfall	Single or multiple rain gages; constant temporal interpolation; spatially uniform or inverse-distance squared spatial interpolation	Temporal interpolation for all rainfall inputs and options: linear. Spatial interpolation for rain gages: generalized inverse distance with radius of influence. New Design Storm (PMP) input: spatially uniform within user-defined sub-areas. Re-implement radar input: rainfall rates defined from radar file; nearest neighbor spatial interpolation. New Observed Extreme or Stochastic Storm Estimate: input as average depth and distribute in time using specified hyetograph and in space with user-entered elliptical parameters; or separate storm generation model that provides input CASC2D rainfall rate grids for watershed at specified intervals.
River Channels	Channel segments connect in x or y direction. Floodplain option (Julien et al., 1995) not in current software version and has not been tested with extreme floods.	New topology to allow channel connectivity in eight directions (includes diagonals). Re-implement floodplain connectivity, new definition for floodplain interaction, and test for extreme floods. New semi-automated processing routines for developing: channel connectivity model input information (links and nodes); spatially-varying channel geometry for each node; channel grid cell checking and optional modification of elevations at flat nodes.
Initial Conditions	Initial water depth in overland plane.	New explicit declaration and input of: initial water depths in both overland plane and channel segments; initial soil moisture content.
Distributions for Process Parameters and Inputs	None.	New ability to specify distributions of Manning *n* and infiltration parameters for use in a monte carlo framework.
Snowmelt	None.	New snowpack and snowmelt model process.

3.2.1 Rainfall Inputs

In order to successfully model large watersheds using CASC2D, and within a practical hydrologic engineering framework, additional rainfall techniques need to be added to the model. These include modifying the rain gage spatial interpolation algorithm, re-implementing use of radar data, and including design storm and stochastic storm techniques.

The existing CASC2D inverse-distance squared spatial interpolation algorithm is modified to a more flexible inverse-distance weighting (IDW) approach. Two changes are made: introducing a user-defined exponent (or power) parameter instead of a strict value equal to 2, and adding a radius of influence parameter. The general spatial interpolation problem described here is based on Tabios and Salas (1985) and Salas et al. (2002). We define rainfall gage coordinates in a regular grid as x_j and y_j. The rainfall process at this gage *j* is defined as h_j,where the number of rain gages (*n*) is defined by $j=1, 2, \ldots , n$. An estimate of the rainfall process (rate or depth) is defined as h_o at any point in space (x_o, y_o). This process h_o can be estimated by a weighted linear combination of the observations via:

$$h_o=\sum_{j=1}^{n} w_j h_j \quad (3\text{-}6)$$

where w_j is the weight of rainfall gage *j*. This weight is a function of the distance d_{oj} between h_o and h_j,. CASC2D uses a straight-line distance estimator:

$$d_{oj}=\sqrt{(x_o-x_j)^2+(y_0-y_j)^2} \quad j=1, \ldots , n \ (3\text{-}7)$$

The weight w_j for station h_j is (Tabios and Salas, 1985):

$$w_j=\frac{f(d_{oj})}{\sum_{i=1}^{n} f(d_{oi})} \quad (3\text{-}8)$$

where $f(d_{oj})$ represents a function of the distance d_{oj} between the estimation point h_o and the gage point h_j. The new power function that is implemented in CASC2D is:

$$f(d_{oj})=\frac{1}{d_{oj}^{\alpha}} \quad (3\text{-}9).$$

Common values for α are 1, 1.5 and 2. Simanton and Osborn (1980) tested α values from 0 to 4.0 for summer thunderstorm rainfall and recommended using 1.0 in areas where air-mass thunderstorms dominate. If α is 1, the function is known as reciprocal distance, and if α is 2, it is called the inverse distance squared method. If higher values of this exponent are used, less weight is given to gages at increasing distance from the estimate point h_o. A restriction is placed on d_{oj}. We define a radius of influence parameter r_{max} to be the maximum distance between the point of interest (x_o, y_o) and the gage location (x_j, y_j). If d_{oj} is less than r_{max}, this gage is considered in the weighting calculations. Otherwise, the gage is excluded as w_j is zero. This parameter allows one to model partial-area rain storm cases directly with one or more rainfall gages covering discrete areas of a watershed.

A related approach is implemented for spatial interpolation of radar data. Instead of the inverse distance, a restricted nearest neighbor approach is implemented. As a point interpolator, the Theissen method is essentially a proximal or nearest distance neighbor technique (Salas et al., 2002). To interpolate radar data, the simple technique is to search over all radar grid locations and map the rainfall process value from the nearest distance location to the CASC2D grid cell center. First, equation 3-7 is used to obtain the distance d_{oi} from each radar pixel (x_j, y_j) to the grid cell location (x_o, y_o). We then determine the distance $d_{oi} = min(d_{o1}, \ldots , d_{on})$, and subject it to the following restriction:

$$\begin{aligned} d_{oi} &= d_{o1} \quad for\ d_{o1} \leq r_{max} \\ d_{oi} &= 0 \quad otherwise \end{aligned} \qquad (3\text{-}10).$$

The weights in (3-6) are estimated for the case where $d_{oi} < r_{max}$ from:

$$\begin{aligned} w_j &= 1 \quad for\ j = i \\ w_j &= 0 \quad for\ j \neq 1 \end{aligned} \qquad (3\text{-}11).$$

This technique is used because the radar data are specified as an intensity or depth over a fixed area (typically a square grid cell). The radar cell geometry (size and orientation) can be different than the CASC2D model grid. A restricted nearest neighbor interpolator allows one to easily handle these geometric discrepancies in a straightforward manner, and handle cases when the input radar grid does not cover the entire watershed.

A new design storm method is added to CASC2D in order to effectively simulate PMP design storms. When estimating PMP for a particular watershed, the standard procedure is to determine an average rainfall depth for a specified duration over the entire watershed. A design storm is then estimated by distributing this depth in time using alternating blocks with the maximum at the 2/3 point, and in space using successive subtractions for subbasins (Cudworth, 1989). The PMP storm is entered into CASC2D using an index grid map of subbasins and a rainfall time series for each subbasin. A subbasin index grid map consists of integer values denoting the location of each subbasin ($i = 1, \ldots, nsubbasins$) in the watershed. A rainfall time series is entered for each subbasin i and the rainfall rate is applied uniformly over that subbasin.

A stochastic design storm method is added to CASC2D in order to use depth-area-duration (DAD) data from an existing extreme storm catalog (USACE, 1945-) and to simulate extreme storms. The general storm spatial geometry used is that of "standard" design elliptical patterns and storm orientation (Hansen et al., 1982), including variations for ellipse parameters and area relationships (Foufoula-Georgiou, 1989; Wilson and Foufoula-Georgiou, 1990). The DAD inversion procedure described by Fontaine and Potter (1989) will be implemented. Temporal distributions will be estimated from existing storm mass curves, by comparisons with rainfall gage data, and resampled from 6-hour amounts (e.g., Huff, 1967; Hansen et al., 1982) or modeled (e.g., Koutsoyiannis and Foufoula-Georgiou, 1993) to capture temporal variability.

3.2.2 Channel Improvements and Floodplain Interactions

Several improvements are made to CASC2D to enhance the modeling of channels on large watersheds. These include changes to topology, floodplain modeling, and new data processing techniques. Channels are segments that connect from overland grid cell center to grid cell center, and represent rivers or creeks in a watershed. The location of channel cells within the DEM is typically determined from stream network generation techniques within a GIS. The tools of choice to estimate locations of channel cells and the stream channel network in this research are ArcGIS/ArcInfo 8.3 (ESRI, 2003) and Tarboton (2002).

One of the most difficult aspects of using CASC2D on large watersheds is the development of connectivity relationships required for modeling channels. In order to model channels, the user first specifies a stream network that defines the location of cells that contain channel segments. The topology of this network is then used to specify two maps to CASC2D that contain the connectivity information. The first map is called a “link” map and contains a grid of integers that denote channel locations for each grid cell within the watershed, and how each channel segment or “river reach” is connected to another. Link segments follow current GIS connectivity rules for flow modeling in eight directions (D8) from a grid (Tarboton, 2002). A “node” map is derived from a link map and contains integer numbers that designate the connectivity between each grid cell (and thus flow direction) within an individual link. For example, if a link contains five grid cells, these cells are numbered 1, 2, 3, 4, and 5 for that link. Example link and node maps are shown in Figures 3-1a and 3-1b, respectively. CASC2D input pre-processing routines that automate development of channel connectivity model input information (link and node maps) have been developed as part of this research and are listed in Appendix C.

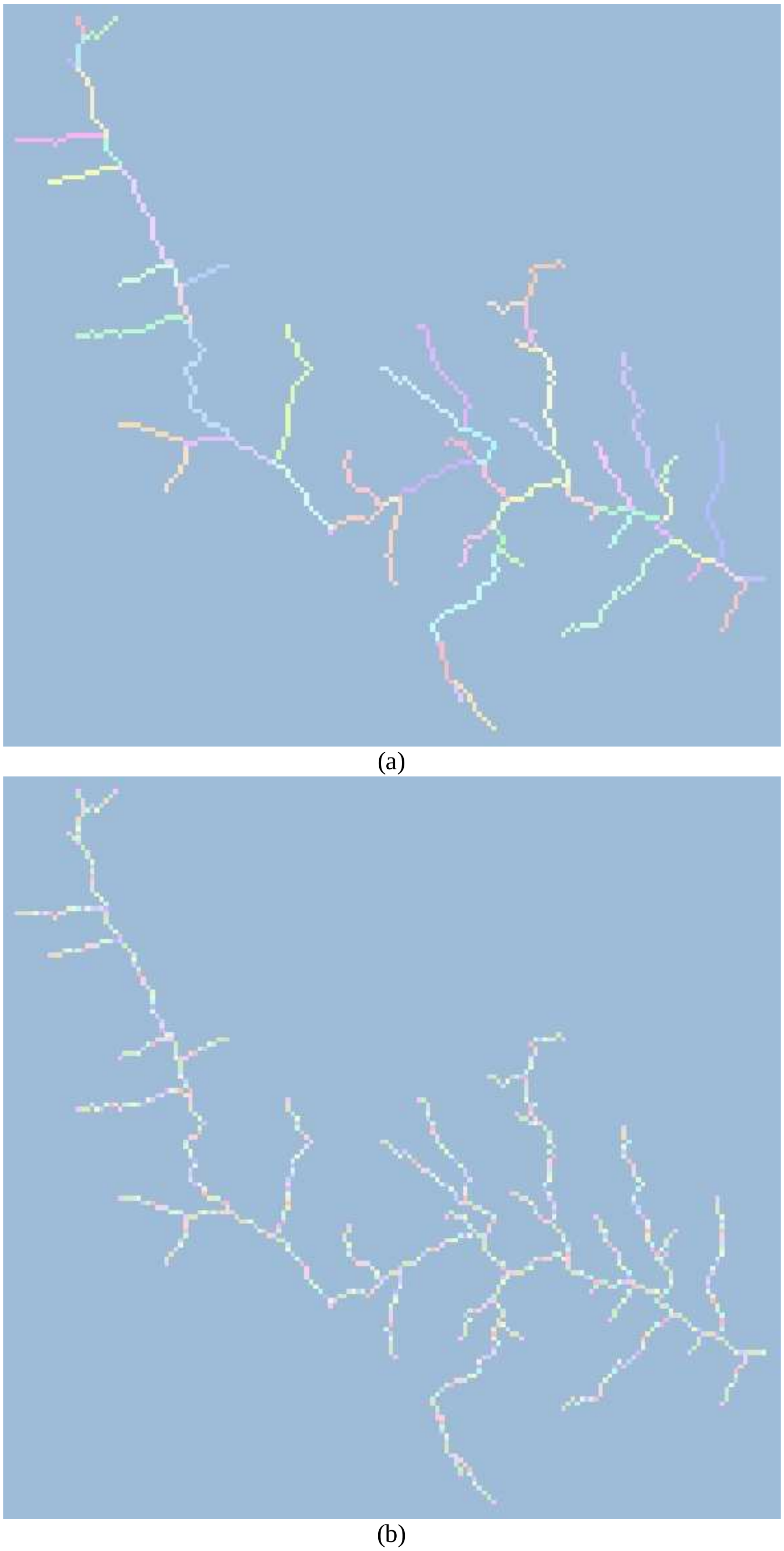


Figure 3-1: Example link map (a) and node map (b) for modeling channels in the Arkansas River basin. Grid cell size is 960m.

The new topology feature that is required for modeling large watersheds is the ability for channel segments to be connected in eight directions. The current version of CASC2D only supports channels connected in north-south or east-west directions. One can readily observe that many channel cells are connected on diagonals within the Arkansas River basin (Figure 3-1). The CASC2D topology routine is modified to directly use information from a flow direction grid. The flow direction grid is defined by TauDEM (Tarboton, 2002). Flow directions (1-8) are defined counter-clockwise from the east: 1: East, 2: Northeast; 3: North, 4: Northwest; 5: West, 6: Southwest, 7: South, 8: Southeast (see Figure 3-2).

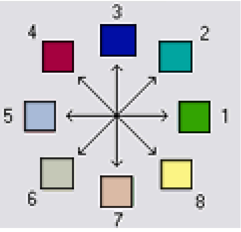


Figure 3-2: Flow directions as defined by Tarboton (2002) in TauDEM.

One important process in modeling large watersheds is the floodplain connection between overland cells and channel sections. CASC2D originally had the ability to model floodplains (Julien et al., 1995). This process has been re-implemented in the current version with some modifications. It will then be used for extreme flood modeling. The relative importance of this floodplain process, as compared to other factors, will be evaluated. The major assumption in modeling floodplain connectivity with the adjacent overland portion of the grid cell is the enforcement of an equal water surface elevation in the channel and overland plane sections of the grid cell (Julien et al., 1995). CASC2D was expanded to handle three cases:

1. overland water surface elevation > channel water surface elevation
    a. channel water depth < bank height
    b. channel water depth >= bank height
2. channel water surface elevation > overland water surface elevation (channel flow depth always greater than bank height)
3. overland water surface elevation = channel water surface elevation (no water transfer)

These cases are handled by first comparing water surface elevations, then computing water volumes in the overland and channel portions, respectively. For example, in the case where the channel is dry and water is on the overland plane, the volume in the overland plane is computed. If this volume is less than or equal to the available volume in the channel section, all flow is transferred to the channel. If there is insufficient volume available in the channel to hold the entire overland flow volume, the volume is then proportioned between the overland and channel segments. The original floodplain process code only redistributed water from the channel back onto the overland portion of the cell for case 2, and performed the calculation based on flow depth.

Another difficult aspect of modeling channels in large watersheds with CASC2D is estimation of channel geometric properties and parameters. The geometric properties can include base width, bank height, sideslope, dead storage depth, and channel sinuosity; parameters include Manning *n.* Bed slope is determined from the DEM elevation at each grid cell and subtracting the bank height. Channel length is determined by multiplying the channel segment length (*w* or *1.414*w*, where *w* is the grid cell size) times the sinuosity. A cross section of an example channel cell and required geometry is shown in Figure 3-3. The current version of CASC2D allows trapezoidal cross sections; these can include regular trapezoids, rectangles, or triangles.

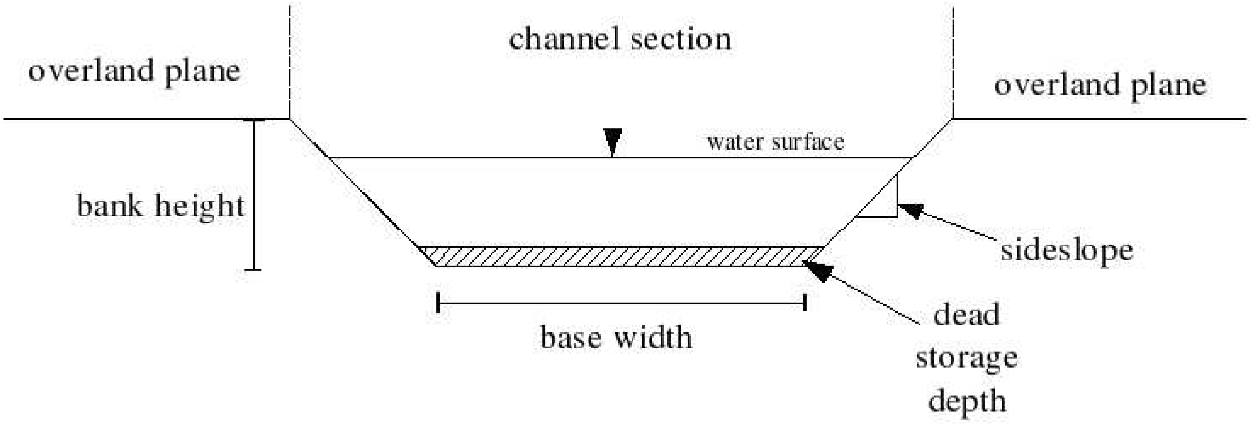


Figure 3-3: CASC2D channel cross section with user-input dimensions: base width, bank height, sideslope, and dead storage depth.

