

Peak Flow Forecasting with Radar Precipitation and the Distributed Model CASC2D

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Abstract: *The processing speed of computers and availability of spatial hydrologic data make distributed watershed models a viable approach for many applications, including peak flow forecasting. This study demonstrates the feasibility of using radar precipitation data with a distributed watershed model to obtain increased lead-time for peak flow forecasting. The CASC2D watershed model is applied to the Hassayampa River watershed in central Arizona using radar-based rainfall estimates from the National Weather Service WSR-88D weather radar. An application of radar rainfall data as input to the CASC2D model is then presented by which precipitation forecasts are generated by extrapolation of precipitation patterns from radar images. The calibrated model is run for two rainfall events: with and without linear precipitation forecasts. Results of this study confirm that the precipitation forecasts based on extrapolation of rainfall patterns from radar can produce increases in the forecast lead-time. For the two events presented, the forecast lead-time was increased by four to five hours, which can be significant when issuing flood warnings.*

Keywords: *distributed modeling, flow forecasting, lead time, radar precipitation, weather radar, watershed model*

Introduction

Forecasting the peak flow in a stream or river is a very complex process. Many variables impact the ability to generate reliable and useful forecasts including the amount of precipitation, the temporal and spatial distribution of rainfall, the characteristics of a watershed that affect overland runoff, and the characteristics of stream channels. Of these variables, those that have traditionally been most difficult to capture for a specific storm event are the spatial and temporal precipitation characteristics. Historically, the spatial distribution of precipitation over a watershed has been estimated from a sparse network of precipitation gauges located in or near the watershed. As an alternative to precipitation gauges, the National Weather Service (NWS) WSR-88D (Weather Surveillance Radar-1988 Doppler) weather radar units provide rainfall estimates at a spatial and temporal scale that can make a significant difference in the ability to obtain reliable and more accurate forecasts of peak runoff. In this paper, radar data are used in conjunction with a runoff model that is capable of adequately capturing the spatial detail of the precipitation.

Watershed models have traditionally been “lumped” models that employ average values of hydrologic parameters over relatively large sub-areas of a watershed such that the spatial detail of precipitation is often lost when it is averaged over them. The processing speed of computers and increased availability of spatially-distributed hydrologic data have made distributed watershed models a feasible approach in real time forecasting. In a distributed model, the watershed is subdivided into a grid, and hydrologic characteristics are assigned to each grid cell based on the physical land and soil characteristics that exist in that cell. Precipitation is then applied over each cell in the watershed with the runoff being computed and routed in two dimensions to the collecting channel. The strengths of this approach are that model parameters are largely physically based, and this allows the spatial variability of the land, soil, and precipitation to be captured with much greater detail than has previously been practical in watershed modeling.

Over the past 25 years or so, weather radars have become an integral part of operational meteorological observing systems (Collier, 2002). Recent developments in radar-based flood forecasting include the peak flow esti-

mates obtained from a combination of GIS, NEXRAD and internet data by Bedient et al. (2003) and the application to the Allison Flood of June 2001 in Houston, Texas. Applications to large urban areas include the flood warning system of the Metropolitan area of Sao Paulo by Filho and Barros (1998) where flood forecasts of the Tiete River are performed at a 2 km by 2 km scale within Sao Paulo City, with rainfall field estimated from reflectivity data combined with rain gauge measurements.

Applications in mountainous areas and related rainfall biases due to high elevation radar scans have been examined by Borga et al. (2000), and Mecklenburg et al. (2000). From investigations in the Mediterranean basin, future improvements on methods using essentially infrared satellite images may be possible when using multiple channel satellite estimates. Johnson (2000) provided an assessment of alternate flash flood warning procedures to ascertain their suitability for forecast operations using radar-rainfall imagery. The procedure was applied to Buffalo Creek, Colorado where a forest fire occurred a few months before the flood and significantly affected watershed runoff characteristics. In the UK, Bell and Moore (2000a) developed a model assimilating weather radar, satellite infrared and surface weather observations with applications at the Warden Hill Radar in Dorset, Britain. The best performance was obtained from the dynamic model using "inferred up draughts" where up draught velocity is determined from solving the mass balance equations over the last two radar fields.

Models have also been developed by Engeset et al. (2003) in areas significantly influenced by snowmelt. Their analysis includes comparisons of simultaneous data from AVHRR, SAR and Landsat ETM+. The accuracy of radar estimates versus true basin rainfall is still the subject of research (Wood et al., 2000), and the need to recalibrate models for use with rainfall data of a given resolution for convective rainstorms has been examined (Vieux and Bedient, 1998; Bell and Moore, 2000b).

The objective of this paper is to document and demonstrate the feasibility of one potential method for increasing forecast lead-time in predicting peak runoff through the combined use of radar and distributed modeling technologies with radar-based precipitation forecasts. The physically-based distributed hydrologic model CASC2D developed by Julien et al. (1995) is applied to the Hassyampa River watershed in Arizona and radar based rainfall estimates and forecasts are used as precipitation input to the model (Jorgeson, 1999).

CASC2D Model Overview

CASC2D is a physically-based watershed model that uses square grid cells to provide a spatially distributed representation of the watershed and precipitation domains (Julien et al., 1995). The model consists of several major components including infiltration, overland routing, channel routing, upland erosion and sedimentation. Overland

flow routing of excess precipitation and channel routing is based on an explicit solution of the diffusive wave form of the de St. Venant equations with the overland routing being performed in two dimensions and the channel routing in one dimension. Basic input requirements of the model are elevation, surface roughness, soil parameters, channel network, channel cross-sections, channel roughness, and precipitation.

