FINAL REPORT FOR PROJECT NUMBER NA04NWS4620012
Covers the Period 06/01/04 TO 05/31/08
Submitted July 1, 2008

TITLE: **Parameterization and Parameter Estimation of Distributed Models For Flash Flood and River Prediction**

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1. PROJECT OBJECTIVES & SUMMARY OF WORK PROPOSED

1.1. Project Objectives

The shift from lumped to distributed models raises many important questions about the proper choice of model parameterization, including the desirable level of model complexity, while significantly increasing the complexity of the parameter estimation problem. The main objective of this project was to collaborate with and support the Hydrologic Modeling team at the NWS Office of Hydrology in the rapid development of an advanced version of the NWS-OH distributed hydrologic model, with particular attention to the issues of parameter estimation, appropriate model structure, supportable model complexity, and model evaluation, diagnosis and improvement. The unifying theme through our work was to focus on improving distributed watershed modeling through addressing issues of model parameterization (specification of model components), and estimation of the model parameters in both gauged and ungauged settings. The following tasks were listed under this contract:

1. Parameterization of semi-distributed and distributed hydrologic models within Hydrology Laboratory-Distributed Hydrologic Model (HL-DHM) framework,
2. Distributed parameter estimation (automated and/or semi-automated) for the above (this work built on our experience with lumped models, while introducing novel ideas such as regularization that are specifically tailored to distributed models),
3. A priori methods for parameter estimation in ungauged basins using direct inference from watershed properties and statistical regression analysis (existing work by NWS-HL staff will be extended and used to drive this important area of hydrologic modeling research forward).

This work extended our past collaborative work with the NWS by supporting the development of distributed modeling capabilities with particular attention given to ungauged and poorly gauged watersheds, consistent with the aims and future directions of the NWS. This research was implemented in the context of the HL-DHM thereby maximizing technology transfer and ensuring that the work outcome is of direct value to the NWS.

1.2. Summary of Work Proposed

a. Implement HL-DHM at the University of Arizona as a modeling environment. Incorporate currently available calibration algorithms.
b. Investigate and implement a distributed parameter estimation algorithm based on the concept of regularization
c. Investigate the a priori parameter estimation problem using both bottom-up (incl. the development of relationships between the parameters of the NWS conceptual model components to soil and watershed characteristics) and top-down (regionalization) approaches.
d. Combine the research on a priori and distributed parameter estimation into a single procedure.
e. Test the basic equations relating model parameters and watershed properties in a multi-watershed study. Complement this approach with a statistical regionalisation approach using a minimum of 30 watersheds.
f. Implement and test the new tools for a priori and distributed parameter estimation into the HL-DHM.
g. Technology transfer through (in person and telephone) meetings.

2. PROJECT ACCOMPLISHMENTS

This section provides a summary of the project accomplishments for each year of the reporting period.

2.1. Project Accomplishments During the Period 05/31/2004 – 11/30/2004

a. A comprehensive literature review was performed with a focus on the frameworks developed for incorporating watershed physical properties (i.e. geology, soil hydraulic properties, landscape hydrologic units, utilization of remotely sensed information) into model structure identification and parameter estimation methods.

b. The Hydrology Laboratory-Distributed Hydrologic Model (HL-DHM) was set up and run successfully on a Penguin Linux Cluster (16 AMD Athlon 2800+ CPUs with a total of 8GB memory) at the University of Arizona. Ph.D. student Koray Yilmaz performed the implementation and setup process. The implemented HL-DHM was checked for computational accuracy using a test run provided by Dr. Victor Koren.

