Proceedings of the *Open source GIS − GRASS users conference 2002* − Trento, Italy, 11−13 September 2002

Weather Radar Enhanced Flash Flood Forecasting

Scott O’Donnell*

*1820 Winfield Dr, Lakewood, Colorado, USA, 80215−2553,
tel. ++011 30 32 74 56 80, e−mail odonnell@peakpeak.com

1. Abstract

Located in the Rocky Mountains of the United States, Colorado is frequently subjected to high intensity, short duration, summer season convective precipitation. Many mountainous and urbanised watersheds have rapid hydrologic responses to these storms and are prone to flash flooding. By coupling weather surveillance radar reflectivity with a distributed rainfall/runoff model, model results provide an early indication of flooding potential within the downstream watersheds of the intense storms. In real−time, weather radar reflectivity is translated into area distributed rainfall estimates and are used for input to the GRASS rainfall/runoff model, r.hydro.CASC2D. The resulting output maps and files are analysed to notify emergency managers of potentially dangerous flooding conditions caused by the thunderstorms. Storm locations are shown by displaying the radar reflectivity and rainfall intensity maps. The generated graphical displays provide understandable information regarding the location, timing, and flooding potential for the watersheds downstream of the severe storms. At locations selected for their vulnerability to flooding (road crossings, bridges, towns, etc.) any stream forecast exceeding ’Alert’ or ’Alarm’ levels trigger appropriate warning responses. The improved lead−times provide additional time to evacuate the affected areas.

2. Introduction

Despite decades of improvements to observations and warnings, flash floods are the leading weather−related cause of death in the United States. Flash floods are distinguished from other types of flooding by the short time scales over which flood−producing rainfall occurs (generally < 6 hours) over small spatial scales (usually, < 500 km^2 basins). In Dallas, Texas, in May, 1995, a one hour storm caused 16 deaths and over $1 billion in property damage due to a flash flood. Similarly, a brief thunderstorm over a small mountain watershed, Buffalo Creek in Colorado (122 km^2), caused two deaths and several million dollars of damage on the evening of July 12, 1996. This flood caused significant damage to Denver, Colorado’s water supply, as well.

Rainfall−runoff models began by generalizing observed behaviours. The Rational Method dates back to the middle of the 19th century. In the first half of the 20th century, the Unit Hydrograph method was developed. This and other lumped parameter models dominated hydrology for much of the remainder of the century. With the introduction of computerized numerical methods, a variety of rainfall−runoff approaches have since proliferated.

As the capabilities of computers have increased, with faster CPU’s and more memory, hydrologic models have improved proportionately. Higher resolution spatial data sets and improved access to them, combined with new methods for estimating precipitation have all contributed to the improvements. The need to rely on the lumped parameter models, assuming uniform precipitation rates over large watersheds is no longer necessary. By combining high resolution weather surveillance radar for rainfall distributions with high resolution spatial data sets, distributed hydrologic models are superior models.

The goal of creating a watershed model is of course to provide an estimate of the watershed response to rainfall or other stimulus. While many watershed aspects may be simulated, i.e. water quality, water resources management, etc., stream discharge remains the most significant.

The spatial and time dependencies of stream discharge, the time−series of the river response at a particular point, are especially important in a forecast warning system. Knowing where rainfall runoff will affect impact features, such as homes near a stream or road and bridge crossings, occur at random locations throughout the system. Therefore, selecting a spatial scale allowing sufficient distinction to forecast flooding hazards at specific locations is of paramount importance. Selecting too coarse a scale, will miss the finer resolution details, i.e. the specific locations at risk. Selecting too fine of a scale not supported by the data sets, simply increases computational time without the benefit of increased precision.

Using a GIS to manage the cell−to−cell parametric variability of a physically based, distributed model, reduces the data to logical components. Not to diminish the importance of a correctly calibrated database, this data abstraction allows the modeller to focus on the model's dynamics, rather than on the data used in the model.

