# REPORT DOCUMENTATION PAGE

!
Gpsn !Bqqspwfe!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!PNC!OP/!1815.1299!



| | | |
|---|---|---|
| 1. AGENCY USE ONLY ( Leave Blank) | 2. REPORT DATE October 10, 2005 | 3. REPORT TYPE AND DATES COVERED<br>Final Report 26 June 00 - 25 June 05 |

4. TITLE AND SUBTITLE

Hydrologic Investigation of Low Gradient Watersheds

5. FUNDING NUMBERS

DAAD19-00-1-0413

6. AUTHOR(S)
Ehab A. Meselhe
Emad H. Habib

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Louisiana at Lafayette,
Civil Engineering Department
P.O Box 42291, Lafayette, LA 70504-2291

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

40292.1-EV

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The aim of this project is to improve our understanding of the hydrologic characteristics of tidal low-gradient watersheds. Hydrologic and meteorologic measurements as well as distributed and lumped hydrologic modeling were used to gain such understanding. The analysis performed indicated that the tidal cycle, wind setup, and backwater effects dominate the hydrologic response of coastal watersheds to rainstorms. Therefore, predictive tools must incorporate these factors. Hence, and for the purpose of improving our understanding of physical characteristics of these watersheds, Artificial Neural Network and Non-Parametric Regression models have been developed. They were able to reproduce the complex and non-unique stage-discharge relationship. Furthermore, comparisons between distributed and lumped models showed that their predictive ability for mid-size catchments was similar. Specifically, the sensitivity of both approaches to variations in the temporal sampling of rainfall was not significantly different. Their response to variations in the spatial density of rainfall information was also investigated. Efforts done to establish guidelines on the temporal and spatial rainfall sampling requirements for hydrologic predictions indicated that a resolution frequency of up to one hour is adequate for predicting runoff discharges.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OR REPORT | 18. SECURITY CLASSIFICATION ON THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| **UNCLASSIFIED** | **UNCLASSIFIED** | **UNCLASSIFIED** | **UL** |

**REPORT DOCUMENTATION PAGE (SF298)**
**(Continuation Sheet)**

**(1) List of manuscripts**:

(v) Papers published in peer-reviewed journals:

Habib E. H., and Meselhe E. A. (2005): Stage-Discharge Relations for Low-Gradient Tidal Streams Using Data-Driven Models. *ASCE Journal of Hydraulic Engineering* (in press).

(vi) Papers published in conference proceedings:

- Habib E. H., Meselhe E. A., and Kalikivaya S. (2004) "Prediction of Discharge-Stage Relationship for Low gradient Tidal Streams Using Data-Driven Models." Proceedings of Louisiana Transportation Engineering Conference, February 2004, Baton Rouge, Louisiana.
- Meselhe E.A. Habib E.H., Mader C.B., McCorquodale J.A., Georgiou I.Y., Stronach J., and Campanella R. (2004). "Hydro-Ecological Modeling of the Lower Mississippi River" First National Conference on Ecosystem Restoration (NCER) in Orlando, Florida December 6-10.
- Meselhe E.A. and Byrd A. (2004). "Advances to the Model Gridded Surface Subsurface Hydrologic Analysis for Improved Ecosystem Modeling" First National Conference on Ecosystem Restoration (NCER) in Orlando, Florida December 6-10.
- Meselhe E.A., Habib E.H., and Ogden F.L. (2004) "Performance Evaluation of the Physically Based Distributed Hydrologic Model: GSSHA" the 24th Army Science Conference, November 29 – December 2, 2004 in Orlando, Florida.
- Ogden F., Niedzialek J., Zahner J., Byrd A., and Meselhe E. (2004) "Simulating Lakes, Wetlands, Detention Basins, and Storm Drainage Networks using GSSHA." World Water & Environmental Resources Congress, EWRI – ASCE, June 27 – July 1, Salt Lake City, Utah
- Habib E.H., Meselhe E.A, and Kalikivaya S. (2004) "Development of Discharge-Water Level relationship for Low-Slope Tidal Streams Using Non-Parametric Data-Driven Models." World Water & Environmental Resources Congress, EWRI – ASCE, June 27 – July 1, Salt Lake City, Utah.
- Meselhe E.A, Habib E.H., Oche O., and Gautam S. (2004) "Performance Evaluation of Physically Based Distributed Hydrologic Models and Lumped Hydrologic Models." World Water & Environmental Resources Congress, EWRI – ASCE, June 27 – July 1, Salt Lake City, Utah.
- Habib E.H., Meselhe E.A., and Kalikivaya S. (2003) "Development of Discharge Ratings for Low-Slope Streams Under Tidal Effects Using Non-Parametric and Data-Driven Models." American Geophysical Union Fall Meeting, 8-12 December 2000, San Francisco.
- Ogden F.L., Downer C.W., and Meselhe E.A. (2003) "U.S. Army Corps of Engineers Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) Model: Distributed-Parameter, Physically Based Watershed Simulations." Proceedings of the World Water & Environmental Resources Congress, June 23-26, Philadelphia, PA.
- Kheiashy K., Meselhe E.A., and Guwang B. (2002) "Development of an Internet GIS-Based Hydrologic Model for the Vermilion Watershed." Proceedings of the Hydroinformatics 2002, 1-5 July, Cardiff, Wales, U.K.
- Hebert K. J., Meselhe E. A., and Noshi H. M. (2001) "Laboratory Measurements of Unsteady Flows through Culverts" Proceedings of the World Water and Environmental Resources Congress, May 20-24, Orlando, Florida.
- Ogden F. L., Meselhe E. A., Niedzialek J., and Smith B. (2001) "Physics-Based Distributed Rainfall-Runoff Modeling of Urbanized Areas with CASC2D" Urban Drainage Modeling Symposium, the World Water and Environmental Resources Congress, May 20-24, Orlando, Florida.

- Downer C. W., Johnson B. E, Ogden F. L., and Meselhe E.A. (2000) "Advances in Physically Based Hydrologic Modeling with CASC2D" Proceedings of the Watershed Management & Operations Management, the Environmental and Water Resources Institute, June 20-24, Colorado State University, Fort Collins, Colorado.