2.2. Project Accomplishments During the Period 12/01/2004 – 11/30/2005

Our activities during this period focused mainly on two different but overlapping perspectives on improving streamflow predictions. We incorporated a priori knowledge of the watershed physical properties (i.e., soil texture, land cover etc.) into the parameter estimation process, and we also utilized watershed input-output datasets (specifically watershed indices) within a statistical framework to constrain streamflow predictions. Details of these accomplishments are as follows:

a. The Hydrology Laboratory-Distributed Hydrologic Model (HL-DHM) was linked to an automated optimization program called "*Multi Objective Shuffled Complex Evolution – Metropolis Algorithm (MOSCEM)"* (Vrugt et. al, 2003) to enable optimization of the multipliers associated with the a priori hydrologic model parameter grids to enable the model to better match streamflow observations at the watershed outlet.

b. A multi-criteria penalty function framework was devised in which the optimization problem is formulated as requiring the balanced minimization of two objective functions: 1) matching the HL-DHM simulated flows to the observations at the outlet, and 2) penalizing the deviation of the model parameters from the a priori parameter estimates defined by Koren et al. (2000). Assuming that the spatial pattern of the model parameters is adequately defined by the a priori estimates provided by the Koren et al. (2000) approach, we computed optimal estimates for the multipliers of each parameter grid. The objective function for matching the flows was given careful attention to minimize bias, by separately treating the driven and non-driven streamflow segments. Streamflow measurement error was estimated through the use of a wavelet-denoising algorithm. This framework was tested on the Blue River Basin (BLUO2), and enabled an analysis of the extent to which the Koren estimates are consistent with the optimal model parameters required to simulate the dynamic input-output response of the basin. The results indicated that whereas the a priori parameter estimates give simulations having consistently positive flow bias the multi-criteria compromise solutions provide improved input-output response performance (with consistent behavior across calibration and evaluation years) while maintaining physically realistic a priori values for most of the model parameter estimates; adjustments were found to be necessary for only a few key model parameters. Details of this analysis can be found in Yilmaz (2007) and Yilmaz et al. (2008b).

c. A study was undertaken to analyze the propagation of the uncertainty in the soil hydraulic parameters to the a priori hydrologic model parameters. A priori model parameter estimates defined by equations given in Koren et al. (2003) require estimates of soil hydraulic parameters. These soil hydraulic parameters are estimated through Pedotransfer Functions (PTFs), which relate soil texture information to the soil hydraulic parameters. One of the assumptions in these PTFs is that percentages of sand and clay in a soil texture class are defined by the center point of each class within the USDA soil texture triangle. As a preliminary analysis, the uncertainty in soil texture information was estimated by randomly sampling sand and clay percentages for each soil texture class. These samples were then used subsequently within the PTFs and a priori parameter equations to analyze the resulting effects on the model a priori parameter values. Results suggest that given a wide sand/clay percentage variation within a soil texture class, there may be moderate changes in a priori model parameters. This analysis was presented to HL personnel during the site visit on 01/20/2006.

d. A model diagnostics interface was developed within the MATLAB® environment. This interface utilizes the time series and gridded output from the HL-DHM model to build a movie file showing the time propagation of precipitation (both gridded and time series) and corresponding model responses in terms of states as well as model generated fluxes. These variables can be analyzed at a particular time step to visualize the model behavior at different parts of the basin under consideration. This interface was presented to HL personnel during the site visit on 01/20/2006.

e. A pilot study into the regionalization of watershed response characteristics was performed. This included the development of a top-down framework to perform this task in an uncertainty framework and the development of a MATLAB toolbox to calculate indices of hydrologic response behavior. The regionalized ranges of likely watershed responses at ungauged sites provide constraints that can be used to reduce the number of possible parameter sets that can represent the ungauged watershed. This approach allows the inclusion of larger scale characteristics (e.g. topography or drainage area) into the parameter estimation process at ungauged sites. This model independent approach complements the bottom-up approach discussed under point b. This analysis was presented to HL personnel during site visit on 01/20/2006, and has been published in Yadav et al. (2007).

2.3. Project Accomplishments During the Period 12/01/2005 – 11/30/2006

Our activities during this period focused on: a) a strategy for diagnostic evaluation of HL-DHM model, b) development of regularization relations for the HL-DHM model, c) development of a new approach to predictions in ungaged basins through the regionalization of constraints, d) investigation of the sensitivity of the HL-DHM.

a) A model diagnostic strategy was explored with the goal of detecting causes of HL-DHM model performance inadequacies, and to guide appropriate model parameter adjustments. The “core” of the strategy is the identification of measures of model performance that have improved diagnostic power over the aggregate measures used in classical automatic model identification. The diagnostic strategy results in a hybrid approach that combines process-based manual calibration with automated multi-criteria approach.

