Final Report for COMET proposal entitled

Development of a Site-Specific Flash Flood Forecasting Model for the Western Region

University: The University of Arizona

Name of University Researcher Preparing Report: Dr. Hoshin Gupta[1]

NWS Office: Weather Forecast Office (WFO) NWS Tucson, AZ

Name of NWS Researcher Preparing Report: Mike Schaffner[2]

Partners:

Academic: Department of Hydrology and Water Resources, University of Arizona (UA), Tucson, AZ

PIs: Hoshin V. Gupta (UA) and Soroosh Sorooshian (UCI)

Co-Is: Thorsten Wagener (PSU), David Goodrich (USDA-ARS) and Terri S. Hogue (UCLA)

Graduate Students: Soni Yatheendradas (UA) & Anne Stewart (UA)

Other Scientists: Carl Unkrich (USDA-ARS)

Forecast Partner: Weather Field Office (WFO), NOAA's National Weather Service (NWS), Tucson, AZ

Investigators: Glen Sampson (MIC), Mike Schaffner (Service Hydrologist), Evelyn Bersack (ITO)

UCAR Award No.: S03-44674

Date: 8-31-2006

---

[1] Professor, Department of Hydrology and Water Resources, University of Arizona (UA), Tucson, AZ

[2] Service Hydrologist, NWS Tucson, AZ

Section I: Summary of Project Objectives

The general objective of this study is to develop a site-specific flash-flood forecasting system for the Western Region, which is capable of flood forecasting using radar precipitation input. This effort is the result of a collaboration between the researchers at the University of Arizona (UA), the hydrometeorologists at the NWS, and the scientists of United States Department of Agriculture (USDA-ARS). The hypothesis tested is:

> *"A site-specific model for the Western Region (Western slopes of the Rocky Mountains down to the Pacific Ocean) providing specific hydrologic flash flood forecasts has the potential to improve forecast services of the NWS, leading to reduced loss of life and property."*

I.A Background for the present study:

I.A.1 Flash-flood importance

Flash floods are defined as those that occur within six hours of the causative event (i.e., time between rain event and discharge peak) (NWS, 2002). In the western U.S., flash floods are caused mainly by convective storms (thunderstorms), particularly in small semi-arid watersheds (Roeske *et al*., 1989). Flash floods cause significant loss to life and property; by way of civilian casualties, more people are killed annually than by any other natural disaster, accounting for more than eighty percent of all flood related deaths in the continental USA (AMS, 1985). Annual Economic losses consist of property worth billion dollars damaged or lost.

Figure 1: Sabino Creek near Tucson (one of our test basins) affected by flash floods

Flash-floods usually occur in semi-arid and arid regions (Fig. 2). About 50%, if not more, of the western US is classified as having some form of arid or semi-arid climate (i.e., with annual average rainfall <250 & 250-500 mm/year respectively). Such regions currently span approximately 1/3rd of the earth's land surface, negatively affecting water supply for more than one billion humans (FAO, 1993). An increasingly drier and more variable climate trend (UNEP, 1997) significantly increased the incidence of intense (extreme) precipitation events during the 20th century (IPCC, 2001), leading to a continuous growth of extreme-flood-event losses, despite the widespread problem of water scarcity (Kundzewicz and Kaczmarek, 2000). Thus, flash flood forecasting becomes operationally important and highly relevant for the NWS.

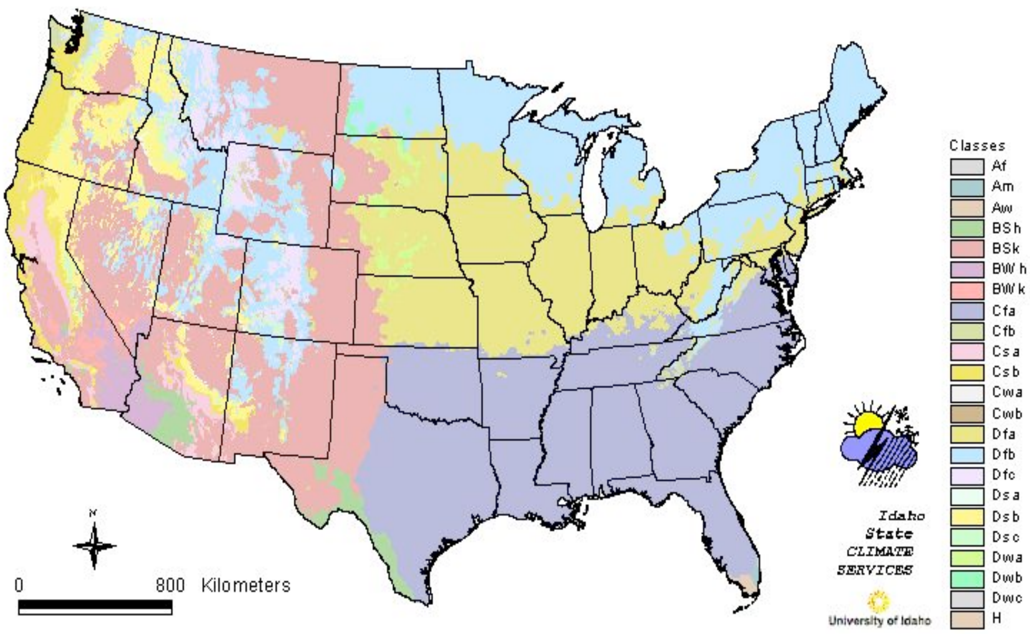

Figure 2: Koppen climate classification over the conterminous United States [from http://snow.ag.uidaho.edu/Clim_map/koppen_usa_map.htm]

In line with the major objectives of the Advanced Hydrologic Prediction Service initiative (AHPS, NWS, 2002):

1) The improvement of forecast accuracy, and
2) The provision of more specific and timely information on flash floods

a specific objective is to "*rapidly identify small basins affected by heavy rainfall, identify excessive runoff locations, and predict the extent and timing of the resulting inundation, by incorporating new techniques for quantifying forecast certainty and conveying this information in products which specify the probability of reaching various water levels*" (NWS, 2002).

I.A.2 Current NWS Flood-Forecasting procedures

The NWS procedures currently in place for qualitative/quantitative flood prediction need refinement to enable accurate flash-flood forecasting.

I.A.2.i Current basis for operational flood forecasting: The two approaches typically used by the NWS for flood forecasting are either the use of a rainfall-runoff model, or by empirical estimation of flood potential based on areal rainfall amounts. The River Forecast Centers (RFC's) apply the former approach, using two continuous, lumped rainfall-runoff models -- the physically-based Sacramento Soil Moisture Accounting Model (SAC-SMA; Burnash et al, 1973), and the empirically-based Continuous-API Model (CONT-API; Sittner *et al.*, 1969) based on the Antecedent Precipitation Index (API; Kohler and Linsley, 1951). The Mid-Atlantic RFC (MARFC) uses the CONT-API method. Depending upon the developmental stage and needs of the RFC, these models run at either 1-hour or 6-hour time steps; the 6-hour time step is inadequate for many watersheds due to the short reaction time of their rivers, and therefore the finer time step is typically preferred.

The Weather Forecast Offices (WFO's) have the ability to produce 'site-specific' hydrologic guidance at required forecast points on small local rivers and streams that are not supported by the RFC. Again, both types of approaches (rainfall-runoff models, and flood potential based on areal rain) are applied. The operational models used are the lumped SAC-SMA, or the lumped API, usually ingesting user-selected Mean Areal Precipitation (MAP) time-series. Both models are run using a half-hour or 1-hour time step using 4 km resolution inputs provided by the Multisensor Precipitation Estimator (MPE; see the hourly Weather Forecast Office Hydrologic Forecast System; http://www.weather.gov/om/whfs/documentation/SSHP_OB5_Ref_Guide.doc).

The Flash Flood Monitoring and Prediction tool (FFMP, Fig. 3) computes area-average rain at 4-5 minutes and 1° by 1 km resolution from the radar rainfall product. In the FFMP, the area accumulated rainfall is checked either for areally accumulated rainfall amounts either upstream to, or over, the forecast area. These amounts are then compared to either the flash flood guidance values (FFG) issued by the RFC, or to empirical guidelines based on local experience. The FFMP is based on the Areal Mean Basin Estimated Rainfall

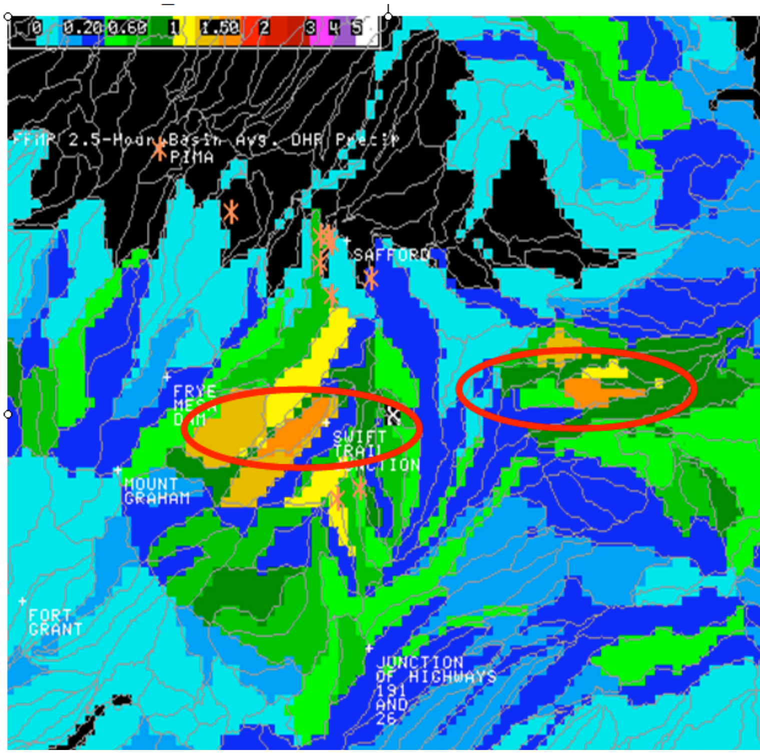

Figure 3: FFMP used for flood warning purposes, with high rain amount areas shown encircled

algorithm ***(***AMBER***;*** http://www.erh.noaa.gov/er/rnk/amber/). In addition, other sources of rain information are sometimes used, including rain gauges to provide ground truth, satellite rain estimates and spotter reports.
*I.A.2.ii Current strategies for model parameter specification****:*** The rainfall-runoff models require calibration of several key parameters before they can provide reliable forecasts in an operational setting. Such calibration is traditionally done using an expert-manual approach, which can provide excellent results. In the manual-expert approach, the ”closeness” of the model to the observed watershed behavior is typically evaluated in terms of several subjective visual measures, and a semi-intuitive trial-and-error process is used to perform the parameter adjustments (Boyle *et al*., 2000). A long-standing cooperation between the UA and the NWS has focused on the development of “hybrid” calibration procedures that exploit both the expertise of the NWS hydrologist and the speed and power of the digital computer. These procedures include the Multi-step Automatic Calibration Scheme (MACS; Hogue et al., 2000) for “lumped” basins, and the Automatic Multi-Criteria procedure (AMC; Gupta et al., 1998; Boyle *et al*., 2000). These procedures enable an operational hydrologist to use a computer to quickly produce acceptable calibration results, which can then be refined by manual adjustment as required.