When one models large watersheds, it is a challenge to define these properties for every channel link and node. In order to model the Arkansas River watershed using 960m grid cell sizes, there are 764 cells that have channel segments in them out of the 12,879 total cells within the watershed. Semi-automated techniques are needed to define channel properties on this many channel nodes. A tool has been developed to estimate channel properties, including spatially uniform, uniform within a link, and spatially varying properties from node to node options (Appendix C). The Arkansas River watershed may also be modeled using 150m grid cell sizes. In that case, there are 527,524 cells within the watershed, and channel properties need to be defined for 5,341 cells with channel segments. It is infeasible to do this without developing semi-automated tools. In addition to channel properties estimation, a tool is developed that enables channel grid cell elevation and thalweg profile checking and optional modification of elevations at flat nodes. One of the critical pre-processing steps that must be done when using CASC2D is developing a relatively accurate and error-free grid mesh. The CASC2D model predictions are entirely dependent on and reflect the cell sizes and elevations of the grid mesh.

3.2.3 Explicit Initial Conditions Specifications

One crucial feature for simulating extreme floods with an event model such as CASC2D is the estimation and specification of initial conditions. Differing initial conditions can sometimes have a dramatic effect on model predictions. One new feature that has been added to CASC2D as part of this research is the explicit capability to specify three important initial states:

1. the initial depth of water on the overland plane cells within the watershed;
2. the initial depth of water in channels; and
3. the initial soil moisture.

The initial soil moisture is now entered as a spatially-varying grid and expressed as a saturation fraction S_e, where $0 \le S_e \le 1$ (e.g., Saghafian, 1992; Rawls et al., 1993). The Green-Ampt soil moisture deficit M_d is then determined by:

$$M_d = \theta_e (1 - S_e) \quad (3\text{-}12).$$

The program requires the user to input values for these three states prior to running CASC2D. Initial water depths on the overland plane and in the channel are entered directly. Initial soil moisture is also a direct user input. The initial soil moisture and the initial water depths in overland planes can play an important role in predicted runoff volume and peak for extreme floods (e.g., Goldman, 1987; Goldman et al., 1990; Fontaine and Potter, 1993; Franchini et al., 1996; De Michele and Salvadori, 2002).

3.2.4 Snowmelt Model

The proposed method to model snowmelt with CASC2D is a simple temperature-index approach with melt spatially distributed based on elevation and radiation. The goals of the snowmelt model are to: include melt volume from an initial, deep, ripe snowpack; predict melt from the pack; and add the melt to each cell for runoff at each time step. The main state variable is snow-water equivalent (SWE). This new snowmelt capability will add flexibility to CASC2D so that one can model extreme floods that have a snowmelt component. The main factors that contribute to snowmelt on large watersheds are: (1) the area of snow cover; (2) the initial snow depth (expressed as SWE); and (3) the snowmelt rate.

The proposed snowmelt approach consists of four components: data and analysis, a point snowmelt model, a point temporal disaggregation model, and a spatial interpolation model. The data that will be used are from the Natural Resources Conservation Service (NRCS) SNOTEL and snow course sites, and snow cover grid maps from the National Operational Hydrologic Remote Sensing Center (NOHSRC). The SNOTEL data consist of daily SWE and temperature minima and maxima. Snow course data (end of month SWE) will be used to supplement the SNOTEL data. Snow cover grid maps will be used to determine snow-covered areas within the watershed. The point snowmelt model approach that will be used is that from Julien and Frenette (1986) and Julien (2002). Here, the cumulative snowmelt (SWE) will be estimated at each SNOTEL site using a power function:

$$h_s = \alpha_f t_f^{\beta_f} \quad (3\text{-}13)$$

where h_s is the cumulative snowmelt in meters, t_f is the cumulative snowmelt time and α_f and β_f are model parameters. The cumulative distributions of daily snowmelt may potentially be approximated with an exponential distribution:

$$F(i_f) = 1 - e^{-\lambda_f i_f} \quad \text{(3-14)}$$

where i_f is the snowmelt intensity and λ_f is a parameter. Here, we estimate the average snowmelt intensity with:

$$\bar{i}_f = 1/\lambda_f \quad \text{(3-15)}$$

and the average snowmelt rate can be estimated by dh_s/dt_f from eqn. 3-13 (Julien, 2002). A simple, sinusoidal temperature pattern based on minimum and maximum temperature will be used to temporally disaggregate the daily melt estimates at each SNOTEL point (e.g., Huber and Dickinson, 1988).

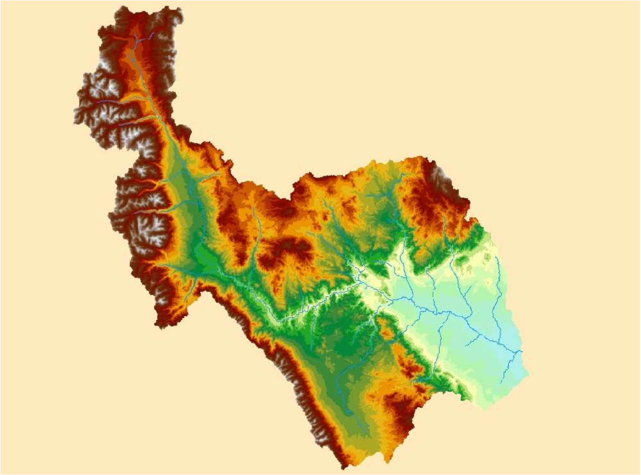
Given the point snowmelt estimates at each time step, spatial estimates will be made using the ABC model by Williams and Tarboton (1999). This model uses point estimates of melt at a particular time step and at select locations in the watershed and estimates melt at the other locations based on elevation and radiation and a map of snow-covered area:

$$h_{mi} = max\left[(A(t) + B(t) * elev_i + rad_i * C(t)), 0 \right] \quad \text{(3-16)}$$

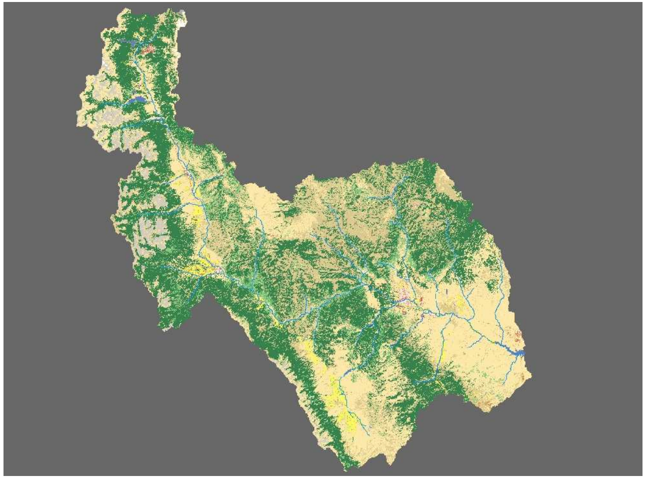
where h_{mi} is the depth of melt that occurs over the time step at location i expressed in SWE, rad_i is the direct, exoatmospheric radiation at location i determined from slope, aspect and shading, and $elev_i$ is the elevation of location i. The terms $A(t)$, $B(t)$ and $C(t)$ represent time-dependent model coefficients. Williams (1998) and Williams and Tarboton (1999) provide further details of this simple model.

3.3 CASC2D INITIAL TESTS ON A LARGE WATERSHED

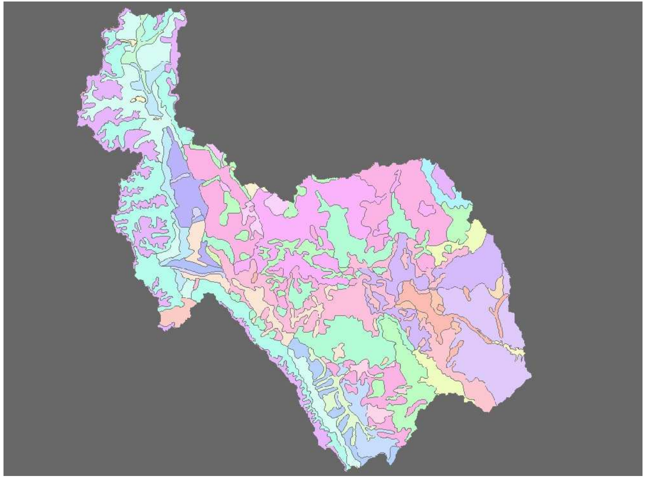
As part of this research, CASC2D has been initially applied to the Arkansas River above Pueblo, Colorado. The available data within the Arkansas River watershed for CASC2D model parameter estimation and calibration consists of three main types: GIS data, physical data, and hydrographic and atmospheric measurement data from gages. The GIS data that will be used includes: a Digital Elevation Model (DEM) of elevations in the watershed (Figure 3-4a); a map of land use and land cover (Figure 3-4b); a surficial soils map (Figure 3-4c); a bedrock map; hydrography (rivers and lakes); and snow cover information. Physical data consists of river channel dimensions (thalweg elevations, widths, bank heights, sideslopes, lengths, sinuosity). The measurement data includes precipitation (rainfall rates and total accumulations), streamflow (peaks, daily flows, unit values), snow depth and water equivalent at SNOTEL sites, and radar data from Pueblo and Denver. There are six main land use classes present in the watershed based on the USGS National Land Cover Data (NLCD): evergreen forest (35%), grasslands/herbaceous (29%), shrubland (23%), deciduous forest (7%), bare rock/sand/clay (3%) and pasture/hay (2%). A description of each class is in Anderson et al. (1976). Areas of the watershed with elevations greater than 3,000 m are usually snow-covered from November through mid-April. Snowmelt is the dominant runoff mechanism in much of the watershed.



(a)



(b)



(c)

Figure 3-4. Arkansas River study watershed main GIS data layers: (a) DEM; (b) landuse; and (c) soils.

After the pre-processing and GIS work was done, a basic model run applying CASC2D to the Arkansas River basin was completed. The focus is on exploration of the model and grid, and applying it on this large watershed of interest. A 960-m grid cell size was selected in order to capture spatial heterogeneity and for faster run times. The number of active grid cells within the watershed is 12,879. One model run is presented. Processes that have been simulated include spatially uniform rainfall with a constant value (5 mm/hr) for a fixed duration (12 hours), spatially varying Manning *n* (Table 3-4), spatially varying infiltration (Table 3-5), and channels. Channel properties that were assumed are base width equal to 61 m, vertical sideslopes (1:0); bank height equal to 5 m, sinuosity equal to 1.0, and Manning *n* equal to 0.040. A constant time step equal to 5 seconds was used for the model run.

Table 3-4: Initial Manning *n* Estimates for Overland Flow Grid Cells

Map No.	Land Use Class No.	USGS NLCD Land Use Class Name (Combined)	Manning *n* estimate	Percent of Watershed
1	11	Open Water; Perennial Ice/Snow	0.05	0.71
2	21	Low Intensity Residential; High Intensity Residential; Commercial/Industrial/Transportation	0.02	0.60
3	31	Bare Rock/Sand/Clay; Quarries/Strip Mines/Gravel Pits; Transitional	0.02	3.14
4	41	Deciduous Forest; Evergreen Forest; Mixed Forest	0.40	42.07
5	51	Shrubland	0.45	22.85
6	71	Grasslands/Herbaceous	0.15	28.36
7	81	Pasture/Hay	0.35	2.09
8	82	Row Crops; Small Grains; Fallow	0.16	0.15
9	85	Urban/Recreational Grasses	0.25	0.04

Table 3-5: Initial Green-Ampt Infiltration Parameters for Overland Flow Grid Cells

Soils No.	USDA Texture Class from STATSGO Database	Porosity ϕ (cm^3/cm^3)	Effective Porosity θ_e (cm^3/cm^3)	Assumed Effective Saturation S_e (%)	Effective Suction Head ψ (cm)	Saturated Hydraulic Conductivity K_s (cm/hr)	Percent of Watershed
1	very bouldery sandy loam	0.363	0.455	0.5	27.72	0.43	6.22
2	cobbly loam	0.437	0.450	0.5	20.76	0.68	7.89
3	very cobbly sandy loam	0.321	0.407	0.5	19.03	0.81	1.36
4	clay loam	0.528	0.426	0.5	27.42	0.28	2.61
5	channery loam	0.464	0.418	0.5	22.63	0.57	4.99
6	fine sandy loam	0.465	0.411	0.5	12.58	1.71	9.73
7	gravelly coarse sandy loam	0.377	0.352	0.5	23.75	0.43	2.03
8	gravelly sandy loam	0.446	0.415	0.5	20.24	0.72	12.83

Soils No.	USDA Texture Class from STATSGO Database	Porosity ϕ (cm^3/cm^3)	Effective Porosity θ_e (cm^3/cm^3)	Assumed Effective Saturation S_e (%)	Effective Suction Head ψ (cm)	Saturated Hydraulic Conductivity K_s (cm/hr)	Percent of Watershed
9	very gravelly loam	0.498	0.463	0.5	30.54	0.32	3.40
10	very gravelly sandy loam	0.431	0.400	0.5	29.81	0.30	28.52
11	loam	0.473	0.408	0.5	26.21	0.36	1.98
12	loamy sand	0.472	0.422	0.5	7.44	6.26	0.13
13	silt loam	0.491	0.413	0.5	34.97	0.19	6.97
14	sandy loam	0.528	0.460	0.5	7.75	5.61	1.84
15	stony sandy loam	0.448	0.399	0.5	10.74	2.24	0.75
16	very stony loam	0.165	0.470	0.5	20.64	0.75	0.71
17	very stony sandy loam	0.257	0.418	0.5	16.17	1.30	0.31
18	extremely stony loam and extremely stony sandy loam	0.050	0.408	0.5	31.41	0.26	7.73

The result from this simulation is shown via a hydrograph in Figure 3-5 and a depth map at hour 11 in Figure 3-6.

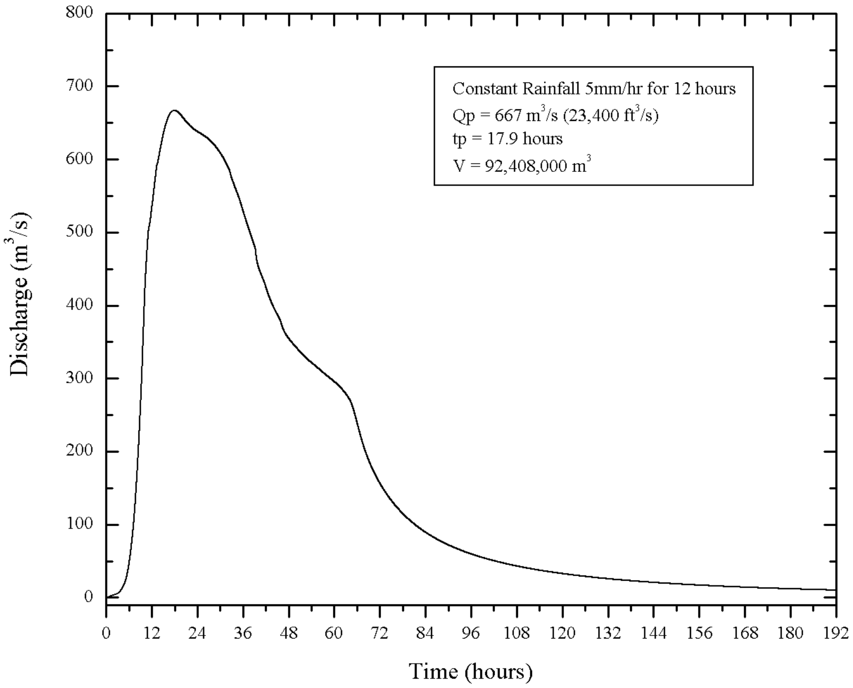


Figure 3-5. Arkansas River watershed outlet hydrograph of CASC2D basic run.