The diagnostic strategy was tested using the HL-DHM model applied to the Blue River basin (BLU02). A necessary analysis prior to model diagnosis was to resolve major inconsistencies related to initial model setup (input-output data, model initial states). This analysis utilized both graphical (Budyko curve, inter annual plot, intra-annual plot) and numerical measures (runoff ratio) to ensure a reasonable water balance at longer time scales (annual, monthly). The inter-annual plot of major water balance components was used to detect major errors in evapotranspiration estimates and model initialization. Accounting for such major errors in model setup are necessary to enable further efforts towards model diagnosis.

The proposed model diagnostic strategy followed a hierarchy of timescales. At each timescale, signature measures were formulated to test the ability of the model to represent hydrological processes dominant at that timescale. Our analysis considered three of the four major behavioral functions of any watershed system; overall water balance, vertical redistribution, and temporal redistribution (timing of flows). Spatial redistribution was not addressed and left for future work. Instead of using classical statistical measures (such as mean squared error), we used multiple hydrologically relevant "signature measures" to quantify the performance of the model at the watershed outlet in ways that correspond to the functions mentioned above and therefore helped to guide model improvements in a meaningful way.

While model components/parameters related to water balance were tested with measures formulated at long timescales (annual, monthly), shorter timescales were used to test model components/parameters related to water partitioning and timing (daily and hourly). For example, the diagnostic measure selected to summarize the water balance function of the model was the percent flow bias (compared to observed flows). The daily flow duration curve (FDC) was another signature used to understand parameter functioning and hence guide parameter identification. Our preliminary analysis indicated that parameters related to water partitioning change the slope of the mid-section of FDC while parameters affecting total water balance do not change the slope but create shifts in overall FDC level. Parameter perturbations were performed by assuming that a priori model parameters adequately represented the spatial distribution of hydrological processes. Therefore each parameter map was perturbed using a single coefficient.

While the common approach reported in the literature is to use the coefficient as a multiplier to the parameter map and to choose the feasible range of coefficient subjectively, in this study a novel non-linear transformation was applied to the spatially distributed parameter values to maintain the parameter values within the range of feasible values, without the requirement for a subjectively selected threshold (see Yilmaz et al., 2008a and Yilmaz 2007 for details). One-at-a-time and random sampling-based perturbation analyses were performed to identify the HL-DHM model parameters that dominate the control of the aforementioned watershed/model functions. The analysis indicated that the water balance function is highly controlled by parameters related to evapotranspiration (UZTWM, LZTWM, PFREE) and the flow partitioning function is highly controlled by the parameters affecting the percolation in the model (REXP, LZFSM, ZPERC, LZFPM, LZSK, UZFWM). Details of the diagnostic evaluation strategy can be found in Yilmaz 2007 and Yilmaz et al. (2008a).

b) Regularization relations were developed to constrain the high-dimensional parameter space of HL-DHM for use within automatic calibration. Regularization is a mathematical technique that utilizes additional information or constraints about the parameters to solve over-parameterized problems. In this research the information embodied in the 11 SAC-SMA a priori estimates, derived using the Koren approach (Koren et al. 2000), was utilized to develop the constraints (in the form of regularization relations).

The general procedure adopted to derive the regularization relations was to identify the physically observable watershed characteristics (elevation, slope and soil depth) or properties derived from physically observable characteristics of the watershed (curve numbers, curvature of the ground, topographic index and specific catchment area) that may, in theory, influence the spatial distribution of parameters in a watershed. We further analyzed the distribution of the a priori parameter with respect to the watershed characteristics and identified trends or relationship between them that could be expressed in the form of simple empirical relations. Finally, we calibrated the super-parameters pertaining to these relations, instead of directly adjusting the original SAC-SMA parameters.