I.A.3 Features required to model semi-arid flash-flood hydrology

Semi-arid flash-flood hydrology in the southwest is highly non-linear, being mainly initiated by the phenomenon of convective storm cell thunderstorms with a limited areal extent of typically less than 10-14 km in diameter (Michaud, 1992), developing very rapidly into intense summertime convective thunderstorms. Such thunderstorms tend to be severe (Costa, 1987) due to the natural physiographic characteristics of semi-arid watersheds. The Hortonian infiltration-excess mechanism that dominates semi-arid runoff production (Horton, 1933) and the scarcity of the vegetation increase the potential for localized flash flooding (Michaud, 1992). Streamflow infiltrates into the beds of channels formed in alluvial sediments, resulting in significant transmission loss (e.g., Michaud, 1992). The complex interaction of distributed watershed and rainfall properties strongly influences the flood hydrograph shape and volume (Michaud, 1992).

A good flash-flood forecasting model therefore requires the following features, several of which make it different from a model appropriate for humid regions (Pilgrim et al, 1998):

- High spatial and temporal variability of rain input
- Distributed structure to account for the scale of interaction between the semi-arid storm and the basin geometry (Osborn,1964)
- Inclusion of an infiltration excess runoff mechanism (in contrast to the saturation-excess overland flow mechanism prevalent in humid regions)
- Representation of processes for transmission loss in stream channels

I.A.4 Difficulties encountered in the practice of operational forecasting

Some of the difficulties and deficiencies associated with current operational flash-flood forecasting are:

- Operational models consistent with the highly non-linear hydrologic processes of semi-arid regions are required (as compared to humid region hydrology). Current operational models, such as the SAC-SMA, are based on humid region hydrology.
- To be 'site-specific' and forecast flash-floods that can form in 15 minutes or less, models with fine spatial and temporal resolution (having short reaction times) are needed. Current models have a relatively coarse time and space resolution.
- Distributed models are necessary to capture the complexities of the distributed interaction between rainfall and watershed properties. Current operational models, however, are mostly lumped. The Hydrology Lab (HL) of the NWS has recently developed a distributed modeling system referred to as Research Modeling System (HL-RMS) (Reed *et al.*, 2002) for flow forecasting, using structural elements of the Sacramento Soil Moisture Accounting (SAC-SMA) model and a kinematic routing procedure. It has been successfully applied to a range of catchments in the Arkansas River and Blue River basins (Reed *et al.*, 2002), but is still in development. It has not been tested on semi-arid or arid catchments. The HL is very interested in comparison studies between a semi-arid model and the HL-RMS (John Schaake, HL, Personal Communication).
- Forecasts need to be provided as quantitative estimates with acceptable accuracy on the timing and magnitude of the peak. In forecasts which directly use areal rain estimates to make flash-flood alerts, the effects of initial soil moisture and the high non-linearity of the rainfall-runoff transformation are not considered. Such forecasts are, therefore, qualitative with uncertain (unknown) accuracy in the peak timing and magnitude.
- Forecasts need to be replicable by forecasters who do not have experience and skill with manual calibration. However, when areal rain estimates from the FFMP are directly used to make flash-flood alerts (based on judgment & experience), the skill of the forecaster affects the forecast accuracy, and replication of the forecasts is both difficult and time-consuming.
- The model parameter specification procedure should be relatively fast so that new basins can be set up quickly. Implementation of the manual approach to model parameter calibration is typically very time intensive, even for an expert.

- Uncertainties stemming from the model input and parameters and their effect on the model predictions need to be displayed in model forecasts. Current manual and automated approaches typically do not provide these.
- A robust method to estimate distributed rainfall-runoff model parameters is essential. Reed *et al*. (2002) conclude that a robust method to estimate distributed rainfall-runoff model parameters has not yet been found.

***I.A.5 R*equirements for a Western Region site-specific flood forecasting system:** With the above considerations in mind, the NWS Western Region (NWS-WR, 2002) listed the following requirements for a site-specific model, presented as two groups -- “suggested” and “further desirable”. The objectives of the project to be enumerated next follow these requirements:

I.A.5.i Suggested requirements:

(1) Modular design to allow flexibility in sophistication, as WFO needs dictate and resources allow.
(2) Ability to handle basins with a time of concentration on the order of up to 8hrs.
(3) Continuous time capability, with event-based capability initialized to current conditions.
(4) Short computational time-steps of 15 minutes or less.
(5) Well-documented calibration system, which allows for relatively quick and satisfactory calibrations (capability to complete individual basin calibrations in an average time of 2-4 hours).
(6) Inputs as appropriate to the scale of the model, including Quantitative Precipitation Forecasts (QPF).
(7) Capability for the user to edit input.
(8) Output: forecast guidance on which warnings can be based. Categorical forecasts at an absolute minimum. Observed, simulated, and forecast hydrographs, and precipitation plotted as inverted hyetographs highly desirable.
(9) Model must be accessible from Advanced Weather Interactive Processing System (AWIPS) workstations (UNIX) and have user accessibility via a graphical user interface (GUI). The GUI should contain selections for all input parameters, with defaults for all applicable parameters.
(10) Model must permit multiple runs (not necessarily concurrently) with various input scenarios to obtain a range of contingency forecasts.
(11) Model must be capable of using radar precipitation input.

I.A.5.ii Further desirable requirements:

(1) Routing available to combine sub-areas of small rivers with tributaries and confluences.

(2) Capability to adjust model for effects of land use change, *i.e*. fire.
(3) Snow accumulation and ablation model available for use if desired.
(4) Other outputs: confidence interval hydrographs; inundation maps.
(5) Ability to run model on past events for evaluation purposes. Including ability to toggle between Mean Areal Precipitation (MAP) along with total losses, or observed MAP along with past basin QPF (to enable visual QPF tracking while also viewing the differences between observed and forecasted hydrographs). This information is needed so that WFO forecasters can assess the validity of forecasts based on past performance and to identify causes of poor past performance.
(6) A site-specific model that will work for all areas of the Western Region. While the development of some capabilities may need to be delayed, the model must be designed with enough flexibility to accommodate their development and assimilation. For example the model needs to be able to incorporate rain gage data in addition to or instead of radar precipitation estimates.

I.A.6 **Related developments**

- The event oriented, distributed, physically-based Kinematic Runoff and Erosion (KINEROS2) model has been developed at the USDA-ARS to describe the processes of interception, infiltration, surface runoff and erosion (Woolhiser *et al*., 1990; Smith *et al*., 1995) in the southwest U.S. KINEROS2 has been successfully applied to small and mid-sized watersheds both in the southwest (e.g.,Goodrich, 1990 and Michaud,1992) and outside (e.g. Nearing *et al*, 2005 in Belgium).
- Recently, a geographic information system (GIS) based tool called the Automated Geospatial Watershed Assessment (AGWA, http://www.tucson.ars.ag.gov/agwa/) to support the set-up and parameterization of KINEROS2 has been implemented by the United States Department of Agriculture Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center, in cooperation with the U.S. Environmental Protection Agency (EPA) Office of Research and Development. This removes the difficult obstacle of building distributed *a priori* input parameter files for KINEROS2.
- The Digital Hybrid Reflectivity Scan (DHR) product from the WSR-88D (Weather Surveillance Radar 88 Doppler) radar is now available, providing reflectivity and hence the radar rainfall values on a polarimetric grid of 1° × 1 km, at every volume scan (~5 minutes). At each surface pixel, the precipitation is estimated from the lowest beam reflectivity possible, from the surface to 8 km AGL, and always from one of the four lowest-elevation tilts (O'Bannon, 1997; Fulton et al. 1998). Data taken at the lowest radar elevation angle above the terrain are identified as the hybrid scan bins, with two exceptions: 1) the bottom of the radar beam must clear the terrain by at least 500 ft (150 m) and 2) the radar beam cannot be blocked by 50%, or more, at ranges beyond an intervening terrain obstruction. These constraints are partially illustrated in Fig. 4 (taken from Maddox *et al*,

2002). This removes as much as possible the atmospheric evaporation effects between the cloud level and the surface for the falling rain, making it suitable as input for real-time models.

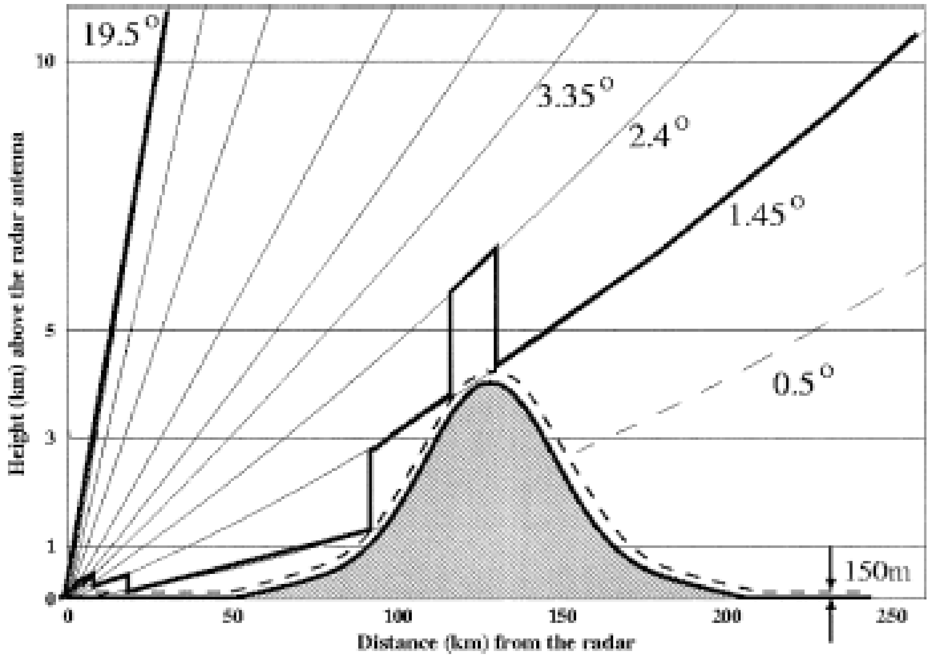

FIG. 3. This vertical section shows the height of the bottoms of the radar beams (VCP-21) above the terrain. The radar is assumed to be at sea level. The shaded area represents a mountain, and the dashed line following the terrain approximates the 150-m height surface above the ground. The upper, bold line indicates the bottom of the 19.5° elevation radar beam, The lower, bold line indicates the bottom of the hybrid scan beams.