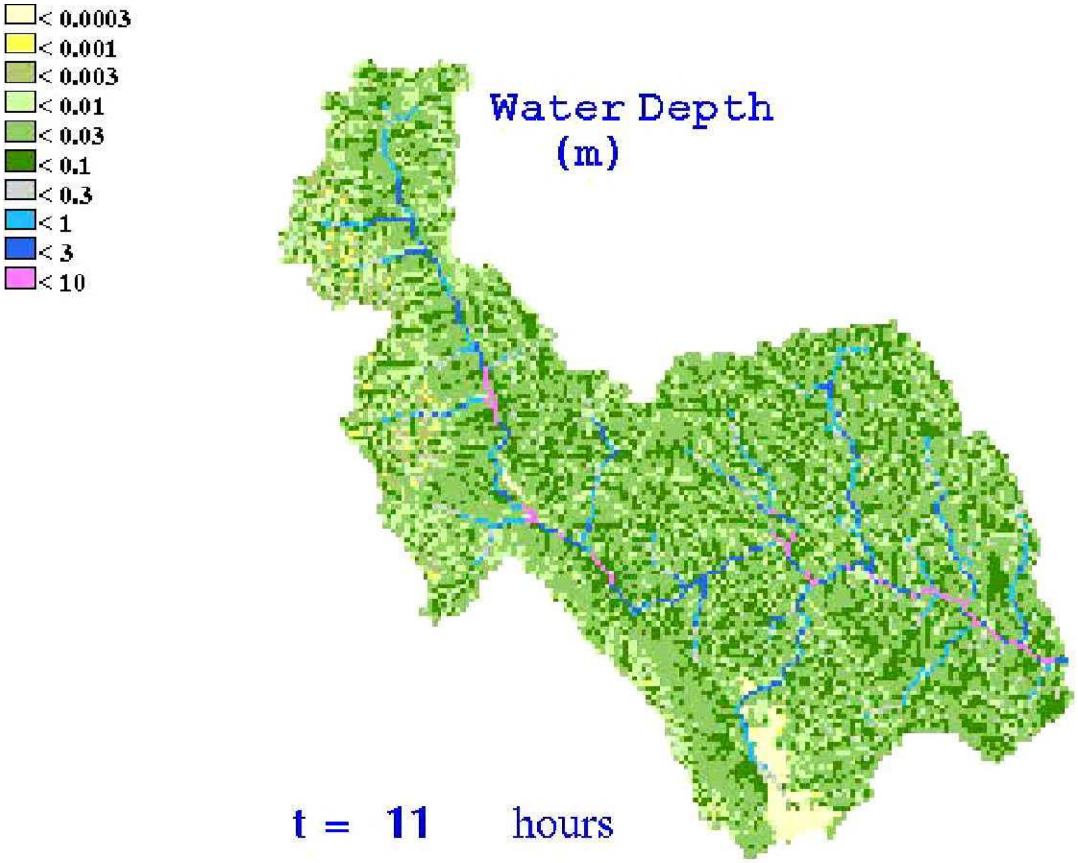


Figure 3-6. CASC2D basic run watershed depth map at 11 hours.

The model result, displayed as a hydrograph, depth map and movie, demonstrates that it is feasible to apply CASC2D to a watershed of this scale (12,000 km^2). However, there is remaining work that needs to be done. Spatially-varying channel parameters need to be estimated based on data at gaging stations. The model now needs to be calibrated to several observed storms and floods.

It is feasible for CASC2D to simulate extreme floods. A model run has been completed with a hypothetical extreme rainfall. For this case, processes that were simulated include spatially uniform rainfall with a constant value (12 mm/hr) for a fixed duration (12 hours), spatially varying Manning *n* (Table 3-4), spatially varying infiltration (Table 3-5), and channels. Channel properties that were assumed are the same as the base run. A constant time step equal to 5 seconds was used for the model run. The result from this simulation is shown via a hydrograph in Figure 3-7. Notice that the estimated peak flow approximates that from the June 1921 flood (2,800 m^3/s).

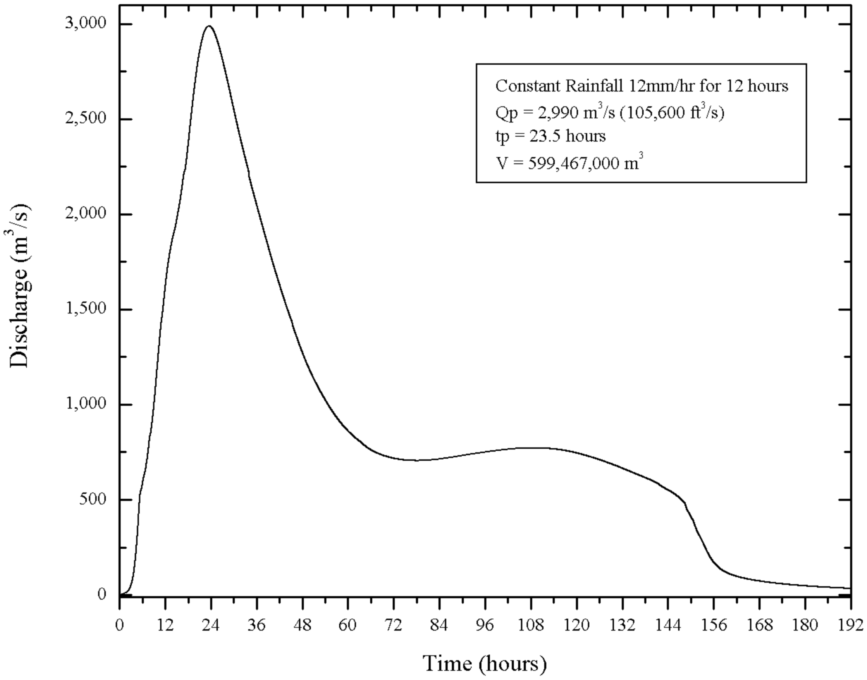


Figure 3-7. Arkansas River watershed outlet hydrograph of CASC2D extreme flood run.

One additional run has been completed: an initial run of PMP with constant spatial storm properties. This run has been done to test the CASC2D model ability to simulate floods from the largest rainfalls considered for risk analysis and design (Reclamation, 2002). There are two existing PMF design hydrographs for Pueblo Dam – a general storm PMF based on a 72-hour duration rainfall and a local thunderstorm PMF based on a 6-hour rainfall (Bullard and Leverson, 1991). A simple representation of the general storm PMP was used in CASC2D to model runoff. For this test, the precipitation hyetograph placed over subbasin 10 (Figure 3-8) was used to represent the rainfall over the entire basin. The model was run with a one second time step, no infiltration, a spatially uniform overland flow Manning *n* equal to 0.30, and channels with constant properties as described above. The results of this simulation are shown in Figure 3-9.

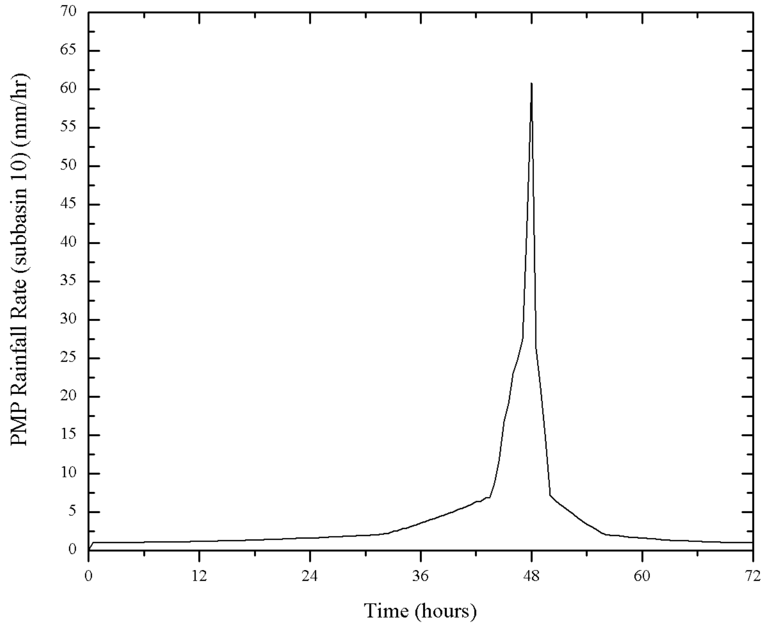


Figure 3-8. PMP 72-hour storm hyetograph, assumed spatially uniform over entire watershed.

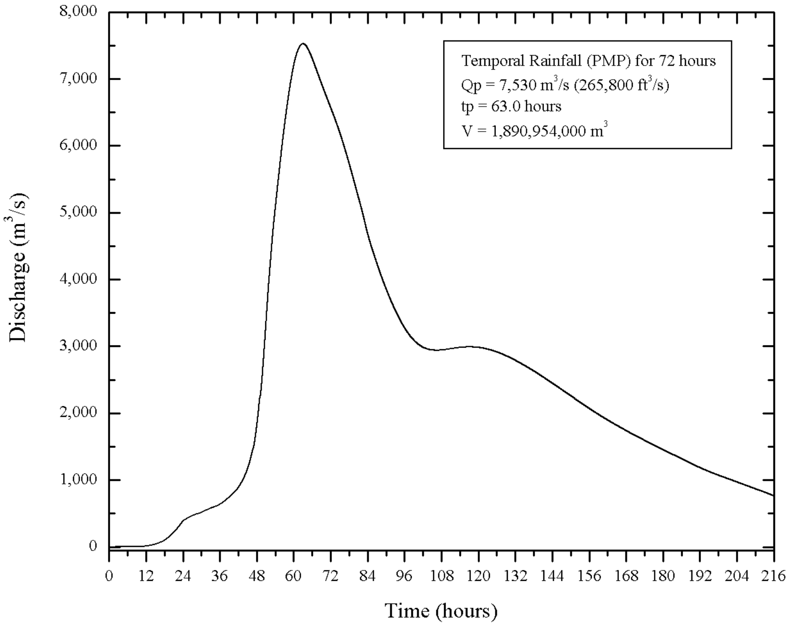


Figure 3-9. CASC2D runoff hydrograph at outlet based on PMP.

The result shown in Figure 3-9 demonstrates that CASC2D can be used to generate extreme floods and show the effects of temporally varying rainfall. Notice that the time to peak is dramatically different than the runs with uniform rainfall. Remaining work consists of implementing the snowmelt model and conducting sensitivity on the spatial distribution of rainfall with elevation, mixed-population rainfall and snowmelt, initial soil conditions, and channel floodplains.

4.0 EXAMPLE APPLICATION AND DISCUSSION

4.1 STOCHASTIC COMPONENTS, STORMS AND PROBABILITIES

A hypothetical example is provided to illustrate the derived flood frequency concepts outlined in Section 2. The focus is to show how one would implement the methods at a particular site. The estimates provided in this example are not meant to be used as absolute values, or to answer a particular hydrologic risk question. The first step is to develop a basin-average rainfall depth and associated probability. In this case, we will assume that the basin is a point, and that basin-average rainfall probabilities are assumed for a particular depth (Figure 4-1). The simplest way to use equation (2-3) to derive the probability for a given peak flow is to treat all the inputs, except for rainfall, in a quasi-deterministic fashion (e.g., Goldman, 1987). In this way, we can examine the peak flow probability based on the rainfall probability (e.g., Nathan and Weinmann, 1999). The example peak flow frequency curve is shown in Figure 4-2. This is based on the constant rainfall intensity model runs illustrated in Section 3.3. While this example is overly simplistic, the crucial feature of this method hinges on rainfall depths and associated probability estimates. Fontaine (1989) and Fontaine and Potter (1993) clearly show that the major source of uncertainty in estimating extreme flood probabilities using SST is the analysis of rainfall probabilities.

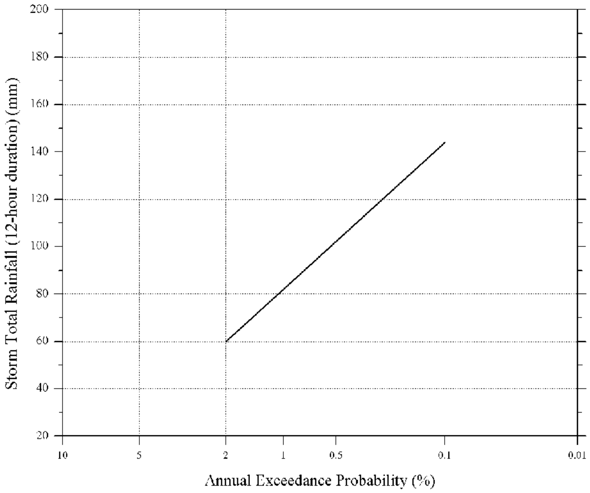


Figure 4-1. Example basin-average depth rainfall frequency curve.

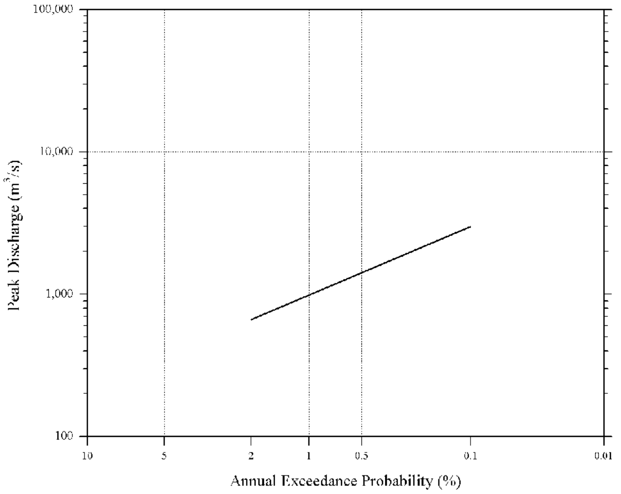


Figure 4-2. Example peak-flow frequency curve given assumed rainfall characteristics.

In order to fully develop the derived distribution concept for a particular site, the hydrologist must first determine what variables may be held fixed (deterministic), and what variables may be considered as random. Goldman (1987, p. 228) notes this as:

$$Y_i = h(x_i, c)$$

where x_i is a vector of stochastic parameters, c is a vector of deterministic parameters, and $h(.)$ is the transformation of input rainfall to output flows that the watershed model represents. These correspond to the vectors in equation (2-3): Ω is the vector of storm characteristics and locations, W_o is the initial storage condition, Ψ is the vector of runoff model properties, and $T(t)$ is the temporal distribution of storm depths. The vector of storm characteristics has six variables: D_o*, $K*$, N, C, Φ and (X,Y), where D_o* is the maximum d-hour storm center depth, $K*$ and N are the depth-area parameters, C is the major-to-minor axis ratio, Φ is the orientation of major axis, and (X,Y) is the random vector of spatial coordinates of the storm. The initial storage condition has four parameters: S_e, the initial soil saturation; SWE, the initial snow water equivalent depth; h_{ov}, the initial water depth on overland flow planes; and h_{ch}, the initial water depth in channels. The vector of model parameters consists of: n_{ov} and n_{ch} Manning coefficients for overland and channel flow transport; and saturated hydraulic conductivity and wetting front suction head for infiltration. Note that the third parameter for infiltration is described under the initial storage condition vector. Also, the overland cell dimensions and channel geometry (width, bank height, etc.) are considered to be fixed. The vector $T(t)$ is user-entered probability distribution function (pdf) for the temporal distribution during the storm; it is typically four probability groups, as in Huff (1967).

After the random components are selected from each vector, the distributions of random input variables are determined based on available data. For example, Franchini et al. (1996) chose Ψ to be represented by one parameter (average storage capacity) out of 14 ARNO model parameters. One challenge with CASC2D is to represent the few number of parameters in a spatially-distributed context. For example, overland flow Manning *n* is a vector that depends on the number of land use classes for a particular watershed (e.g., Table 3-3).

4.2 LARGE WATERSHED PROCESSES AND VERIFICATION

Based on the test runs presented in Section 3.3, there are several issues related to modeling extreme floods on large watersheds that need to be discussed. The first is the use of the diffusive wave model to represent a physical basis for flood frequency extrapolation. This model can readily include watershed and channel storage and attenuation of peak flows. The hydrographs shown in Section 3.3 clearly demonstrate this phenomenon. The “bump” in the hydrographs after the peak is water coming out of storage in the overland plane and channels, and making its way to the watershed outlet. This can be a very important process in large watersheds. The storage and timing of the peak flow are also affected. In addition, the watershed is not at equilibrium for these simulated storms. What that means is that there is a distinct nonlinear runoff response for both peak and volume because the rain duration is less than the time to equilibrium. One complicating factor with using CASC2D is that model results are grid-dependent, that is, they depend on the grid resolution and the properties of the overland elevations and channel geometry derived from a DEM. Channel slopes need to be checked for adverse slopes, long “flat” spots and other artifacts. One of the programs written as part of this research (listed in Appendix C) helps the user diagnose this potential problem.

The CASC2D model, as with any other hydrologic model, needs verification with independent data to insure that extreme flood predictions are within the range of some observations. One way to do this is to verify model estimates with paleoflood data. The model has parameters that can be used to accomplish this verification. The model parameters first must be determined as in Section 3.3, then be adjusted through calibration to one or more extreme floods. When the model results are compared to a peak-flow frequency curve with paleoflood data, model parameters and input need to be adjusted if the comparison is not satisfactory. Given the derived flood frequency framework with SST and CASC2D, the parameters that should potentially be adjusted are those in the four vectors described above. In addition, the basin-average depth and probability estimates from SST should be reviewed.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made based on the research work presented in this report.

1. A derived distribution framework has been developed for estimating probabilities of extreme floods for Reclamation dams. The framework consists of Stochastic Storm Transposition as a rainfall component and the CASC2D rainfall-runoff model to transform the rainfall into a flood.