Output from lumped parameter models is generally limited to discharge hydrographs for the various sub-basins in the model. The CASC2D model, however, offers much more. In addition to discharge hydrographs, which can be defined for any number of locations in the channel network, the model computes and can generate time series maps of spatial output. These time series maps include surface water depth, cumulative infiltration depth, surface soil moisture, infiltration rate, and distributed rainfall intensity. For each of these, a map can be saved at specified time increments during a simulation. These maps can be animated similar to a videotape or film loop to allow the user to easily see the complete temporal and spatial variation of each of the above parameters for the simulation.

Modeling the Hassyampa Watershed

The Watershed

The Hassyampa River basin covers approximately 1,111 km² and is located to the northwest of Phoenix with the outlet of the basin near Wickenburg, Arizona. The Hassyampa River's headwaters are located in the Prescott National Forest, and the majority of the basin is in fairly mountainous terrain. The streams in the basin are generally steep and well incised with some washes in the lowest part of the basin. The elevations in the basin range from 2,400 meters to the low elevation of 750 meters at the basin outlet. Downstream of the gauging station near Wickenburg, the river flows south and ultimately into the Gila River. Precipitation events in the area are typically of two distinct varieties. High intensity, short duration thunderstorms are common in the late summer months while rainfall from slower moving frontal systems generally occur in the winter and spring months (CH2M Hill, 1990). Figure 1 provides a map of the Hassyampa River basin with the watershed boundary, stream network, and rain gage locations used in this study indicated.

Data Collection

The data collected for modeling the watershed with CASC2D included digital elevation data, land use/land cover data, soil data, channel cross section and roughness data, precipitation data, and stream flow data. Elevation data for the model was obtained from the United States Geological Survey (USGS) in the form of 1:250000 scale Digital Elevation Model (DEM) (USGS, 1987). The drainage basin area was delineated using the TOPAZ (TOPographic PARAMeteriZation) model (Brigham Young University, 1998), and the resultant elevation grid was re-sampled from

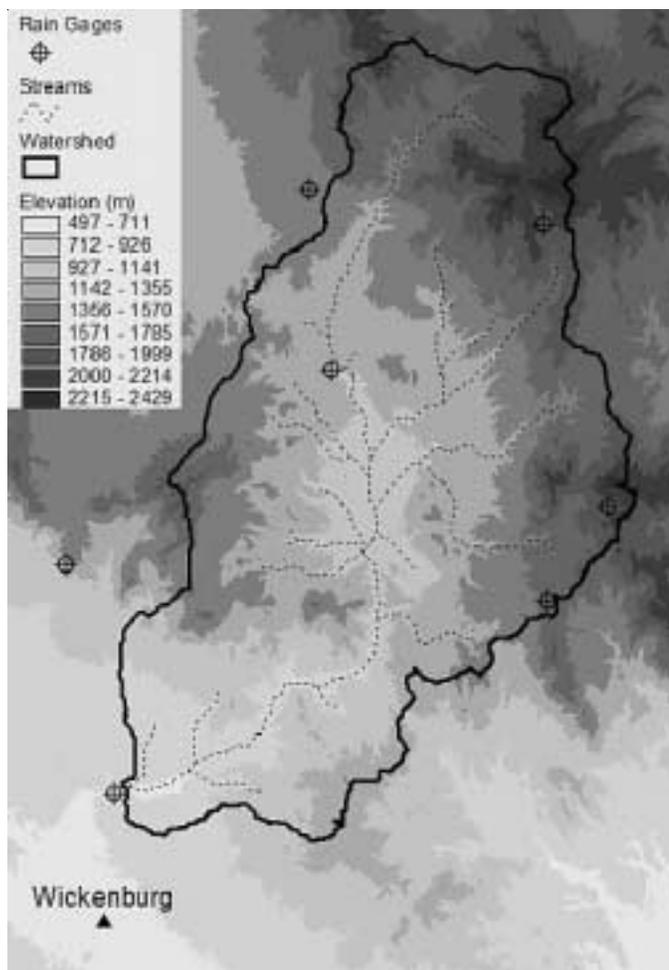


Figure 1. Hassyampa River Watershed map

the original resolution of approximately 90 meters to a spatial resolution of 200 meters. Molnar (1997) showed that outlet runoff can be simulated using CASC2D at coarser grid resolutions, provided that the model parameters are specifically calibrated at that coarser resolution. This generally requires a higher overland surface roughness coefficient to compensate for the fact that surface runoff reaches the channel more quickly at coarser grid size.

Overland routing in CASC2D requires a Manning n roughness parameter for each grid cell. Manning n values were assigned based on the land use and vegetative cover that exists on a given cell. Land use/land cover data at 1:250000 scale were obtained from the USGS which provide raster coverage at a spatial resolution of 200 meters (USGS, 1990), and roughness coefficients based on data from Engman (1986) were assigned based on the land use category. Predominant land use categories in the Hassyampa watershed were crops, rangeland and forest.

To compute infiltration, CASC2D uses the Green-Ampt approach that requires values of saturated hydraulic conductivity, effective porosity, capillary suction head, and soil moisture deficit for each cell. Soil moisture deficit represents initial soil moisture conditions where 0 percent deficit would indicate complete saturation. Soil data were obtained

from the Natural Resources Conservation Service (NRCS) State Soil Geographic (STATSGO) Data Base (USDA, 1994), and parameters assigned based on data from Rawls et al. (1983). The two primary soil types used in the Hassyampa watershed model were clay-loam and sandy-clay.

