Distributed Modeling of Extreme Floods on Large Watersheds

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Abstract

Estimates of extreme floods and probabilities are needed for hydrologic engineering and dam safety risk analysis. 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 two dimensional, physically-based rainfall-runoff model (CASC2D) to estimate extreme floods and probabilities for dam safety on a large (12,000 km^2) watershed, the Arkansas River above Pueblo, Colorado. New tools have been developed so the model can be applied at this scale. CASC2D can be successfully used to model extreme floods based on observations of extreme rainfall (from both rain gage networks and weather radar) for large watersheds. Future research will focus on the storm transposition concept and linkages with radar.

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. Typical extreme flood estimates include peak flow, volume, timing, 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 analysis 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 complete flood hydrograph.

Reclamation currently uses risk analysis to assess the safety of dams and prioritize expenditures (Reclamation, 1999, 2003). The ideal flood inputs required for risk analysis are frequency distributions of peak flows, volumes, and peak reservoir stages which, for dams with potentially high loss of life, might extend to very low probabilities. 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). The PMF is currently recognized as a practical upper limit to flood frequency extrapolations at a site for storm durations defined by the PMP (Reclamation, 2002; Swain et al., 2004). One of the main 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.

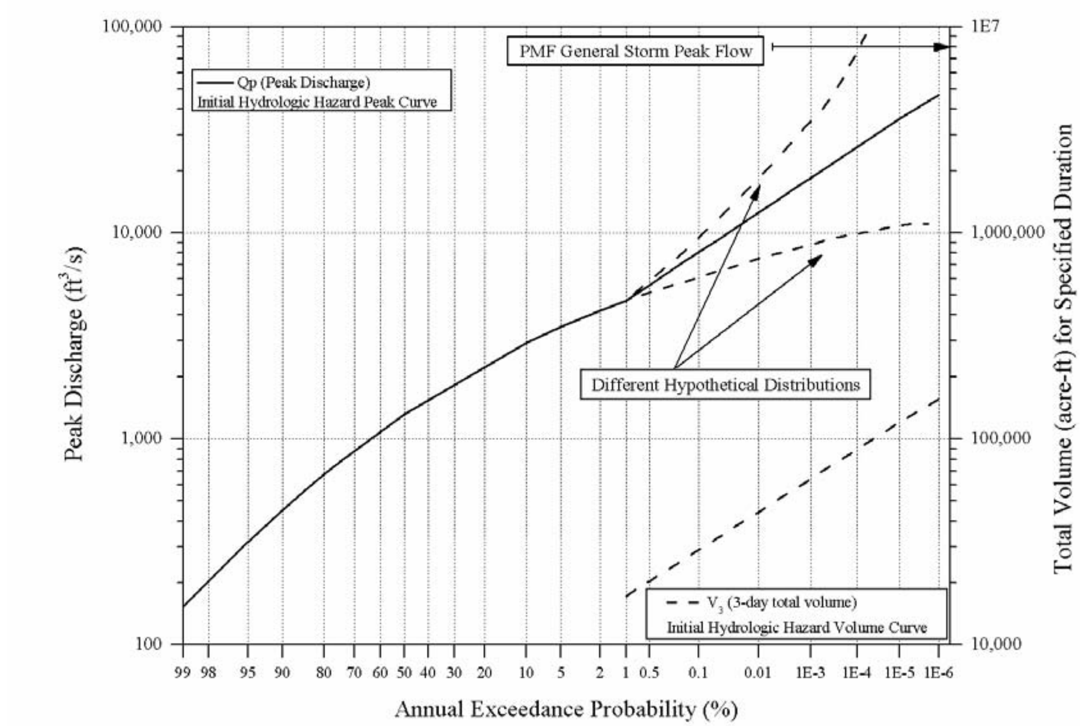

Figure 1. Example hydrologic hazard curve (after Swain et al. 2004). Different hypothetical extrapolation assumptions are shown.

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) suggest 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 to investigate this issue. The eventual goal is to develop improved methods to extrapolate flood frequency curves and develop extreme flood hydrographs. The remainder of this paper describes ongoing improvements to the CASC2D model for extreme floods on large watersheds, a framework for derived flood frequency, preliminary results on the 12,000 km^2 Arkansas River basin, and some comments on further work that is in progress.

CASC2D Rainfall-Runoff Model and Improvements

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. CASC2D is appropriate for simulating extreme floods and physically-based extrapolations of frequency relationships, combined with a derived distribution approach. CASC2D is also a somewhat experimental model that has not previously 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) 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 1. The model requires four main parameters for each grid cell, and one parameter for each channel segment (Table 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. The CASC2D components that have been modified, tested and enhanced as part of this research are summarized in Table 2.

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 an improved basis for derived flood pdf extrapolation.

