Final Report for COMET Partners Project

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Partners or Cooperative Project: Partner Project

Project Title: Investigating the HEC-HMS model for watershed-scale flood prediction in the Des Moines Weather Forecast Office region

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SECTION 1: SUMMARY OF PROJECT OBJECTIVES

The current National Weather Service (NWS) hydrologic forecasting system software inhibits the quick introduction of new modeling technologies into operations because it is built on a rather rigid infrastructure. As a result, forecasters are limited to tools that may not be suitable for all basins or forecasting situations, contributing to the uncertainty in streamflow predictions. There are currently three main tools available to NWS hydrologists. (1) The Sacramento Soil Moisture Accounting (SACSMA) model (Burnash et al., 1973) is run by the NWS River Forecast Centers (RFCs) to generate daily to seasonal streamflow predictions. The commonly used 6-hour modeling timestep disregards basin-specific hydrologic response times and is inadequate for small watersheds. Only a few forecast watersheds, such as the Blue River in the Missouri Basin, have been transitioned to run the SACSMA at an hourly timestep. (2) The Site Specific model (SSM) was designed for small headwater basins, which is not typical of many central Iowa forecast basins. Experience has shown that the SSM is not accurate for forecasting discharge from basins with tributaries in the DMX region, particularly when initial soil conditions are dry. (3) Flash Flood Guidance (FFG) is used to generate watches and warnings for a specific basin based on antecedent moisture conditions and current rain rates (NRC, 2005). However, FFG is based on historical observations of streamflow events and is seldom updated as new data becomes available (Ntelekos et al., 2006). A recent National Research Council (NRC) panel concluded that the scientific basis that underpins flash flood forecasting could be improved through the use of modern modeling techniques (NRC, 2006).

This study evaluated the application of the U.S. Army Corps of Engineers Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (USACE, 2006) for use in flood prediction in the NWS Des Moines, IA region. The highly flexible HEC-HMS allows the watershed to be modeled in a distributed manner, accepts data in time increments of minutes to hours, and runs easily on a PC platform (USACE, 2006). Therefore, the HEC-HMS could be operated at a WFO without major software development or alterations to current forecast systems. This project examined steps that would be necessary to implement the model for real-time forecasting and assess the current feasibility of its application at a NWS WFO. We made every attempt to consider the ease with which the HEC-HMS could be applied operationally in order to provide relevant information to other NWS forecast offices.

The HEC-HMS was calibrated and evaluated for historical streamflow simulations in two watersheds near Ames, IA by Scott Lincoln, an Environmental Science M.S. student at ISU, under the direction of Dr. Kristie Franz. The model was first developed using ground-based rain gage data from the Ames ALERT network as model input. Precipitation time series developed from the University of Iowa experimental radar-based precipitation product (Hydro-NEXRAD) were then tested as input to the calibrated HEC-HMS. Finally, one significant precipitation event occurred during spring 2009, for which Lincoln operated the HEC-HMS in pseudo-operational mode.

The NWS Des Moines Senior Hydrologist Jeff Zogg and Science and Operations Officer, Karl Jungbluth, met with Franz and Lincoln approximately every two months to review and discuss progress on the project. Zogg and Jungbluth evaluated the final model from the operational perspective. The results were also presented to streamflow forecasters at the North Central River Forecast Center (NCRFC).

The specific objectives of this project were:

- Objective #1: To calibrate and evaluate the skill of the HEC-HMS for predicting the timing and magnitude of high discharge and flood events in a rapidly responding central Iowa watershed.
- Objective #2: To evaluate the feasibility of implementing the HEC-HMS in the NWS operational environment.

SECTION 2: ACCOMPLISHMENTS AND FINDINGS

The HEC-HMS has been configured and tested for the Squaw Creek and Skunk River watersheds located near Ames, IA (Figure 1). The model has been set-up to use a distributed modeling approach with three subbasins created within each larger basin. The Green-and-Ampt infiltration equation was used to estimate runoff within each subbasin, and flow was routed to the subbasin outlet using the SCS synthetic unit hydrograph. Muskingum routing was used to route streamflow to the outlets of downstream watersheds.

Identification of the data sources needed for model calibration, validation and input is one of the major challenges in any modeling study. In this study, data identification was complicated by the need to assure the tested data, or something similar, would be available during real-time forecasting. For model development, land cover, basin area and soils information was needed. Input to the model was a precipitation time series, and the initial soil moisture deficit had to be initialized. Finally, discharge was required for model validation.