No detailed cross-section data were available for the Hassyampa River basin, so channel properties for that basin were assumed to be similar to those in the nearby Cave Creek basin based on topography and contributing drainage area. Channel data for the Cave Creek basin were obtained from a floodplain delineation study that was performed during 1997 for the Flood Control District of Maricopa County, Arizona (George V. Sabol Consulting Engineers, 1997a; 1997b). Similarly, channel roughness values for the Hassyampa River basin were assigned based on those for similar channels in the Cave Creek basin.

The radar data used for this study were from the National Weather Service WSR-88D radar system in Phoenix, Arizona. The specific data format used was the Stage I Digital Precipitation Array (DPA). The Stage I DPA data are produced directly from the reflectivity measurements of the radar system using an assumed rainfall-reflectivity relationship. These data are produced at the radar site in real time and undergo no quality control or calibration based on ground observations. For this study, validation of the radar rainfall estimates was performed through calibration of the Z-R relationship. This calibration process involved comparing the rainfall intensity measurements from the radar with those from rain gauges for four precipitation events and adjusting the Z-R relationship for the radar data to match the rain gauge data. The rain gauge data were from 19 gauges located in the region of the Hassyampa River watershed, and those data were provided at 15-minute time intervals. After this calibration process, the total precipitation measured over the Hassyampa River watershed by radar for the February and March events was within 1 percent of the rainfall total measured by the rain gauges in the basin (Jorgeson, 1999).

Model Calibration and Verification

The CASC2D model of the Hassyampa River was calibrated using observed precipitation from seven rain gauges located in and near the basin and discharge data from a stream gage at the basin outlet for an event in February 1995. The two principal criteria used in the calibration process were the peak discharge and the time to peak. Adjustments were made to the initial assumed values for the soil moisture deficit and surface roughness parameters, and Table 1 provides a summary of the model results compared to the observed data. Figure 2 shows

Table 1. Calibration results for Hassyampa River—February event

Hydrograph	Peak Flow	Time to Peak
Observed	370 m ³ /s	45.00 hr
CASC2D	391 m ³ /s	44.95 hr
% Difference	5.7 %	0.1 %

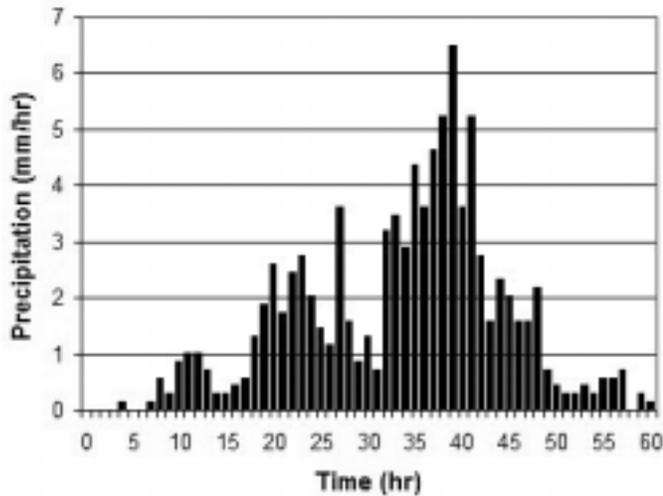


Figure 2. Average hourly precipitation intensity over watershed – February event

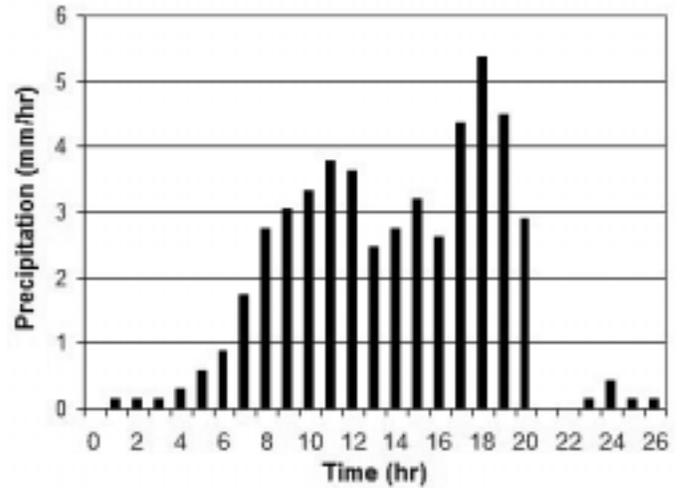


Figure 4. Average hourly precipitation intensity over watershed – March event

the temporal distribution of the average precipitation over the watershed during the February calibration event, and Figure 3 shows the CASC2D computed and the observed hydrographs for that same event.

Data were available for one additional runoff event from March 1995 with which to verify the calibration parameters for the Hassyampa River model. For verification of the model, the same parameter values as the calibration were used, with the exception of the initial soil moisture conditions. The initial soil moisture conditions for the March event were different than in February, and the initial soil moisture deficit in the verification process was adjusted accordingly. With this sole adjustment to the parameters, the validation model was run. The temporal distribution of the average precipitation intensity over the watershed during the March validation event is shown in Figure 4, and the validation hydrograph is shown in Figure 5 along with the observed runoff from that event.