Figure 4: (From Maddox et al, 2002): Elevation tilts selection method at each radar bin for rain estimates in the DHR product

- For complex, and especially spatially distributed models, there exists high dimensionality both of the number of parameters to be estimated, and of number of criteria to be considered. A sensitivity analysis is highly beneficial in the pre-calibration stage to reduce the parameter dimensionality. Sensitivity analysis evaluates the sensitivity of the model response to changes in the model parameters, state variables, or input data (e.g. Wagener and Kollat, *in preparation*). Recently, global sensitivity analysis has extended to investigating the contribution that the model and input uncertainties make the uncertainty in the output (e.g. Saltelli et al., 2004). The most popular of these, called variance-based measures, tend to be robust and model-free, i.e., applicable for non-monotonic, non-additive models, and even applicable for the case of non-orthogonal (i.e., correlated) a priori input parameters.

I.A.7 **Objectives and stages of this project**

Based on the above background, the following specific objectives (and corresponding stages/tasks) were identified to guide development of an improved Western Region site-specific flood-forecasting model:

(1) *Development and implementation of model code:* The objective of this task was to develop a version of KINEROS2 adapted to flash flood prediction in the Western Region using radar precipitation measurements. The site-specific model must be capable of using either the radar DHR product or (in future) the Multi-sensor Precipitation Estimator (MPE) product. The model interface must be simple to facilitate operational use. To achieve these objectives, the existing KINEROS2 model code required modifications. We note that the available version of KINEROS2 was designed to use rainfall estimates from rain gages and the NOAA II Atlas. Further, it was designed for event-based predictions and therefore does not keep track of the soil moisture state between storm events. Another consequence of the event-based design was that the time-loop is embedded inside the space loop, in contrast to the reverse required for real-time forecasting. The model therefore required considerable re-coding. In addition, modification to the AGWA code was required to derive pixel weights for converting rainfall estimates from DHR pixels to KINEROS2 polygon elements.

(2) *Development and implementation of automatic calibration system:* The objective of this task was to develop and implement a forecaster-friendly automatic calibration system that allows for the rapid estimation of model parameters (in less than 2-4 man hours). The system was designed based on the longstanding experience of the UA research team in developing automatic procedures for operational purposes (e.g. for SAC-SMA at the NWS).

(3) *Testing of the forecasting and calibration system on a representative set of test watersheds:* The objective of this task was to demonstrate and evaluate the forecast and calibration system using a set of representative test watersheds similar to the operational situations and hydrologic settings to be encountered. The catchments selected for this purposes were representative of the specific hydrological characteristics of semi-arid regions in the Southwestern US and having good data coverage. Preference was given to forecast points at which the local NWS has interest in the issuance of local warnings, thus providing improved services and reducing loss to life and property.

(4) *Development of a simple approach to allow the forecaster to consider the effect of precipitation uncertainty on the model forecast:* The objective of this task was to enable the forecast system to provide estimates of the confidence in the predictions (uncertainty bounds), in addition to the “best” forecast estimate. The strategy implemented is to propagate estimates of the rainfall uncertainty into uncertainty bounds on the output hydrograph.

(5) *Operational testing and evaluation of the current approach:* The objective of this task was to apply the developed tool, including the new calibration procedure, in an operational setting in parallel to current approaches to verify the procedure. This required development of a simple interface that allows the forecasters to specify initial conditions at the beginning of every event.

(6) *Training and reporting:* The objective of this task was to ensure continuity of close cooperation between the NWS and the University of Arizona throughout the development, training and reporting stages. Training ensures that the operational hydrologists directly involved are able to run the system and teach its usage to others. A technical report would contain relevant information regarding the models. This report will be disseminated throughout the Western Region and will also be made available on the Internet. Scientific publications will disseminate the findings to the larger operational and research hydrology community.

Fulfillment of the above specific objectives would achieve the major objective of this project of developing a site-specific model for the Western Region and to evaluate this tool in an operational setting.

Section II: Project Accomplishments and Findings

II.A Accomplishments related to each of the project objectives

Accomplishments and findings related to each of the objectives discussed in Section I are presented below.

II.A.1 Accomplishments related to objective 1 (Development and implementation of model code)

Discussed here are the components: KINEROS2, AMBER and AGWA used in the run setup and shown in Fig. 5.

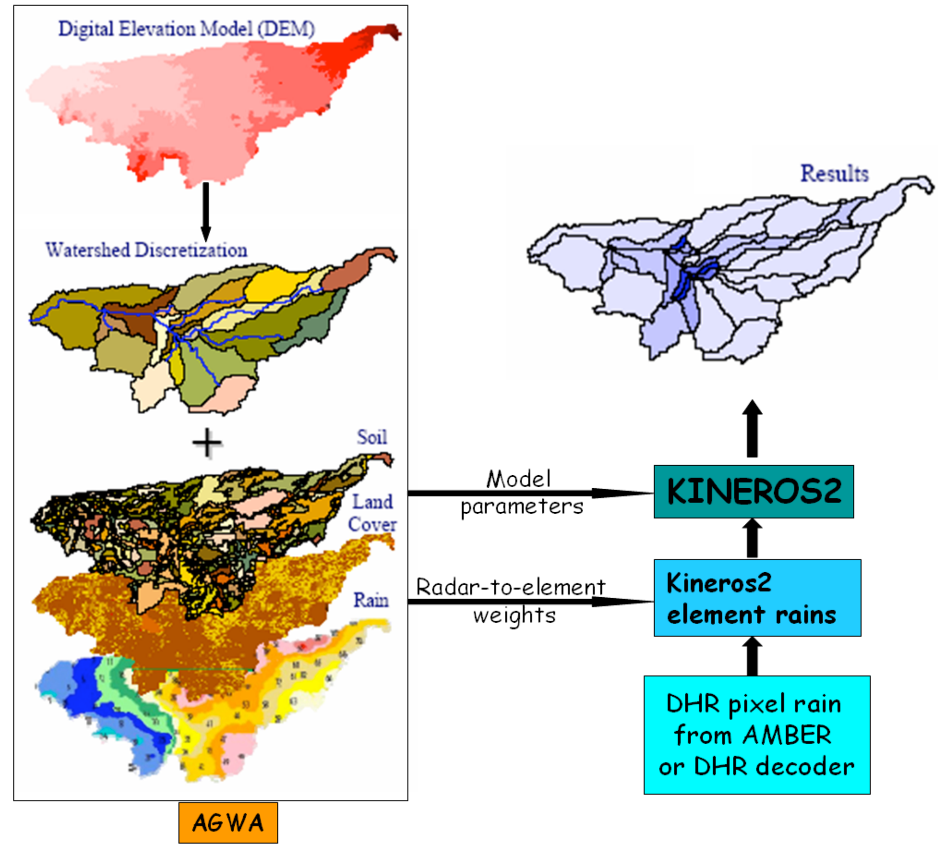

Figure 5: Example setup of a model run over the Walnut Gulch Experimental Watershed

<u>*II.A.1.i KINEROS2:*</u> The code changes to KINEROS2 described here are also discussed in Goodrich *et al.* (2006).

Features of the earlier version: KINEROS2 was originally a procedural paradigm-based Fortran 77 code having the time loop embedded inside the space loop as mentioned before (in project objective # 1, i.e., in subsection I.A.7-(1)). This was an artifact of the design which aimed to accommodate an unlimited number of model elements (planes, channels, etc.), while keeping the compiled program size well under the 640 KB limit imposed by the original MS-DOS operating system. These two criteria are met primarily by three design features. First, the element parameter blocks in an input file to the code appeared in sequential processing order, eliminating the necessity of storing element information in arrays. This saved on memory overhead and facilitated an unlimited number of elements by avoiding arrays which need to be of a fixed size in Fortran 77. The second feature is the mentioned space-time looping. Since all of the individual process models (overland flow, infiltration, etc.) in the program required values from the prior time step in their computations, this looping structure minimizes memory usage because the output value time series only had to be carried over to one downstream element from each element. The third design feature tried to address the need to efficiently store a certain number of these outflow hydrographs until they are used as inflow to downstream elements. The program used a carefully orchestrated 'revolving door' scheme to manage a single, fixed-length array that is partitioned into blocks, each of which equal to the number of time steps. In this scheme, maximum utilization of the array is achieved by allowing new outflow values to immediately occupy memory spaces just vacated by values used for inflow of the upstream elements that have finished processing. Although KINEROS2 is composed of well-defined components, those components were designed to be parts of a whole and not to function independently. This monolithic nature of KINEROS2 has led to a number of modified versions for each specific application, each of which must be maintained as a separate program.

Current version of KINEROS2: Currently, the hardware and operating system issues that the memory-efficient design features of KINEROS2 were designed to address no longer exist, due to the tremendous processing power and huge memory resources available on personal computers, both in hardware and through the use of virtual memory strategies like page file swapping. Also, Fortran itself has advanced to a new standard (Fortran 90/95) that has a more robust object-oriented paradigm. Fortran 90/95 provides dynamic memory allocation, a proprietary pointer mechanism, and modules that encapsulate data structures and procedures, allowing a rudimentary object-oriented programming approach. Accordingly, the KINEROS2 code was deconstructed and rebuilt by Carl Unkrich at the USDA-ARS and Soni Yatheendradas at the UA, with input from Roger Smith of the USDA-ARS, into a library of Fortran 90/95 modules, with each module implementing a single process model. The self-contained nature of these modules should encourage their incorporation into new programs that could benefit from their capabilities rather than modifying KINEROS2 to address specialized needs. The modules declare data structures to hold parameter values and the variables necessary to preserve its internal state between time steps, necessary for the time-space looping in real-time forecasting. The recoded modules also contain procedures to create and initialize the data structure, set parameter values, advance the computations by one time step, and free memory allocated when the data structure is no longer needed. Additional procedures may be included as needed to return copies of internal data or useful computed quantities. A module can also allocate an array of the data structures (objects), and contains procedures which allow the calling code to use an index into the array as a proxy for a given object. Module procedures that take a single data structure as an argument are intended for inter-module use within the library, such as for example, between overland flow and infiltration. Other equivalent module procedures that operate on a specified element of the internal array of data structures, comprise an application programming interface (API) for use by the host program or procedure. The strategy is to simplify use of the library by applications written in languages other than Fortran. This is desirable in that none of the popular and full-featured graphical user interface development products are based on Fortran. Other aspects of this strategy include restricting data types of procedure arguments to simple integer or real types and letting the host application perform all input and output. In addition to the core process models, there are utility modules to conveniently support backward-compatibility, such as one to extract parameters from a KINEROS2 input file. Compatibility between future versions of the module library is also ensured by not allowing existing procedures to be removed, or their names or argument lists to change, although they can change internally. Additional procedures that support extensions to a module's capabilities can be added in the future as long as suitable defaults can allow existing programs to use the module without calling the procedures.

Numerical/computational issues in recoding: The recoded KINEROS was seen to display memory leaks, which resulted in the Monte-Carlo repetition loop getting terminated after a certain number of repetitions during the sensitivity analysis procedure. This is when the accumulating memory leakage exceeded the total available system swap memory. This needed to be removed for successful implementation of the sensitivity/optimization procedure (for project objective # 2, i.e., in subsection I.A.7-(2)) which did not have a specific number of repetitions during convergence to an optimal region in the parameter space. These memory leaks have been plugged.