(vii) Papers presented at meetings:

- Habib, E., E. A. Meselhe and A. Vishnu (2005) "Analysis of Radar-Rainfall Error and its Effect on Runoff Predictions", American Geophysical Union Joint Assembly, 23-27 May, 2005, New Orleans.
- Meselhe E. A., Habib E. H., and Ogden F. L. (2004) "Performance Evaluation of the Physically Based Distributed Hydrologic Model: GSSHA." the 24th Army Science Conference.
- Habib E. H., Meselhe E. A., and Kalikivaya S. (2004) "Development of Discharge-Water Level relationship for Low-Slope Tidal Streams Using Non-Parametric Data-Driven." Proceedings of World Water and Environmental Resources Congress2004, June 27 - July 1, Salt Lake City, Utah.
- Meselhe E. A., Habib E. H., Oche O. C., and Gautam S. (2004) "Performance Evaluation of Physically Based Distributed Hydrologic Models and Lumped Hydrologic Models." Proceedings of World Water and Environmental Resources Congress2004, June 27 - July 1, Salt Lake City, Utah.
- Habib E.H., Meselhe E.A., and Kalikivaya S. (2003) "Development of Discharge Ratings for Low-Slope Streams Under Tidal Effects Using Non-Parametric and Data-Driven Models." American Geophysical Union Fall Meeting, 8-12 December 2003, San Francisco.

(viii) Manuscripts submitted but not published:

- Meselhe E. A., Habib E. H., Oche O. C., and Gautam S. (2004) "Performance Evaluation of Lumped Conceptual and Distributed Physically Based Hydrologic Models." Submitted to Water Resources Research Journal.
- Habib E.H., Meselhe E.A., and Kalikivaya S. (2003) "Development of Discharge Ratings for Low-Slope Streams Under Tidal Effects Using Non-Parametric and Data-Driven Models." American Geophysical Union Fall Meeting, 8-12 December 2003, San Francisco.

**(2) Demographic Data for this Reporting Period:**

(a) Number of manuscripts: 19
(b) Papers published in peer-reviewed journals: 1
(c) Papers in non-peer reviewed journals or in conference proceedings: 18
(d) Papers presented in meetings: 18

**(3) Demographic Data for the Life of this Agreement Reporting Period:**

(a) Number of Scientists Supported by this agreement: 4 (2 faculty and 2 research associates)
(b) Number of Inventions resulting from this agreement: 0
(c) Number of PhD(s) awarded as a result of this agreement: 0
(d) Number of Bachelor Degrees awarded as a result of this agreement: 0
(e) Number of Patents Submitted as a result of this agreement: 0
(f) Number of Patents Awarded as a result of this agreement: 0
(g) Number of Grad Students supported by this agreement: 10
(h) Number of FTE Grad Students supported by this agreement: 0
(i) Number of Post Doctorate Students supported by this agreement: 0
(j) Number of FTE Post Doctorate Students supported by this agreement: 0
(k) Number of Faculty supported by this agreement: 2
(l) Number of Other Staff supported by this agreement: 2 (research associates)
(m) Number of Undergrads supported by this agreement: 3
(n) Number of Master Degrees awarded as a result of this agreement: 7

**(3) Report of inventions**: None

**(4) Scientific progress and accomplishments**.

- Based on the field measurements and the modeling effort performed , it is clear that the tidal cycle, the wind setup, and the backwater effects dominate the hydrologic response of coastal low-gradient watersheds to rain storms. Therefore, in order for any predictive tool to produce accurate and reliable predictions it has to incorporate these factors.
- A well-trained Artificial Neural Network and Non-Parametric Regression models have been developed and validated. The models were able to reproduce the complex and non-unique stage-discharge relationship observed at the outlet of tidal low-gradient watershed. It should be emphasized that standard statistical tools completely failed to capture this complex stage-discharge pattern.
- The comparison between physically-based and lumped hydrologic models applied to the Goodwin Creek watershed showed:
    - The predictive ability of both modeling approaches (when well calibrated) for mid-size catchment was surprisingly similar.
    - Their response to variations in the temporal sampling of rainfall was also similar.
    - Their response to variations in the spatial density of rainfall information is currently being investigated.
- An extensive modeling effort was preformed to establish guidelines on the temporal and spatial rainfall sampling requirements for hydrologic prediction. A resolution frequency of up to one hour seems adequate for practical purposes of predicting peak runoff discharges.
- An equipment grant from the State of Louisiana was received in support of the data collection and modeling efforts of this project. The equipment purchased included telemetric units of precipitation, stage, runoff discharge, total weather stations, and rainfall distrometer.
- A supplement funding through the Louisiana Transportation Research Center was also received to develop a comprehensive drainage plan for the low-gradient Vermilion watershed.
- A proposal to the State of Louisiana Board of Regents was recently funded to set up an experimental study to investigate the uncertainty of radar rainfall estimates and effects on hydrologic flood prediction.

**(5) Technology transfer**.

- Work closely with the Coastal Hydraulics Laboratory (CHL) of the Engineering Research and Development Center (ERDC) hydrologic research group. The research activities of this project include continuous improvements and development to the GSSHA model.
- The development work for GSSHA is coordinated with the University of Connecticut and BYU.

c.1) TABLE OF CONTENTS

**c.2) List of Illustrations**

**c.3) Statement of the Problem Studied**

The goal of the project is to assess the ability to make hydrologic predictions for low-gradient watersheds, and to determine the challenges that such watersheds pose to hydrologic models. The Vermilion Watershed and its sub-catchments in southwest Louisiana were selected to test widely used numerical hydrologic models. The Vermilion watershed has a very low-gradient topography and very complex fluvial systems and tidal channels. Making accurate hydrologic predictions for these systems is a challenging task because of the dominant role of hydraulics.

Research activities of this project focused on the following research problems:

i. Collection and analysis of hydrological and meteorological measurements in a low-gradient watershed in southwestern Louisiana.
ii. Development of a comprehensive GIS database for the watershed, including the topographical and the hydrological characteristics; e.g. land use, soil types, storage, infiltration parameters and roughness.
iii. Development of data-driven models (Artificial Neural Networks and non-parametric local regression) for predictions of complex discharge-stage relations in low-gradient streams.
iv. Performance evaluation of GSSHA modeling system compared to other widely used hydrologic models such as MIKE-SHE and HEC-HMS.
v. Assessment of sensitivity of runoff predictions to spatial and temporal rainfall sampling.
vi. Using radar rainfall information for hydrologic modeling with GSSHA.