Using the procedure outlined above, 11 regularization relations were identified, that take the form of exponential, logarithmic or linear relations. These equations were expressed in the generalized form:

$$\theta = \alpha_\theta \times [X]^{\beta_\theta} \pm \gamma_\theta \qquad (1)$$

where θ refers to the SAC-SMA parameter, α, β and γ are the coefficients of the equations which have to be calibrated, and X is the observable watershed characteristic whose value is available.

The regularization strategy was tested using the UA version of the HL-DHM model applied to the Blue River basin (BLUO2). The regularization super-parameters were calibrated using the Multi-objective Shuffled Complex Evolution Metropolis (MOSCEM) algorithm (Vrugt et al. 2003). The regularization strategy reduced the number of parameters to be calibrated from 858 (78 grids x 11 parameters/grid) to 33 (3 regularization equations x 11 super-parameters). Calibration of the super-parameters was done in three steps. Firstly the intercepts of the equations (Gamma) were calibrated, followed by the curvatures (beta), and finally the slopes (alpha). This calibration order was selected after trying all the six combinations. The objective functions used were the Mean Squared Error (MSE) and the Log Mean Squared error (LMSE). Calibration of the parameters resulted in significant reductions in the objective function values and clear visual improvements in the properties of the simulated hydrograph when compared with the a priori model simulations. The details of this work can be found in Pokhrel (2007) and Pokhrel et al. (2008).

c) A new approach to predictions in ungauged basins was developed through the regionalization of constraints. Approaches to modeling the continuous hydrologic response of ungauged basins commonly use observable physical characteristics of watersheds to either directly infer values for the parameters of hydrologic models, or to establish regression relationships between watershed structure and model parameters. Both these approaches have severe limitations, including being affected by model structural uncertainty. In this work we introduced an alternative, model independent, approach to streamflow prediction in ungauged basins based on empirical evidence of relationships between watershed structure, climate and watershed response behavior. Instead of directly estimating values for model parameters, different hydrologic response behaviors of the watershed, quantified through model independent streamflow indices were estimated and subsequently regionalized in an uncertainty framework. This resulted in expected ranges of streamflow indices for a set of ungauged watersheds. A pilot study using 30 UK watersheds showed how this regionalized information could be used to constrain ensemble predictions of any model at ungauged sites. Dominant controlling characteristics were found to be climate (wetness index), watershed topography (slope), and hydrogeology. The most useful streamflow indices were found to be the high pulse count, runoff ratio, and the slope of the flow duration curve. The approach provided sharp and reliable predictions of continuous streamflow at the ungauged sites tested. The details of this work can be found in Yadav et al. (2007).

d) A study was conducted to investigate the sensitivity of the HL-DHM via a step-wise analysis of the HL-DHM. We evaluated model parameter sensitivities for annual, monthly and event time periods with the intent of elucidating the key parameters impacting the forecasts of the distributed model. The methodology balances the computational constraints posed by global sensitivity analysis with the need to fully characterize the HL-DHM's sensitivities. HL-DHM parameter sensitivities were assessed for annual and monthly periods using distributed forcing and identical model parameters for all grid cells at 24-hour and 1-hour model time steps respectively for two case study watersheds within the Juniata River Basin in central Pennsylvania, USA. The study provided detailed spatial analysis of the HL-DHM's sensitivities for two flood events based on 1-hour model time steps selected to demonstrate how strongly the spatial heterogeneity of forcing influences the model's spatial sensitivities. Our verification analysis of the sensitivity analysis method demonstrated that the method provides robust sensitivity rankings and that these rankings can be used to significantly reduce the number of parameters that should be considered when calibrating the HL-DHM. Overall, the sensitivity analysis results revealed that storage variation, spatial trends in forcing, cell-connectivity, and cell proximity to the gauged watershed outlet are the four primary factors that control the HL-DHM's behavior. The details of this work can be found in Tang et al. (2007).