DHR input to KINEROS2: Additional code/software was added to the KINEROS2 setup for aspects like reading the rain amounts over each DHR radar bin, and to combine that with the 'DHR bin areal fraction in KINEROS2 element' weight files, derived using the AGWA tool (see below), so as to yield the rain amount inputs over each KINEROS2 element. Extracting the rain amounts over each DHR radar bin depends currently on the setting: in the research setting, this is done using the AMBER program (see 'AGWA' subsection below) and is outside the main KINEROS2 driver, while in the operational setting, this is done inside the main KINEROS2 driver using a module (prepared by Carl Unkrich at the USDA-ARS in consultation with the NWS) that is a modified version of the NWS FFMP DHR decoder.

Forecasting enhancement to KINEROS2: In addition, operationally, a key enhancement was added during the restructuring process to facilitate use in a real-time predictive mode, where, after simulating the latest real- time interval, the simulation continues into the future with assumptions about the input conditions. When the next interval of data arrives, KINEROS2 would have to start over from the very beginning of the simulation in order to arrive at a point where it could process the next interval of real data. The new modules were given the capability to save their internal states at a point in time and return to that state at a later time. So after the predictive interval, the modules can 'rewind' back to the end of the last interval of real data, and the program does not have to start over. This will be particularly important when the program is expanded to operate continuously. In addition to the overland flow and open channel process modules, the NWS program takes advantage of two utility modules in the library. One reads a KINEROS2 input file, then creates and configures all of the planes and channel elements as specified in the file. The other transfers outflow values from upstream elements into inflows to downstream elements at each time step.

*II.A.1.ii AMBER****:*** The AMBER program is used for two purposes in the current project. Firstly, for the research setting, the AMBER was customized to provide the timestep areal rainfall amounts over the radar bin areas as against over the basin areas that is typically done. This adapted version was provided by Paul Jendrowski of the Virginia WFO, along with the basin database keys (i.e., files containing the radar bin information for each watershed) for a few basins initially selected. Database keys for additional basins, e.g. Canada Del Oro at Ina Road were added at the UA, and can be replicated easily any other research setting with the obtained executable running on any HP-Unix machine similar to the one at the UA. Secondly, for both the research and operational settings, the GIS shape files for the radar grid required in the AGWA tool were generated by the ArcView extension that supports the NWS Areal Mean Basin Estimated Rainfall (AMBER) program.

*II.A.1.ii AGWA****:*** A modified version of AGWA, provided by Soren Scot at the USDA-ARS, intersects the polygons from which Kineros overland flow planes were derived and the radar grid from the ArcView extension of AMBER, to produce the 'DHR bin areal fraction in KINEROS2 element' weight file that's input to KINEROS2.

II.A.2 Accomplishments related to objective 2 (Development and implementation of automatic calibration system) The model parameter specification procedure being implemented for this project follows a combined strategy of parameter/objective function (OF) constraining, sensitivity analysis and automatic calibration. Uncertainty analysis is done as a part of project objective 4 (see subsection I.A.7-(4)). Recently, sensitivity analysis has emerged as a superset of the uncertainty analysis problem, involves investigating the contribution that the uncertainties in the parameters and the inputs, individually or in combination, make on the uncertainty in the output, both individually and in combination with other parameters (see Fig. 6). Combined with the potential of the sensitivity analysis procedure to reduce the parameter and objective function dimensionalities, sensitivity analysis becomes important to model calibration. These are applied in a multi-criteria framework in this project, attempting to emulate the skilled manual calibration of different parts of the hydrograph by the NWS. Information about the change in the required aspect of the hydrograph (e.g. peak magnitude) with respect to the different model parameters would be provided to the forecaster in case some manual adjustment needs to be made after the model parameter calibration process. Currently, we are in the process of implementation of these techniques, and would soon incorporate these into the forecasting system GUI tool.

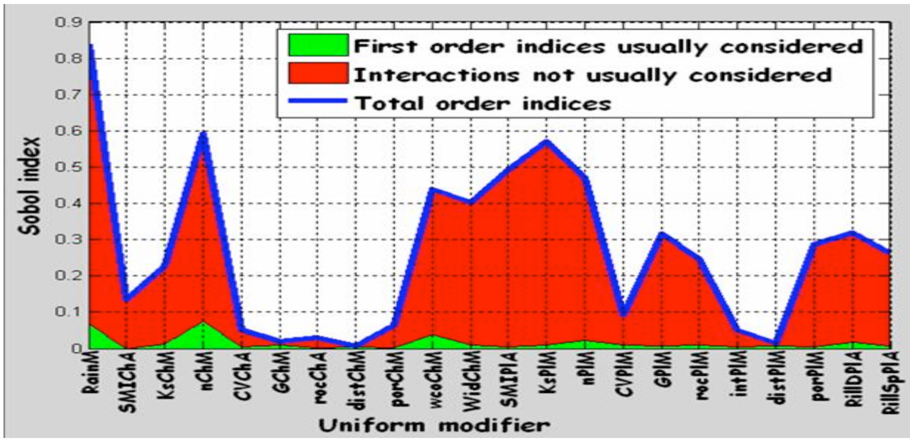

Figure 6: Example figure showing sensitivity to factors (on X-axis) like model parameters, inputs and initial conditions over the Walnut Gulch

For basins affected by wildfires (discussed in section II.A.3 below), some of the hydrologic parameters recover slowly over time scales of years (Robichaud *et al.,* 2000). Fig. 7 (from Canfield and Goodrich, 2006), shows an example model element-scale model parameter recovery rate derived for the KINEROS2 using a single-objective deterministic optimization algorithm (SCE-UA; Duan et al 1992). While these rates would be different for different vegetation types in terms of the extent and the base time period, these rates, depending upon the confidence of the USDA-ARS on the parameter recovery rate, make a good starting point for constraining the model parameters over time and can be refined following future studies over different vegetation types. The recovery rates of changing model parameters can thus be investigated.

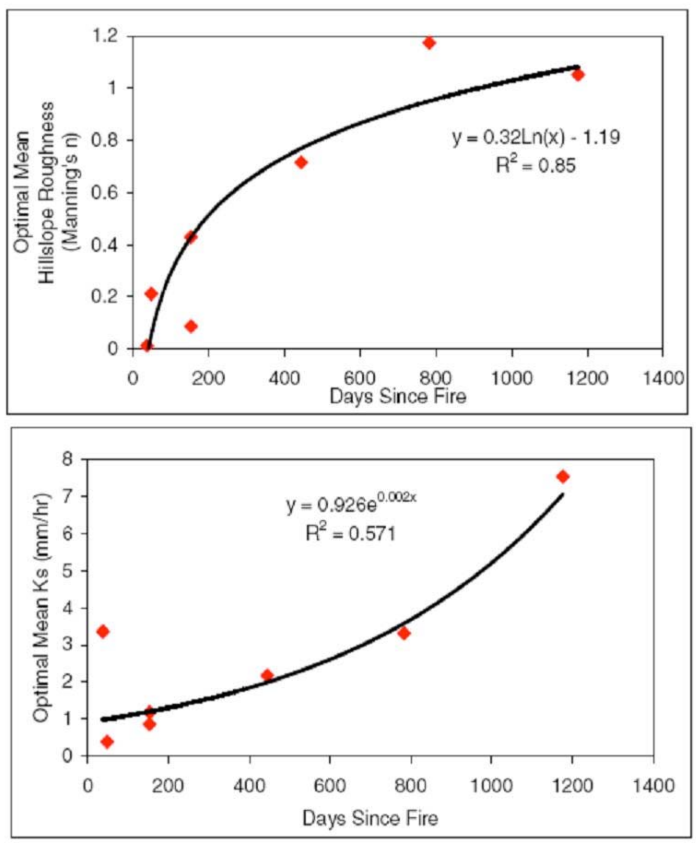

Figure 7: Optimal hillslope roughness and hillslope hydraulic conductivity for events following the Cerro Grande fire plotted versus time (From Canfield & Goodrich, 2006)

II.A.3 Accomplishments related to objective 3 (Testing of the forecasting and calibration system on a representative set of test watersheds): Initially, many test (sub-) basin forecast points in Arizona covered by the Tucson NWS radar were considered for this project, many of which are listed here: [1] Walnut Gulch Experimental Watershed near Tombstone, [2] Sabino Creek near Mt. Lemmon, [3] Sabino Creek near Tucson, [4] Canada del Oro Wash near Coronado Camp, [5] Canada del Oro Wash at Rancho Solano, [6] Canada del Oro Wash at Golder Ranch Road Bridge, [7] Canada del Oro Wash at Ina Road, [8] Santa Cruz river near Lochiel, and [9] Leslie Creek near McNeal. However, data collection for these forecast points was hampered by lack of events. Due to drought that has impacted Arizona since the late 1990's, flow events have been scarcer. Even in case of the short list of flow events that happened, the archived DHR data (starting in 2003) sometimes could not be retrieved. This, coupled with the requirement of bankfull/high flow events (to be discussed in the subsection titled Status on Objective # 5) for the range of flows against which the flood-forecasting tool needed to be calibrated against, has drastically cut down the number of events available for the model parameter specification procedure. In addition, the Tucson NWS provided a preference list of forecast points where the forecasting tool is to be deployed to provide improved services and reducing loss to life and property. Coincidentally, these are basins burned by recent wildfires (

i.e., Aspen Fire of June-July, 2003 on over 87450 acres), hence respond to much smaller amounts of precipitation that would normally have produced a significant flow in its pre-burned state. Data collection on the burned Sabino Creek and Canada del Oro Wash basin is an ongoing process where the parameter/input uncertainty estimates (and hence the forecasts with uncertainty estimates) can be continuously refined with new events added to the model specification tool as and when they occur.

The basins selected till now and in various stages of analysis/implementation in the research/operational settings respectively are (shown in Fig. 8): [1] Walnut Gulch Experimental Watershed (WGEW) near Tombstone (148 km^2 area), [2] Sabino Creek near Tucson (91 km^2 area), and [3] Canada del Oro (CDO) Wash at (a) Rancho Solano (111 km^2 area), (b) Golder Ranch Road Bridge (168 km^2 area), and (c) Ina Road (670 km^2 area). The CDO wash at Ina gives an opportunity to apply the KINEROS2 model over areas much larger than applied before (e.g., the mid-sized WGEW). Note that the highly instrumented WGEW (e.g., Michaud, 1992) is the only basin used in a research setting only as opposed to the other two. Also, note that the CDO Wash is a doubly nested watershed, thus having the three forecast points (3a, 3b and 3c) mentioned above (Fig. 9). In addition, the Walnut Gulch also has internal runoff measurement points, making it also feasibly for nested basin studies (Fig. 10).