Table 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)

Table 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.

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. 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:

$$\bar{d}_c(\Delta t) = \frac{1}{|A_c|} \int\int [d(x, y, t_s + \Delta t) - d(x, y, t_s)] dxdy$$

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:

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

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):

$$G(q) = 1 - \int\int\int\int pr\left[Q_p \le q \mid \omega, w_o, \psi, \tau(t)\right]$$
$$\times f_\Omega(\omega) f_{Wo}(wo) f_\Psi(\psi) f_{T(t)}(\tau(t)) d\omega \omega d_o d\psi \psi d(t)$$

where W is the vector of storm characteristics and locations, W_o is the initial storage condition, Y is the vector of runoff model properties, and $T(t)$ is the temporal distribution of storm depths. Difficulties in implementing SST procedures arise from spatial heterogeneities in the distribution of extreme rainfall. These features are especially important in mountainous regions, like the upper Arkansas River basin. To address these issues, we have developed a catalog of space-time rainfall patterns in the upper Arkansas River basin from analyses of high-resolution weather radar observations (Javier et al., 2004). This "local" storm catalog for the upper Arkansas River basin will be used along with conventional storm catalogs of extreme rainfall to develop SST tools that reflect the orographic controls of extreme rainfall.

Arkansas River Basin Application

The study watershed is the 12,000 km^2 Arkansas River basin and Reclamation's Pueblo Dam, immediately upstream from Pueblo, Colorado. A general outline of the watershed, including major tributaries, towns, and gage locations is shown in Figure 2.

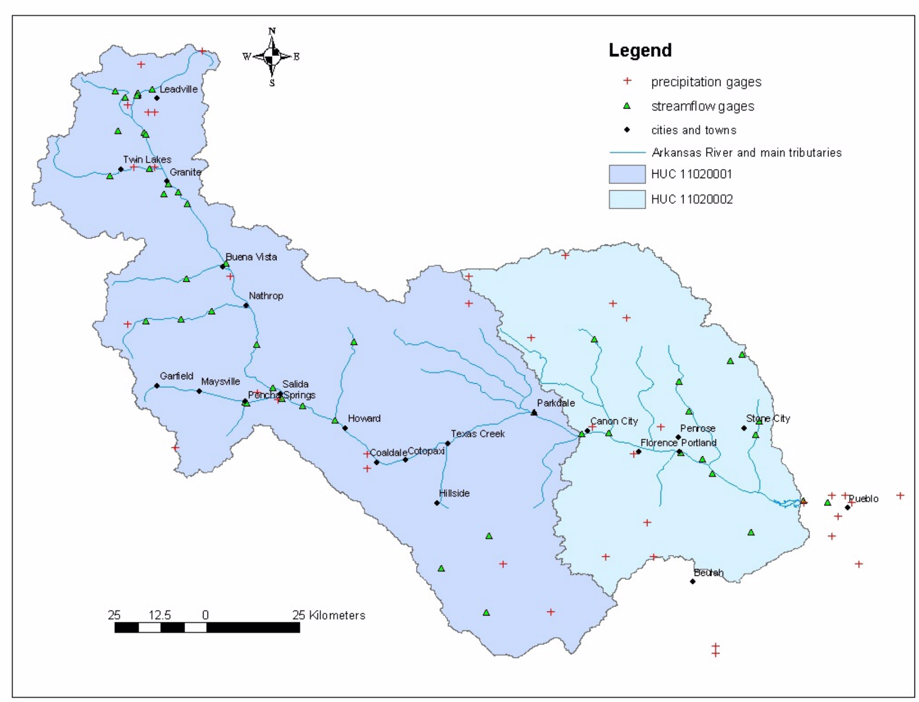

Figure 2. Arkansas River Basin study watershed upstream from Pueblo, Colorado.

The available data within the Arkansas River watershed for CASC2D model parameter estimation and calibration consists of: a DEM, land use and land cover, surficial soils, 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%). Areas of the watershed with elevations greater than 3,000 m are usually snow-covered from November through mid-April. The Arkansas River watershed is subject to extreme flooding in the warm season (April through August) from cloudburst rainfalls, snowmelt runoff, and spring general rainstorms. Topography is the major influence on extreme precipitation. The largest recorded floods at streamflow-gaging stations on the Arkansas River main stem upstream of Cañon City have been from snowmelt. At Cañon City and downstream, the largest peak flows have been from rainfall-runoff, including the disastrous June 1921 flood.

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*, spatially varying infiltration, 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. Further input details of this run are described in England (2005). The result from this simulation is shown via a hydrograph in Figure 3, and depth maps at hour 11 (Figure 4) and hour 18 (near peak) in Figure 5.