2. The CASC2D model source code has been obtained from Colorado State University. The model has been nearly completely rewritten and major portions of the code enhanced so it can be applied to large watersheds. Four main pre-processing programs were developed as part of the

research in order to estimate model inputs. Methods to develop other model inputs using a GIS have been outlined and tested.

3. The CASC2D model has been tested for applicability on a large watershed and to simulate extreme floods in the range of interest for dam safety. The model can simulate extreme floods on large watersheds, but further work is needed to calibrate and verify the model.

Based on this research, two recommendations are made.

1. The physically-based, derived flood frequency framework needs complete testing on a watershed and dam of interest to Reclamation. It is proposed that the CASC2D model be implemented on the Arkansas River at Pueblo Dam, with existing project funds.

2. The Stochastic Storm Transposition concept needs complete investigation and testing. As the concept was just demonstrated here, an actual application is needed on a particular site, to examine the performance when estimating basin-average rainfalls and annual exceedance probabilities in the range of 10^{-3} to 10^{-8}.

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APPENDIX A

CASC2D PROGRAM AND INPUT SUMMARY LISTING

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This appendix provides a current listing of water (hydrologic/hydraulic) routines (C source and header files) that, when compiled and linked, make the CASC2D program. A summary of input requirements is also listed. The CASC2D model has been completely rewritten by John England and Mark Velleux (Colorado State University) based on the CASC2D-SED version documented by Rojas-Sanchez (2002). The CASC2D-SED code and model is described at:

http://www.engr.colostate.edu/%7Epierre/ce_old/Projects/CASC2D-Rosalia/Index.htm

The current CASC2D model is continuously undergoing changes and improvements. The water version of CASC2D consists of 21 general C routines, two general header files, 39 water C routines and two water header files. These routines are listed in Table A-1 in alphabetical order by type. The ability to model both solids and sediment transport and chemicals with contaminant transport is being added and improved by Mark Velleux. These sediment and chemical options are not currently included here, but will be available to Reclamation in the near future, when implementation and testing are complete.

Table A-1: CASC2D program routine listing

General Routines	
casc2d-r2.c	The CASC2D main program.
ComputeFinalState.c	Computes the final state of variables (water, solids, and chemicals) at the end of the simulation.
ComputeInitialState.c	Computes the initial state of variables (water, solids, and chemicals) at the end of the simulation.
FreeMemory.c	Free allocated memory at the end of a model run.
Grid-r2.c	Write output at each grid cell at specified time gdt[idt] in an individual file indexed by gridcount.
Initialize.c	Initialize is called at the start of the simulation to allocate memory and initialize values for variables used in computations but not read from input files.
NewState.c	NewState is called to store new water depths, particle concentrations, and chemical concentrations for use during the next (upcoming) time step (t + dt).
ReadDataGroupA.c	ReadDataGroupA is called at the start of the simulation to read Data Group A (general controls) from the model input file.
ReadDataGroupF.c	ReadDataGroupF is called at the start of the simulation to read Data Group F (output controls) from the model input file.
ReadInputFile.c	ReadInputFile is called at the start of the simulation to read the model input file.
RunTime-r2.c	Computes elapsed cpu time for a simulation run.
SimulationError.c	SimulationError is called when errors occur (and are trapped) during a simulation.
StripString.c	StripString is called to remove (strip) leading and trailing blanks and the final carriage return from character stings read using the fgets command.
TimeFunctionInit.c	TimeFunctionInit is called at the start of the simulation to set the starting values of parameters used to control time series functions.
UpdateTimeFunction.c	UpdateTimeFunction is called to interpolate values of time-dependent functions for a given dt based on input values at specific times.
UtilityFunctions.c	Concatenated group of general utility functions for statistics

WriteDumpFile.c	Write (dump) specified state variables and conditions for water (flow depths, rates, velocity, etc.), solids (total and individual particles concentrations), and chemicals (total concentrations, dissolved, bound, and particulate concentrations, etc.) in the water column and soil/sediment over time to a file.
WriteGrids.c	Write optional output at each grid cell at time t. Specification details are in Data Group F.
WriteMassBalance.c	Write detailed mass balance summary of flow (hydrology and hydraulics), solids, and chemicals on a cell and node basis at the end of a succesful model run.
WriteSummary.c	Write water, solids and chemical summaries at the end of a model run.
WriteTimeSeries.c	The module writes times series reports of water, solids and chemical export at each specified location (reporting stations) for the current time t.
General Headers	
casc2d_general_declarations.h	Global declarations header file for casc2d. Used in concert with casc2d_general_definitions.h.
casc2d_general_definitions.h	Global definitions header file for casc2d. Used in concert with casc2d_general_declarations.h
Water Routines	
ChannelWaterDepth-r5.c	Channel water balance accounting for subsequent explicit one-dimensional channel routing.
ChannelWaterRoute-r7.c	Explicit, one-dimensional channel water routing using diffusive wave approximation.
ComputeChannelElevation.c	Computes channel bed elevation from overland elevation and channel bank height
ComputeChannelLength.c	Computes length of each channel node of each link in the channel network.
ComputeChannelTopology-r5.c	Computes channel topology from link and node maps.
ComputeFinalStateWater.c	Computes the final state of water variables at the end of the simulation.
ComputeInitialStateWater.c	Computes the total volume of water stored in the overland plane and channel network at the start of the simulation.
FreeMemoryWater-r2.c	Free allocated memory for water variables from ReadDataGroupB, InitializeWater, and functions called within ReadDataGroupB
Infiltration-r2.c	Infiltration.c computes the infitration rate and cumulative depth of infiltration for each cell in the overland plane.
InitializeWater-r2.c	Allocate memory for and initialize water variables used in computations but not read from input files.
Interception.c	Computes interception depth and net rainfall from gross rainfall
NewStateWater.c	NewState is called to store new water depths for use during the next (upcoming) time step (t + dt).
OverlandWaterDepth-r5.c	Updates overland flow depths (x,y) in each grid cell; checks for negative depth value.
OverlandWaterRoute.c	Explicit, two-dimensional overland water routing using diffusive wave approximation.
Rainfall-r2.c	Spatial interpolation of gross rainfall intensity for each cell for the current time step.
ReadChannelFile.c	ReadChannelFile is called to read properties of each node of each link and in the channel network.
ReadDataGroupB-r2.c	ReadDataGroupB is called at the start of the simulation to read Data Group B (hydrologic and hydraulic simulation parameters) from the model input file.
ReadDesignRainGrid.c	Reads the design rain gage number that is applied to each cell within the spatial domain.
ReadElevationFile.c	ReadElevationFile is called to read the elevation file that specifies the elevation of each active cell (in the overland plane) within the spatial domain of the simulation.
ReadInfiltrationFile.c	ReadInfiltrationFile is called to read the initial depth of water infiltrated specified at the start the simulation for each cell (in the overland plane) within the spatial domain of the simulation.
ReadInitialWaterChannelFile-r2.c	ReadInitialWaterChannelFile is called to read the initial water depth file that specifies the depth of water in channels (link, node) at the start of the simulation.
ReadInitialWaterOverlandFile-r2.c	Reads the initial water depth for each cell in the overland plane at time zero.
ReadLandUseFile.c	ReadLandUseFile is called to read the land use classification file that the land use of each active cell (in the overland plane) within the spatial domain of the simulation

ReadLinkFile.c	ReadLinkFile is called to read the location (row and column) where each link of the channel network occurs within the overland plane.
ReadMaskFile.c	ReadMaskFile is called to read the mask file (x-y grid) that defines the extent of the simulation spatial domain.
ReadNodeFile.c	ReadNodeFile is called to read the location (row and column) of each node for each link of channel network within the overland plane.
ReadRadarRainLocations.c	Reads the (x,y) UTM cell center locations for radar rainfall.
ReadRadarRainRates.c	Reads the rain rates (mm/hr) derived from radar data for each (x,y) UTM cell center locations.
ReadSoilTypeFile.c	Reads the soil type classification file that defines the soil type for each active cell (in the overland plane) within the spatial domain of the simulation.
ReadSpaceTimeStorm.c	Reads the space-time storm parameters and rain rates (mm/hr) for design storms (DAD) from USACE/USBR storm catalog or stochastic storm transposition.
ReadStorageDepthFile.c	ReadStorageDepthFile is called to read the storage depth file that specifies the storage depth of each active cells (in the overland plane) within the spatial domain of the simulation.
TimeFunctionInitWater.c	TimeFunctionInitWater is called at the start of the simulation to set the starting values of parameters used for controlling water transport time series functions.
UpdateTimeFunctionWater-r2.c	UpdateTimeFunctionWater is called to interpolate values of time-dependent functions for a given dt based on input values at specific times.
WaterBalance.c	WaterBalance is called to update water depths in overland cells and channels for the next time step (t + dt)
WaterTransport.c	WaterTransport is called to compute derivative terms (rates) for water transport processes: rainfall, snowmelt, interception, infiltration, overland flow/routing, and channel flow/routing.
WriteMassBalanceWater.c	Write detailed mass balance summary of flow (hydrology and hydraulics),on a cell and node basis at the end of a succesful model run.
WriteGridsWater.c	Write optional water output at each grid cell at time t. Specification details are in Data Group F.
WriteSummaryWater-r2.c	Write summary flow (hydrology and hydraulics) information at the end of a successful model run.
WriteTimeSeriesWater.c	The module writes times series reports of water export (discharge in m3/s or mm/hr) at each specified location (reporting stations) for the current time t.
Water Headers	
casc2d_water_declarations.h	Global declarations header file for hydraulic/hydrologic calculations. Used with casc2d_water_definitions.h.
casc2d_water_definitions.h	Global definitions header file for hydraulic/hydrologic calculations. Used with casc2d_water_declarations.h.

CASC2D DATA GROUPS

Data groups are collections of information for creating a program input file.

General Notes

Variables starting with "i" are local counters. Variables starting with "n" describe the number of elements associated with a model parameter (i.e. nsolids = number of solids types, nchems = number of chemicals, ndt = number of time steps, etc.) Variables ending with "opt" are switches that toggle operation of model processes. Variables containing "ic", "bc", and "w" are associated with initial conditions (ic), boundary conditions (bc), and loads/forcing functions (w).

Model controls for time steps (dt), printout, ICs, BCs, and loads are input as paired time series of values (i.e. pairs of {function value at time t, time t}). Time steps and print intervals are step functions (i.e. the input value is used until time t, after which the next value is used). ICs, BCs, and loads are piecewise linear functions (i.e. values are linearly interpolated between times specified).

Descriptions and Organizations of Data Groups

Data Group A: General Controls

Record	*Description*
1	Header1 (string)
2	Header2 (string)
3	"KSIM" (char), ksim (int) {1 = hydrology, 2 = sediment, 3 = chemical} "NROWS" (char), nrows (int) "NCOLS" (char), ncols (int) "DX" (char), dx (float) (m) "DY" (char), dy (float) (m) "TSTART" (char), tstart (float) (hrs)
4	"NDT" (char), ndt (int) {number of time step values}, "SLNOPT" (char), slnopt (int) {mass limiting solution option: 0 = use it; 1 = no use}
	for idt = 1, ndt
5	dt[idt] (float) (s), dttime[idt] (float) (hrs)
Note	Record 5 is repeated for idt = 1, ndt
6	"NPRINTOUT" (char), nprintout (int) {number of print intervals for tables}
	for iprntout = 1, nprintout
7	printout[iprntout] (float) (hrs), printouttime[iprntout] (float) (hrs)
Note	Record 7 is repeated for iprntout = 1, nprintout
8	"NPRINTGRID" (char), nprintgrid (int) {number of print intervals for grids}
	for iprntgrid = 1, nprintgrid
9	printgrid[iprntgrid] (float) (hrs), printgridtime[iprntgrid] (float) (hrs)
Note	Record 9 is repeated for iprntgrid = 1, nprintgrid
10	"ECHO" (char), echofile (string)

Data Group B: Hydrologic Simulation Parameters

Record	*Description*
1	Header (string)
2	“MASK” (char), maskfile (string)
	call ReadMaskFile
3	“ELEVATION” (char), elevationfile (string) (m)
	call ReadElevationFile
4	“INFOPT” (char), infopt (int) (0 = no infiltration, 1 = infiltration)
	if ksim = 1 {for ksim > 1, see Data Group C}
	if infiltopt = 1 {there is infiltration but no sediment transport}
5	“NSOILS” (char), nsoils (int) (number of soil types)
	for isoil = 1, nsoils
6	kh[isoil] (float) (m/s), capsh[isoil] (float) (m), soilmd[isoil] (float) (dimensionless), soilname[isoil] (string)
Note	Record 6 is repeated for isoil = 1, nsoils
7	“SOIL_TYPES” (char), soilfile (string)
	call ReadSoilFile
	endif infiltopt
8	“NLANDS” (char), nlands (int) (number of land use types)
	for iland = 1, nlands
9	nmanning_ov[iland] (float) (n units), interceptionclass[iland] (float) (mm), LandName[iland] (string)
Note	Record 9 is repeated for iland = 1, nlands
10	“LAND_USE” (char), landusefile (string)
	call ReadLandUseFile
	endif ksim = 1
11	“STORAGE_DEPTHS” (char), storagedepthfile (string) (m)
	call ReadStorageDepthFile
XX	“SNWOPT” (char), snwopt (int) (0 = no snowmelt, 1 = snowmelt)
	Add “global” snowmelt parameters entered here...
12	“CHNOPT” (char), chnopt (int) (0 = no channels, 1 = channels)
	if chnopt = 1 then
13	“TPLGYOPT” (char), tplgyopt (int) {0 = compute topology from channel property file and link, and node masks, 1 = topology read from topology file}, “OUTOPT” (char), outopt (int) {0 = pour water from overland to channel portion of cell before routing overland, 1 = route water overland before pouring into channel}
	if tplgyopt = 0 then
14	“LINK” (char), linkfile (string)
	call ReadLinkFile
15	“NODE” (char), nodefile (string)
	call ReadNodeFile
16	“CHANNEL” (char), chanfile (string) {includes channel “dead” storage}
	call ReadChannelFile
	call ComputeTopology
Note	Records 14, 15, and 16 are only input if tplgyopt = 0.
	elseif tplgyopt = 1
17	“TOPOLOGY” (char), topofile (string) {combines the channel property, and the link and node masks} {also includes channel “dead” storage}
	call ReadTopologyFile {for future use...}
Note	Record 17 is only input if tplgyopt = 1.
	endif tplgyopt
	endif chnopt
	if snwopt > 0
(ICsnow)	“INITIAL_SNOW_OVERLAND” (char), initialsnowfile (string) (m)
	endif snwopt > 0
18 (ICov)	“INITIAL_WATER_OVERLAND” (char), initialwaterovfile (string) (m)
	call ReadWaterOverlandFile
	if infopt = 1
19 (ICsoil)	“INITIAL_INFILTRATION” (char), initialinfiltrationfile (string) (m)
	call ReadInfiltrationFile
	endif infopt = 1
	if (chnopt = 1) then
20 (ICch)	“INITIAL_WATER_IN_CHANNELS” (char), initialwaterchfile (string) (m)
	call ReadWaterChannelFile
	endif chnopt