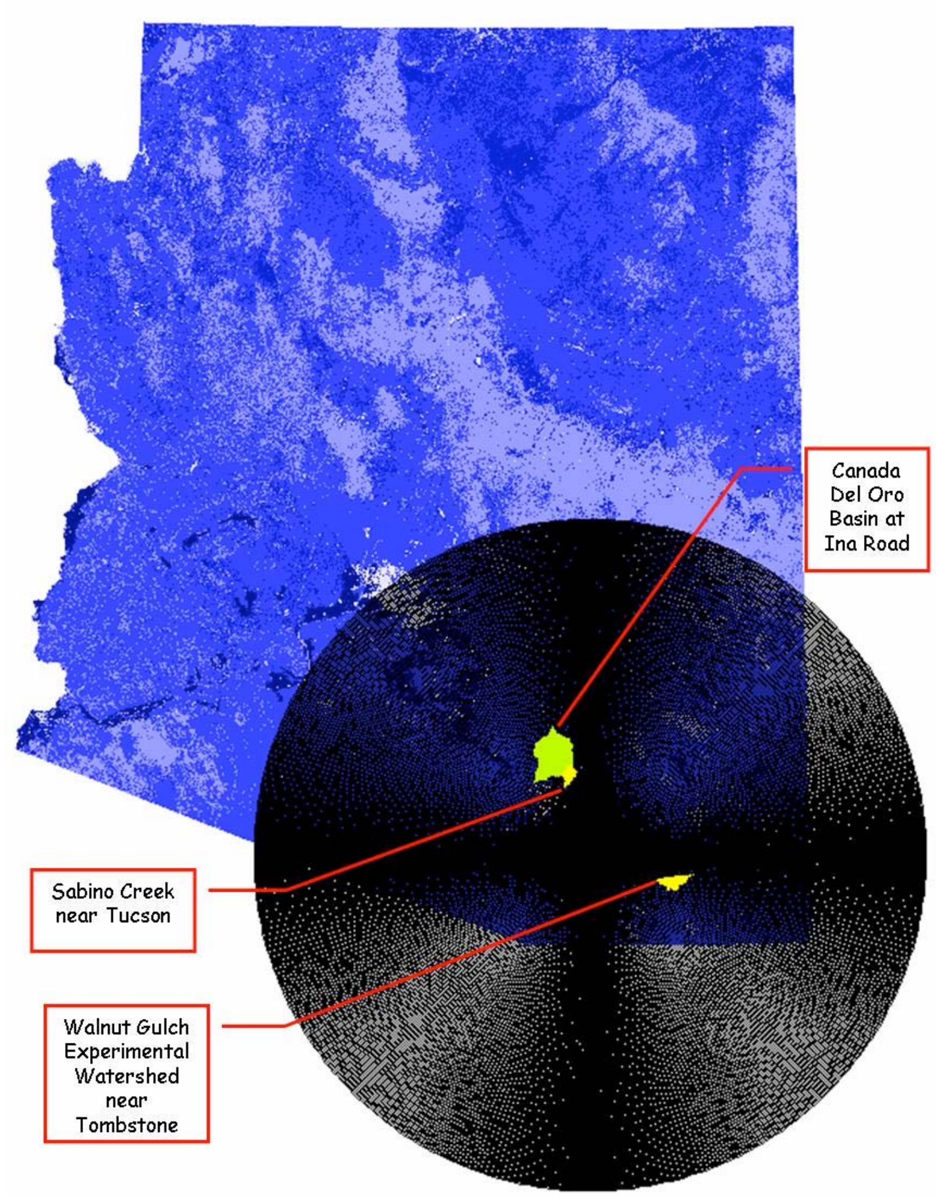

Figure 8: Location in Arizona of basins being analyzed till now against the background of Tucson NWS radar coverage

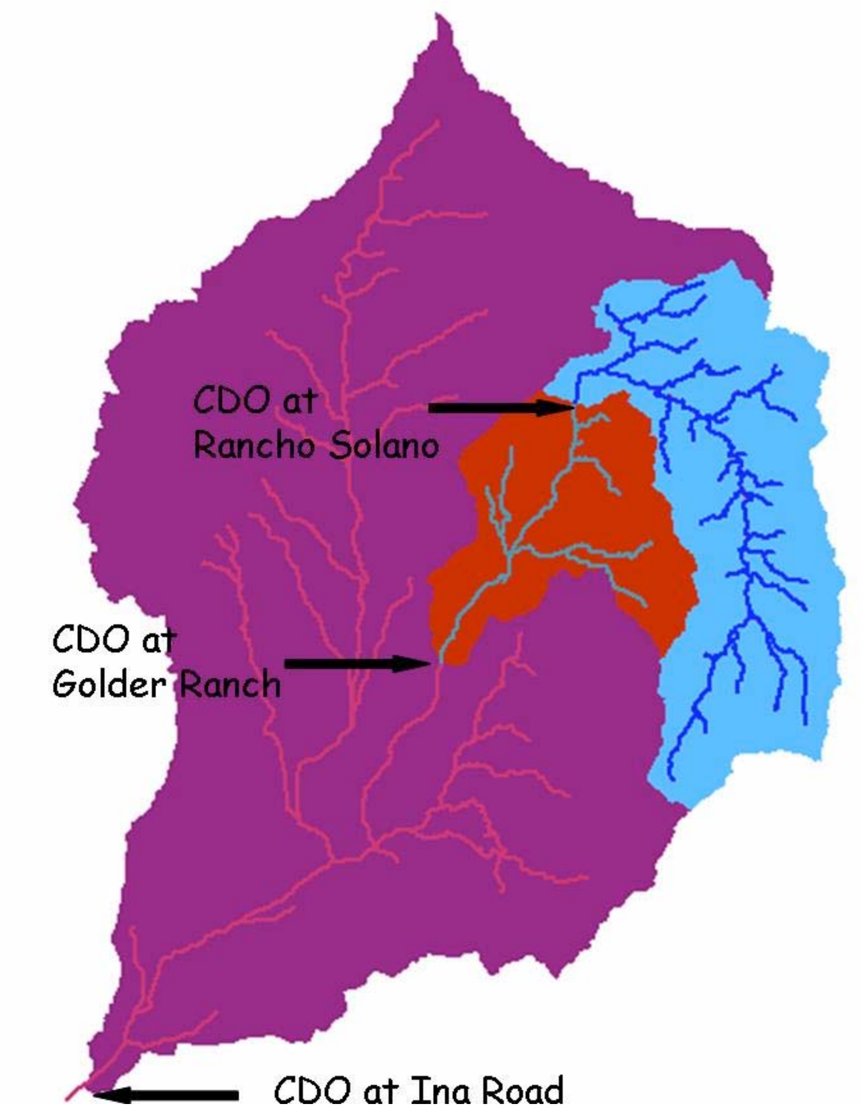

Figure 9: Nested forecast points in the Canada Del Oro (CDO) basin

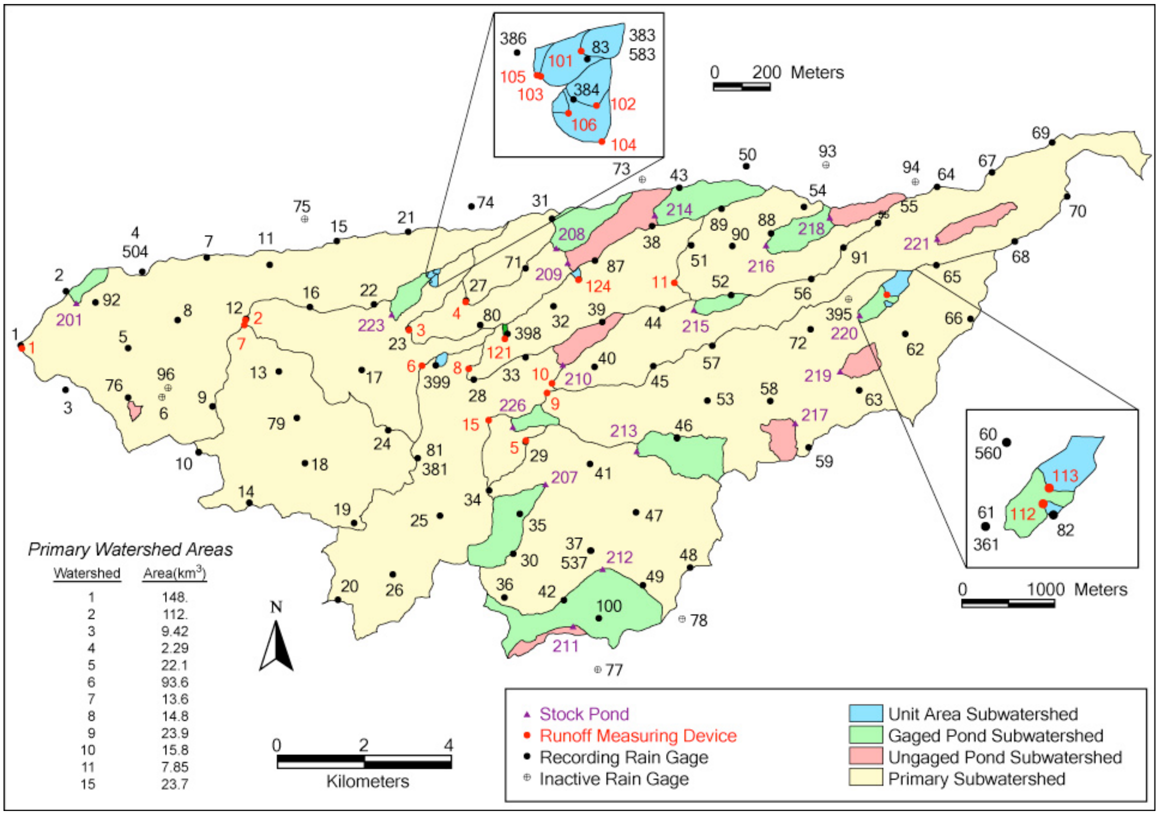

Figure 10: Internal runoff locations in the Walnut Gulch basin for nested basin study (image from http://www.tucson.ars.ag.gov/dap)

We have conducted field trip surveys and taken channel geometry measurements over both the Sabino basin and the CDO to get accurate measurements of the channel morphology and to understand the basin morphology. While field trips over the Sabino have indicated the presence of many reaches with higher roughness and possibly lower permeability values, the field trip surveys over the CDO Wash have indicated the presence of many overbank section reaches, which can be accurately modeled only with compound channel geometries (Fig. 11) as opposed to the simple main channel geometries (as per the experience of the Tucson USDA-ARS-SWRC) modeled over the Sabino forecast point. Channel morphology measurements have been taken at specific representative points on the reach, both on field and using fine-resolution elevation models available for purchase from the Pima County Association of Governments. All this information has been incorporated into the models for the respective basins.