3. Model Description

This model uses weather surveillance radar reflectivity for its distributed precipitation estimates and uses a modified version of r.hydro.CASC2D as the runoff model. The stream discharge results derived from the rainfall−runoff model are then compared to flood guidance values to forecast the likelihood of flooding. See Diagram 1.

r.hydro.CASC2D (CASCade of planes; 2−Dimensional) is a physically−based, distributed parameter, infiltration−excess (Hortonian), finite−difference model. The r.hydro.CASC2D (*Casc2d*) hydrologic model is included in the GRASS distribution. It was developed through a U.S. Army Corps of Engineers grant to Colorado State University. Dr. P.Y.Julien, wrote the original APL version of the code ported and expanded by B.Saghafian and F.Ogden. This model was included in the GRASS distribution in the early 1990's. The model accepts fully varied rainfall−input, uses Green and Ampt infiltration, two−dimensional diffusive wave overland flow routing, and one−dimensional diffusive wave channel routing. This modified version of *Casc2d* accounts for the accumulation of excess rainfall in the watershed, translating it across the watershed land surfaces, accumulating in the channels, and routing down the channels to the watershed outlet in this model.

The version of r.hydro.CASC2D, checked into the GRASS 'src.contrib/CERL/raster' portion of the distribution, required extensive modification to make it functional. The coding style is unsophisticated and contains numerous coding errors making the original program unusable. This author took the time to correct these errors, add function prototypes, extensively reorganize the data type and variable declarations used by this program. Many of the exceptionally long code blocks were decomposed into smaller, manageable. logical functions. After doing this, the author was able to simulate runoff from historical rainfall events which were used to calibrate the watersheds used in this model.

The *Casc2d* distributed rainfall−runoff model operates on a square raster grid. The primary model input is US Geological Survey (USGS) Digital Elevation Map (DEM) data providing samples of the elevations at regular intervals across the watershed. From these data, slope,

Schematic Model Diagram

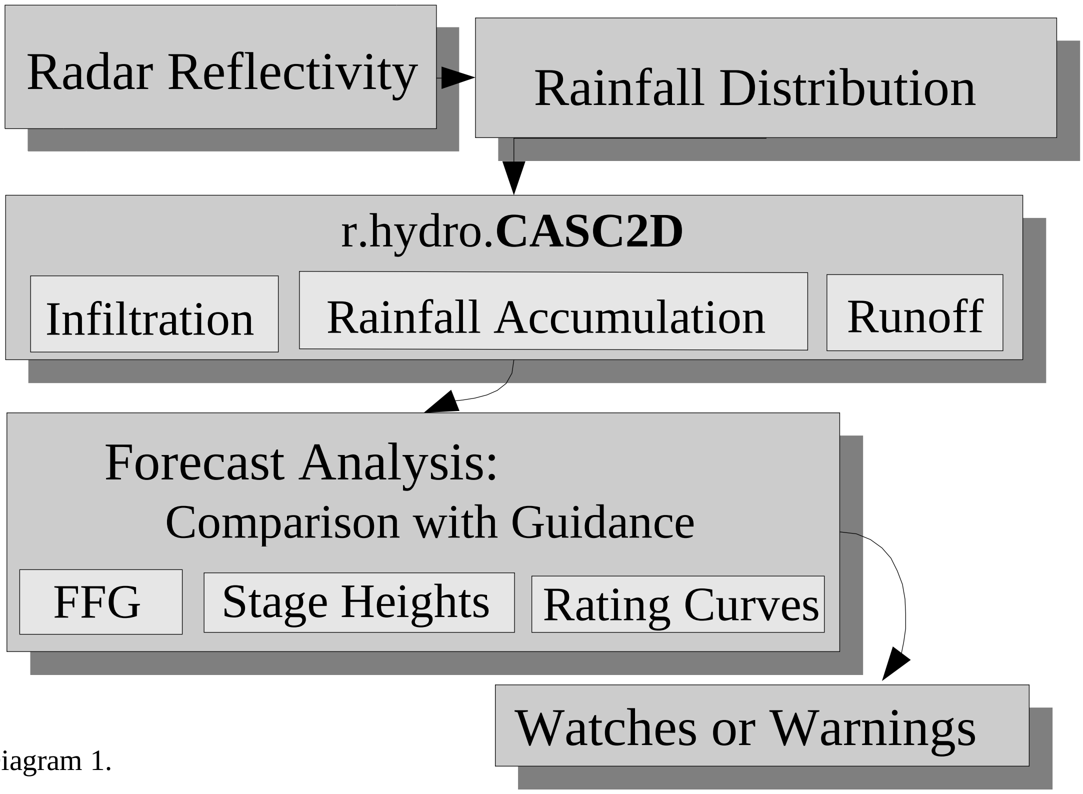

Diagram 1.