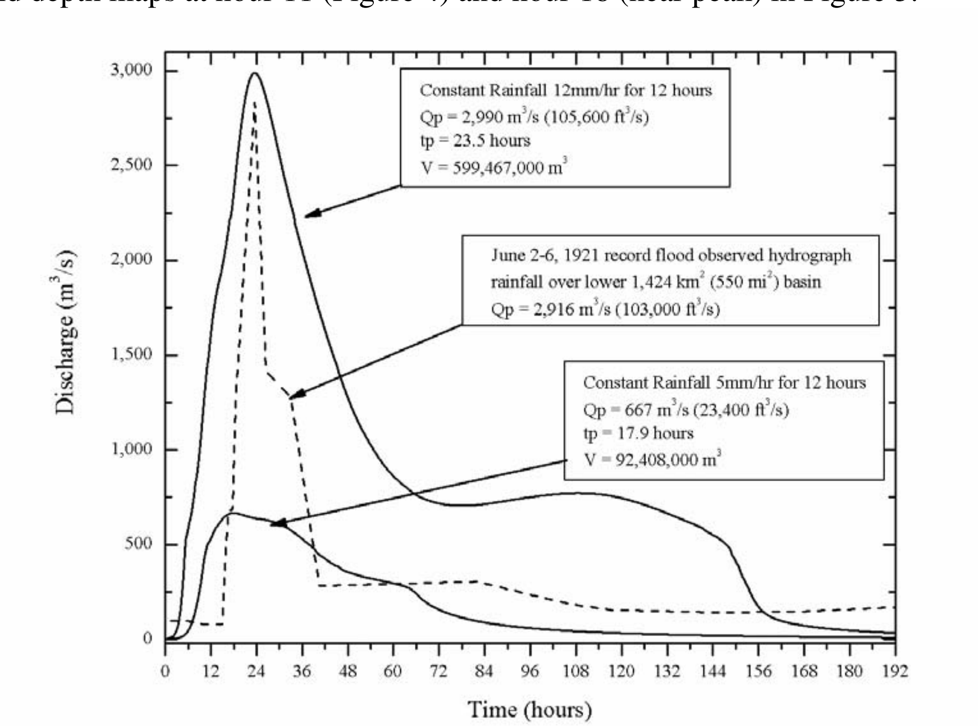

Figure 3. Arkansas River watershed outlet hydrograph of CASC2D basic and extreme flood runs, compared with the record June 2-6, 1921 observed hydrograph.

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.

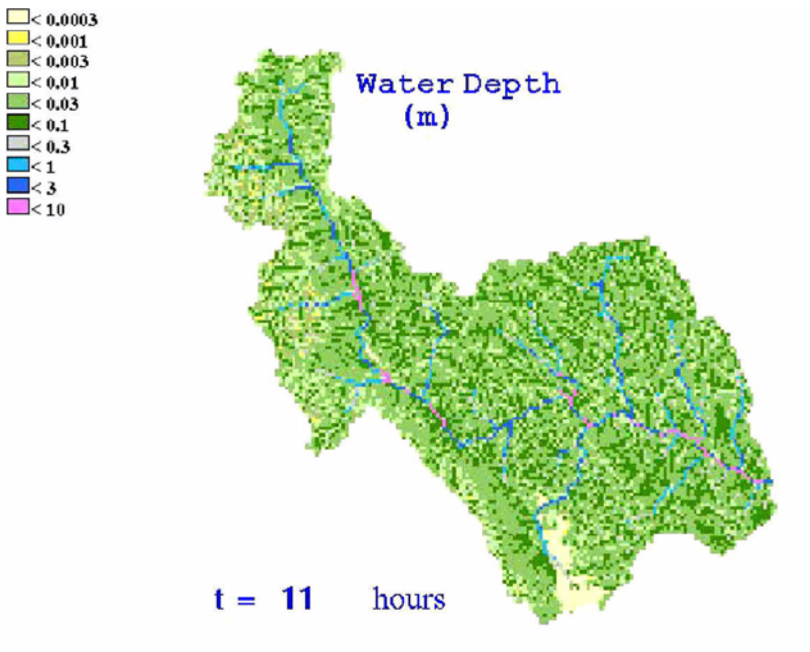

Figure 4. CASC2D basic run watershed depth map at 11 hours.