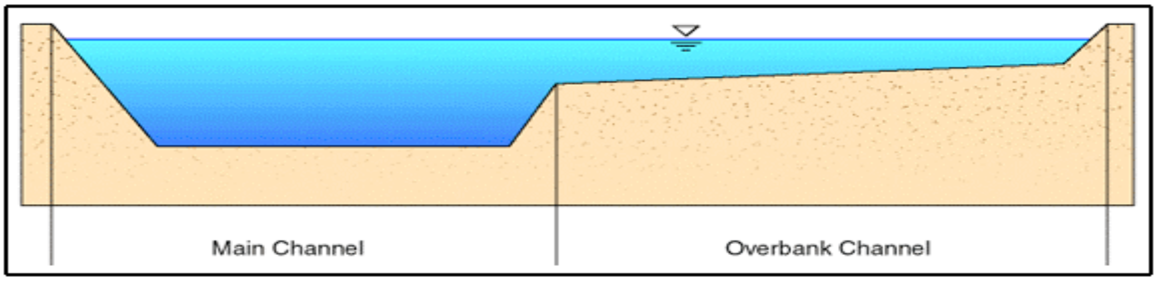

Figure 11: Compound channel geometry modeled in KINEROS2 for the CDO basin main reaches

As mentioned in subsection II.A.2, we are currently in the process of implementation of sensitivity analysis/calibration techniques on these watersheds.

II.A.4 Accomplishments related to objective 4 (Development of a simple approach to allow the forecaster to consider the effect of precipitation uncertainty on the model forecast): Some aspects needed to be considered in conversion of the reflectivity from the DHR product into rain rates:

II.A.4.i The Z-R relationship uncertainty: The DHR reflectivity grid is converted to rain input (e.g., in AMBER) typically using a standard NWS *Z–R* relationship for convective rainfall of the following form (Fulton *et al*., 1998):

$$Z = 300 \cdot R^{1.4} \quad (1)$$

where the reflectivity Z is in mm^6m^{-3}, and the rain R is in mm/hr.

Morin *et al*. (2005) analysed thirteen separate storm events over the Walnut Gulch watershed and found that the parameters used in this relationship (equation (1)) can result in a gross overprediction of rainfall for certain locations in Arizona, thus suggesting that a re-calibration to local conditions might be required. One potential reason for this is that cloud bases may be well above the surface, resulting in a possibility of significant evaporation between cloud base and the surface, especially pronounced over the southwestern United States. Morin *et al*. (2005) derived the following relationship which yielded smaller and more accurate values than equation (1):

$$Z = 655 \cdot R^{1.4} \quad (2)$$

This relationship was derived for the third tilt data (elevation angle of 2.4º equivalent to approximately 3-km altitude above ground over the study area) of the base radar reflectivity product. In this study, the use of the DHR product with a different tilt at each radar bin could change this estimate. Also, initial comparisons of the observed gage rain and the DHR rain over the basin show the Z-R parameters to be in between these relationship rain estimates (equations (1) and (2)). Therefore, calculating the uncertainty in the precipitation estimates becomes crucial to this study.

<u>II.A.4.ii The upper hail threshold uncertainty:</u> Hail highly increases the reflectivity values, and hence the rain estimates. Since most summer storms over the southwest are extremely continental in nature, radar data obtained at and above elevations of 2–4 km MSL are likely to contain hail and/or graupel (Morin *et al*., 2005). Morin *et al*. (2005) applied an upper threshold of 103.8 mm/hr (i.e., ~ 4 in/hr) to the estimated rain intensity, which is a default threshold used by the NWS for reducing unreasonably large estimates caused by hail cores in thunderstorms. However, this threshold can be anywhere between 75-150 mm/hr depending on local conditions (Fulton et al., 1998). For example, the use of the tropical Z-R relationship ($Z = 250 \cdot R^{1.2}$) is accompanied with a hail threshold of 154.2 mm/hr (i.e., 6 in/hr).

Mendez *et al.* (2003) analyzed the maximum point rainfall intensities for different durations and return periods and found for summer thunderstorms over Walnut Gulch and found that the mean 10-year return 5 min duration (i.e., same as the radar DHR timestep) intensity from WG gage groups is 146.3 mm/hr, and that exceeding 103.8 mm/hr for a 5 minute intensity is not uncommon. Maximums for the gages examined were in the range of 250 mm/hr for 5 minute duration intensities. Also, Morin *et al*. (2006) found high maximum rain intensity (α) values of the modeled rain cells, which taken together with the corresponding cell rain spread (β) values, can give theoretical areal average values above the 103.8 mm/hr threshold. The basin rain depth and runoff volume can be significantly sensitive to these parameters (see Fig. 12). Considering these two studies (one at point-scale and another at radar bin scale with point values provided), we are of the opinion that a higher hail threshold is worth experimenting with, even with the risk of having measurements with hail present. Hopefully, more researchers would be encouraged to investigate this problem of setting a higher threshold (e.g., 146.3 mm/hr for Walnut Gulch, assuming flash-flood forecasting deals with high-intensity rain estimates over short return periods like 10 years).

Table 1: Summary of theoretical rain-cell characteristics for 13 storms analyzed over the Walnut Gulch by Morin *et al.* (2006)

Summary of modeling results

Storm	Maps with cells	Total number of cells	β (mm/h)			α (km^{-1})		
			Aver.	Min.	Max.	Aver.	Min.	Max.
1	19	49	51	11	225	0.37	0.25	0.54
2	29	112	47	13	193	0.38	0.15	0.67
3	86	370	62	11	228	0.41	0.23	0.67
4	13	28	90	20	239	0.46	0.34	0.67
5	29	80	44	11	129	0.40	0.22	0.53
6	17	35	58	14	142	0.44	0.31	0.60
7	30	124	70	14	211	0.39	0.22	0.63
8	39	167	74	9	225	0.36	0.19	0.57
9	12	36	47	16	132	0.38	0.25	0.54
10	28	129	65	14	203	0.41	0.26	0.58
11	31	72	41	10	95	0.41	0.29	0.60
12	21	182	69	13	214	0.37	0.15	0.56
13	23	54	86	12	247	0.39	0.25	0.55
14 (tilt 1)	26	193	42	12	117	0.37	0.21	0.59
14 (tilt 2)	18	152	50	14	159	0.37	0.20	0.60
14 (tilt 3)	18	111	60	14	218	0.40	0.20	0.56

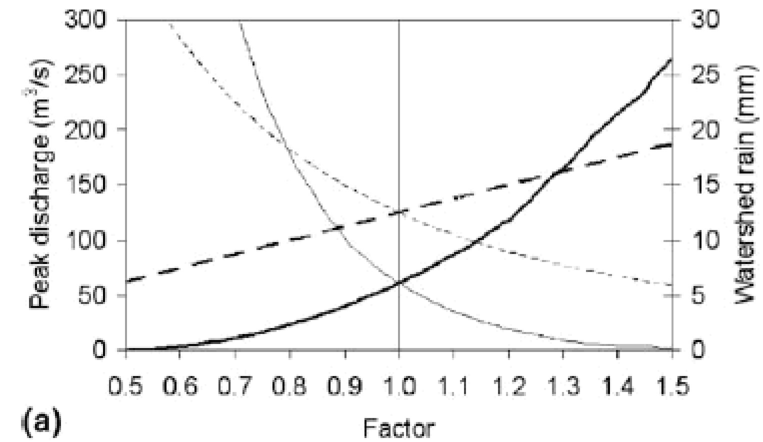

Figure 12: Sensitivity of basin rain depth (dashed lines) and of computed outlet discharge (solid lines) to maximum rain cell intensity (thick lines) and rain cell spread (thin lines). X-axis is multiplicative factor either to the maximum rain cell intensity (247 mm/hr) or to the rain cell spread [From Morin *et al.*, 2006]

II.A.5 Accomplishments related to objective 5 (Operational testing and evaluation of the current approach *Operational testing and evaluation of the current approach**):***

The GUI: To make flood forecasting user-friendly, a graphical user interface (GUI) was developed by Carl Unkrich of the USDA-ARS by using the newly developed modular KINEROS2, another module to compute area-weighted rainfall rates from DHR, and a modified version of the FFMP DHR decoder. This GUI was written in the Delphi development environment, which is based on object-oriented Pascal. The GUI was deployed on a PC within the AWIPS network at the Tucson NWS since the latter part of the 2005 monsoon season, and is shown in action during the summer 2006 forecasting season over the Sabino basin in Fig. 13 below.

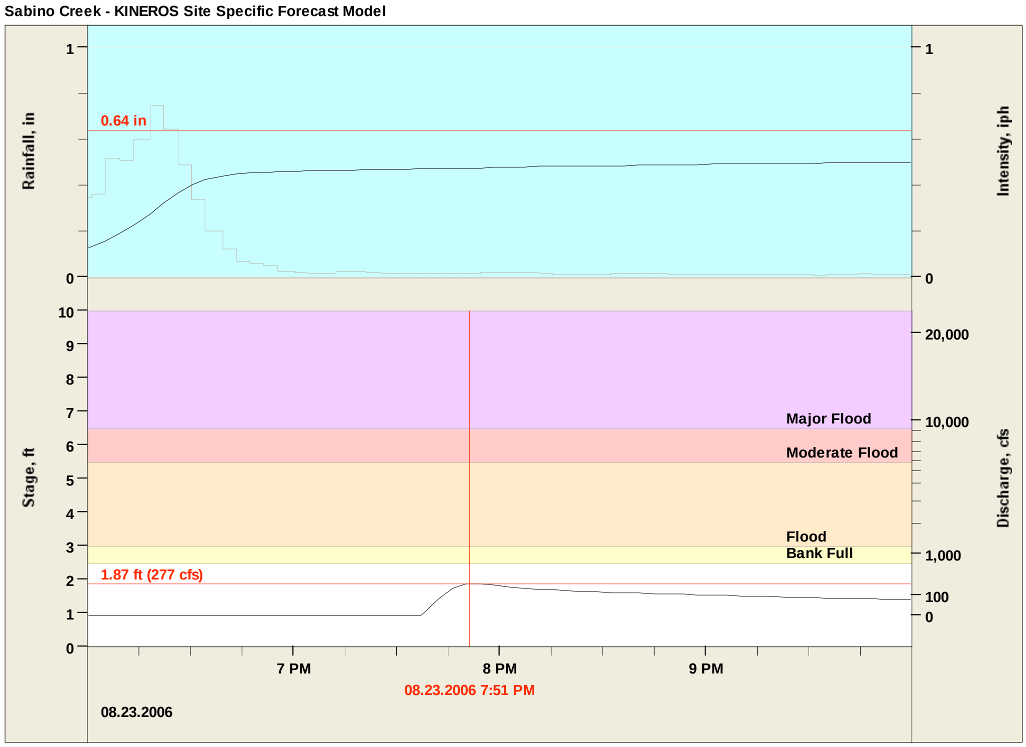

Figure 13: The COMET-developed flash-forecasting system interface in action over the Sabino Creek near Tucson during the 2006 monsoon season

An audible alarm capability is included to alert the forecaster when the maximum predicted stage level exceeds the critical stage or stages selected by the forecaster. The taskbar button will also flash to identify which watershed is in alarm mode when multiple watersheds are running on the same PC. The rainfall graph shows both accumulation and intensity, with current accumulation shown in red. The runoff graph shows stage and equivalent discharge rate, and indicates the peak stage (discharge) and time of peak in red. A snapshot of the GUI at a given instant can be printed directly or saved as a windows metafile, or snapshots can be automatically saved at regular intervals. Note that the snapshots do not show the scrollbar across the bottom, and in Fig. 12, the graph window has in fact been scrolled back to show the peak flow (current time is indicated by a vertical black line which is out of view to the left).