21 (Wov)	rainopt (int) {0 = uniform in space over entire watershed, 1 = IDW spatial interpolation, 2 = design storm constant in space from grid index map, 3 = radar-derived rainrates from file, 4 = design storm basin-average (SST) input via file and distributed via elliptical pattern or time series grid read}
	if rainopt = 1
22	“IDWradius” (char), idwradius (float) (m), “IDWexponent” (char), idwexponent (float) (dimensionless)
	endif rainopt (=1)
Note	We do not need to check for rainopt = 0 because there are no parameters to enter for this case...
	if rainopt <= 2 {NOTE: User enters rain gages here for options 0, 1 and 2}
23	“NRAINGAGES” (char), nrg (int) {by default rain is uniform if only one rain gage is specified and distributed if there is more than one gage}
Check	if rainopt = 0 and nrg > 1, warn and abort...
	if nrg > 0
24	“CONV1” (char), convunits (float), “CONV2” (char), convtime (float), “SCALE” (char), scale (float)
	for irg = 1, nrg
25	“GAGE” (char), rgid[irg] (int), rgx[irg] (float) (m), rgy[irg] (float) (m), nrpairs[irg] (int)
	for irpairs = 1, nrpairs[irg]
26	rfintensity[irg][ipairs] (float) (m/s), rftime[irg][ipairs] (float) (hrs)
Note	Records 25 and 26 are repeated as a group for irg = 1, nrg. Record 26 is repeated for ipairs = 1, npairs[irg].
Also Note	Records 23-26 apply for rainopt = 0, 1 and 2 involving rain gage data entered in main input file
	endif nrg > 0
	if rainopt = 2
26a	“DESIGN_RAIN_GRID” (char), designraingridfile (string)
	call ReadDesignRainGrid
	endif rainopt = 2
	endif rainopt <= 2
	if rainopt = 3
26b	“RADAR_RAIN_LOC” (char), radarlocationfile (string)
	call ReadRadarRainLocations
26c	“RADAR_RAIN_RATE” (char), radarrainfile (string)
	call ReadRadarRainRates
	endif rainopt = 3
	if rainopt = 4
26d	“SPACE_TIME_STORM” (char), spacetimestormfile (string)
	call ReadSpaceTimeStorm
	endif rainopt = 4
	if snwopt > 0...
XX (Wsnw)	Add records for specifying snow forcing functions here...
	endit snwopt > 0
27 (Wov)	“NUMBER_OF_OVERLAND_FLOW_SOURCES” (char) (Flows point sources that enter or leave the overland plane by means other than rainfall or runoff, i.e. a well, a spring, irrigation diversion, etc.), nqwov (int)
	if nqwov > 0
28	“CONV1” (char), convunits (float), “CONV2” (char), convtime (float), “SCALE” (char), scale (float)
	for i = 1, nqovw
29	qwovrow[i] (int), qwovcol[i], nqwovpairs[i] (int), qwovdescription[i] (string) {qwovdescription is read to end of line as character}
	for ipairs = 1, nqovwpairs[i]
30	qwov[i][ipairs] (float) (m3/s), qwovtime[i][ipairs] (float) (hrs)
Note	Records 29 and 30 are repeated as a group for i = 1, nqwov. Record 30 is repeated for ipairs = 1, nqwovpairs[i]. qwov units: m^3/s.
	endif nqwov > 0
	if chnopt = 1
31 (Wch)	“NUMBER_OF_CHANNEL_FLOW_SOURCES” (char) (Flows that enter or leave the model domain by means other than rainfall, i.e. a mine adit, a spring, irrigation diversion, etc.), nqwch (int)
	if nqchw > 0
32	“CONV1” (char), convunits (float), “CONV2” (char), convtime (float), “SCALE” (char), scale (float)
	for i = 1, nqwch
33	qwchlink[i] (int), qwchnode[i], nqwchpairs[i] (int), qwchdescription[i] (string) {qdescription is read to end of line as character}
	for ipairs = 1, nqwchpairs[i]
34	qwch[i][ipairs] (float) (m3/s), qwchtime[i][ipairs] (float) (hrs)
Note	Records 33 and 34 are repeated as a group for i = 1, nqwch. Record 34 is repeated for ipairs = 1, nqwchpairs[i]. qwch units: m^3/s.
	endif nqwch > 0

	endif chnopt = 1
35 (BC)	"NUMBER_OF_WATERSHED_OUTLETS/BOUNDARIES" (char) (Locations where flows leave the model domain via the overland plane and channel network), noutlets (int)
	for i = 1, noutlets
36	"OUTLET_CELL" (char), iout[i] (int) (m), jout[i] (int) (m), sovout[i] (float) (dimensionless), dbcopt[i] (int) {0 = normal depth ($s_f = s_o$), 1 = specified water depth time series}
	if dbcopt[i] > 0
37	"CONV1" (char), convunits (float), "CONV2" (char), convtime (float), "SCALE" (char), scale (float)
38	nqbcpairs[i] (int), qbcdescription[i] (string) {qbcdescription is read to end of line as character}
	for ipairs = 1, nqbcpairs[i]
39	qbc[i][ipairs] (float) (m), qbctime[i][ipairs] (float) (hrs)
Note	Records 36-38 are repeated as a group for i = 1, noutlets. Records 37-39 are only input if dbcopt > 0. If dbcopt > 0, Records 37 and 38 are input once and Record 39 is repeated for ipairs = 1, nqbcpairs[i]. qbc units: m.
40	"NQREPORTS" (char), nqreports (int)
	for iqreport = 1, nqreports
41	qreprow[iqreport] (int), qrepcol[iqreport] (int), qarea[iqreport] (float) (m2), qunitsopt[iqreport] (int) (1 = m3/s, 2= mm/hr)
Note	Record 41 is repeated for iqreport = 1, nqreports

Data Group F: Ouput Specification Controls

Record	*Description*
1	Header (string)
	if nqreports > 0
2	Header (string) such as “EXPORT TIME SERIES OUPUTS”
3	“WATER_EXPORT” (char), waterexpfile (string)
	if ksim > 1 and nsedreports > 0
4	“SEDIMENT_EXPORT_ROOT” (char), sedexprootfile (string)
5	“SEDIMENT_EXPORT_EXT” (char), sedextension (string)
	if ksim > 2 and nchemreports > 0
6	“CHEMICAL_EXPORT_ROOT” (char), chemexpfile (string)
7	“CHEMICAL_EXPORT_EXT” (char), chemextention (string)
	endif ksim > 2
	endif ksim > 1
8	Header (string) such as “POINT-IN-TIME GRID OUPUTS”
9	“RAINFALL_RATES” (char), rainrategrid (string) (Path and file name)
10	“RAINFALL_DEPTH” (char), raindepthgrid (string) (Path and file name)
11	“INFILTRATION_RATE” (char), infrategrid (string) (Path and file name)
12	“INFILTRATION_DEPTH” (char), infdepthgrid (string) (Path and file name)
13	“WATER_DISCHARGE” (char), qgrid (string) (Path and file name)
14	“WATER_DEPTH” (char), waterdepthgrid (string) (Path and file name)
Note	if other water related grids are desired (i.e. snowmelt), add them here...
	if ksim > 1
15	“SOLID_CONC_WATER_ROOT” (char), solidsconcwatergridroot (string) (report for total and groups) (Path...\root)
16	“SOLID_CONC_SURFACE_LAYER_ROOT” (char), solidsconcsurfgridroot (string) (report for total and groups) (Path...\root)
	if ksim > 2
17	“TOTCHEM_CONC_WATER_ROOT” (char), totchemconcwatergridroot (string) (report for total and groups) (Path...\root)
18	“DISCHEM_CONC_WATER_ROOT” (char), dischemconcwatergridroot (string) (report for groups) (Path...\root)
19	“BNDCHEM_CONC_WATER_ROOT” (char), bndchemconcwatergridroot (string) (report for groups) (Path...\root)
20	“PRTCHEM_CONC_WATER_ROOT” (char), prtchemconcwatergridroot (string) (report for groups) (Path...\root)
21	“TOTCHEM_CONC_SURFACE_LAYER_ROOT” (char), totchemconcsurfgridroot (string) (report for total and groups) (Path...\root)
22	“DISCHEM_CONC_SURFACE_LAYER_ROOT” (char), dischemconcsurfgridroot (string) (report for groups) (Path...\root)
23	“BNDCHEM_CONC_SURFACE_LAYER_ROOT” (char), bndchemconcsurfgridroot (string) (report for groups) (Path...\root)
24	“PRTCHEM_CONC_SURFACE_LAYER_ROOT” (char), prtchemconcsurfgridroot (string) (report for groups) (Path...\root)
	endif ksim > 2
	endif ksim > 1
25	Header (string) such as “SIMULATION SUMMARY OUPUTS”
26	“DUMP_FILE” (char), dmpfile (string) (Path and file name)
27	“MASS_BALANCE” (char), msbfile (string) (Path and file name)
28	“SUMMARY_STATISTICS” (char), statsfile (string) (Path and file name)

Descriptions and Organizations of Spatial Domain Characteristics Files

General Format for Spatial Domain Characteristics Files (Grid Files)

Record	*Description*
1	Header1 (string)
2	"ncols" (char), gridcols (int)
3	"nrows" (char), nrows (int)
4	"xllcorner" (char), xllcorner (float)
5	"yllcorner" (char), yllcorner (float)
6	"cellsize" (char), cellsize (float)
7	"nodatavalue" (char), nodatavalue (int or float depending on grid)
	for i = 1, gridrows
	for j = 1, gridcols
8	girdvalue[i][j] (int or float depending on grid) {gridvalue is a sample name...}
Note	Record 8 is repeated for j = 1, grid cols and then repeated again for i = 1, gridrows.
Also Note	Data input is unformatted. However, a typical file will have gridrows number of lines with gridcols number of entries on each line.
Grid Types	Grid files are input for: the simulation mask (int) (Iimask[][]), ground elevation (float) (elevation[][]), soil types (int) (soiltype[][]), land use classes (int) (landuse[][]), links (int) (link[][]), nodes (int) (nodes[][]), storage depths in the overland plane (float), initial water depths in the overland plane (float), and soil stack elements (int).

Description and Organization of Channel Property and Topology Files

Channel Property File {input for tplgyopt = 0}

Record	*Description*
1	Header {string}
2	CHANLINKS (char), chanlinks (int)
Note	The number of links in the network (nlinks) is already known from the link file. This information is used to check that the channel properties file is compatible with the link file.
	for ilink = 1, nlinks
3	linknum (int) {dummy}, nnodes[ilink] (int)
	for inode = 1, nnodes[ilink]
4	bwidth[ilink][inode] (float), sideslope[ilink][inode] (float), hbank[ilink][inode] (float), nmanning_ch[ilink][inode] (float), sinuosity[ilink][inode] (float), deadstoragedepth[ilink][inode] (float)
Note	Records 3 and 4 are repeated as a group for ilink = 1, nlinks. Record 4 is repeated for inode = 1, nnodes[ilink].

Description and Organization of Channel Initial Water Depth File

Channel Initial Water Depth File

Record	*Description*
1	Header {string}
2	CHANLINKS (char), chanlinks (int)
Note	The number of links in the network (nlinks) is already known from the link file. This information is used to check that the channel properties file is compatible with the link file.
	for ilink = 1, nlinks
3	linknum (int) {dummy}, nnodes[ilink] (int)
	for inode = 1, nnodes[ilink]
4	hch0[ilink][inode] (float)
Note	Records 3 and 4 are repeated as a group for ilink = 1, nlinks. Record 4 is repeated for inode = 1, nnodes[ilink].

APPENDIX B

CASC2D ARCGIS PROCESSING STEPS

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TWO-DIMENSIONAL RAINFALL-RUNOFF MODELING (CASC2D)
WITH ARCGIS PRE- AND POST-PROCESSING
TASK 1 SUBMITTAL
IMPROVED FLOOD FREQUENCY EXTRAPOLATIONS
DAM SAFETY OFFICE RESEARCH

November 19, 2002

INTRODUCTION AND OBJECTIVES

The focus of Task 1 work is rainfall-runoff modeling with CASC2D, using ArcGIS for pre- and post-processing. CASC2D is a fully unsteady, physically-based, distributed-parameter, two-dimensional, infiltration excess (Hortonian) hydrologic model that simulates the response of a watershed subject to an input rainfall field (ASCE, 1999). The model uses a two-dimensional, explicit finite difference solution to the diffusive wave equation for surface overland flow. Channel flow is solved using a one-dimensional diffusive wave approximation. The Green-Ampt infiltration model is used to estimate precipitation excess for surface overland flow.

The model was originally developed by the Center for Geosciences at Colorado State University (CSU) (Julien and Saghafian, 1991). Further enhancements and research with the model have been conducted at CSU, including upland erosion (Johnson, 1997), grid size selection (Molnar and Julien, 2000) and at the University of Connecticut for continuous simulation (Ogden, 1998).

The CASC2D model is considered a state-of-the-art rainfall-runoff model (ASCE, 1999). Because it is a distributed model, the model input requirements are much larger than traditional lumped-parameter models. A GIS is required to facilitate developing the input data for the model and for viewing the results. The Watershed Modeling System (WMS), funded by the U.S. Army Corps of Engineers Waterways Experiment Station, has been developed for pre-and post-processing for CASC2D, but this interface is very expensive as it is commercial software. In addition, the CASC2D for WMS source code is not available, so one can not trace errors or debug input/output. Most recently, ArcInfo 7 has been used by Rosalía Rojas-Sánchez (CSU Ph.D. candidate) to develop input files and display results for CASC2D. For this Task, ArcGIS is used to develop the majority of input data for CASC2D and will be used for post-processing.

There are three objectives for this Task:

1. Explore CASC2D as a physical basis for extrapolating large floods by using the model and apply it to a watershed;
2. Demonstrate how ArcGIS can be used to create input data for CASC2D; and
3. Demonstrate how ArcGIS can be used for post-processing results.

TEST WATERSHED

Rainfall-runoff modeling is performed on the Soda Creek near Livesey, Colorado watershed. Soda Creek (USGS Gage No. 07099250) is a small, 8.35 mi^2 (21.63 km^2) right-bank tributary to the Arkansas River upstream of Pueblo, Colorado (Figure 1). The site is of interest because good rainfall-runoff data are available for model calibration. The U.S. Geological Survey collected rainfall and runoff data at this site from April 14, 1970 to November 1978. The site was part of the rainfall-runoff program for small watersheds in Colorado, to define flood characteristics for storm drainage and design of hydraulic structures. The watershed is an excellent location for a trial site for the first USBR application of CASC2D for extreme flood modeling, as it is a tributary to Pueblo Reservoir, and is subject to extreme floods.

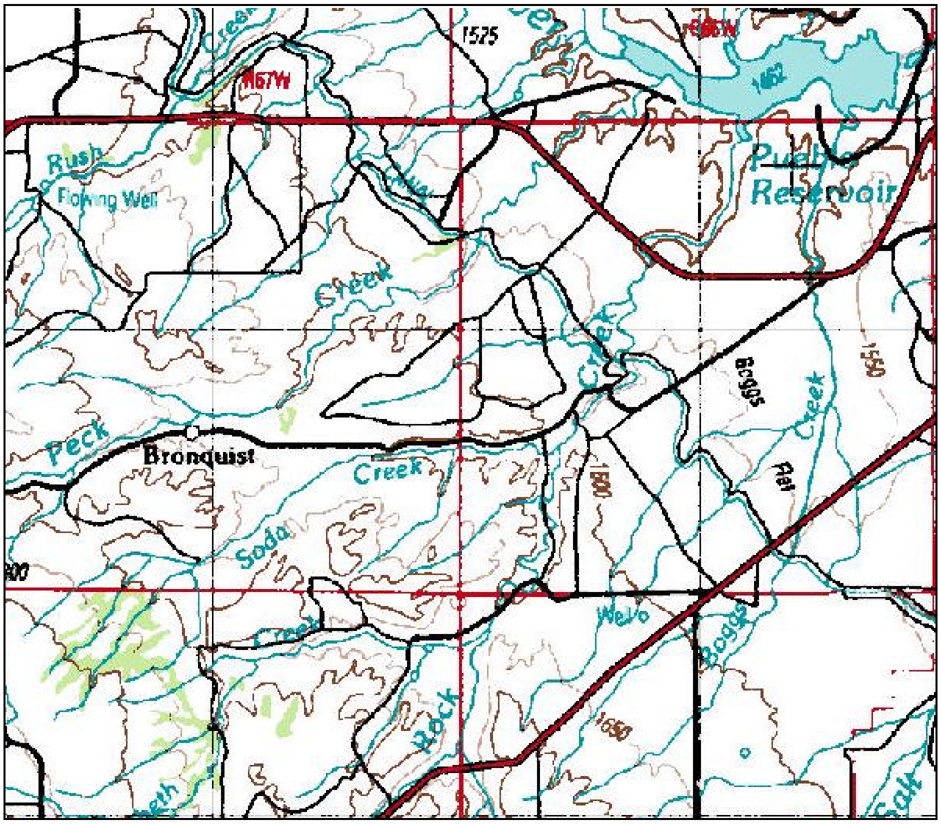


Figure 1 Soda Creek near Livesey, Colorado. Pueblo Reservoir is located in the upper right corner of the figure.

DATA

Two broad classes of data are needed to run the model: “physiographic” data that describes the watershed; and hydrologic data. The physiographic data consists of:

1. A 30 meter Digital Elevation Model, based on the USGS National Elevation Dataset;
2. Hydrography Data (streams) from USGS 1:24,000 DLG files;

3. Soils information from the NRCS STATSGO (1:250,000) database;
4. Land Use and Land Cover (LULC) from USGS NCLD (30 m);
5. DRG raster graphic of USGS topographic maps in Mr.SID format;
6. a DLG index map of UGSG quadrangles; and
7. Sixth-level Hydrologic Unit Code (HUC) polygons from NRCS.

Hydrologic data consists of rainfall and runoff data for individual storms and has been obtained in paper form from the USGS. These data consist of five-minute point rainfall and 5-minute runoff data. Model parameters (infiltration and overland flow roughness coefficients) will be calibrated based on data from one to two rainfall-runoff events.

COMPUTER SOFTWARE AND MODELS

The ArcGIS computer software package, the CASC2D rainfall runoff model, and Microsoft Excel spreadsheet are used to complete the Task objectives. The ArcINFO version of ArcGIS is required to complete DEM processing and for advanced grid conversion tools in ArcToolbox. ArcINFO command line software (grid) is also required to execute fill commands for DEM processing. The “grid to ascii” and “ascii to grid” conversions in the ArcINFO version of ArcToolbox are required to develop CASC2D input and view output.