**c.4) Summary of the Most Important Results**

i. <u>Collection and analysis of hydrological and meteorological measurements</u>:
Through preliminary applications of CASC2D, it became apparent that the existing network of monitoring stations for rainfall, stage, and discharge was not adequate to setup and calibrate a numerical hydrologic model. The investigators were able to purchase equipment to collect such data though state and local funding. The investigators determined that it would be more feasible to focus on a mid-size sub-catchment of the Vermilion Watershed, namely Isaac Verot. The instrumentations were placed in this sub-catchment with an adequate density such that thorough hydrologic analysis can be conducted. A brief summary of the acquired equipment is listed below:

- 13 dual-rain gauge stations with automatic data loggers.
- A total of five discharge gauges installed at the watershed outlet and at interior sites. All gauges are YSI Sontec Side and bottom-looking acoustic devices.
- One weather station that measures solar radiation, wind speed and direction, soil moisture, relative humidity, air temperature, and barometric pressure.
- One Joss-Wldvogel acoustic rainfall distrometer.
- All monitoring stations are equipped with telemetric units.

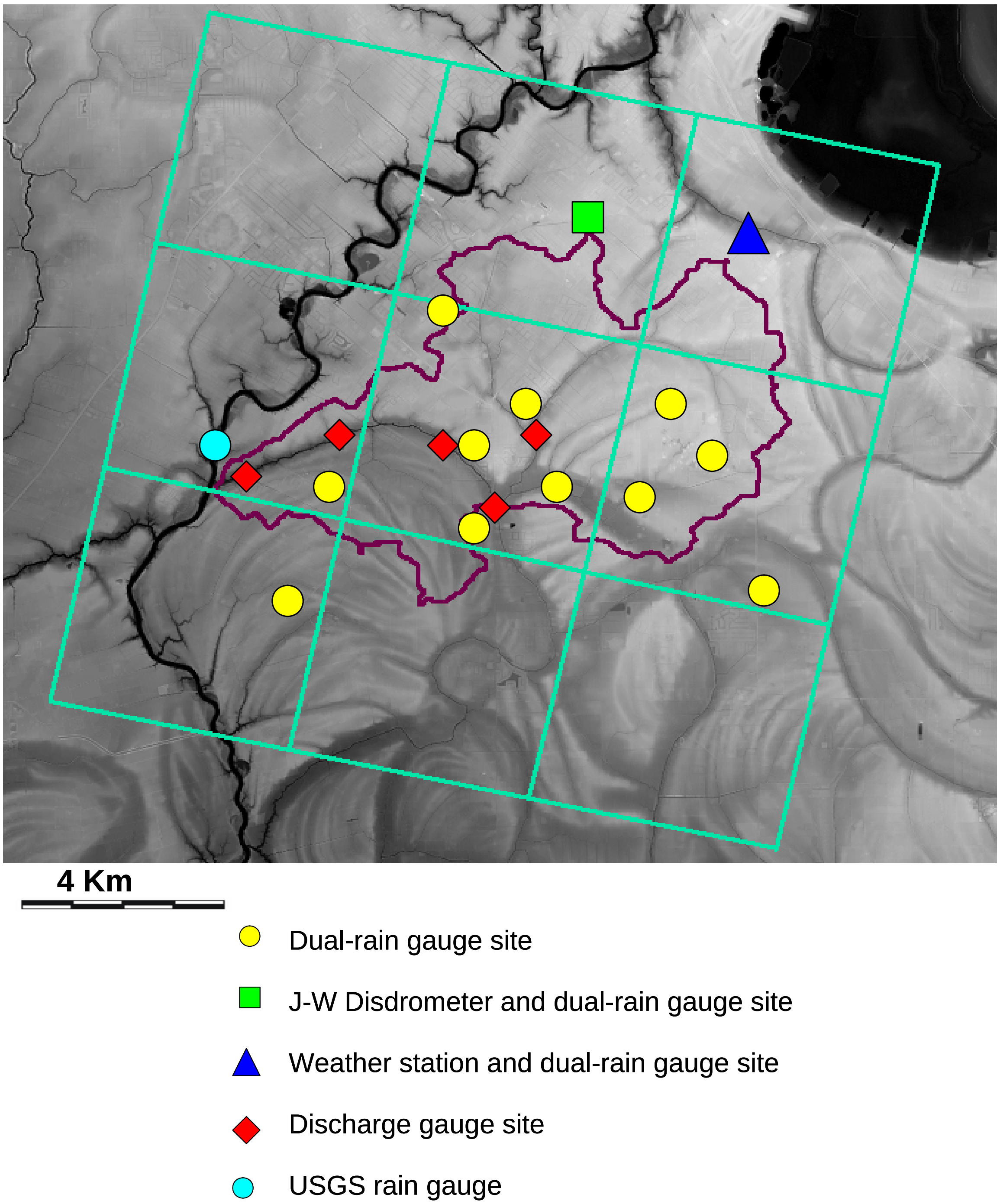


Figure 1: Layout of Isaac Verot catchment (southwestern Louisiana) along with the equipment installed. The rectangular grid represents the 4x4 $km^2$ Stage III radar pixels.

ii. Development of a comprehensive GIS database:

A comprehensive GIS database for the watershed was developed. For accurate and consistent representation of the watershed drainage area, the US Geological Survey (USGS) hydrologic unit boundaries were adopted. The environmental analysis system BASINS developed by the Environmental Protection Agency (EPA) was used to provide these boundaries in a GIS geo-referenced format. BASINS database was also integrated in the GIS database for land use information, locations of existing meteorological and flow measurements stations, and detailed stream network within the watershed. The topography of the watershed was determined from the 30-meter USGS Digital Elevation Models (DEM). Soil types and characteristics were compiled and incorporated into the database. In addition, recent high-resolution LIDAR topography data were collected and compiled for the Isaac-Verot watershed.