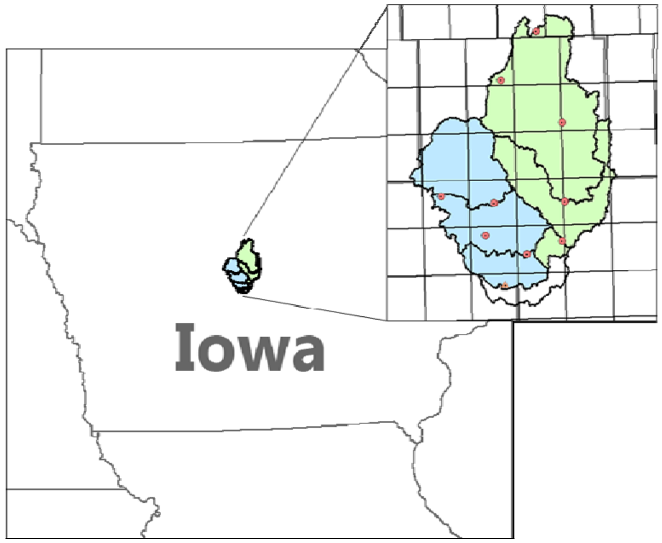

Figure1. Map of the study area. The subbasins highlighted in blue are in the Squaw Creek watershed. The subbasins highlighted in green are in the Skunk River watershed. Precipitation gauges are marked with red dots.

Ground-based precipitation and discharge data were obtained from the Ames ALERT network through the City of Ames FTP site. Streamflow discharge at two US Geological Survey stream gages was also used. This data is available online. Radar-based precipitation estimates from the University of Iowa Hydro-NEXRAD database were also tested to determine the model response to radar inputs. Although the Hydro-NEXRAD application is not yet widely available, it was much easier for ISU to access and process the data through this source compared to other possible sources of radar data. These data time series were input and stored in the HEC-HMS data archive system, from which the model retrieved the data to run simulations.

Initial soil moisture estimates had to be estimated prior to running the model to produce a forecast because the Green & Ampt infiltration model does not include soil recovery between rainfall events, and cannot track soil moisture change over long time periods. Soil moisture values produced from the Water Erosion Prediction Project (WEPP) model, which is run daily and available online (http://wepp.mesonet.agron.iastate.edu/), were used to estimate basin wide soil moisture variability. The NRCS Soil Climate Analysis Network (SCAN) sensor near Ames, IA provided a single in-situ soil moisture measurement. The different between the WEPP soil moisture value at the grid corresponding to the SCAN site was computed and all WEPP grids were adjusted according to this difference. This was done to remove model bias in the WEPP soil moisture values, assuming that the ground-based SCAN site was the more reliable estimate of soil moisture. Two ArcGIS scripts were used to make the adjustments to the WEPP data and to compute basin-averaged soil moisture. The soil moisture state was then updated manually in the model.

Although the WEPP data and the SCAN site data are easily available online, we are concerned that the bias adjustment procedure may be time consuming in an operational setting. Simplification of the soil moisture data processing method may be possible by using a batch program created with a scripting language such as R, which is a freeware. Another alternative is to develop correlations between soil moisture values in the HEC-HMS and the SACSMA, in which case the initial soil moisture states could be obtained from the RFC. The obvious drawback in this option is that any error in the SACSMA soil moisture states would also be influencing the HEC-HMS forecast.

Once data sources were identified, model development (calibration and verification) was conducted using the ground-based precipitation data. Values for percent impervious land cover and initial abstraction of precipitation were determined through GIS analysis and were not changed once quantified. Hydraulic conductivity, lag time for the unit hydrograph, and wetting front suction head were identified by calibrating the modeled discharge to observed discharge. Model development went through several iterations as we learned more about the model behavior, parameter sensitivity, and model limitations. Several lessons were learned that will have implications for application of the HEC-HMS to operations.