ArcGIS is used to develop the watershed maps and spatial input, and to make maps of the results. The latest CSU version of CASC2D is currently called CASC2D-SED, and is an event-based rainfall-runoff model that includes upland erosion (Johnson, 1997). This model is used for runoff computations. In this study, only the rainfall-runoff portion of the model is used; upland erosion and sediment transport will not be modeled. In addition to the above software, Microsoft Visual C++ is used to run CASC2D-SED and debug the model. The Task could not have been completed with a simple executable version of the model. The source code was accessed in order to debug functions and subroutines and to obtain results.

APPROACH

The approach for the Task consists of the following major steps:

1. Obtain remaining physiographic data in electronic format and input into ArcGIS.

2. Convert datums and projections of data as necessary.

3. Resample the DEM and other raster data layers to develop grids at a larger resolution (approximately 90m), to be able to run the model much faster with coarse grids, and simplify input.

4. Process data in ArcGIS to develop the major input grid maps to CASC2D-SED. Six grid maps will be created: elevation (grid elevation), soil (soil type index), land use (LULC index),

shape (watershed and channel network definition), link (link numbers), and node (node numbers) maps.

5. Develop three text input files to CASC2D-SED: data control, precipitation, and channel characteristics files.

6. Successfully run the model.

7. Use ArcGIS to display the model output grids, and Excel for plotting hydrographs.

After the grid maps are created, several simplifications will initially be made to understand CASC2D-SED performance. The model will be first run with a constant rainfall intensity, impervious watershed (no infiltration), constant Manning *n*, and the watershed will be treated as all overland flow (neglect channel routing). These simplifications will then be relaxed one-by-one until a close representation of the actual watershed is made.

CASC2D INPUT WITH ARCGIS AND EXCEL

ArcGIS was used to develop grid maps for input to CASC2D-SED. The first step, after obtaining data, was to convert coverages and data layers to a common base. All data were converted to UTM Zone 13, NAD 83. Substantial effort was needed to convert the data, because certain coverages did not contain projection information. The "define projection" tool in ArcToolbox was used, along with the "convert projection" tool (only available in ArcINFO version).

After major processing was completed, final maps used as input to the model are shown below. The soils and landuse maps are later simplified (discussed below) to obtain initial results with CASC2D-SED.

DEM

There are major ArcGIS and ArcINFO processing steps to generate surface runoff characteristics, correct DEM errors and define watersheds. These functions include: flow direction, sink, fill, and flow accumulation.

The first major processing step is to create a smooth DEM that is free of sinks or pits. This step was done by following ArcINFO help commands. First, sink depth was estimated using commands in raster calculator:

Calculate flow direction by: flow_dir = flowdirection (elevation)

Then, calculate sink depth by running two functions:

Grid: sink_areas = watershed (flowdir, sink (flowdir))

Grid: sink_depth = zonalfill (sink_areas, elevation) - zonalmin (sink_areas, elevation)

After sink_depth is estimated, fill was run at the command line. It is this author's understanding that at this time, the fill command only works at the grid: command line in arc. There are hydrology tool add-ons available for ArcGIS; however these were not tested. The tools will be investigated at a later date. To start fill, one starts arc:, then types "w" at arc; to see what the current workspace is. The user then changes directories to the workspace of interest, such as:

```
arc: w d:\gis\soda_creek\
```

Then, start grid by typing:

```
arc: grid
```

Now, at the grid: command, type the fill command:

```
FILL <in_grid> <out_grid> {SINK | PEAK} {z_limit} {out_dir_grid}
```

and use "SINK" to fill sinks (instead of cutting peaks) and put the fill depth calculated above as the z_limit.

After the 30m grid was filled, a 150m DEM grid was created by resampling. This grid was then filled to create a final 150m DEM (Figure 2). From this DEM grid, flow directions (Figure 3) and flow accumulations (Figure 4) were calculated. The 24k hydrography DLG layer was used to check the location and extent of flow accumulations (like channels). Flow accumulations from the 150m DEM are acceptable, but some sacrifices have been made in accuracy.

The user can determine the watershed from a flow accumulation grid. This may not be the "actual" watershed boundary, but this is what the DEM thinks the watershed boundary is. One uses the known watershed size (in km^2) and grid cell size (in m) to determine the flow accumulation cell that defines the watershed outlet. This cell is found using the identify tool. A new point coverage is created by digitizing a point at the watershed outlet. The HUC map, hydrography and DRG topography are used to check the reasonableness of the watershed point.

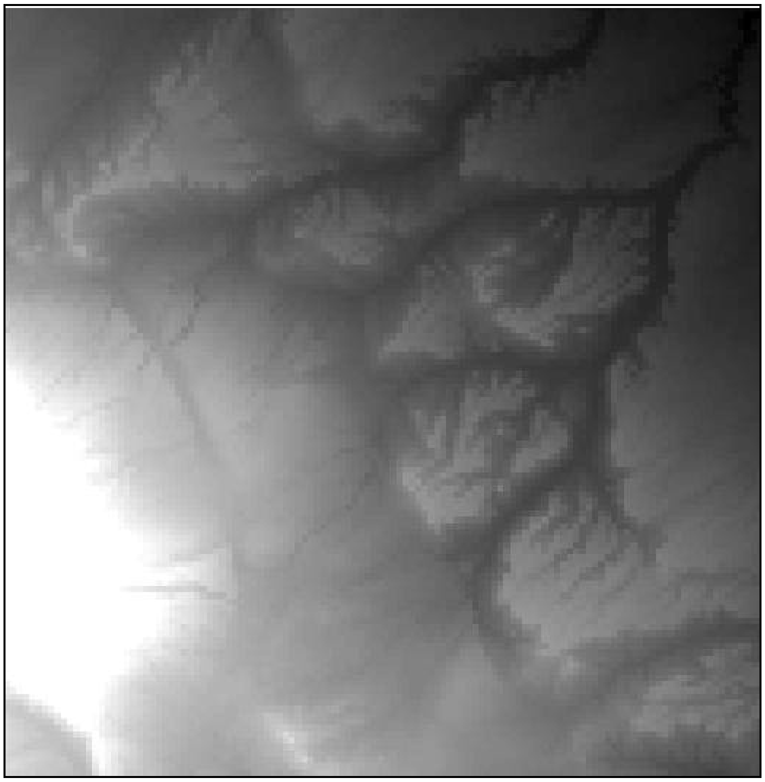


Figure 2 Final DEM for Soda Creek region. The DEM was filled at 30m, resampled to 150m, and filled again at 150m.

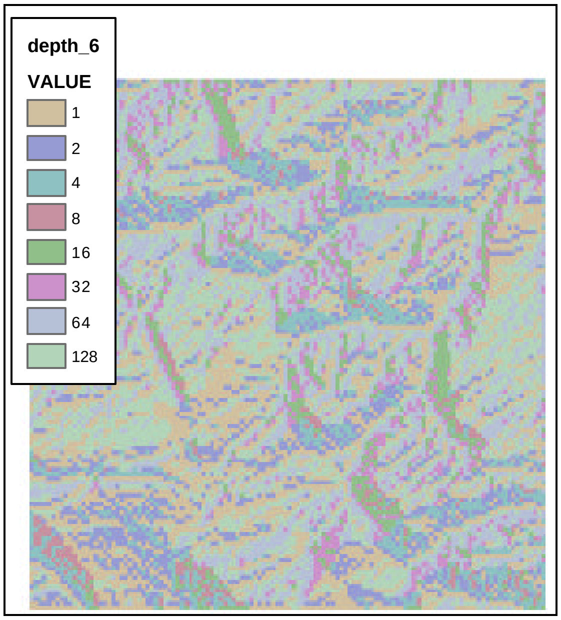


Figure 3 Flow direction map (150m grid cell size) that was used to derive flow accumulation and watershed.

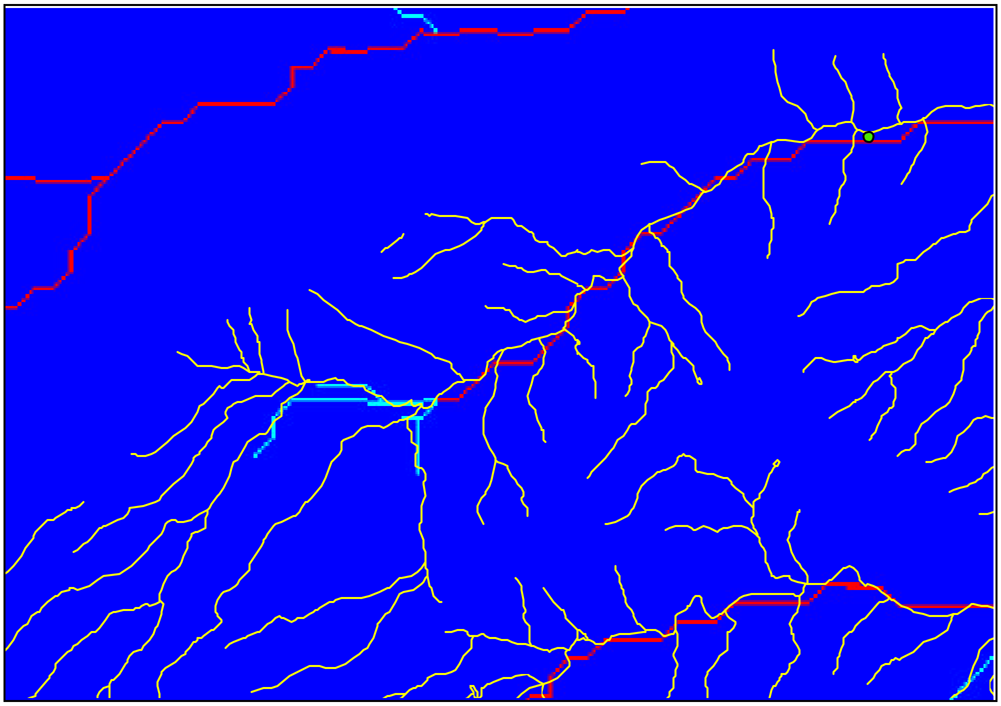


Figure 4 Flow accumulation map used to derive Soda Creek watershed. Known watershed point coverage is shown as green point. Significant streamflow accumulations shown in red. The 24k hydro DLG line coverage is shown in yellow for comparison.

<u>Watershed Mask</u>

The watershed point (green, Figure 4) was converted to a grid. This point and the flow direction grid were used to delineate the watershed in raster calculator. The command is: WATERSHED(<dir_grid>, <source_grid>)

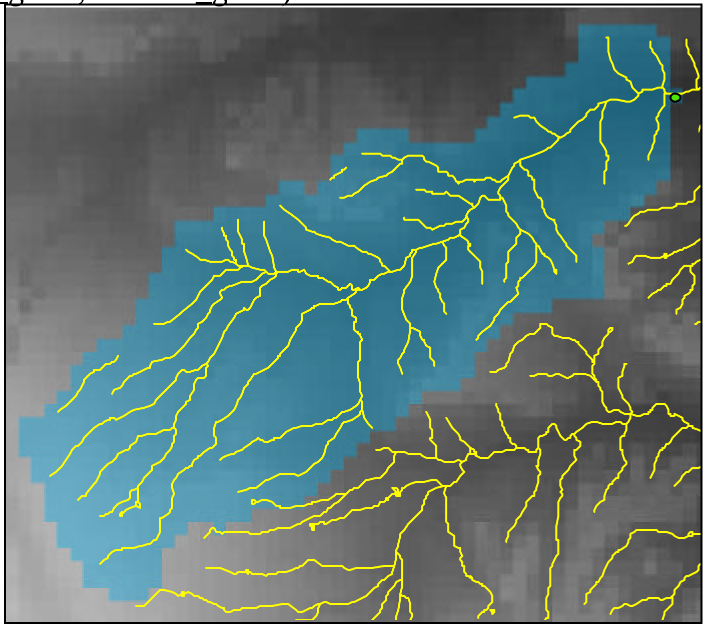


Figure 5 Soda Creek Watershed and mask. Green point at upper right corner of screen is watershed outlet. Yellow lines are 24k DLG hydro, used to confirm the watershed delineation from DEM.

After resampling, the watershed (Figure 5) has 962 cells with cell size 150m. The total watershed area is 21.65 km^2.

Soils

A soils map was constructed (Figure 6) by overlaying the watershed mask and selecting overlapping polygons. One can readily see that the STATSGO database is inadequate for this rainfall-runoff modeling problem. All the variability is lost because the soils have been aggregated into large polygons at 1:250,000. Two soils are found for the Soda Creek watershed. The soils characteristics were determined by making a new polygon coverage of just the two soils types, and relating three tables mapunit, comp and layer by muid. Soils map characteristics are listed in Table 1, and are based on Julien and Saghafian (1991).

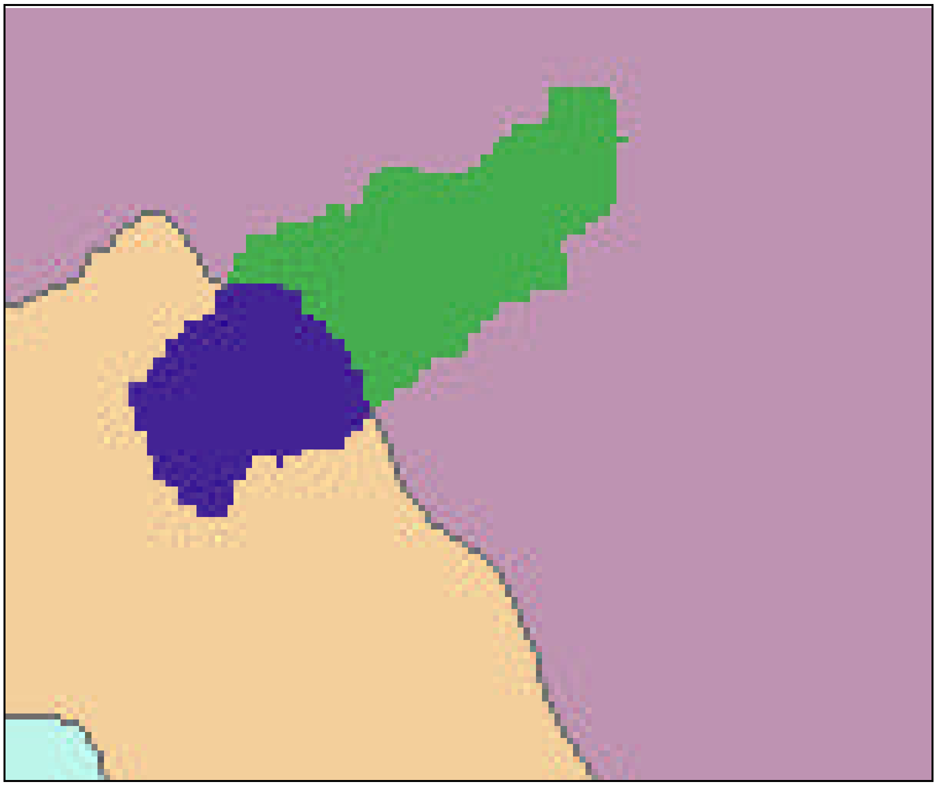


Figure 6 Soda Creek 150m soils map from STATSGO. The green cells are silt-loam texture class; the dark purple cells are loam texture class.

Table 1 Soda Creek Soils Characteristics from STATSGO database

Index	Watershed Location	NRCS Soil ID (MUID)	Dominant USDA Texture (Layer 1)	Sat. Hydraulic Conductivity (cm/h)	Wetting Front Capillary Head (cm)	Moisture Deficit
1	Northeast	CO361	SIL – Silt Loam	0.65	16.68	0.015
2	Southwest	CO304	L - Loam	0.34	8.89	0.029

Landuse

The NLCD landuse data has 21 main classes (Table 2), that use a numbering system out of 100, with the first digit being the broad class. However, values in the Arkansas River data set include many cells with missing values, other than the major class (e.g., 44-50, 52-60, etc.). Based on lulc classes observed within the Soda Creek watershed, missing values and those with classified values were reclassified into five main groups: forested upland (41), shrubland (51), non-natural woody vegetation (61), grasslands (71) and pasture/hay (81). These 30m data were then aggregated to 150m cells, using the nearest neighbor approach. After resampling, four classes remained (Figure 7), excluding pasture /hay, because this class had very few cells (about 10 out of 24,000 30m cells). Landuse and overland flow estimates are shown in Table 3.