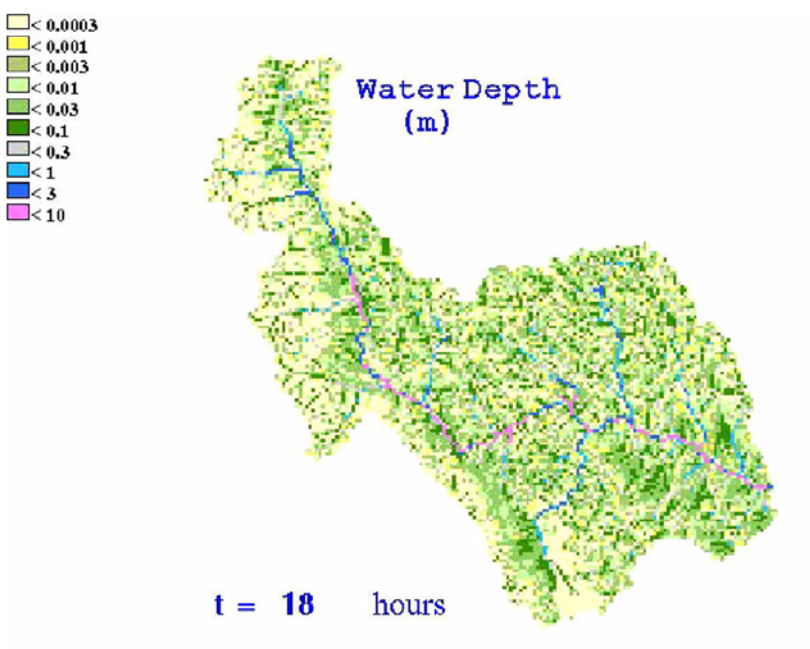

Figure 5. CASC2D basic run depth map at 18 hours (peak); largest depths are in channel network.

It is also 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*, spatially varying infiltration, 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 with the June 1921 hydrograph in Figure 3. The estimated peak flow approximates that from the June 1921 flood of record (2,900 m^3/s). Notice that the hydrographs have approximately the same shape, even with no calibration. The simulated hydrograph has a larger volume as it was assumed to rain over the entire basin, rather than the limited area of the June 1921 storm. Future work will address this issue.

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 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 6.

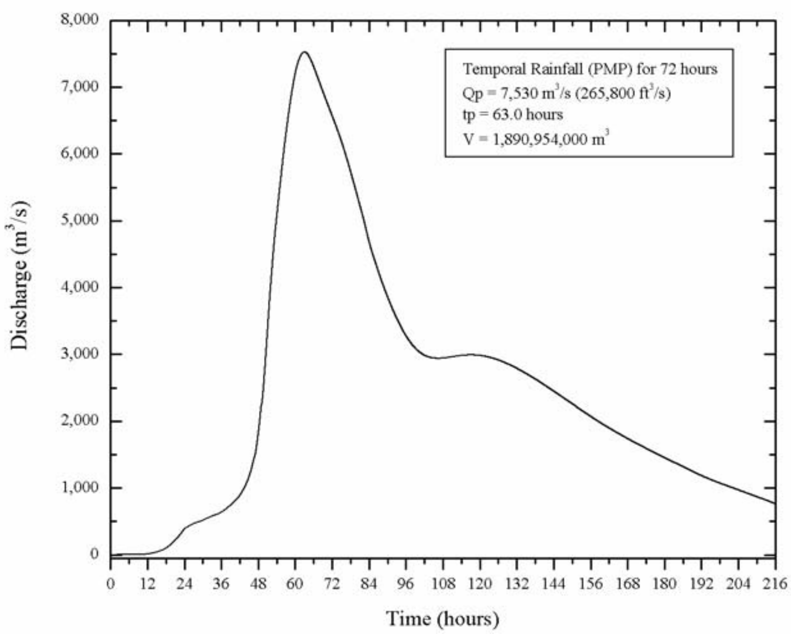

Figure 6. CASC2D runoff hydrograph at outlet based on PMP.

The result shown in Figure 6 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, due to the PMP rainfall temporal pattern with a peak at 48 hours. 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.

Conclusions and Further Work

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. In order to successfully apply CASC2D on large watersheds, four data preprocessing routines that facilitate channel grid generation have been written, initially tested, and applied to the Arkansas River basin. GIS data has been processed and initial model parameter estimates have been made. The model has been run on this large watershed as well.

It has been demonstrated that CASC2D can be used to simulate extreme floods on large watersheds. Two initial extreme flood runs of CASC2D have been completed on the Arkansas River basin. The results indicated the model is stable for spatially uniform extreme rainfall rates and can produce reasonable hydrographs. One sensitivity run with spatially-uniform, time varying PMP rainfall has been completed.

The CASC2D model can simulate extreme floods on large watersheds, but further work is needed to calibrate and verify the model on this watershed. Flood frequency with paleoflood data will be used in-part for this purpose. The physically-based, derived flood frequency framework needs complete testing on the Arkansas River basin. Further work is needed on applying and testing the Stochastic Storm Transposition concept for regions of complex terrain, like the upper Arkansas River basin. In particular, ongoing efforts will provide the tools for linking conventional storm catalogs to radar-derived storm catalogs that capture the orographic controls of extreme precipitation.

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