Several illustrations of the types of spatial output that are available from CASC2D are presented in Figures 6a through 6e. Figure 6a shows an image of the spatial distribution of rainfall from the model based on radar rainfall input, while Figure 6b provides a different image of rainfall as it is distributed over the watershed based on inverse distance weighting from rain gauge input. Note that these two images do not show the same rainfall event but are included to illustrate the “block” pattern of rainfall from the radar data which can clearly be seen in Figure 6a as compared to the pattern that results from inverse distance weighting of the data from rain gauges in Figure 6b. Figures 6c through 6e depict the surface water depth at three points in time during the February runoff event. In the first image, surface runoff is just beginning to accumulate over portions of the basin. The second image is taken near the peak of the rainfall event and shows widespread surface runoff along with flow beginning to accumulate in the chan-

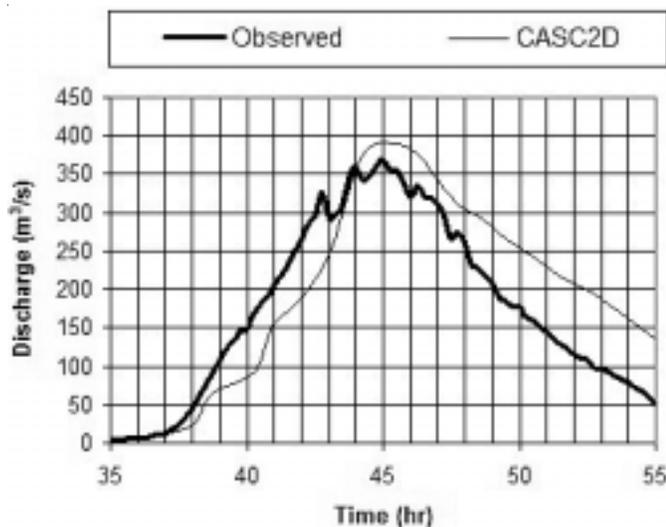


Figure 3. Hassyampa River calibration hydrograph - February event

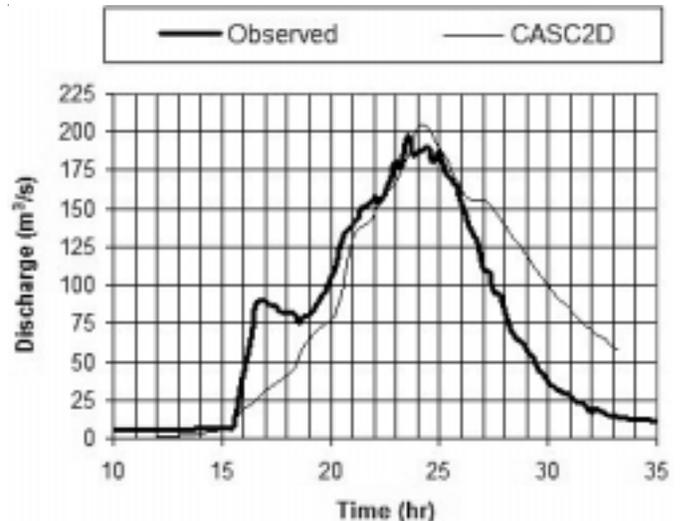


Figure 5. Hassyampa River validation hydrograph - March event

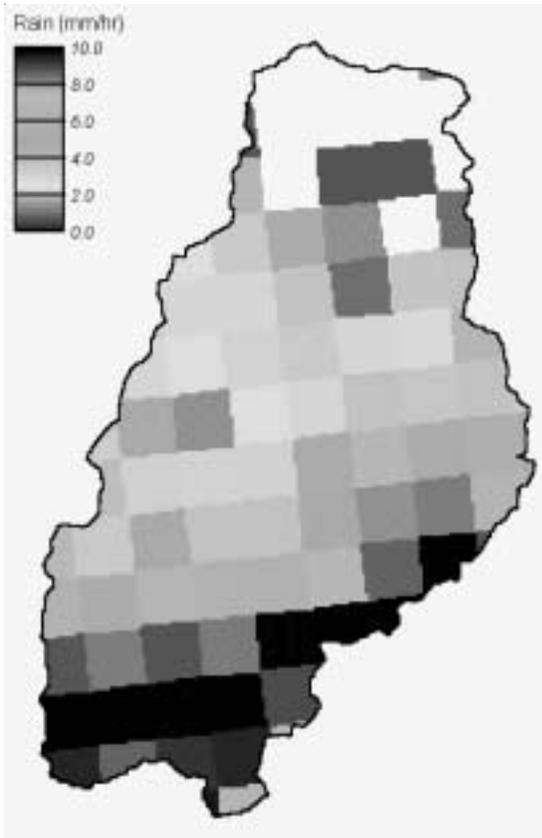


Figure 6a. Precipitation intensity derived from radar

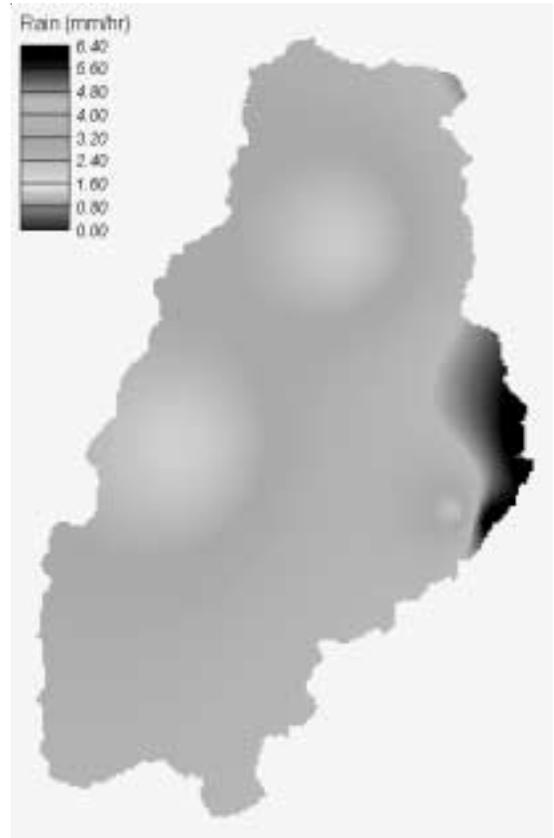