Table 2 USGS NLCD land cover class definitions

General Category	Number	Class
Water	11	Open Water
Water	12	Perennial Ice/Snow
Developed	21	Low Intensity Residential
Developed	22	High Intensity Residential
Developed	23	Commercial/Industrial/Transportation
Barren	31	Bare Rock/Sand/Clay
Barren	32	Quarries/Strip Mines/Gravel Pits
Barren	33	Transitional
Forested Upland	41	Deciduous Forest
Forested Upland	42	Evergreen Forest
Forested Upland	43	Mixed Forest
Shrubland	51	Shrubland
Non-Natural Woody	61	Orchards/Vineyards/Other
Herbaceous Upland Natural/Semi-natural Vegetation	71	Grasslands/Herbaceous
Herbaceous Planted/Cultivated	81	Pasture/Hay
Herbaceous Planted/Cultivated	82	Row Crops
Herbaceous Planted/Cultivated	83	Small Grains
Herbaceous Planted/Cultivated	84	Fallow
Herbaceous Planted/Cultivated	85	Urban/Recreational Grasses
Wetlands	91	Woody Wetlands
Wetlands	92	Emergent Herbaceous Wetlands

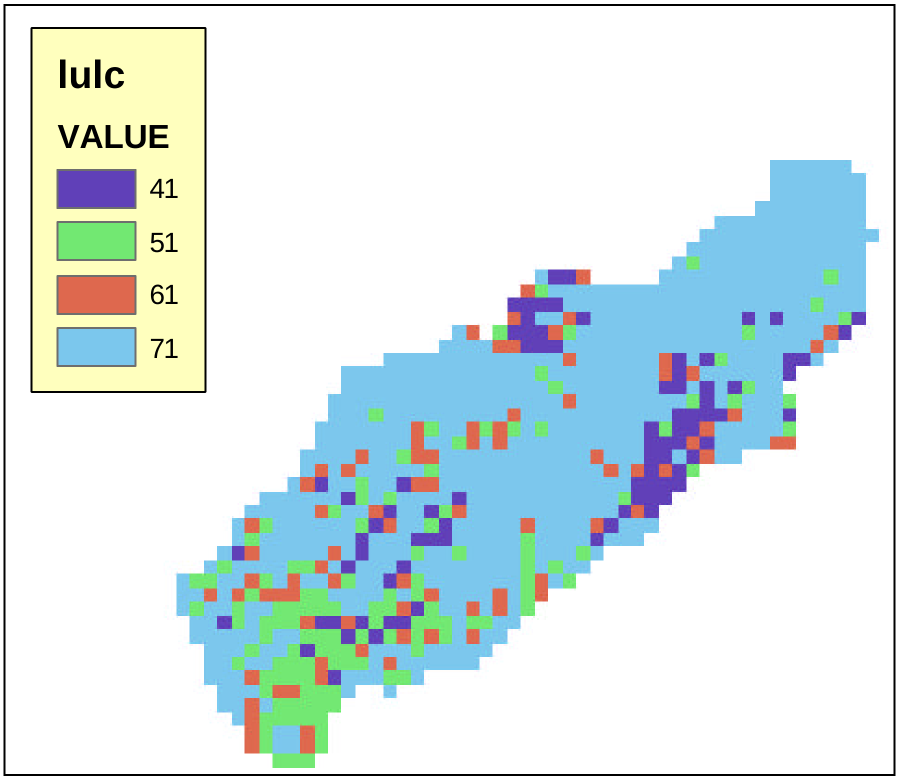


Figure 7 Landuse classification for Soda Creek watershed, LULC values are listed in Table 3.

Table 3 NLCD reclassification and aggregation to 150m, and overland flow roughness estimates

NLCD Number	Class	Percentage in Watershed	Manning *n* Estimate
41	Forest	8.8	0.25
51	Shrubland	13.4	0.45
61	Non-natural Woody	8.8	0.20
71	Grasslands	69	0.35

Channel network maps

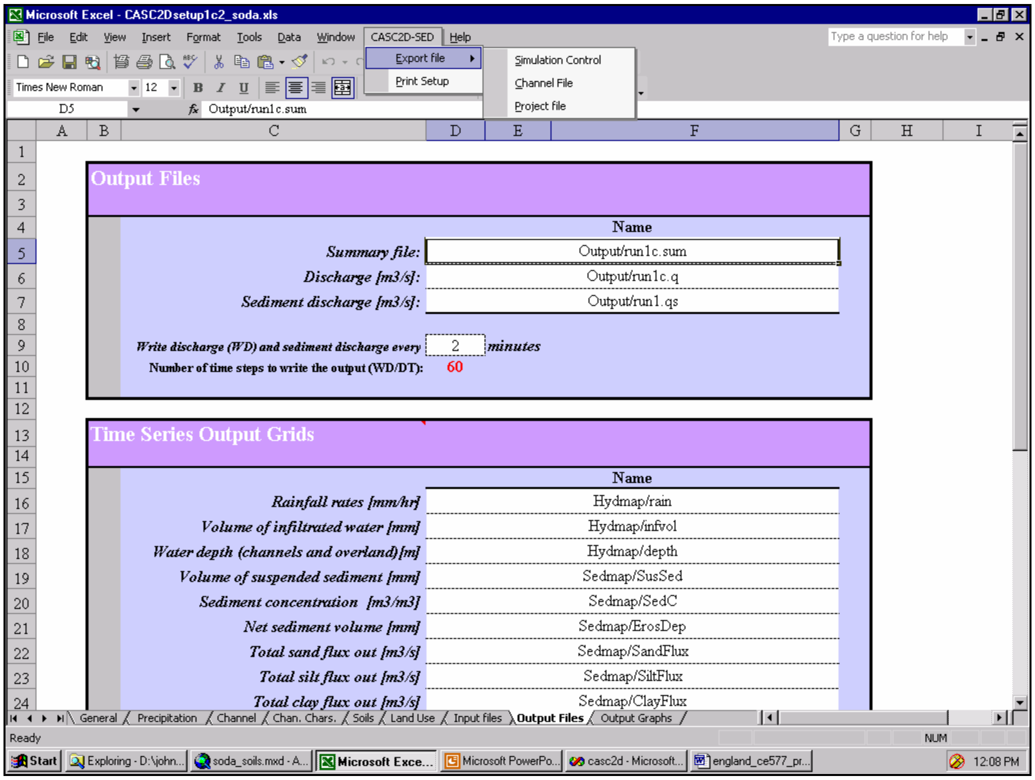
Due to time constraints on this Task, and the difficulties in obtaining results from CASC2D-SED while simultaneously learning the model, link and node maps were not developed. This step will be completed as part of the larger Arkansas River basin flood study. For this Task, only overland flow was simulated. These areas will be explored as part of continuing work.

Input Rainfall and Simulation Duration

A simple test case was run for Soda Creek. A constant rainfall intensity equal to 15 mm/hr was run for two hours. Total simulation time was 6 hours. This was found by trial – running the model several times to get an idea of watershed response to capture the falling limb of the hydrograph. A two-second computational time step was assumed, in order to take care of any numerical instability. The model was successfully run with this time step. In subsequent applications, the time step will most likely be lengthened, until some instabilities occur, so the model runs faster.

Data Set Creation and Program Execution

A simplified data set was created to run CASC2D-SED. This case included: no infiltration (impervious watershed), constant Manning *n* for overland flow, no channels, and constant rainfall intensity. An Excel spreadsheet was used to facilitate creation of input Task and control files to run the model. Macros in the spreadsheet generate the files for a user (Figure 8).



Output/run1c.sum

Output Files

	Name
Summary file:	Output/run1c.sum
Discharge [m3/s]:	Output/run1c.q
Sediment discharge [m3/s]:	Output/run1.qs

Write discharge (WD) and sediment discharge every 2 *minutes*

Number of time steps to write the output (WD/DT): 60

Time Series Output Grids

	Name
Rainfall rates [mm/hr]	Hydmap/rain
Volume of infiltrated water [mm]	Hydmap/infvol
Water depth (channels and overland) [m]	Hydmap/depth
Volume of suspended sediment [mm]	Sedmap/SusSed
Sediment concentration [m3/m3]	Sedmap/SedC
Net sediment volume [mm]	Sedmap/ErosDep
Total sand flux out [m3/s]	Sedmap/SandFlux
Total silt flux out [m3/s]	Sedmap/SiltFlux
Total clay flux out [m3/s]	Sedmap/ClayFlux

Figure 8. CASC2D-SED Project and control file generator using Excel.

There were some difficulties in using the spreadsheet file generator. The current version, developed by Rosalía Rojas-Sánchez, is excellent and a major help to develop input files. However, there were some bugs in the file generator macros. These were debugged and fixed over a several day period. One major limitation of the spreadsheet template is the macros ONLY work in MS Office XP, which includes new VBA libraries. The macros crash when using Excel 97 and Excel in Office 2000, so the user needs to use Office XP.

There were several difficulties encountered when running CASC2D-SED. The program crashed many times because of data input problems and formats. The program, as it is in research mode, currently requires the user to input all the data, including channels, links, landuse, soils, model sediment transport, and input file locations. It does not allow the user to have several features turned off, such as overland erosion, impervious surface, etc. Over a period of about six to seven days, the current version of the source code was examined and debugged using Developer Studio and Visual C++. Minor changes were made to three subroutines to fix errors, and allow the user to run a case with no defined channels. The program was recompiled and executed successfully.

CASC2D SIMULATION RESULTS

Results from CASC2D are viewed by using Excel (or other software) to plot hydrographs, and ArcGIS to view output grids. ArcToolbox is used to convert the ascii output files to ESRI grids. The results, shown below, consist of the outflow hydrograph at the watershed outlet and depth maps at selected time steps. The user determines how many maps are created; here rain, infiltration and overland flow depth maps were generated every 10 minutes. The hydrograph plot (Figure 9) indicates reasonable model behavior for this trivial case.

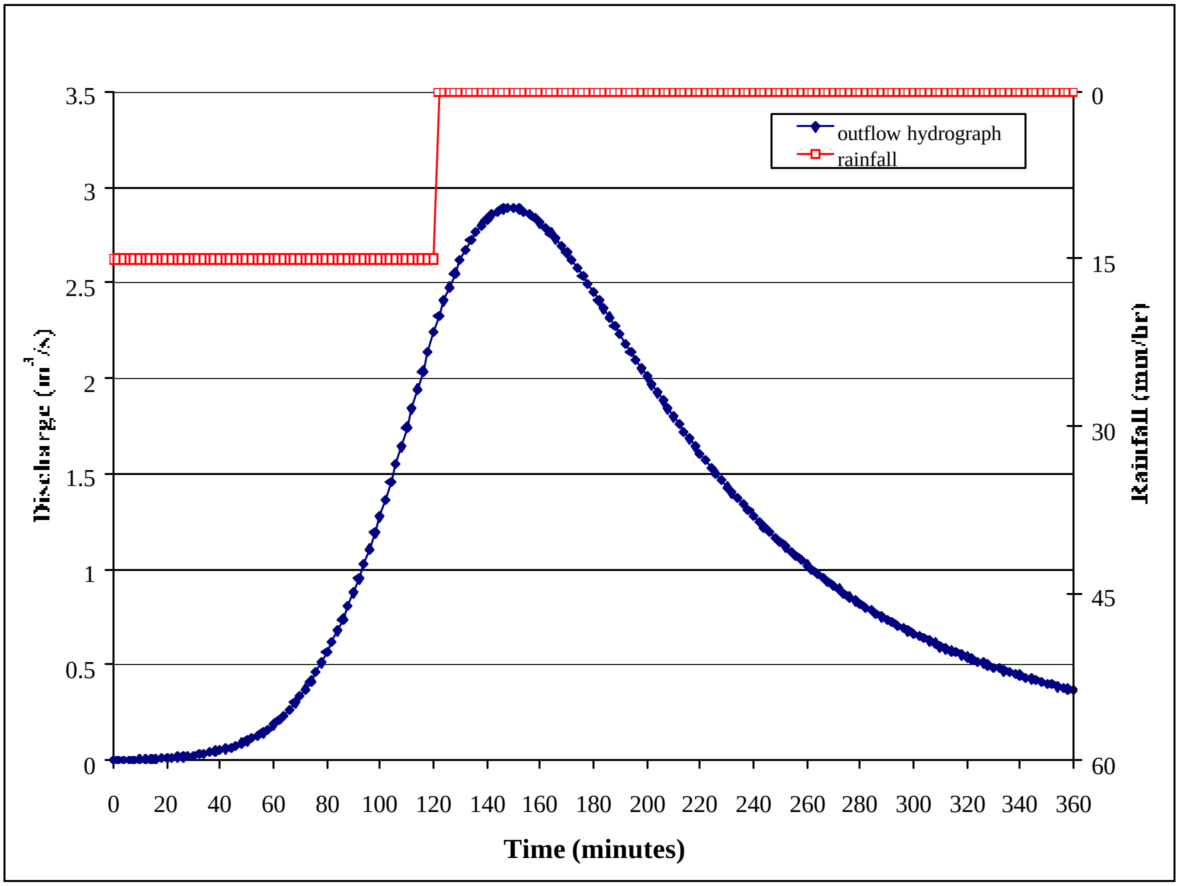


Figure 9 Outflow hydrograph at watershed outlet from CASC2D.

Seven overland flow depth plots (Figures 10-16) clearly demonstrate the spatial capabilities of CASC2D. Based on these plots, the model appears to be doing an adequate job of simulating runoff. One can examine the outflow hydrograph time in Figure 9 (0 to 360 minutes) to see the behavior of the outlet cell and gain an understanding of the watershed runoff at different times. One problem that was not resolved for this Task was how to classify and clearly display the depth maps. A simple color classification was used for this report. However, it is inadequate as the legend is not constant from map to map (colors do not represent constant depth intervals). This will be improve in future studies.

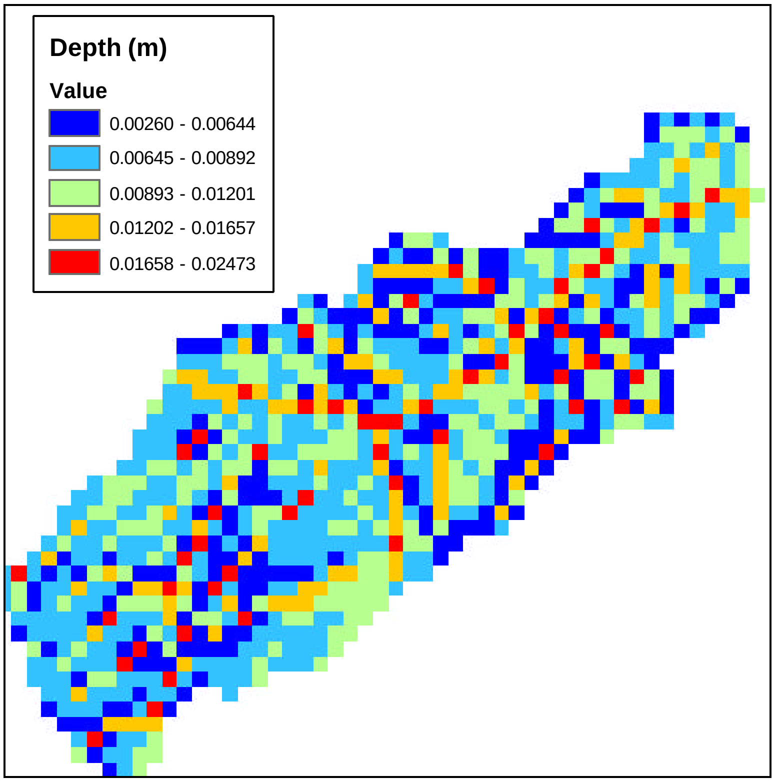


Figure 10 CASC2D depth map output at time = 40 minutes.

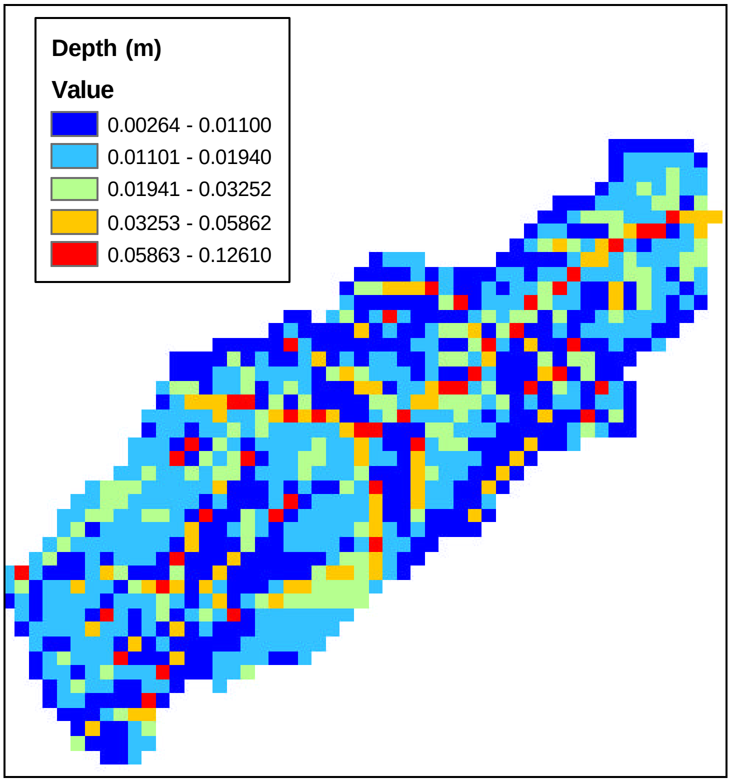


Figure 11 CASC2D depth map output at time = 80 minutes.