When the forecasting system is started, an initial window asks the user to specify the following options:

- *Initial condition*: This can be 'Very Dry', 'Dry', 'Wet', or 'Very Wet', which corresponds to 20%, 40%, 60%, or 80% of soil pore space filled.
- *Baseflow*: Used when there is interstorm flow present in the main channel stem of the watershed.
- *Archived vs. real time run*: Using this option, past events can be evaluated or used for training purposes. The only difference between these two is that the archived run does not search for additional incoming files when

the existing files in the input directory are processed, while the real-time runs periodically search for new input DHR files added to the directory.

- *Current time start vs. past time start*: This option is used in real-time forecasting, when the forecasting system is started after rainfall has commenced. It allows the program to start at an earlier time and 'catch up'.
- *Auto-save:* If checked, saves images once per hour.

Ongoing refinements: The KINEROS2 parameter input files have been continuously undergoing refinements, depending upon the additions required to the watershed/flow representation based on the geology/morphology of the basin over which it is deployed. For example, the Sabino Canyon near Tucson forecast point over which the forecasting system is now operational, did not provide accurate forecasts for the unusually huge flood event of July 31st, 2006. This indicated additions required like specification of the baseflow, and/or a two-layer soil profile, to capture the geology of the watershed where soil overlies impermeable bedrock close to the surface, with most of the basin, especially the downstream part, having the upper layer depth less than around a foot, to some of the upstream parts having deeper soil of a few feet (Bezy, 2004; and field trips surveys conducted by the COMET team). Currently, the baseflow specification feature-added version is operational, with a new version having the double soil layers expected to be out soon.

Similarly, field trip surveys over the CDO Wash have indicated the presence of many overbank section reaches, which can be accurately modeled only with compound channel geometries as opposed to the simple channel geometries (as per the experience of the Tucson USDA-ARS-SWRC) modeled now for the Sabino forecast point. These compound channel geometries have not been rigorously tested, and while they are used in the research setting here, the operational setting may see some delay in their usage, possibly with no deployment this monsoon. Also, currently, the hydrologist does not have the option to override either the default parameters or the optimized ones in this deterministic version. This is now done manually by the hydrologist after the parameter file is created by AGWA. With the planned addition of the parameter calibration/specification module to KINEROS2 in the GUI to give ensemble forecasts, this feature would be added. The quality aspect of the evaluation of the forecasts is an ongoing process with continuous refinements added to the model specification/calibration tool as and when new events occur.

II.A.5 Accomplishments related to objective 6 (Training and reporting):

- There has been and is a continuous ongoing discussion between the UA, the NWS, and the USDA-ARS about procedures, practical problems, limitations of available tools and suggestions of how the forecasting skills of new tools could be evaluated.

- The Tucson NWS has the site specific model deployed for the Sabino creek near Tucson, and for the Canada Del Oro (CDO) Wash forecast points. The Sabino creek forecast point model is currently in use and is almost close to its final operational version. The models for the CDO forecast points need additional work to incorporate the overbank river reach geometry information; hence currently have only a simple main channel geometry built in. These are integrated into NWS flash flood forecasting as additional quantitative forecast guidance.
- Training was held in May 2006 for operational staff at WFO Tucson. This allowed forecasters to gain a much better understanding of rainfall-runoff modeling and processes in a semi-arid environment. Valuable input from forecasters for making the display and usage more user-friendly, were incorporated into the GUI.
- NWS Service Hydrologist, Mike Schaffner, presented preliminary results of the COMET project at the 2nd NWS Hydrologic Program Manager's Conference in New Orleans the week of December 5th 2004. This included a poster at the Wednesday evening poster session and a presentation at the Western Region breakout session Friday morning.
- NWS Service hydrologist, Mike Schaffner, demonstrated the KINEROS Specific Forecast at Phoenix and Park City during the NWS Subregional Spring Weather Workshop of 2006 at WFO Phoenix
- Technical memos and scientific publications related to the work on this project are under preparation and would be out soon.

II.B Updated status of the Western Region site-specific flood forecasting system as a result of this project

Based on the work done and in progress during the project, we again enumerate below the 'Requirements for a Western Region site-specific flood forecasting system' from 'Section 1: Summary of Project Objectives', along with the corresponding status:

***II.B.1 Suggested requirements*:**

#	*Requirement*	*Status*
1	Modular design to allow flexibility in sophistication, as WFO needs dictate and resources allow	Done
2	Handle basins with a time of concentration on the order of up to 8hrs	Done
3	Continuous model, with event-based capability initialized to current conditions	Refinements continuing
4	Short time-step model, increment of 15 minutes or less	Done
5	Model must have a well-documented calibration system which allows for relatively quick and satisfactory calibrations (capability to complete individual basin calibrations in an average time of 2-4 hours)	Continuing development
6	Inputs: as appropriate to the scale of the model, including Quantitative Precipitation Forecasts (QPF)	Done with radar input. QPF not within scope of current project.
7	Ability for user to edit input	Continuing development
8	Output: forecast guidance on which warnings can be based. Categorical forecasts at an absolute minimum. Observed, simulated, and forecast hydrographs, and precipitation plotted as inverted hyetographs highly desirable	Done, except for observed real-time hydrograph display, which must be coordinated with the data collection agencies (e.g., USGS, Pima County) in future
9	Model must be accessible from Advanced Weather Interactive Processing System (AWIPS) workstations (UNIX) and have user accessibility via a graphical user interface (GUI). The GUI should contain selections for all input parameters, with defaults for all applicable parameters	In progress, currently running on an AWIPS Windows PC. Options for overriding the default/optimized parameters will be added as part of the model calibration module.
10	Model must permit multiple runs (not necessarily concurrently) with various input scenarios to obtain a range of contingency forecasts.	Done, currently, with multiple runs on a single PC for output evaluation based on different conditions (e.g., initial conditions, or rain input.)
11	Model must be capable of using radar precipitation input	Done: currently based on radar rain input

II.B.2 Further desirable requirements:

#	*Requirement*	*Status*
1	Routing available to combine sub-areas of small rivers with tributaries and confluences	Done: feature is part of KINEROS2
2	Capability to adjust model for effects of land use change, *i.e*. fire	In progress, based on parameter recovery rates from limited studies earlier
3	Snow accumulation and ablation model available for use if desired	Future work: not part of the current project
4	Other outputs: confidence interval hydrographs; inundation maps	Confidence intervals implementation in progress; inundation maps are future work & not part of the current project
5	Be able to run model on past events for evaluation purposes. Including ability to toggle between Mean Areal Precipitation (MAP) along with total losses, or observed MAP along with past basin QPF (to enable visual QPF tracking while also viewing the differences between observed and forecasted hydrographs). This information is needed so that WFO forecasters can assess the validity of forecasts based on past performance and to identify causes of poor past performance	Model output based on radar DHR input being evaluated for past events. Similar distributed precipitation sources (not part of this project) can be incorporated in the future
6	A site-specific model that will work for all areas of the Western Region. While the development of some capabilities may need to be delayed, the model must be designed with enough flexibility to accommodate their development and assimilation. For example the model needs to be able to incorporate rain gage data in addition to or instead of radar precipitation estimates	Varies, depending on the flexibility required. For example, the Thiessen polygon method of the original KINEROS code for using rain gage information can be recoded for rain gage input.

Section III: Benefits and Lessons Learned: Operational Partner Perspective

- NWS personnel gained a better understanding of and gave valuable input to the development of a site-specific model to produce a forecast hydrograph in real time for small basins.
- WFO forecasters were exposed to GIS, rainfall-runoff modeling, burn-area hydrology, and simple model calibration/setup, and provided necessary resources and information to the research partners as required.
- NWS personnel gained better understanding of the role of the geomorphology of the basin on flash-flood forecasts from the unusually large Sabino Creek event of July 29th through 31st 2006.
- This study is showing potential to add value and increase lead times for flash flood warnings using additional guidance from this forecasting system. The WFO forecasters would be able to issue flash flood warnings by basins and give the timing and magnitude of flash flood events.
- This study shows potential to give improved flash flood forecasts for basins with burned areas.

- This study shows future work potential to forecast flash floods for ungaged basins.

Section IV: Benefits and Lessons Learned: University Partner Perspective

- The improvements in the KINEROS2 model made within this project have sparked wider interest to support additional improvements outside the (financial) scope of this project. This will allow additional students to work on this project.
- Continuous ongoing discussion between us and our NWS partners about procedures, practical problems, limitations of available tools and suggestions of how the forecasting skills of new tools could be evaluated.
- The project needed more resources in terms of finance, skill and time than we had originally expected. The skill and time contributed by the scientists at the USDA-ARS is greatly appreciated.
- This close cooperation would not be possible without the funding provided by the COMET program. It offers our students a unique experience to perform scientifically and society relevant research.
- This study makes a good reference point for detailed future research on semi-arid basin recovery from wildfires and flash flood forecasting for ungaged basins.
- Comparison of distributed radar rain data against rain gage data (ALERT), if required, has been hampered due to limited technical personnel resources. As noted by graduate student Anne Stewart, this is because of the lack of tools to convert the acquired raw ALERT data to usable form.
- Data potentially available from before 2003 during, for example, the 1999-2000 wet years would be very useful for calibration. We reported earlier about the potential benefits of using the CODE (Common Operations and Development Environment, ftp://ftp.nws.noaa.gov/software/88D_CODE) software, which can greatly increase the number of events available for each basin. This aspect was looked into, but lack of time and technical resources has hampered its implementation.

Section V: Publications and Presentations till now

Journal papers/book chapters:

- Yatheendradas, S., Wagener, T., Gupta, H.V., Unkrich, C., Schaffner, M. and Goodrich, D. 2005. A distributed real-time flash-flood forecasting model for semi-arid regions. In Franks, S., Wagener, T., Gupta, H.V., Bogh, E., Bastidas, L., Nobre, C., Oliveira Galvao (eds.) 2005. Regional hydrologic

impacts of climate change - Hydro-climatological variability. IAHS Redbook Publ. no. 296, 108-117.