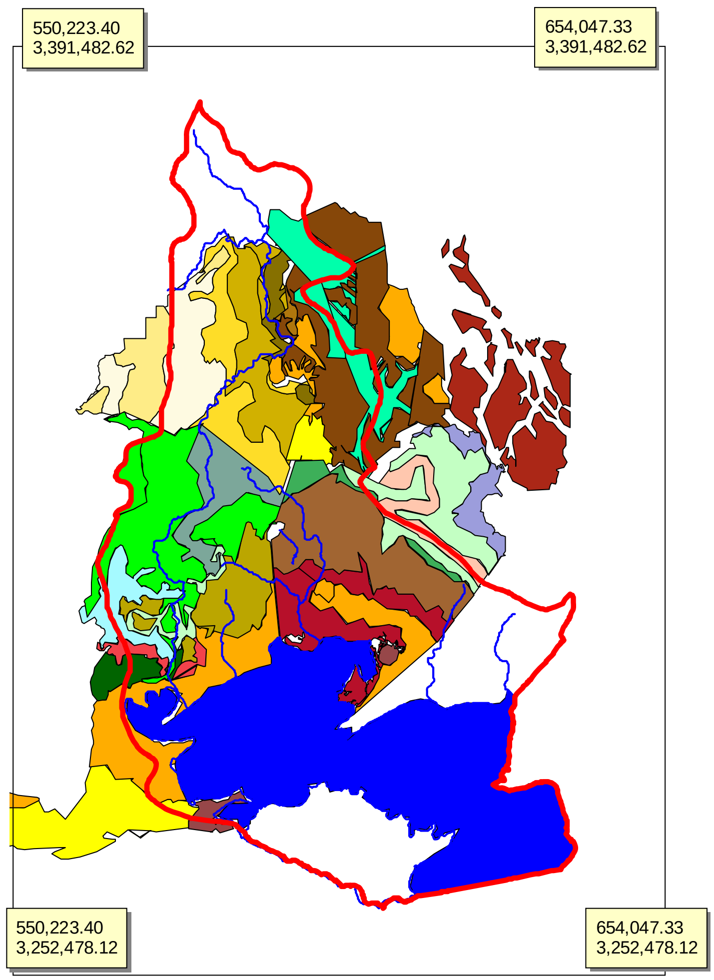


Figure 2: An example of GIS analysis: Soil classifications maps within the Vermillion Watershed.

iii. Development of data-driven models for predictions of complex discharge-stage relations in low-gradient streams.

The field measurements showed that development of stage-discharge relationships for coastal low-gradient streams is a challenging task. Such relationships are highly nonlinear, non-unique, and exhibit multiple loops. The investigators efforts to use conventional parametric regression methods to model these relationships were unsuccessful. Therefore, attempts were made to take advantage of two data-driven computation-intensive modeling techniques, artificial neural networks and local nonparametric regression. The results show considerably better performance of both modeling techniques over conventional regression techniques (Habib et al., 2005). Both neural network and local regression models were able to predict and reproduce the stage-discharge multiple loops observed at the outlet of Isaac Verot catchment.

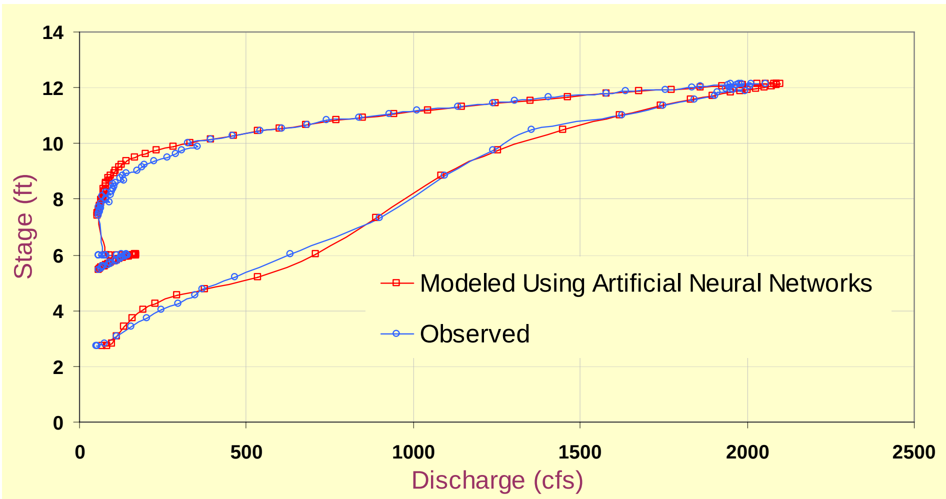


Figure 3: Relationship between stage and discharge in flat watersheds subjected to tidal influence is complex and quiet challenging. Data-driven models, such neural networks, can reproduce these relationships with relatively high accuracy

iv. Performance evaluation of GSSHA modeling system compared to other widely used hydrologic models.

The purpose of this analysis was to gauge the performance of GSSHA against MIKE-SHE which represents a more mature modeling system that has been tested and proved accurate in numerous research and applied studies. Both modeling systems have similar formulations and representations of various rainfall-runoff processes. In addition, a third modeling system, HEC-HMS, was also included in the assessment exercise due to its rather simplified and conceptual formulation. The three models were calibrated and validated for the Goodwin Creek watershed for a series of continuous simulation periods during 1982, 1987, 1997, 1998, and 2002. The three models were evaluated based on their ability to reproduce times and magnitudes of runoff peaks and also runoff volumes.

The overall comparison shows that GSSHA's results are highly comparable with those of MIKE-SHE and HEC-HMS. Although the different statistics for the three models have close values, GSSHA's errors show different trends from the other two models. Generally, both MIKE-SHE and HEC-HMS tend to overestimate the observed peaks and runoff volumes, while GSSHA tends to underestimate them. As for the error in time to peak, GSSHA's results are more comparable to HEC-HMS than MIKE-SHE. Both GSSHA and HEC-HMS have mostly positive time to peak error, which indicates a slower watershed response in both models representations than the real watershed response to the same given precipitation. Comparatively, MIKE-SHE had mostly negative time to peak error values. The RMSE values for GSSHA's results are also comparable with those of the other two models. It is obvious that GSSHA has the highest RMSE value when the observed peaks are small in magnitude. GSSHA's RMSE values become more comparable with those of the other two models when the peaks have larger magnitude.