1) The automatic calibration option in the HEC-HMS system was not useful in our case. Although the calibration algorithm frees up the model user from manually testing parameter values, it was still time consuming because the model had to be calibrated one event at a time. Because the model, as configured, had no soil moisture recovery function, multiple events could not be tested in a single calibration run. The calibration gave inconsistent results for hydraulic conductivity among the events tested and the values were often lower than expected. Calibration of the lag time value was more successful.
2) A sensitivity analysis was conducted for the wetting front suction head, moisture deficit, and hydraulic conductivity of the Green & Ampt infiltration model, and for the lag time of the transform function (see Lincoln, 2009 for further explanation). The most sensitive parameter was found to be the hydraulic conductivity, with the moisture deficit being the second most sensitive. Given these results, we concluded that the wetting front suction head could be set to a default value with little impact on results, while identifying a proper hydraulic conductivity was important.
3) Lincoln (2009) describes several ways in which potential hydraulic conductivity values were estimated and tested. After significant effort in identifying values for this parameter, we found published values based on the soil type in the region resulted in simulated discharge that was as accurate as our calibrated values on average. Although we feel the use of published values requires further testing at other basins, this result is encouraging because the calibration efforts took up considerable time. If published values could be used with confidence, development of the HEC-HMS with the Green & Ampt method for several regions would be relatively quick.
4) Although the lag time of the SCS unit hydrograph was not the most sensitive parameter, it was important for determining the simulated time of peak. Through analysis of several events, we found that the lag time of the SCS unit hydrograph varies linearly with the time since the last rainfall event (Figure 2). Although this may seem intuitively correct (i.e. more moisture in the basin means a quicker response), unit hydrographs are assumed to be constant in time and a function of physical features of the watershed (e.g. area, drainage density). However Mike DeWeese at NCRFC said the unit hydrographs used in conjunction with the SACSMA need to be adjusted occasionally for varying conditions to improve the simulation. In addition, when running the HEC-HMS for flood prediction and monitoring, the City of Ames personnel adjust the lag time of the SCS unit hydrograph depending upon whether or not the tile lines draining the agricultural fields were flowing. Our finding that the unit hydrograph requires adjustment under different conditions is supported by the experiences of these forecasters. If the relationship shown

in Figure 2 holds for other regions, it may provide an objective means for unit hydrograph adjustment in the HEC-HMS or other models. We have not yet explored the impact of the spatial pattern of precipitation in the basin on the performance of the unit hydrograph. Additionally, the impact of tiling on the basin response and unit hydrograph in tile drained regions should be further investigated.

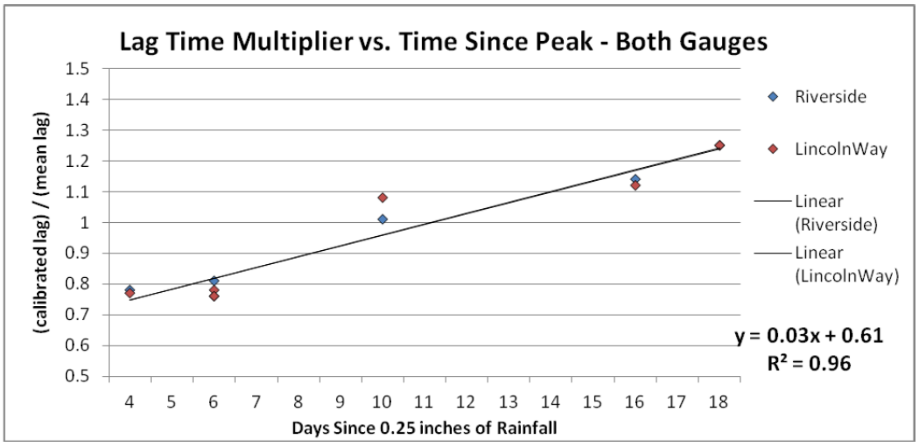

Figure 2. Relationship between the SCS unit hydrograph lag time and the number of days passed since prior rainfall has occurred. The Y axis is a multiplier defined by the calibrated lag time values of both the LincolnWay and Riverside watersheds.

5) Because the hydraulic conductivity parameter in the Green and Ampt equation was the most sensitive parameter in the model, we tested the possibility of creating multiple simulations by varying the hydraulic conductivity value by +/- 25% and +/-50%. The objective was to investigate the uncertainty in our model by producing a simple ensemble-type simulation. The streamflow events were captured within the uncertainty bounds in 50% of the cases examined during verification. Although using multiple hydraulic conductivity values requires the model to be run several times, changing parameters and rerunning the model takes only a few minutes.
6) NEXRAD precipitation estimates were computed using the CAPPI 1.3km AGL algorithm and the standard Z-R relationship of the NWS PPS. The timestep of the data was 15 minutes. Average bias in NEXRAD precipitation estimates were computed using the ALERT precipitation gages. Biases were computed at the basin scale and were found to increase with increasing distance from the radar. The NEXRAD data for 10 events were adjusted using the average computed bias, and model simulations were conducted. In general, the model simulations improved using the bias-corrected NEXRAD data compared to the rain gage data. The bias correction approach developed here considers long-term average errors at the basin scale, and is therefore not sensitive to gage errors that may occur during any individual event. This approach requires the bias to be computed only one time. The improvement in the model simulations with the use of NEXRAD data is encouraging, and NEXRAD with a simple bias correction scheme may prove to be reliable for hydrologic forecasting. This is particularly important for improving prediction in ungaged basins. The ability to process the NEXRAD data for model input given the time constraints of the operational setting still needs to be assessed.