Presentations:

- Goodrich, D., S. Yatheendradas, T. Wagener, H.V. Gupta, C. Unkrich, M. Schaffner, 2007: Evaluation of a distributed real-time semi-arid flash-flood forecasting model utilizing radar data in the Tucson, Arizona area, AMS 21st Conference on Hydrology, San Antonio, Texas, Jan 14-18 (Presentation).
- Schaffner, M., et al., 2006: Demonstration of the KINEROS Site Specific Forecast Model. NWS Subregional Spring Weather Workshop, WFO Phoenix, AZ (Presentation).
- Yatheendradas, S., Gupta, H.V., Wagener, T., Unkrich, C., Schaffner, M. and Goodrich, D. 2005: Toward improved calibration of a semi-arid distributed flash-flood model: a hierarchical sensitivity analysis scheme for model evaluation. 2005 AGU Fall Meeting, San Francisco, 5-9 December, 2005. (Poster)
- Schaffner, M., Gupta, H., Yatheendradas, S., Wagner, T., Unkrick, C., Stewart, A., and Goodrich, D., 2005: Real-Time Distributed Modeling at a Local Weather Forecast Office. NWS Western Region Hydro-Science Workshop, Park City, UT (Presentation).
- Yatheendradas, S., Gupta, H., Wagner, T., Unkrick, C., Schaffner, M., and Goodrich, D., 2005: Hierarchical Sensitivity Analysis of a Semi-Arid Distributed Flash-Flood Model. SAHRA 5th Annual Meeting, Tucson, AZ (Poster).
- Yatheendradas, S., Wagener, T., Gupta, H.V., Unkrich, C., Schaffner, M. and Goodrich, D. 2005. A distributed real-time flash-flood forecasting model for semi-arid regions. 7th IAHS Scientific Assembly, Foz do Iguazu, Brazil, 3-9 April, 2005. (Poster)
- Yatheendradas, S., Wagener, T., Gupta, H.V., Unkrich, C., Schaffner, M. and Goodrich, D. 2005. Continuous distributed flash-flood hydrologic modeling for semi-arid regions using radar data. AMS, San Diego, USA. (Poster)
- Schaffner, M., Gupta, H., Yatheendradas, S., Wagener, T., and Unkrich, C. 2004. A distributed real-time flash-flood forecasting model for the semi-arid west. NWS 2nd Hydrologic Program Manager's Conference, December 6 - 10, 2004, New Orleans, LA. (Poster)
- Schaffner, M., Gupta, H., Yatheendradas, S., Wagener, T., and Unkrich, C. 2004. A distributed real-time flash-flood forecasting model for the west. NWS 2nd Hydrologic Program Manager's Conference, December 6 - 10, 2004, New Orleans, LA. (Presentation)
- Schaffner, M., 2004: Development of a Site-Specific Flash-Flood Forecasting Model for Western Region. NWS Hydrologic Program Manager's Conference, WR Breakout Session, New Orleans, LA (Presentation).
- Schaffner, M., Yatheendradas, S., Wagener, T., Scott, S., Unkrich, C. and Gupta, H. 2004. A distributed real-time flash-flood forecasting model for the

semi-arid west. Arid Regions 10th Biennial Conference, Restoration and Management of Arid Watercourses, November 16 – 19, 2004, Mesa, Arizona. (Presentation)

- Yatheendradas, S., Wagener, T., Gupta, H.V., Unkrich, C., Schaffner, M. and Goodrich, D. 2004. A distributed real-time flash-flood forecasting model for the semi-arid regions utilizing radar data. SAHRA 4th Annual Meeting, October 13-15, 2004, Albuquerque, USA. (Poster)
- Schaffner, M. and Pytlak, E. 2004. Development of a site-specific flash flood forecasting model for the Western Region. CBRFC Basin Meeting, June 2, 2004. (Presentation)

Section VI: Summary of University/Operational Partner Interactions and Roles

- There is and has been a continuous ongoing discussion between the UA, the NWS, and the USDA-ARS about procedures, practical problems, limitations of available tools and suggestions of how the forecasting skills of new tools could be evaluated. This has been in form of meetings etc. between the university and operational partners.
- The close collaboration of the UA, the Tucson USDA-ARS and NWS has been critical to this project. Software development, user interface and analysis are done jointly by the UA and USDA-ARS, with the NWS providing operational expertise, data and other resources.
- The project has provided important and invaluable training for several graduate students. The results are expected to provide the basis for ongoing training.

Section VII: Ongoing and future work

VII.A. Ongoing and future work in this project:

- The Tucson NWS now has the site specific model deployed for the Sabino creek near Tucson, and for the Canada Del Oro (CDO) Wash forecast points. The models for these are integrated into NWS flash flood forecasting as additional quantitative forecast guidance.
- The Sabino creek forecast point model is currently in use and is almost close to its final operational version.
- The CDO forecast point models need additional work to incorporate the overbank river reach geometry information; currently only a simple main channel geometry is built in. The current 2006 monsoon season might not see this feature addition to the models for CDO forecast points.
- Work on the parameter calibration module and the ensemble forecasting with uncertainty bounds is in progress.

- Currently, the model is not fully continuous. The continuous version will be implemented in the near future.
- Work on conditional calibration of nested basins (i.e., fixing nested basin parameters) to assess prediction improvement downstream, given observations available upstream is ongoing.

VII.A. Desirable future work (not part of this project)

- Rain input from Quantitative Precipitation Forecasts (QPF's) or the Multi-sensor Precipitation Estimator (MPE) can be used in the future in place of the current project radar DHR input.
- Addition of snow model for high elevations of the southwest which receive snowfall.
- Inundation maps based on forecast outlet discharge could be useful in providing additional information to the public during forecast warnings.

References

AMS, 1985. Flash floods – A statement of concern by the American Meteorological Society. Bull. Am. Meteorol. Soc., 66(7), 858-859.

Anderson, E. A., 1993. A Continuous, Incremental Antecedent Precipitation Index (API) Model for use with the National Weather Service River Forecast System. In: Engineering Hydrology, Proceedings of the Symposium sponsored by the Hydraulics Division of ASCE, San Francisco, CA, July 25-30, 1993, by Chin Y. Kuo, (editor), ASCE, publication series, pp. 934-939

Bezy, J.V., 2004, A guide to the geology of Sabino Canyon and the Catalina Highway, Arizona Geological Survey, Down-to-Earth 17, 45 p.

Burnash, R.J.C., R. L. Ferral, and R. A. McGuire, 1973: A generalized streamflow simulation system—Conceptual modeling for digital computers. Joint Federal–State River Forecast Center Tech. Rep., Department of Water Resources, State of California and National Weather Service, 204 pp.

Canfield, H.E., & Goodrich, D.C., 2006, Suggested Changes to AGWA to Account for Fire (V 3.0), USDA-ARS publication *In Preparation*, Southwest Watershed Research Center, Tucson, Az. 85719

Duan, Q., Sorooshian, S. and Gupta, V.K. (1992) "Effective and Efficient Global Optimization for Conceptual Rainfall-runoff Models." *Water ResourcesResearch*. 28(4):1015-1031

FAO (1993) Sustainable Development of Drylands and Combating Desertification. FAO Position Paper. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fulton, R. A., J. P. Breidenbach, D. J. Seo, D. A. Miller, and T. O'Bannon, 1998: The WSR-88D rainfall algorithm. Wea. Forecasting, **13,** 377–395.

Goodrich, D.C., Unkrich, C.L., Smith, R.E., 2006, KINEROS2 - NEW FEATURES AND CABABILITIES, Proceedings of the Joint 8th Federal Interagency Sedimentation Conference And 3rd Federal Interagency Hydrologic Modeling Conference, April 2-6, 2006, Silver Legacy, Reno, Nevada.

Gupta, H.V., S. Sorooshian, and P.O. Yapo, 1998, Toward improved calibration of hydrologic models: Multiple and non-commensurable measures of information, *Water Resour. Res.*, 34 (4), 751-763.

Hall, J., Tarantola, S., P.D.Bates, and M.S.Horritt: Distributed sensitivity analysis of flood inundation model calibration, Journal of Hydraulic Engineering, DOI:10.1061/(ASCE)0733-9429(2005)131:2(117), 2005.

Hartmann, H.C. 2001. Stakeholder driven research in hydroclimatic context. Ph.D. Dissertation, Department of Hydrology and Water Resources, The University of Arizona, Tucson, USA.

IPCC, 2001. 3rd assessment report. Cambridge University Press. Also at http://www.grida.no/climate/ipcc_tar/wg1/

Kohler, M. A. and R. K. Linsley, 1951. Predicting Runoff From Storm Rainfall. U.S. Weather Bureau, Research Paper 34.

Kundzewicz, Z. W., and Kaczmarek, Z. 2000. Coping with hydrological extremes, Water International, 25(1): 66-75

Maddox, R.A., J. Zhang, J.J. Gourley, and K.W. Howard, 2002: Weather radar coverage over the contiguous United States. *Wea. Forecasting,* **17**, 927-934.

Mendez, A., Goodrich, D.C., Osborn, H.B. 2003. Rainfall point intensities in an air mass thunderstorm environment: Walnut Gulch, Arizona. J. Am. Water Resour. Assoc. 39(3):611-621.

Michaud, J.D. 1992. Distributed rainfall-runoff modeling of thunderstorm-generated floods: A case study in a mid sized, semi-arid watershed in Arizona. Ph.D. Dissertation, Department of Hydrology and Water Resources, The University of Arizona, Tucson, USA.

Morin E, Maddox RA, Goodrich DC, Sorooshian S (2005) Radar Z-R Relationship for Summer Monsoon Storms in Arizona. Weather and Forecasting 20(4): 672

Morin, E., Goodrich, D.C., Maddox, R. A., Gao, X., Gupta, H. V., and Sorooshian, S. 2006. Spatial patterns in thunderstorm rainfall events and their coupling with watershed hydrological response. Advances in Water Resources, 29 (6), Pages 843-860

Nearing, M.A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M.H., Nunes, J.P., Renschler, C.S., Souchere, V., van Oost, K. 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61(2-3):131-134.

NWS, 2002. Advanced hydrologic prediction services – Concept of services and operations. Report U.S. Department of Commerce – NOAA – NWS.

O'Bannon, T., 1997: Using a terrain-based hybrid scan to improve WSR-88D precipitation estimates. Preprints, *28th Conf. on Radar Meteorology,* Austin, TX, Amer. Meteor. Soc., 506–507.

Pilgrim, D. H., Chapman, T. G. & Doran, D. G. (1988) Problems of rainfall–runoff modelling in arid and semiarid regions. Hydrol. Sci. J. 33(4), 379–400.

Reed, S., Koren, V., Zhang, Z., Smith, M., Seo, D.-J. 2002. Distributed modelling for improved NWS river forecasts. Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV.

Robichaud. P.R. Beyers, J. L., Neary, D.G., (2000) *Evaluating the Effectiveness of Postfire Rehabilitation Treatments.* United States Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-63

Roeske, R.H., Garrett, J.M. and Eychaner, J.H. 1989. Floods of October 1983 in southeastern Arizona. USGS Water Resources Investigations Report 98-4225-c.

Saltelli, A., Tarantola, S., Campolongo, F., and Ratto, M. (2004). Sensitivity analysis in practice: a guide to assessing scientific models. John Wiley & Sons, Ltd., 219p.

Sittner, W., C. Schauss, and J. Monro, "Continuous Hydrograph Synthesis with an API-Type Hydrologic Model," *Water Resources Research* 5(5), 1007-1022, 1969.

UNEP (1997) Climate Change Information Kit. United Nations Environment Programme, Information Unit for Conventions, Chatelaine, Switzerland.

Wagener, T., Kollat, J.B., Numerical and Visual Evaluation of Hydrological and Environmental Models Using the Monte Carlo Analysis Toolbox. *Environmental Modeling and Software*. In Preparation.

Woolhiser, D. A., Fedors, R. W., and Stothoff, S. A. Effects of Topography and Soil Depth on Runon and Focused Infiltration: Upper Split Wash Watershed, Nevada