Figure 6b. Precipitation intensity derived from rain gages

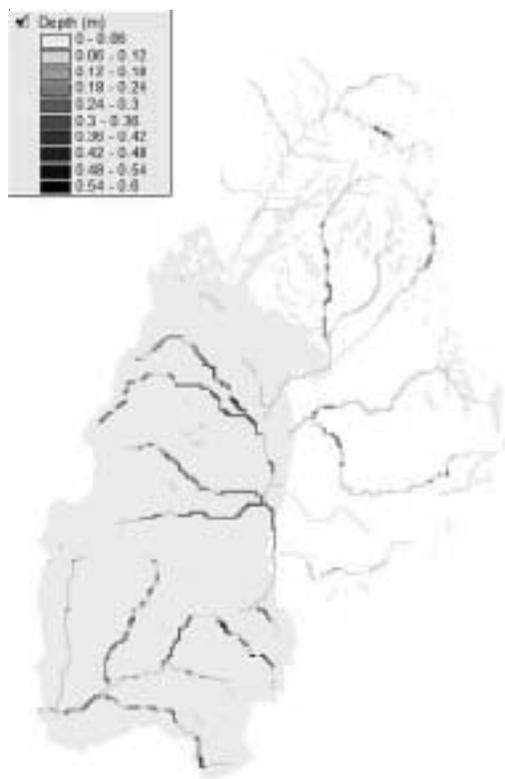


Figure 6c. Surface runoff depth – February event at time = 28 hours

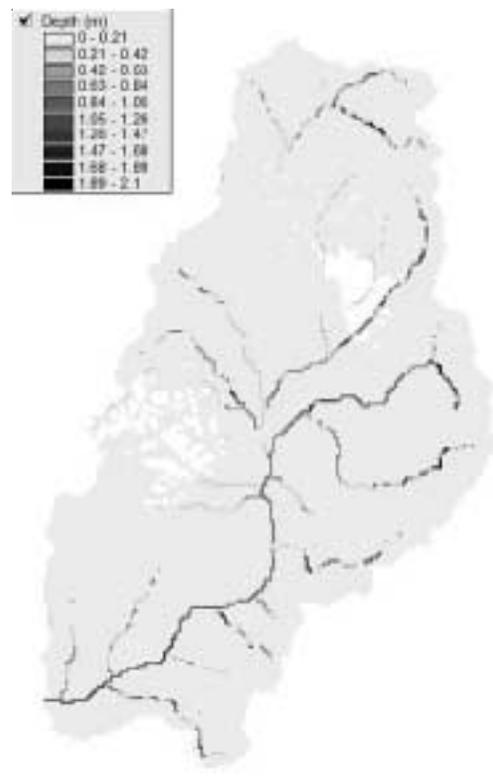


Figure 6d. Surface runoff depth – February event at time = 40 hours

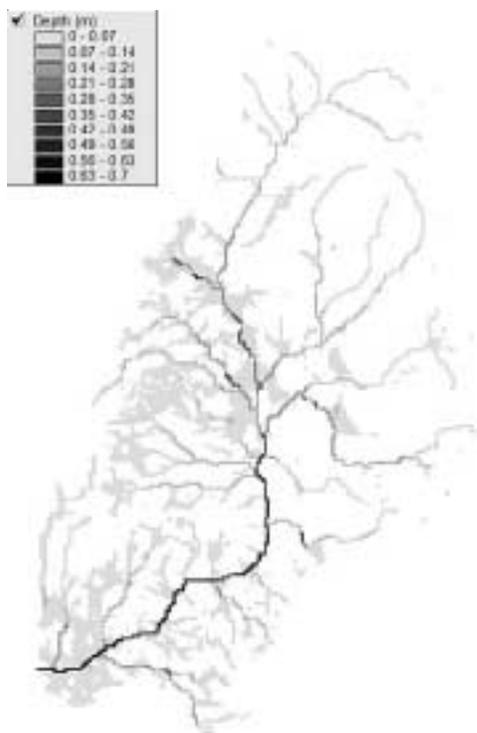


Figure 6e. Surface runoff depth – February event at time = 52 hours

nels. At the time of the final image, the rainfall has almost ended and most of the runoff still in the watershed has accumulated into the channels in the lower end of the basin. These are just a few sample images intended to provide a general feel for the types of spatial and temporal detail that can be obtained from the model output.

Forecasting

Background

In the field of hydrology, the term forecasting refers to the estimation of conditions at some specific future time. Forecasts may be classified based on the forecast lead-time, where lead-time refers to the time interval into the future for which the forecast is made. Forecasts with lead times less than seven days are often referred to as short-term forecasts and long-term forecasts are those with longer lead times that may extend up to several months into the future. Short-term forecasts are generally used for flood warning, real-time operation of water control structures, and for military operations.