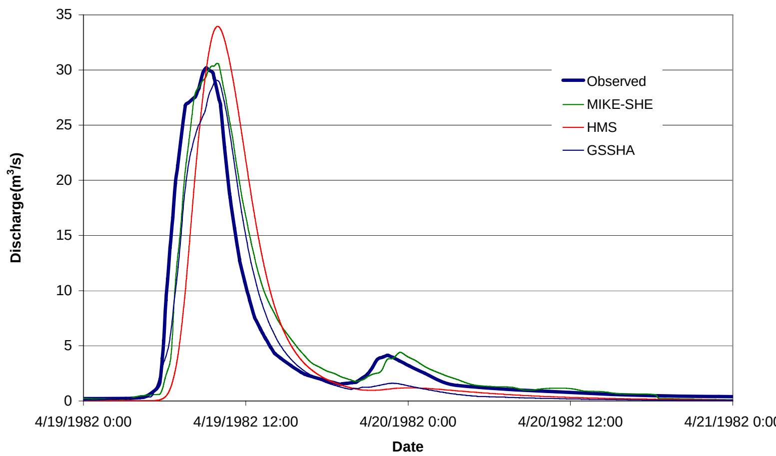


Figure 4: Observed and simulated hydrograph for the three models during calibration period

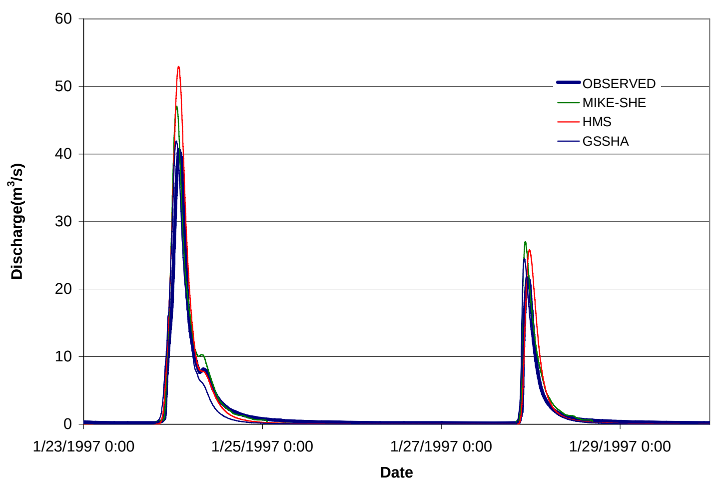


Figure 5: Observed and simulated hydrographs for the three models during a validation period

It is emphasized that interpretation of the above results should take into consideration the fact that the three models were calibrated manually. Although efforts were made to maintain as unified calibration criterion as possible, subjective judgment on when to stop further calibration of a certain model was inevitable. An automated calibration procedure where all models are strictly subjected to the same criterion is one way to eliminate any ambiguities in interpretation of the results.

v. Assessment of sensitivity of runoff predictions to spatial and temporal rainfall sampling.

The purpose of this analysis was to assess the impact of the spatial and temporal sampling resolution of rainfall on the predictive ability of both distributed and lumped hydrologic models. This analysis is intended to address two issues that are important for both research and practical purposes: are distributed physics-based models more sensitive to degrading the rainfall sampling resolution? And what are the rainfall sampling requirements that can be considered sufficient for runoff prediction?

The impact of the temporal and spatial sampling of rainfall on the performance of physically-based and conceptual models was investigated. Simulations were performed with varying the number of rain gauges from 1 to 30 gauges. In addition, temporal resolution of rainfall sampling was varied from 15 minutes to 6 hours. The study showed that errors introduced by coarse sampling scenarios can be significant. Overall, for the particular size of the study watershed, increasing the rain gauge density from 1 to 2 resulted in the most significant improvement for both models. Similarly, a temporal sampling frequency beyond 1 hour showed significant deterioration in the quality of the runoff prediction. This study also showed that the distributed physically-based model was more sensitive to the rainfall temporal and spatial sampling than the conceptual semi-distributed model. Such sensitivity was more pronounced and persistent especially when the spatial sampling was significantly lowered. The combined spatial-temporal sampling experiment showed that increasing the temporal sampling compensates, at least partially, for the loss of rainfall spatial information. It also showed that under poor spatial sampling conditions, the gain in model performance by increasing the temporal sampling frequency becomes negligible.

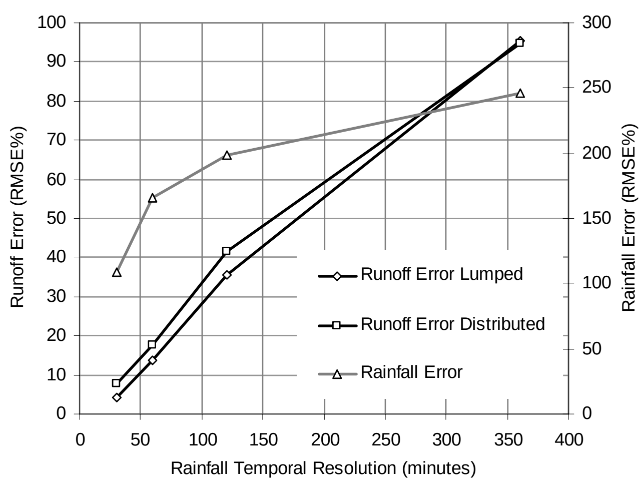


Figure 6: Error in rainfall and runoff due to rainfall temporal resolution.

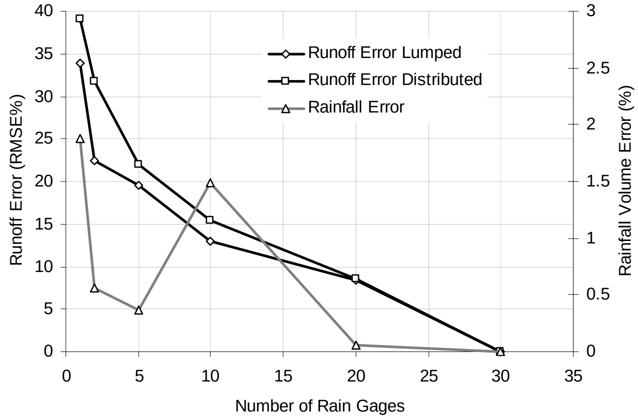


Figure 7: Error in rainfall and runoff due to changes in spatial resolution of rainfall

vi. Using radar rainfall information for hydrologic modeling with GSSHA.