flow direction, aspect (orientation to the sun), flow length, stream network, and basin boundaries are derived. Other watershed parameters, eg. surface and channel roughness, interception, infiltration parameters, etc. are derived from vegetative cover, forest type and density, soil classification and texture, land use and cover. Additional parameters, such as channel geometry, lake and reservoir locations and elevations, initial soil moisture content, and impervious areas in each watershed are provided from other external sources.

Another primary model input is precipitation. While *Cas2d* allows precipitation gage observations, the author had access to and used radar reflectivity data exclusively. These data required decoding from a radial grid and redistributing the data to the model's Cartesian coordinate grid and also required the translation of the radar reflectivity values to precipitation depth. The radar reflectivity to rainfall rate (Z−R) relation is defined as, $Z = 300R^{1.4}$, where Z = radar reflectivity (mm^6/m^3), and R = rain rate. This Z−R relation has been used on the Colorado Front Range to provide reasonable estimates of summer rainfall rates. Because hail contamination causes overestimates of rain rates, the reflectivity is capped at 53 dBZ. [2]. Dixon and Johnson [1] found the mean storm size of Colorado Front Range convective storms to be approximately 30 km^2. The averaging of incident rainfall over basin areas larger than the overall storm results in underestimates of the flash flood threat. Subdivision of watersheds into subbasins of 30 km^2 or less avoids underestimation error.

After the creation and calibration of the model data sets and successful simulations of several case studies, this author adapted the model for real−time radar data input. The model was designed as an analysis tool, requiring all the data to be read into memory before beginning execution with the duration of the storm provided beforehand. In real−time processing, all the data is not known or available before beginning processing and the storm duration is undefined. The author rewrote the rainfall input code responsible for acquiring the radar rainfall, allowing sequential, 'just−in−time' input of the precipitation data at the beginning of the time step. By rolling back the results of previous time steps, the program continued accepting real−time data as it became available.

Processing time was somewhat faster than the radar data input interval. Radar precipitation volume scans are completed in five (5) to ten (10) minutes depending on the scanning strategy being employed. During 'clear air' mode, a frequent scanning strategy is unnecessary, so the scan frequency is limited to six (6) volume scans per hour. Stormy weather automatically switches the scanning strategy to 'storm' mode, or 10 volume scans per hour. As the weather continues to intensify, a 'severe storm' mode provides 12 scans per hour.

Cas2d requires the time step to be specified, so at each time step the most recent radar reflectivity data are re−used for the next precipitation estimate. After five minutes of rainfall−runoff simulation, the model waits for arrival of the next radar volume scan. While this potentially reduces the flood forecast lead time, this keeps the model from over−running the radar scan strategy and improves accuracy.

4. The Study Watershed

This modelling effort focused on the Buffalo Creek watershed. Located In the Pike National Forest, Buffalo Creek is a small tributary stream on the North Fork of the South Platte River. This small, forested, mountain watershed is approximately 48 km (30 mi.) southwest of Denver, Colorado, USA, near the town of Pine. The watershed is about 122.8 km^2 in area. This mountainous region contains land surface slopes in excess of 30%. Elevations in this watershed range from 3654 m on the southwest boundary of the watershed to 2072 m at the watershed outlet on the northeast boundary. The elevation difference occurs over a distance of approximately 16.2 km; an average watershed slope of 9.8%. The Buffalo Creek watershed is depicted in Figure 3 with with radar 'bins' (magenta), the stream network (blue), the watershed boundary (white), and subbasins (gray) depicted. The watershed boundaries and stream network were generated using 30 m USGS DEM data and program elements within GRASS. This watershed is in the upper range of watersheds, (25 −130 km^2), that the US National Weather Service evaluates for flash flood potential.