When choosing a conceptual or deterministic model with which to perform forecasting, the basic choices include models based on channel routing, those based on rainfall-runoff processes, or some combination of these. In determining which class of model best fits the forecasting application, one primary criterion is the relationship between the required forecast lead time and the hydrologic response time of the basin, which is often measured

as the time of travel from the most remote point in the basin to the forecast point. If the required forecast lead-time is greater than the hydrologic response time of the basin, then it is necessary to incorporate forecast of future precipitation into the model. If the forecast lead-time is shorter than the response time of the basin and that response time is dominated by routing of the flood through the channel system, then flow forecasts may be based on flow observations made upstream of the forecast point using channel routing models. For instance, this situation will exist for larger river systems such as the Mississippi. If the forecast lead-time is shorter than the response time and the response time is dominated by the overland flow or time of concentration in the basin, then a rainfall-runoff model may be used to generate forecasts using observed rainfall from the basin. This will typically be the case in smaller watersheds. Another criterion to consider is the ratio of the spatial scale of the precipitation event to the spatial scale of the basin. If the areal extent of the precipitation event is much smaller than the size of the watershed, then a model that assumes uniform precipitation over the entire basin may prove to be inaccurate. In such cases the watershed must be subdivided into smaller sub-basins in order to capture the spatial distribution of the rainfall event adequately (Lettenmaier and Wood, 1993).

Each of the above scenarios could conceivably lead a forecaster to select a different model, i.e., a rainfall-runoff model, a channel routing model, or some combination of both. However, the CASC2D model simulates both the rainfall-runoff and channel routing processes in a basin, and the grid-based structure of the model lends itself ideally to capturing the spatial distribution of even the smallest precipitation events. Thus, it could theoretically function in any of the scenarios discussed in the previous paragraph. It is from this foundation that an investigation of the potential feasibility and applicability of the CASC2D model for flow forecasting has been pursued and is presented herein.

Modeling Procedure

The procedure used to predict peak flow using radar data in this study consisted of using the calibrated CASC2D model of the Hassyampa River basin with calibrated radar rainfall data as the precipitation input. Forecasts of future precipitation generated from radar rainfall images were combined with observed actual precipitation to create the rainfall input file for the model at each forecast time increment. The forecast procedure was repeated and the input data were updated at 30-minute intervals as new observed data became available through the end of the event. The following sections describe the process that was followed for generating precipitation forecasts, how those forecasts were combined with observed precipitation, and how the overall modeling procedure was conducted throughout each of the events.

Precipitation Forecasts

The approach used to generate precipitation forecasts involved extrapolation of precipitation patterns based on the estimated velocity of the storm system from radar images. In this approach, observations of a storm from two successive radar images at 30-minute time intervals were inspected, and the centroid of the rainfall pattern from each observation was determined taking into account both the spatial distribution and intensity of the precipitation. Then, based on the movement of the centroid over the 30-minute time interval between the two observations, an estimate of the velocity of the storm was generated. For example, if during a particular 30-minute time interval the centroid of a rainfall pattern moved 10 km in an easterly direction, then the velocity of the storm was estimated as 20 km/hr to the east. The assumption is also made that this estimated storm velocity and observed spatial rainfall pattern would remain constant into the future. Using this simple approach, the most recent rainfall pattern was simply extrapolated into the future. This is illustrated in Figures 7 and 8, which show an example of a rainfall pattern at two points in time. In Figure 7, the location of the centroid is shown at grid location 354900 m E (meters East), 3785050 m N (meters North) at an arbitrary time "t." Figure 8 then shows this same storm 30 minutes later at time "t + 30 minutes" when the centroid of the rainfall pattern has moved to grid location 362850 m E, 3785000 m N. So, during this 30-minute time interval the centroid of the storm moved 7.95 km East and 0.05 km South. To generate the forecast of future precipitation, the rainfall pattern in Figure 8 would simply be moved in space at a constant velocity of 15.9 km/hr East and 0.1 km/hr South until it passed over the watershed. This precipitation forecast would be combined with observed precipitation that had actually fallen on the watershed prior to time "t + 30 minutes" to construct the precipitation input for the model. This procedure was repeated every 30 minutes using updated radar observations through the end of the event.

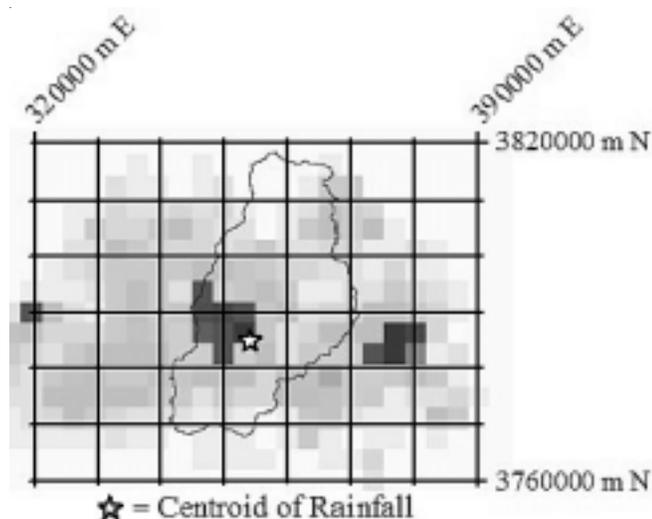


Figure 7. Radar precipitation at time = t

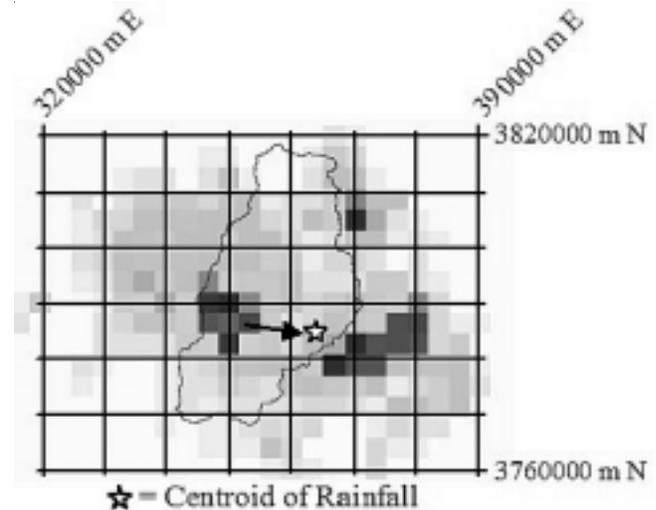


Figure 8. Radar precipitation at time = t + 30 min.