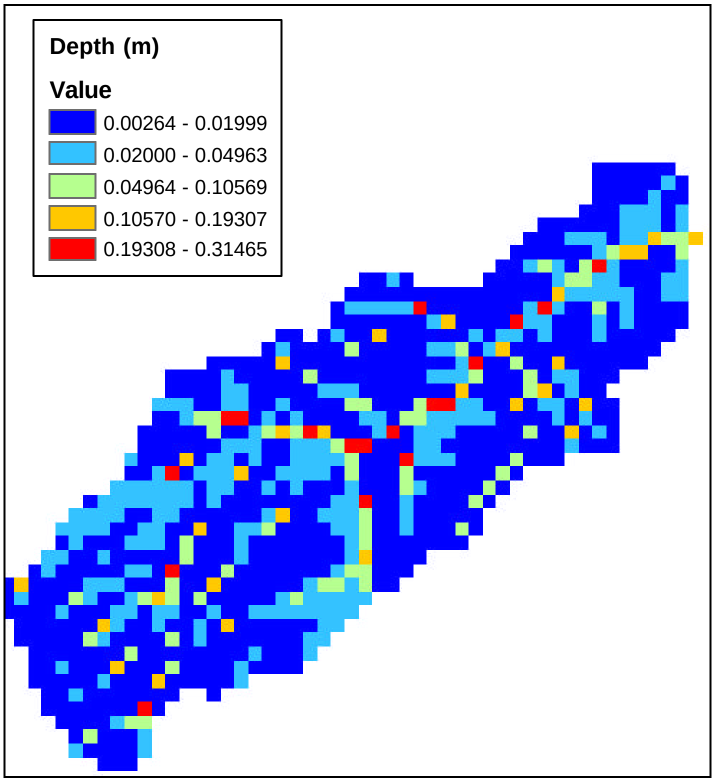


Figure 12 CASC2D depth map output at time = 120 minutes.

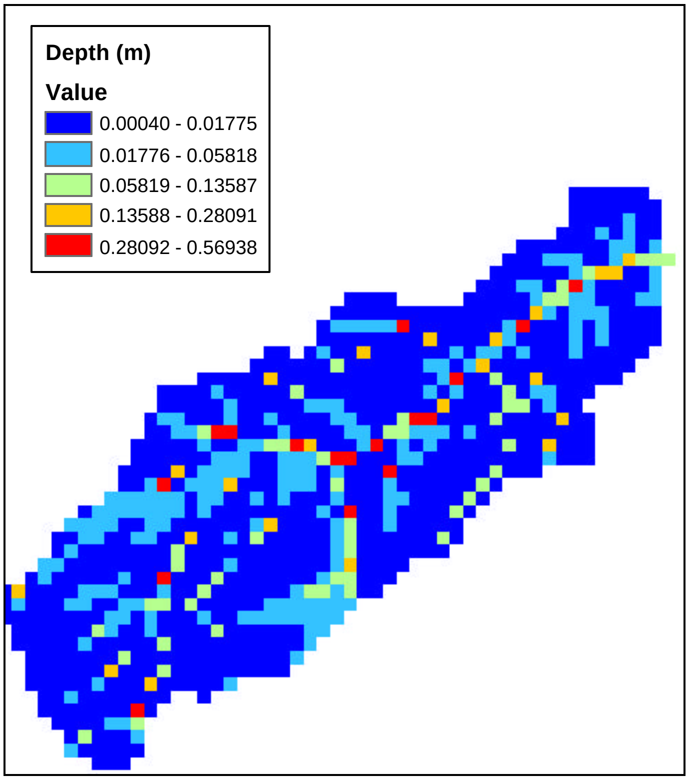


Figure 13 CASC2D depth map output at time = 150 minutes.

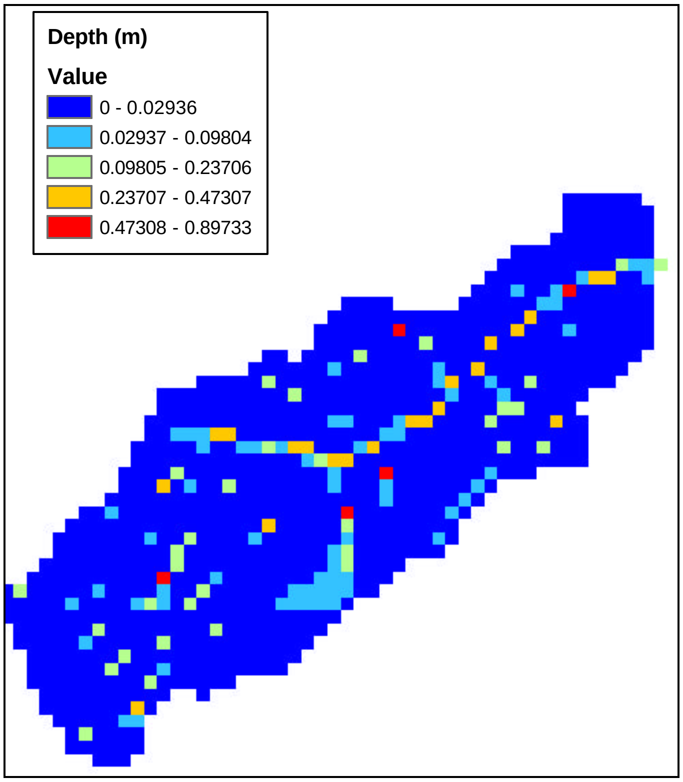


Figure 14 CASC2D depth map output at time = 180 minutes.

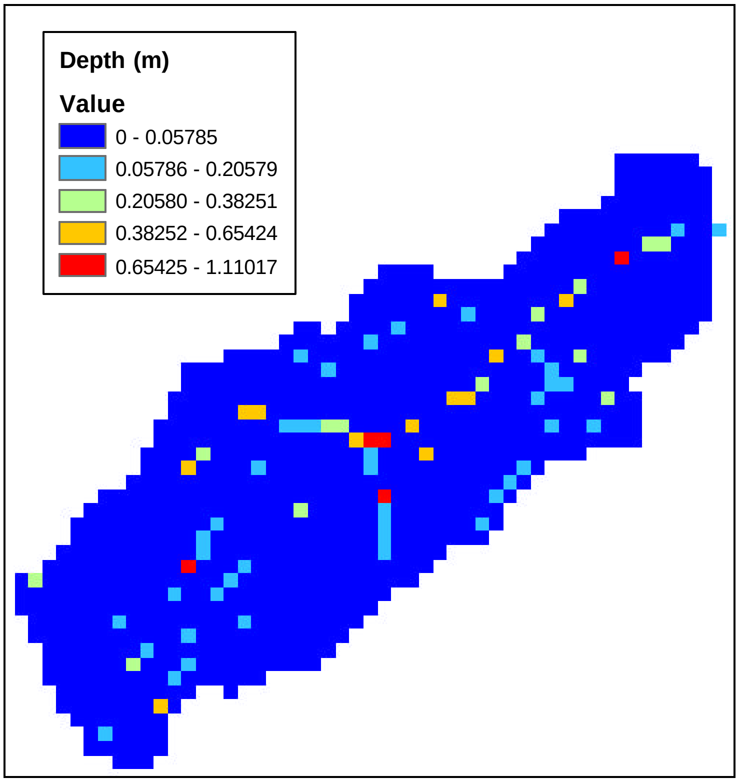


Figure 15 CASC2D depth map output at time = 260 minutes.

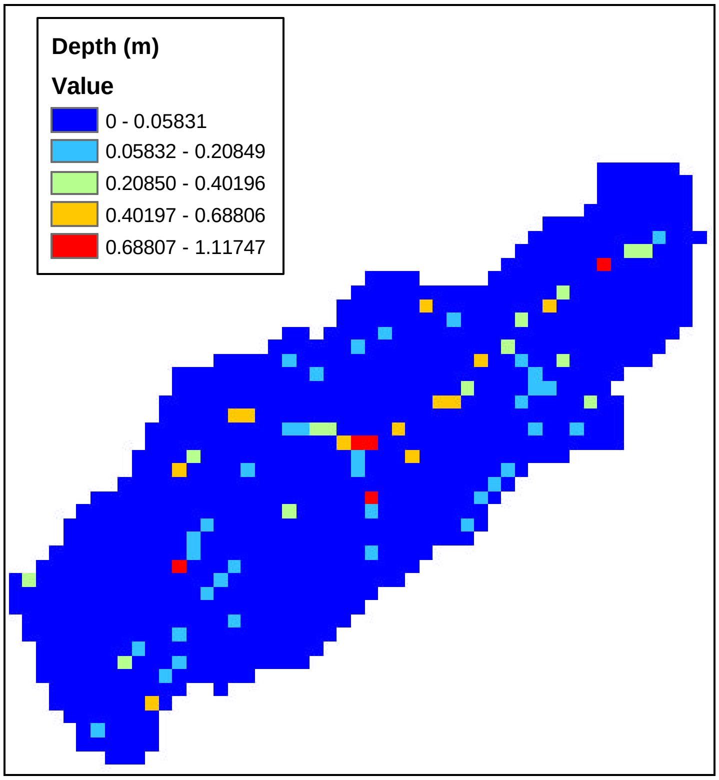


Figure 16 CASC2D depth map output at time = 320 minutes.

CONCLUSIONS AND RECOMMENDATIONS

There were three objectives for this study:

1. Explore CASC2D as a physical basis for extrapolating large floods by using the model and apply it to a watershed;
2. Demonstrate how ArcGIS can be used to create input data for CASC2D; and
3. Demonstrate how ArcGIS can be used for post-processing results.

All these objectives were completed to some degree. The rudiments of CASC2D were learned, including input/output, and some experience was gained with learning C++ and getting familiarized with the model source code. It is clear that ArcGIS can be used to create input data and display output results from CASC2D. The Task is considered a success from this standpoint. In addition, the model results appear reasonable for the simple case considered as part of this study.

There are several recommendations that are made as a result of this study; most are made due to the limited time to complete the Task. The CASC2D source code needs to be modified and improved to handle some basic data cases: no sediment transport and no infiltration. The Excel interface needs some minor improvements. The CASC2D modeling for Soda Creek watershed needs improvement. The actual soils and landuse maps need to be used, instead of single index values. Channels need to be defined, and ArcGIS should be used to create link and node maps, and run the channel routing option. The model needs calibration against several observed rainstorms. In subsequent applications, the grids need to be better clipped closer to watershed boundaries, to conserve computer memory for larger watersheds.

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APPENDIX C

CASC2D PREPROCESSING PROGRAMS SUMMARY

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This appendix provides a current listing of data preprocessing programs, termed CASC-AIDS, to help develop input files for CASC2D. There are currently four programs: row-col-coords, linknodegen, channelfilegen, and netelevcheck. The programs are written in ANSI C. Each of the programs is briefly described below. Complete documentation, source code, and examples for each of the programs are available by contacting the author.

CASC-AID PROGRAM *ROW-COL-COORDS*

Program Purpose and Background

The CASC-AID program *row-col-coords* is used to determine the model grid row and column of user-desired location points (*x*,*y*) for input to CASC2D. The four user-input locations that are currently supported by CASC2D and this program are:

- overland sources (flows, solids, chemicals);
- channel sources (flows, sediments, chemicals);
- outlets (overland or channel); and
- reporting stations (overland or channel for flows, solids, chemicals).

It is important to understand the basic model grid geometric configuration that is used in the CASC2D model, and the data processing tools that are currently used to generate model grids. CASC2D uses a two-dimensional square grid mesh as the geometry to solve overland flow equations for a watershed (Figure 1).

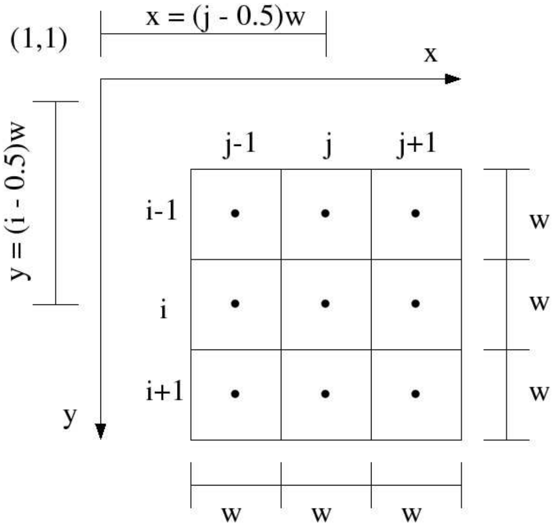

Figure 1. A typical two-dimensional model square grid mesh for CASC2D (after Julien and Saghafian, 1991)

Notice that rows are defined from the upper left corner and start with row 1, column 1 (1,1) (rather than at 0,0). Typically, the variable *i* is used to designate rows and *j* designates columns.

CASC-AID PROGRAM *LINKNODEGEN*

Program Purpose and General Description

The CASC-AID program *linknodegen* is used to develop a link map and node map (grid) files, and a link/node numbering file. The link and node maps can be directly read in by CASC2D. The link/node numbering file can be subsequently used by CASC-AID program *channelfilegen* to derive the channel properties input file for CASC2D. The three ASCII output files from *linknodegen* are:

(1) a link map (grid) file;
(2) a node map (grid) file; and
(3) a link/node numbering text file with a printout of link numbers with the corresponding number of nodes in each link.

The format and contents of the link and node map files are described in the CASC2D Data Groups document.

CASC-AID PROGRAM *CHANNELFILEGEN* (version 2.0)

Program Purpose and General Description

The CASC-AID program *channelfilegen* is used to develop channel input files for watersheds and river networks in a pseudo-automated fashion. Using the program *channelfilegen*, the user can create two files for subsequent input to CASC2D:

(1) a channel properties file; and
(2) an initial water in channels file.

The format and contents of these two files are described in the CASC2D Data Groups document. The program *channelfilegen* currently gives the user three options of base data input to generate the channel properties and initial water in channels files. For the first option, channel properties and initial water depths are assumed constant throughout the entire stream channel network. For the second option, channel properties and initial water depths are assumed constant within a particular link. If desired, the user can manually edit the text output files from the second option to modify channel properties of particular nodes within a link. The third option enables the user to estimate base width and bank height channel properties based on a selected flow and downstream hydraulic geometry techniques. Similar to the first two options, the user may specify constant properties within the entire network or within a link, in addition to spatially-varying base width and bank height estimates.

CASC-AID PROGRAM *NETELEVCHECK*

Program Purpose and General Description

The CASC-AID program *netelevcheck* is used to check and optionally modify elevations of grid cells within the stream channel network in a pseudo-automated fashion. The goal is to smooth the elevations of the channel network cells and eliminate adverse and/or zero slope segments or reaches. Using the program *netelevcheck*, the user can check elevation differences between nodes (adjacent cells) and report them for all nodes. If elevation differences are less than or equal to zero, the user may optionally modify the elevation grid for subsequent input to CASC2D. Output from this program is:

(1) an output file of all nodes with elevation differences less than or equal to zero;
(2) a debug file with elevation differences reported at all nodes; and
(3) an elevation grid with modified elevations for selected channel grid cell locations within the channel network {OPTIONAL}.

The format and contents of the elevation grid is described in the CASC2D Data Groups document. The program *netelevcheck* currently gives the user five options of base data input to check and/or modify the elevation values for the stream channel network.

The first option (Option 0) is a diagnostic run. For Option 0, the user enters the minimum required amount of input, and the output is a diagnostic file of elevation differences at each node. This file then can be interpreted by the user to subsequently modify elevations in the stream channel network. It is recommended that the user run Option 0, determine if any adjustments need to be made, and the method of adjustment.

There are five methods of adjustment to modify channel grid cell elevations for zero channel slopes with grid-based DEMs and watershed modeling with CASC2D (Options numbered 1 to 5). Option 1 allows the user to enter a minimum slope value that will be used to subsequently modify elevations that fall below this criterion (node focus). For this option, minimum slope values between successive node locations are assumed constant throughout the channel network. In addition to Option (1), the other four that are briefly described here are not yet implemented in the *netelevcheck* program. Option 2 allows the user to estimate an average slope for an individual link and modifies the elevations of all the nodes within that link (link focus). For Option 3, the user enters a slope estimate for each specified link. The user can typically estimate the link slopes from: (a) direct field measurements; (b) from higher-resolution DEM data; and /or (c) from USGS topographic quadrangles. The user enters the number of links to modify and a table of link numbers and slopes. Option 4 enables the user to estimate spatially-varying slope properties between successive links/nodes based on a selected flow *Q* (e.g. bankfull) and downstream hydraulic geometry techniques. Power functions are used to estimate discharge based on drainage area and slope based on discharge. Option 5 adjusts elevations so that the reach corresponds to Hack's Law. Currently, Options 2, 3, 4 and 5 are not operational or tested yet. The basic input for these options has been programmed in *netelevcheck*, but processing techniques have not been developed.