The HEC-HMS shows promise to be used in the operational setting; however rigorous real-time testing was not possible during the one year duration of the project. One precipitation event occurred in our study basins during spring 2009, during which ISU ran the HEC-HMS in near real-time. The precipitation started on April 25^{th} and ended on April 27^{th}. The streamflow was modeled from April 26^{th} to May 1^{st} using the HEC-HMS and ALERT precipitation gage data. The HEC-HMS results were compared to the RFC forecasts for the same event. The forecasts for the SAC-SMA were issued at 9:36am and 8:28pm on April 26^{th}, and 2:13am and 9:34am on April 27^{th}. The model runs for the HEC-HMS were completed at 9:00pm on April 26^{th} and 3:00am on April 27^{th}.

In both study watersheds, the SAC-SMA forecasts from the NCRFC generally overestimated the river stage; the Lincoln Way forecast had the larger error (Figure 3, top). Errors in modeled peak stage of the event ranged from a near 100% overestimate in the April 26^{th} 9:36AM forecast to near 33% in the April 27^{th} 9:34AM forecast at that gauge. The likely explanation for the significant overestimation errors in the SAC-SMA was that the precipitation fell mostly towards the mouth of the basins (rather than evenly across the basin), and the unit hydrograph was not adjusted to account for it. Rather, to account for errors observed in the simulation, the forecaster manually adjusted the SACSMA soil states to near saturation (Jeff Zogg, NWS DMX, personal communication, 2009).

The HEC-HMS runs conducted April 26^{th} at 9pm slightly underestimated the peak stage of the event (Figure 3, bottom). This run did not include the last 5 hours of precipitation or QPF, which contributed to the underestimation of that model run. When the April 27^{th} 3:00AM run was computed, all of the precipitation had fallen and the observed peak stage was captured by the uncertainty bounds (which are based on different values of hydraulic conductivity in the model). A key difference between the two sets of forecasts is that only one HEC-HMS run went above flood stage, whereas all SACSMA forecasts did. This is a only a single sample of how the two models compare, and more operational runs are needed to show consistency in results.

Based on our experience to this point, data processing for the HEC-HMS will likely be a challenge in the operational setting. In the above real-time application, from the start of the process until the model simulations were completed took approximately 60 minutes for the two study basins. If more than two basin would require forecasts during the same period, the processing time may become unmanageable. One possible solution for the data management issue is that HEC-RAS is being implemented in the NWS River Forecast System and Community Hydrologic Prediction System (CHPS). HEC-RAS and HEC-HMS both use the same .DSS file structure developed by the US Army Corps. Modules are being developed to take data collected by the NWS and translate it into the .DSS structure. These same data sets could be accessed by either model, and the need for manual development of the input files for the HEC-HMS may be eliminated. Another possible solution is to use an event model that uses the same principles applied here (Green & Ampt, SCS unit hydrograph) but for which the source code is accessible such that a wrapper could be developed to automate the modeling processes to some degree.