On the early evening of July 12, 1996, a thunderstorm occurred near the community of Buffalo Creek, Colorado, close to the outlet of the basin. The storm produced heavy precipitation during a short period of time. The resulting flash flood occurred along Buffalo Creek, Sand Draw, Spring Gulch, the North Fork of the South Platte River (North Fork) below its confluence with Buffalo Creek, and in several other tributary streams in the area. Two lives were lost as a direct result of the flooding. Roads, bridges, water lines, and other utility lines were damaged or destroyed. Numerous homes, outbuildings, and vehicles were damaged or destroyed as well. A large quantity of sediment and debris was carried from the watershed and deposited along the affected stream reaches. Several other, smaller magnitude floods, each exceeding 100−year frequency flows, occurred on Buffalo Creek between June and September of 1996, as well.

The cause of the floods was a common one. Earlier in the year, May, less than two months before the 12 July flood event, a wildland fire burned about 10,000 hectares of forest in the Buffalo Creek watershed. The burned soils exhibited hydrophobic (water repelling) properties and the barren landscape’s natural erosion control and runoff inhibiting characteristics had been burned away. Those conditions, in conjunction with the heavy rainstorm , July 12, were the cause of the Buffalo Creek flash floods.

5. Model Application

The Buffalo Creek watershed was divided into many subbasins. In real−time, this model accumulates the basin average precipitation over the many small watersheds, each subbasin much smaller than the average storm cell size. By comparing the basin average rainfall accumulations with the Flash Flood Guidance (FFG) values issued for the region, the forecaster’s attention will focus on the most susceptible areas for flooding. By evaluating the rainfall accumulation and runoff accumulation maps and resulting hydrographs of the flood prone areas, appropriate watches or warnings can be issued in advance of flooding.

The basin average precipitation is a moving average, an area weighted average of the precipitation falling within the watershed boundaries. The basin average precipitation is updated with every every radar volume scan. Several durations, (0.5, 1, 2, 3, and 6 hours), are continuously updated for each subbasin. For each duration in each subbasin, the basin average precipitation is compared with the correlated FFG value. The comparison provides an easy to understand ranking of flooding potential, by generating a color coded map of the results. The resulting map also generates a table of results, ordered by flooding potential. This table identifies which basins are at highest risk for flooding. Further analysis of basin discharge maps and hydrographs from the continuously running hydrologic model, provides details upon which watches (less severe) or warnings (more severe) are issued by emergency response agencies.

To accumulate basin average rainfall requires creating a mapping of each radar bin to a watershed, then area weighting the rainfall falling into each basin. This is a fairly straight forward procedure.

Creating a basin FFG value for each basing is essentially a operation of distributing provided guidance values to each subbasin. If FFG data are not available, general guidelines can be applied, such as these used by the US National Weather Service in lieu of FFG:

Flood Warning: 0.1 to 0.4 in./hr. for 6 − 24 hrs.
Flash Flood Warning: 1 to 2 in./hr. for 3 − 6 hrs.
Extreme Flash Flooding: 3 to 5 in./hr. for 1 − 3 hrs.

As data are accumulated and more storms experienced, regression analysis on precipitation amounts needed to cause flooding can be substituted. A more rigorous methodology requires determining the amount of precipitation necessary to cause the streams in each subbasin to rise to bankfull under current watershed and soil conditions, then using the computed results as the subbasin guidance value.

Another analytical alternative compares modeled discharge results to known values for stream capacity. Yet another, derives river height (stage) from rating curves for each forecast location and compares computed river heights to surveyed bankfull river heights. By conducting these tests on each sub−watershed, at each time step, for each duration, the maximum lead time is derived, to be used to evacuate the flood hazard zone.