There are certainly other methods of generating precipitation forecasts from radar observations, and this method is but one approach that does have the advantage of simplicity and ease of application. A term that is often used to describe real time generation of precipitation forecasts from radar data is "nowcasting." Browning and Collier (1989) present a review of several nowcasting techniques in which they state that weather prediction models can provide precipitation forecast data, and although these models are improving in spatial resolution, they operationally may not be able to provide the level of detail that is desired for hydrologic forecasting in real time. They further state that for short-term forecasts of a few hours, a reasonable forecast can be achieved by assuming that the current rainfall pattern and movement will continue without change over the short time period of interest into the future. Since extrapolation is the basis for this forecasting method, the quality of the forecast certainly depends on the time ahead for which the linear extrapolation is valid. This may be different for different types of weather patterns, i.e., frontal systems may be able to be extrapolated for several hours while convective activity may not be able to be forecast with this method beyond an hour. The storms over the Hassyampa River watershed chosen for this effort occurred during the late winter and early spring, which is when slower moving frontal systems typically occur in that area of Arizona. Thus, the extrapolation method of generating precipitation forecasts is a reasonable approach for looking up to a few hours into the future under the specific conditions of this study and may not be appropriate for other types of storm events or for longer forecast times.

Peak Flow Prediction

Using the observed radar precipitation and precipitation forecasts discussed in the previous section, predictions of peak flow were generated with the CASC2D model of the Hassyampa River basin for the February and March events. Prior to any rainfall actually falling on the basin,

precipitation that was forecast to move over the basin in the near future was used to drive the model. Once any precipitation was actually observed by the radar to have fallen over the watershed, the rainfall input to the model consisted of that observed radar rainfall data up through the current time coupled with forecast future precipitation generated using the extrapolation method discussed in the previous section. Every 30 minutes, the rainfall input to the model was updated based on the most recent radar data and a new peak runoff forecast generated.

Incorporation of precipitation forecasts into any watershed model is expected to result in the peak runoff from a watershed being predicted sooner than if no future precipitation is taken into account, thus providing greater lead time for issuance of advance flood warnings or similar activities that may benefit from more advance warning. However, if the precipitation forecasts used for this purpose are entirely inaccurate, then these expected results might not be achieved. The issues to be addressed here include whether or not the method used to generate precipitation forecasts in this study is reasonably accurate enough such that it is effective at producing increased peak runoff forecast lead times and also to provide some insight into what limitations there might be in the use of this precipitation forecasting method. To provide an assessment of whether or not the precipitation forecasts produced via linear extrapolation of radar rainfall patterns was effective at producing increased peak runoff forecast lead-time, at each 30-minute time interval throughout both of the precipitation events the CASC2D model of the Hassyampa River was run two times. One run used only observed precipitation up to that point in time and assumed no additional rainfall, and the other run used observed precipitation up to that point in time and forecast precipitation forward in time. The CASC2D program was modified for this purpose to accept two rainfall input files. The first input file contained the observed precipitation data, and the second input file contained the most recent radar image and the projected velocity with which that rainfall pattern should proceed across the watershed. Using that velocity data, the rainfall pattern was moved the appropriate distance at each 30-second model time step to simulate the movement of that storm over the watershed. Updated information was incorporated at 30-minute time intervals to generate new input files for the observed and forecast precipitation and the model was rerun using these updated data.

Peak Flow Results

The following results summarize the model output of both model runs for the two precipitation events. Figures 9 and 10 show the model results for the February rainfall event that were made at times of 12, 10, 8, 6, and 5 hours prior to the occurrence of the runoff peak, along with the observed hydrograph for the event. Fig-

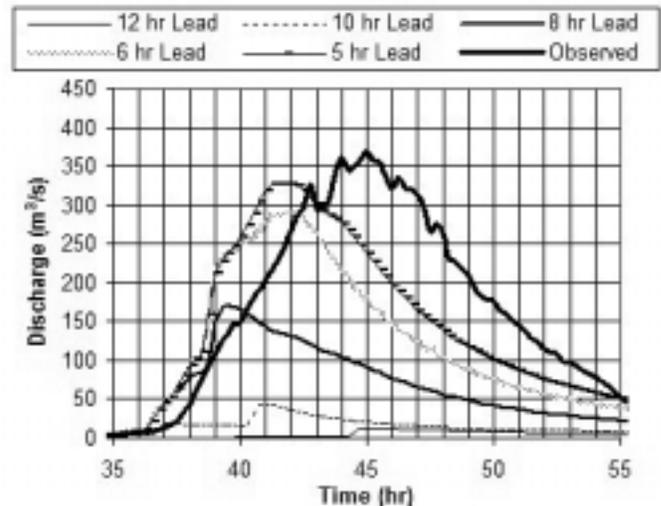


Figure 9. Forecast model results without precipitation forecasts (February event)

ures 11 and 12 show similar information for the March event. As reference points, Figures 9 and 11 include results for the model runs without precipitation forecasts included. Figures 10 and 12 include results for the model runs where the precipitation forecasts were included.