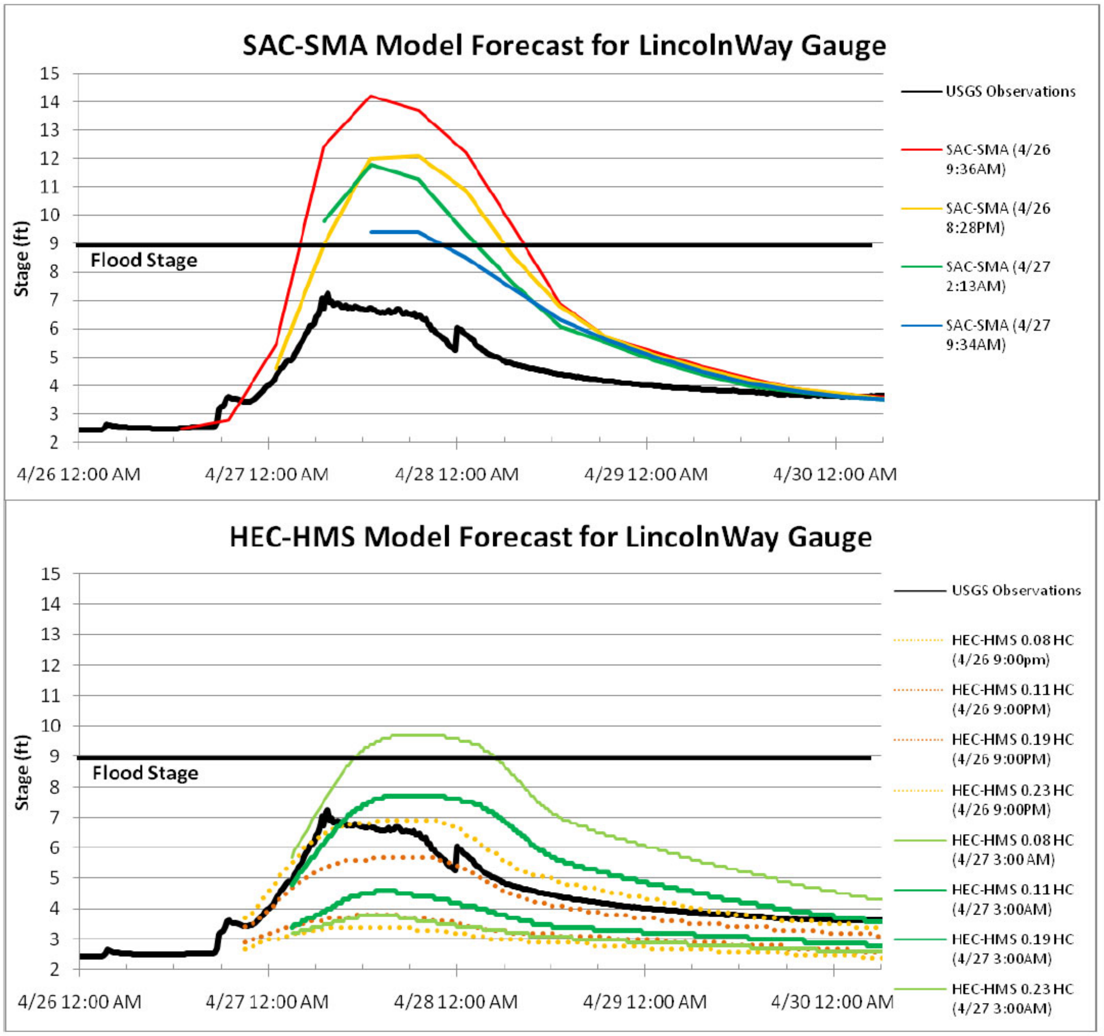

Figure 3. Forecasts of river stage at the LincolnWay gauge from both the SAC-SMA (top) and HEC-HMS (bottom) models for the April 25th-27th precipitation event. The multiple lines in the HEC-HMS results show model runs conducted with different hydraulic conductivity (HC) values, for a given start time.

SECTION 3: BENEFITS AND LESSONS LEARNED: OPERATIONAL PARTNER PERSPECTIVE

Results of this project indicate that the HEC-HMS can provide an additional source of forecast input during flood situations in central Iowa. This is a new frontier and fills a need for higher quality forecasts on fast responding basins, and is a great accomplishment for a short-lived project. What remains to be seen is whether the required time and data inputs can be accomplished under the constraints of an operational setting. Because of the short duration of this project, we were not able to fully test this operationally, but we plan to do so after the project. Lincoln (2009) began to outline the required steps in detail.

Certainly the project has made the NWS Des Moines staff much more aware of the complexities and sensitivities involved with hydrologic modeling. If the complexities of input data can be overcome, the NWS Des Moines staff would readily make use of the model in near-real-time situations. With the floods of 2008 and this project, interest in hydrology and research related to hydrology has reached an all-time high at NWS Des Moines.

A remote desktop was set up to view Lincoln's computer and the model from NWS Des Moines. This capability may prove to have value in other collaborative research efforts.

The NWS is in the process of transitioning to a new paradigm involving hydrologic models. It is called the Community Hydrologic Prediction System (CHPS). One of the goals of CHPS is to provide an open-source type hydrologic modeling environment which draws on hydrologic models and expertise from NWS partner agencies. The hydrologic model which has been developed through this project would be an excellent potential component of CHPS.