6. Results

The response of this model to archived test cases was very good. Clearly indicated, elevated flood potential was demonstrated in watersheds that experienced flooding due to high intensity, short duration rainfall using data from the archived storms. During the operational testing period of this model, a severe drought plagued the western United States, limiting the test opportunities to few, very small cases. The normal Spring rainstorms storms were abnormally sparse, causing no flood events in the test watersheds.

Testing will continue throughout the summer, with the expectation that the normal, mid−summer "monsoon" weather systems will return, bringing new opportunities to test the methodologies described in this paper.

7. Summary

This model :
- Provides an automated flash flood warning tool for flood forecasters .
- Monitors the flash flood potential of regional watersheds using temporally and spatially varied radar− rainfall estimates.
- Summarizes the state of the regional watersheds in multiple formats.
- Designed for use by weather forecasters, integrates radar−rainfall estimates and FFG.
- Alerts forecasters to high flash flood potential in small, local scale watersheds.
- With only a small amount of training, forecasters can use the output of this model to produce effective flash flood forecasts.

References

[1] Dixon, M. and L.E. Johnson, 1998: Stochastic Modeling of Convective Storms from a Lagrangian Perspective. *Fourth International Symposium on Hydrologic Applications of Weather Radar. Hydrologic Research Center, San Diego State University,* San Diego, CA. April 5−9.

[2] Fulton, R.A., J.P. Breidenbach, D−J, Seo, and D.A. Miller, 1998: "The WSR−88D Rainfall Algorithm", Weather and Forecasting, 13, 377−395.

[2] Johnson, L.E. And Brian Skahill, 2000: F2D, A Kinematic Distributed Watershed Rainfall−Runoff Model, NOAA Technical Memorandum, ERL FSL−15, Boulder, CO.

[3] Julien, P.Y. B. Saghafian, and F.L. Ogden, "Raster−Based Hydrologic Modeling of Spatially−Varied Surface Runoff," *Water Resources Bulletin*, June 1995.

[4] Natural Resource Conservation Service, 'State Soil Geographic (STATSGO) Data Base − Data use information'. Miscellaneous Publication Number 1492, 1995.