Recent years have witnessed significant advances in development of operational radar-rainfall products. These products are desirable for several hydrologic applications such as flood forecasting and rainfall-runoff modeling. It is recognized that radar-rainfall estimates are associated with unknown uncertainties. The nature of these uncertainties and their impact on the prediction accuracy of hydrologic models is a challenging research problem that has been identified by the hydro-meteorological community. Full investigation of such a problem is beyond the scope of this project. Therefore, the project focused on one aspect of the radar error characteristics, which is systematic error (bias) and its impact on runoff predictions. Radar-rainfall products used in the study are the hourly, 4x4 km2 resolution NWS Multi-sensor Precipitation Estimator (MPE) radar-rainfall estimates over the Goodwin Creek experimental watershed. The physically based fully parameter distributed model (GSSHA) was used to perform rainfall-runoff simulations driven by different scenarios of radar and rain gauge estimates. Analysis of radar systematic error showed that MPE radar estimates can have large biases in estimating storm-total rainfall volumes. Such biases cause significant deterioration in runoff predictions. Bias adjustment over a storm time scale has lead to a significant improvement in runoff prediction accuracy. However, after removing (adjusting) storm biases, significant random errors still exist in the radar information. Future work will focus on quantifying the spatial/temporal characteristics and dependence structure of random radar errors and how their implications for uncertainties in rainfall-runoff simulations.

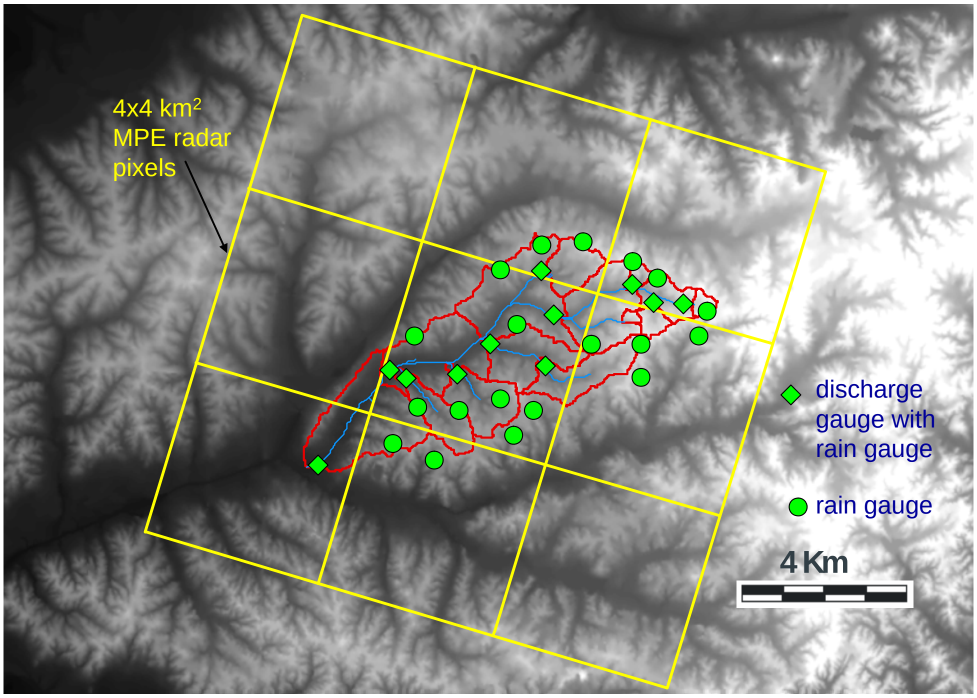


Figure 8: The 21-km$^2$ Goodwin Creek Experimental Watershed in northern Mississippi is selected for radar-rainfall runoff analysis because of its dense coverage with precipitation and surface runoff measuring stations.

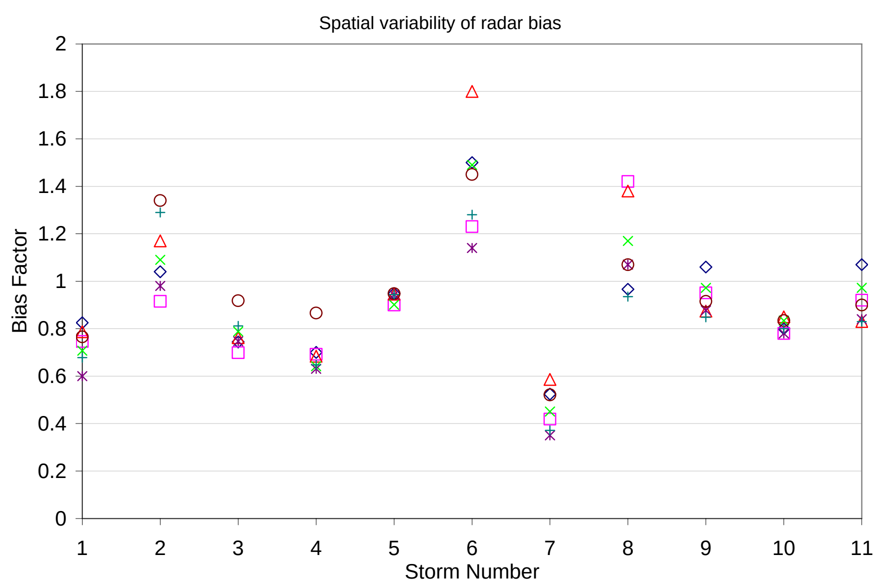


Figure 9: MPE radar estimates were found to have significant bias during most of the 11 storms selected for this study. Storm bias factors for each pixel covering the watershed were computed as the ratio of total radar to total gauge accumulations. Bias factors showed significant variability from one pixel to another.

**c.5) Listing of Publications**

(i) Papers published in peer-reviewed journals:

Habib E. H., and Meselhe E. A. (2005): Stage-Discharge Relations for Low-Gradient Tidal Streams Using Data-Driven Models. *ASCE Journal of Hydraulic Engineering* (in press).