Finally, the NWS has a new focus on decision support during significant weather events and floods. Students such as Scott Lincoln, and others that might be introduced to the project, would be valuable to the NWS workforce for decision support during flood events.

No problems were encountered during the project. Franz and Lincoln have been very easy to work with as the university partner. Their project briefings have been very well prepared and educational. This project has brought to light the need to continue research partnerships outside of the formal university and COMET framework. There is additional work that both parties would like to accomplish, if the proper arrangements can be made.

SECTION 4: BENEFITS AND LESSONS LEARNED: UNIVERISTY PARTNER PERSPECTIVE

This project has elicited several side activities at ISU that have been conducted in support of the objectives of this project. During summer 2008, Lincoln and Franz designed a project for a high school student participating in a summer research experience. This student studied the impact of different radar data process algorithms on the estimated precipitation for our study area. This work proved to be informative for deciding how to process the radar data for our experiment. Lincoln also used the gage and radar precipitation data gathered for this work to conduct a spatial analysis study in order to meet the requirements for GIS certification. The high school student gained experience working in a hydrologic modeling research group.

This project has been particularly beneficial to Lincoln because it helped him develop a skill set (e.g. modeling, GIS) that is in high demand. Additionally, through his interactions with forecasters at NWS Des Moines, he has learned about forecasting procedures at the NWS WFOs. He will be graduating this summer and is actively pursuing a position with the NWS. Lincoln also presented this project in three formal presentations: a Meteorology Department seminar at ISU in December 2008; an AGU poster session in San Francisco, CA in December 2008; and at the North Central River Forecast Center in Chanhassen, MN in June 2009.

NWS Des Moines and the ISU Meteorology program have been strong partners in the past, and this project has provided a basis for expanding collaborations into the area of hydrology. The new activities begun under this COMET proposal are expected to provide future opportunities for student interaction with NWS Des Moines through senior thesis projects and additional funded projects. We have identified several interesting questions related to the NEXRAD precipitation data and the unit hydrograph adjustments. Through this Partners Project and other collaborations with the NWS forecasters, Dr. Franz continues to learn about the operational hydrologic forecasting environment and how to better formulate research questions that help to answer scientific questions relevant to operations.

We have learned that operational experimentation with the model was difficult to achieve within the 1 year timeframe of the grant. The logical next step in our project is to work with the model on station at a forecast office. This could best be accomplished if Lincoln, or another student, spent time at NWS Des Moines and ran the model during potential flood events. Results could then be evaluated against other forecast products over time, and potentially be considered in the flood predictions as confidence in the model developed. Additional refinement and application in other basins could also be explored.

SECTION 5: PRESENTATIONS AND PUBLICATIONS

Presentations

Lincoln, W. S., and K.J. Franz, 2008: A Modeling Approach for Flash Flood Forecasting for Small Watersheds in Iowa, presented at the American Geophysical Union fall meeting, San Francisco, CA.

Franz, K.J., W.S. Lincoln, and P. Butcher, 2008: Advancing Streamflow Prediction, Department of Geological and Atmospheric Sciences Meteorology seminar.

Lincoln, W.S., and K.J. Franz, 2009: A Modeling Approach for Flash Flood Forecasting for Small Watersheds in Iowa, presented at the North Central River Forecast Center, Chanhassen, MN

Publications

Lincoln, W.S., 2009: A modeling approach for operational flash flood forecasting for small-scale watersheds in central Iowa. M.S. Thesis, Iowa State University, Ames, Iowa.

Publications in prep.

Franz, K. J., W.S. Lincoln, J. Zogg, and K. Jungbluth, 2009: Investigation of the HEC-HMS model for operational applications in a small Iowa watershed.

SECTION 6: SUMMARY OF UNIVERSTIY/OPERATIONAL PARTNER INTERACTIONS AND ROLES

Model development and testing was the primary responsibility of the academic partner, and the forecasting partner's role was to provide review and feedback throughout the project. Scott Lincoln, a Masters student in Environmental Science, conducted the majority of the research including data identification, data processing, model calibration, and model validation, under the supervision of Dr. Franz. Evaluation of the model and results was conducted by both the academic and forecast partners. The forecasting partner evaluated the feasibility of applying the model operationally. Both the partners participated in the final analysis of the methodology and reporting of results in this report. Both partners will also collaborate to produce a manuscript for publication in a professional journal to present this project.