Figure.1 Colorado Digital Elevation Map

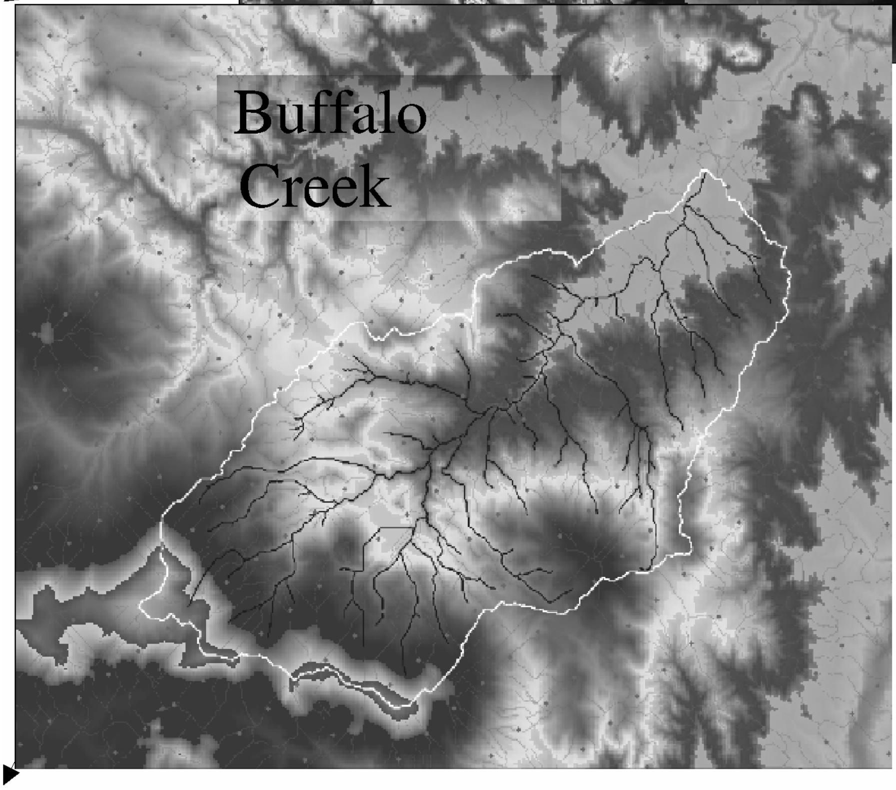

Figure.2 Buffalo Creek watershed boundary, with radar 'bins', and stream network

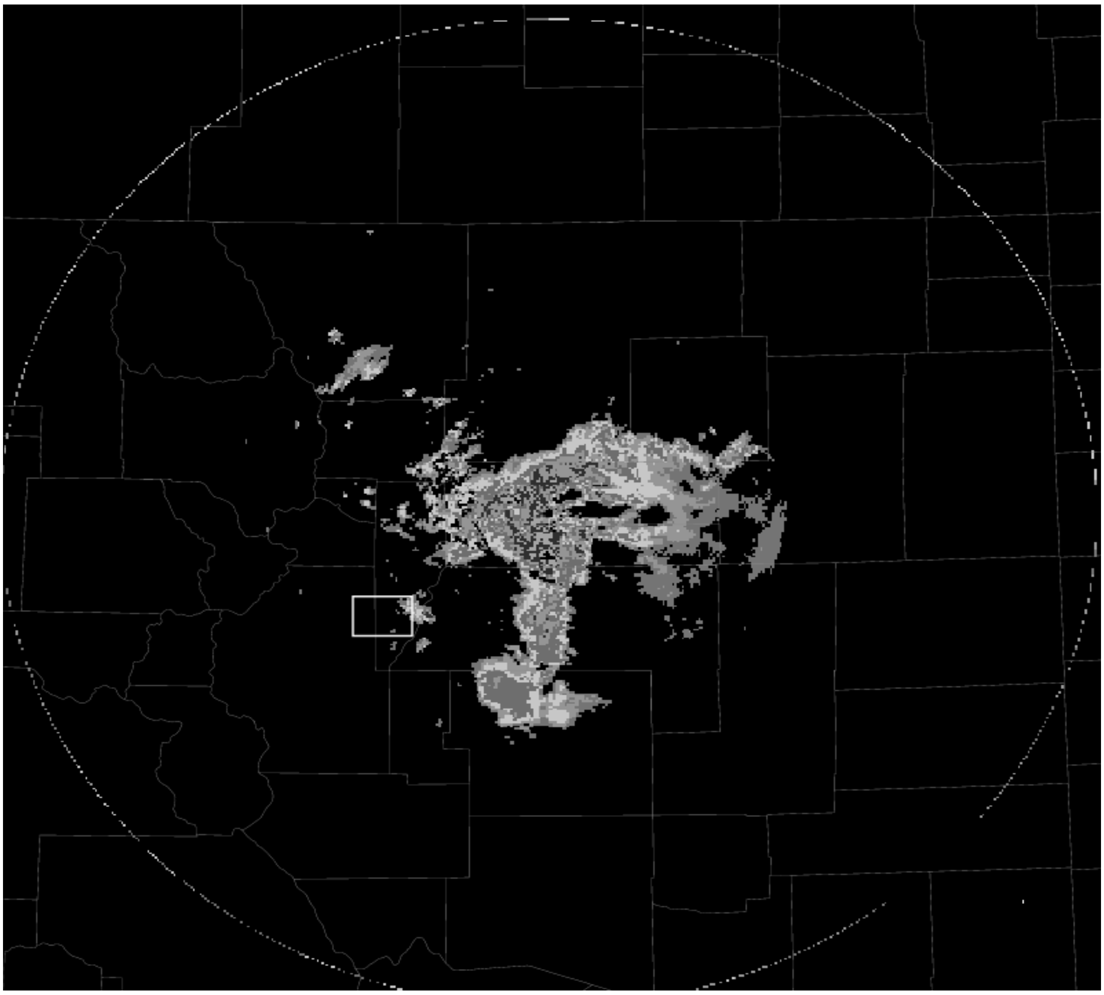

Fig. 3 Radar Reflectivity Image