(ii) Papers published in conference proceedings:

- Habib E. H., Meselhe E. A., and Kalikivaya S. (2004) "Prediction of Discharge-Stage Relationship for Low gradient Tidal Streams Using Data-Driven Models." Proceedings of Louisiana Transportation Engineering Conference, February 2004, Baton Rouge, Louisiana.
- Meselhe E.A. Habib E.H., Mader C.B., McCorquodale J.A., Georgiou I.Y., Stronach J., and Campanella R. (2004). "Hydro-Ecological Modeling of the Lower Mississippi River" First National Conference on Ecosystem Restoration (NCER) in Orlando, Florida December 6-10.
- Meselhe E.A. and Byrd A. (2004). "Advances to the Model Gridded Surface Subsurface Hydrologic Analysis for Improved Ecosystem Modeling" First National Conference on Ecosystem Restoration (NCER) in Orlando, Florida December 6-10.
- Meselhe E.A., Habib E.H., and Ogden F.L. (2004) "Performance Evaluation of the Physically Based Distributed Hydrologic Model: GSSHA" the 24th Army Science Conference, November 29 – December 2, 2004 in Orlando, Florida.
- Ogden F., Niedzialek J., Zahner J., Byrd A., and Meselhe E. (2004) "Simulating Lakes, Wetlands, Detention Basins, and Storm Drainage Networks using GSSHA." World Water & Environmental Resources Congress, EWRI – ASCE, June 27 – July 1, Salt Lake City, Utah
- Habib E.H., Meselhe E.A, and Kalikivaya S. (2004) "Development of Discharge-Water Level relationship for Low-Slope Tidal Streams Using Non-Parametric Data-Driven Models." World Water & Environmental Resources Congress, EWRI – ASCE, June 27 – July 1, Salt Lake City, Utah.
- Meselhe E.A, Habib E.H., Oche O., and Gautam S. (2004) "Performance Evaluation of Physically Based Distributed Hydrologic Models and Lumped Hydrologic Models." World Water & Environmental Resources Congress, EWRI – ASCE, June 27 – July 1, Salt Lake City, Utah.
- Habib E.H., Meselhe E.A., and Kalikivaya S. (2003) "Development of Discharge Ratings for Low-Slope Streams Under Tidal Effects Using Non-Parametric and Data-Driven Models." American Geophysical Union Fall Meeting, 8-12 December 2000, San Francisco.
- Ogden F.L., Downer C.W., and Meselhe E.A. (2003) "U.S. Army Corps of Engineers Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) Model: Distributed-Parameter, Physically Based Watershed Simulations." Proceedings of the World Water & Environmental Resources Congress, June 23-26, Philadelphia, PA.

- Kheiashy K., Meselhe E.A., and Guwang B. (2002) “Development of an Internet GIS-Based Hydrologic Model for the Vermilion Watershed.” Proceedings of the Hydroinformatics 2002, 1-5 July, Cardiff, Wales, U.K.
- Hebert K. J., Meselhe E. A., and Noshi H. M. (2001) “Laboratory Measurements of Unsteady Flows through Culverts” Proceedings of the World Water and Environmental Resources Congress, May 20-24, Orlando, Florida.
- Ogden F. L., Meselhe E. A., Niedzialek J., and Smith B. (2001) “Physics-Based Distributed Rainfall-Runoff Modeling of Urbanized Areas with CASC2D” Urban Drainage Modeling Symposium, the World Water and Environmental Resources Congress, May 20-24, Orlando, Florida.
- Downer C. W., Johnson B. E, Ogden F. L., and Meselhe E.A. (2000) “Advances in Physically Based Hydrologic Modeling with CASC2D” Proceedings of the Watershed Management & Operations Management, the Environmental and Water Resources Institute, June 20-24, Colorado State University, Fort Collins, Colorado.

(iii) <u>Papers presented at meetings:</u>

- Habib, E., E. A. Meselhe and A. Vishnu (2005) “Analysis of Radar-Rainfall Error and its Effect on Runoff Predictions”, American Geophysical Union Joint Assembly, 23-27 May, 2005, New Orleans.
- Meselhe E. A., Habib E. H., and Ogden F. L. (2004) “Performance Evaluation of the Physically Based Distributed Hydrologic Model: GSSHA.” the 24th Army Science Conference.
- Habib E. H., Meselhe E. A., and Kalikivaya S. (2004) “Development of Discharge-Water Level relationship for Low-Slope Tidal Streams Using Non-Parametric Data-Driven.” Proceedings of World Water and Environmental Resources Congress2004, June 27 - July 1, Salt Lake City, Utah.
- Meselhe E. A., Habib E. H., Oche O. C., and Gautam S. (2004) “Performance Evaluation of Physically Based Distributed Hydrologic Models and Lumped Hydrologic Models.” Proceedings of World Water and Environmental Resources Congress2004, June 27 - July 1, Salt Lake City, Utah.
- Habib E.H., Meselhe E.A., and Kalikivaya S. (2003) “Development of Discharge Ratings for Low-Slope Streams Under Tidal Effects Using Non-Parametric and Data-Driven Models.” American Geophysical Union Fall Meeting, 8-12 December 2003, San Francisco.

(iv) <u>Manuscripts submitted but not published:</u>

- Meselhe E. A., Habib E. H., Oche O. C., and Gautam S. (2004) “Performance Evaluation of Lumped Conceptual and Distributed Physically Based Hydrologic Models.” Submitted to Water Resources Research Journal.
- Habib E.H., Meselhe E.A., and Kalikivaya S. (2003) “Development of Discharge Ratings for Low-Slope Streams Under Tidal Effects Using Non-Parametric and Data-Driven Models.” American Geophysical Union Fall Meeting, 8-12 December 2003, San Francisco.