The results shown in Figures 9 through 12 confirm that under the conditions of this study the forecast lead-time for the peak runoff computed by the model was increased when the precipitation forecasts generated from linear extrapolation of radar rainfall patterns were used. For the February event, the precipitation forecasts enabled the model to predict the peak runoff reasonably well ten hours prior to the occurrence of the peak, while the model without precipitation forecasts was not able to predict the peak very closely until five hours before the occurrence of the peak. Similarly for

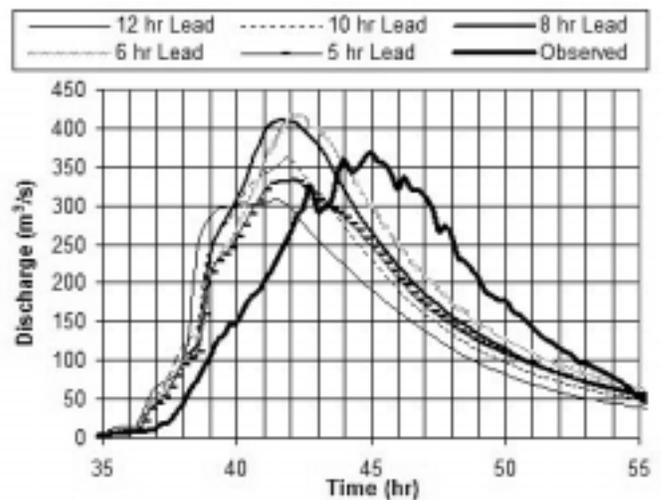


Figure 10. Forecast model results with precipitation forecasts (February event)

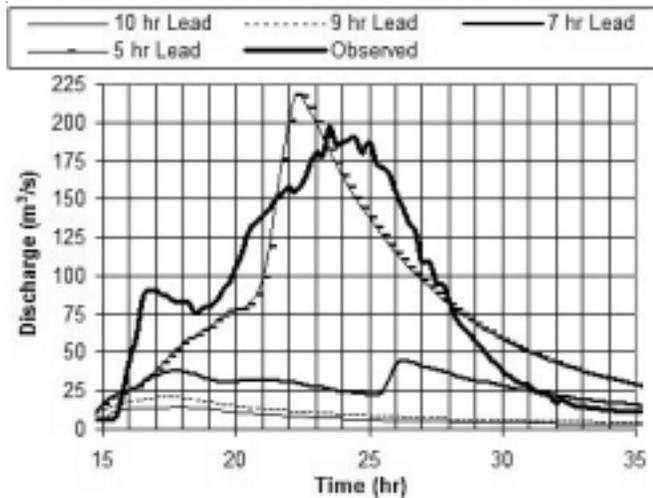


Figure 11. Forecast model results without precipitation forecasts (March event)

the March event, the peak was predicted nine hours in advance using precipitation forecasts and only five hours in advance without. Thus, for these two storm events on the Hassyampa River watershed, the forecast lead-time for the peak runoff was increased by approximately five hours for the February event and by approximately four hours for the March event. These results also highlight the fact that there are clear limitations as to how far into the future these precipitation forecasts are useful. As discussed earlier, the linear extrapolation of rainfall patterns is only applicable for very short-term forecasts of a few hours into the future. For the two storm events studied here, the forecasts made more than four or five hours into the future did not enable the model to predict the eventual peak very closely at all.

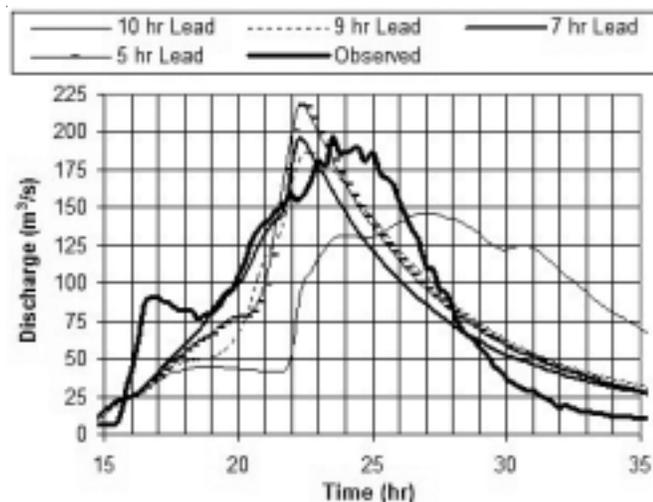


Figure 12. Forecast model results with precipitation forecasts (March event)

Conclusions

The CASC2D distributed watershed model was used to simulate rainfall-runoff events on the Hassyampa River watershed in Central Arizona. The CASC2D model was calibrated using observed rainfall data and observed stream flow data for an event that occurred in February 1995, and the model was then validated using data from a March 1995 event after changing only the antecedent soil moisture conditions. The model was able to reproduce the peak flow from this validation event matching both the peak runoff and time of peak extremely well.

An application demonstrating the use of radar rainfall data as input to the CASC2D model was then presented. Observed radar rainfall data was coupled with precipitation forecasts based on a method of linear extrapolation of the radar precipitation pattern to create precipitation input files for the CASC2D model of the Hassyampa River. For two rainfall events, the model was run both with precipitation forecasts and without precipitation forecasts at 30-minute intervals. The results show that the short-term precipitation forecasts generated via linear extrapolation of radar rainfall patterns for the two rainfall events studied here were accurate enough to produce increases in the forecast lead-time of five hours and four hours for the February and March events, respectively. Results of this study also underscored the limitations of linear extrapolation as a method of predicting future rainfall by showing that forecasts generated more than a few hours into the future may not be expected to produce desirable results. However, even a few hours of additional lead-time in predicting the peak runoff from a watershed can make a significant difference when flood warnings, evacuation orders, or similar operations may be necessary.

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