**c.6) Scientific Personnel who earned advanced degrees under this project**

- Elrawady, M., (2005) "Performance Assessment of the Hydrologic Model GSSHA for the Goodwin Creek and Isaac Verot Watresheds." MS thesis, Civil Engineering Department, University of Louisiana, Lafayette.
- Gautam S. (2004). "Sensitivity of Runoff Prediction to Spatial and Temporal Rainfall Sampling Using a Distributed Hydrologic Model." MS thesis, Civil Engineering Department, University of Louisiana, Lafayette.
- Oche O. C. (2004) "Performance Evaluation of Physically Based Distributed Hydrologic Models and Lumped Hydrologic Models." MS thesis, Civil Engineering Department, University of Louisiana, Lafayette.
- Sarada Kalikivaya (2004) "Discharge-Stage Relationship for Low-Gradient Tidal Streams Using Physically Based and Data-Driven Models." MS thesis, Civil Engineering Department, University of Louisiana, Lafayette.
- Karim Keiashy (2003) "Field Measurements and Hydrologic Modeling of Low-Gradient Watersheds." MS thesis, Civil Engineering Department, University of Louisiana, Lafayette.
- Kirby Hebert (2001) "Laboratory Measurements of Unsteady Flows Through Culverts." MS thesis, Civil Engineering Department, University of Louisiana, Lafayette.
- Kepmike Ogouma (2001) "Unsteady One-Dimensional Model of The Vermilion River." MS thesis, Civil Engineering Department, University of Louisiana, Lafayette.

**c.7) Report of Inventions (by title only)**

**N/A**

**c.8) Bibliography**

Alonso, C. V., and R. L. Bingner (2000), Goodwin Creek Experimental Watershed: A unique field laboratory, *ASCE, J. Hydraulic Eng.*, *126*, 174-177.

Bell, V. A., and R. J. Moore (2000), The sensitivity of catchment runoff models to rainfall data at different spatial scales, *Hydrol. Earth System Sci.*, *4*(4), 653-667.

Beven, K. J., and G. M. Hornberger (1982), Assessing the effect of spatial pattern of precipitation in modeling stream flow hydrographs, *Water Resour. Bull.*, 823-829.

Blackmarr, W. A. (1995), Documentation of hydrologic, geomorphic, and sediment transport measurements on the Goodwin Creek Experimental Watershed, Northern Mississippi, for the period of 1982-1993, preliminary release, *Res. Rep. No. 3*, USDA-ARS National Sedimentation Laboratory, Oxford, Miss. ed.

Downer, C. W., and F. L. Ogden (2004), Appropriate vertical discretization of Richards' equation for two-dimensional watershed-scale modeling, *Hydrological Processes, 18* (1), 1-22.

Fleming, M., and V. Neary (2004), Continuous hydrologic modeling study with the hydrologic modeling system, *J. Hydrologic Eng.*, *9*(3), 175-183.

Gautam, S. (2004), Sensitivity of runoff prediction to spatial and temporal rainfall sampling using a distributed hydrologic model, M. S. thesis, Uni. of Louisiana at Lafayette, Lafayette, Louisiana.

Holman-Dodds, J. K., A. A. Bradley, and P. L. Sturdevant-Rees (1999), Effect of temporal sampling of precipitation on hydrologic model calibration., *J. Geophy. Res.*, *104*(D16), 19645-19654.

Hydrologic Engineering Center (HEC) (2000), Hydrologic modeling system HEC-HMS: Technical reference manual, U.S. Army Corps of Engineers, Davis, California.

Johnson, M. S., W. F. Coon, V. K. Mehta, T. S. Steenhuis, E. S. Brooks, and J. Boll (2003), Application of two hydrologic models with different runoff mechanisms to a hillslope dominated watershed in the northeastern US: a comparison of HSPF and SMR, *J. Hydrol.*, *284*, 57-76.

Klemes, V. (1986), Operational testing of hydrological simulation models, *Hydrol. Sci. J.*, *31*(1), 13-24.

Krajewski, W. F., V. Lakshmi, K. P. Georgakakos, and S. C. Jain (1991), A monte -carlo study of rainfall sampling effect on a distributed catchment model, *Water Resour. Res*., *27*(1), 119-128.

Loague, K. M., and R. A. Freeze (1985) A comparison of rainfall-runoff modeling techniques on small upland catchments, *Water Resour. Res.*, *21*(2), 229-248.

Michaud, J. D., and S. Sorooshian (1994a), Comparison of simple versus complex distributed runoff models on a midsize semiarid watershed, *Water Resour. Res.*, *30*(3), 593-605.

Michaud, J. D., and S. Sorooshian (1994b), Effect of rainfall-sampling errors on simulations of desert flash floods, *Water Resour. Res.*, *30*(10), 2765-2775.

Obled, C. H., J. Wendling, and K. Beven, (1994), The sensitivity of hydrological models to spatial rainfall patterns: an evaluation using observed data, *J. Hydrol.*, *159*, 305-333.

Oche, O. C. (2004), Performance evaluation of physically based distributed hydrologic models and lumped hydrologic models, M. S. thesis, Uni. of Louisiana at Lafayette, Lafayette, Louisiana.

Ogden, F. L., and P. Y. Julien (1993), Runoff sensitivity to temporal and spatial rainfall variability at runoff plane and small basin scales, *Water Resour. Res.*, *29*(8), 2589-2597.

Perrin, C., C. Michel, and V. Andréassian (2001), Does a large number of parameters enhance model performance ? Comparative assessment of common catchment model structures on 429 catchments, *J. Hydrol.*, *242*(3-4), 275-301.

Reed, S., V. Koren, M. Smith, Z. Zhang, F. Moreda, D.J. Seo, and DMIP Participants (2004), Overall Distributed Model Intercomparison Results, *J. Hydrol.*, accepted for the upcoming DMIP special issue.

Refsgaard, J. C., and J. Knudsen (1996), Operational validation and intercomparison of different types of hydrological models, *Water Resour. Res*, *32*(7), 2189-2202.

Refsgaard, J. C., and B. Storm (1995), MIKE SHE, in *Computer Models of Watershed Hydrology*, edited by V. P. Singh, pp. 809-846, Water Resour. Publ., Highlands Ranch, Colo.

Shah, S. M. S., P. E. O'Connell, and J. R. M. Hosking (1996), Modeling the effects of spatial variability in rainfall on catchment response. Experiments with distributed and lumped models, *J. Hydrol.*, *175,* 89-111.

Smith, M., V. Koren, Z. Zhang, S. Reed, D. J. Seo, F. Moreda, V. Kuzmin, Z. Cui, and R. Anderson (2004), NOAA NWS distributed hydrologic modeling research and development, NOAA technical report NWS 45, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 62 pp.

Wilson, C. B., J. B. Valdes, and I. Rodriguez-Iturbe (1979), On the influence of the spatial distribution of rainfall on storm runoff, *Water Resour. Res*, *15*(2), 321-328.

**c.9) Appendixes**

**N/A**