2.4. Project Accomplishments During the Period 12/01/2006 – 11/30/2007

Our activities during this period focused on: a) improving the strategy for diagnostic evaluation of HL-DHM model, b) extending the regionalization approach introduced by Yadav et al. (2007) to identify behavioral parameter sets.

a) The diagnostic model evaluation strategy discussed earlier was extended to detect streamflow timing errors in the HL-DHM model predictions. The HL-DHM model parameterized by the Koren et al. (2000) approach was used as a baseline model to benchmark the model performance improvements obtained by diagnostic model evaluation strategy. Upon reviewing the timing measures commonly used in the hydrologic literature, two flow timing measures were formulated: an event-based measure and an overall time period measure. The event-based measure is based on isolating representative flow events from a hydrograph. Each flow event is then partitioned into rising and falling segments and time location of the flow centroid calculated for each segment. One-at-a-time and random sampling based parameter perturbations were performed to isolate the parameters affecting the time location of simulated flow centroid of the rising limb (signature measure for flow timing). The perturbation analysis revealed that UZFWM and ROUTQ0 (specific discharge parameter of the channel routing model) are the dominant parameters controlling the timing of flow in HL-DHM model. The details of this work can be found in Yilmaz (2007).

   Another timing measure based on processing of rainfall (mean areal rainfall) and streamflow observations for the overall time period was formulated. The goal was to estimate, in a simple way, the intrinsic time lag of the watershed. In the procedure, the time-shift (hours) providing the maximum correlation between mean areal rainfall and streamflow time series was selected as time-lag of the watershed. In this manner, the time lag can be calculated for flows above a threshold value. The parameter perturbation analysis revealed that UZFWM and ROUTQ0 are the dominant parameters controlling time-lag of the watershed, and hence supported the findings from event-based flow timing analysis. The details of this work can be found in Yilmaz et al. (2008a).

b) An automated random sampling-based parameter sensitivity analysis was developed and integrated into the diagnostic model evaluation strategy. The automated parameter sampling procedure incorporates a priori parameter grids as spatial constraints to reduce the dimensionality of the distributed model parameterization problem. It was assumed that the spatial pattern of a priori parameters, in terms of both location and *relative* magnitude of parameters, is well-defined (reasonable and reliable). Then, the procedure simplifies to that of finding the parameters of a transformation function that modifies the *absolute* magnitude of the parameters in each a priori parameter grid. A novel non-linear transformation function was devised for this purpose (see Yilmaz, 2007) which contains only one parameter, β *(0,2]*, to be calibrated. A random procedure was utilized to sample 1600 parameter sets (β) from the HL-DHM model. The relationship between signature measures and parameters was used to constrain parameter space. Further random sampling was performed on the constrained parameter space to select those parameter sets that provide improved signature measure values compared to the baseline simulation. The details of this work can be found in Yilmaz et al (2008a).

c) The regionalization approach introduced by Yadav et al. (2007) was extended to include a global multi-objective optimization approach to identify behavioral parameter sets. Yadav et al. (2007) showed that regionalized indices of watershed response characteristics (e.g. runoff ratio) could be used to considerably reduce the uncertainty in ensemble streamflow predictions at ungauged locations. Indices of hydrologic response were regressed against physical and climatic watershed characteristics including uncertainty. The regression thus provides ranges for response indices at ungauged locations. Models (parameter sets) not producing indices within these ranges can be eliminated as unacceptable from ensemble forecasts. A drawback of the proposed strategy was the inefficient Monte Carlo approach used to identify acceptable parameter sets, which limited the approach to simultaneous use of only a very few indices, and to simple watershed model structures. The problem of finding acceptable parameter sets was therefore reformulated as a multi-objective optimization problem and solved using a evolutionary genetic algorithm. Running the algorithm on a parallel cluster, we showed that for 30,000 function evaluations a relatively consistent population of about 10,000 acceptable parameter sets could be found. This improvement to the approach will now allow us to test it on spatially explicit watershed models such as the HL-DHMS. The details of this work can be found in Zhang et al. (2008).

2.5. Project Accomplishments During the Period 12/01/2007 – 05/31/2008

Our activities during this period focused on preparation of the journal articles related to findings from this project,

a) The Diagnostic Evaluation approach has been reported in Hydrological Processes and Water Resources Research (Gupta et al, 2008, Yilmaz et al 2008a).

b) The Multi-criteria Penalty Function Approach has been extended to include non-linear multipliers on the spatially distributed model parameters and reported in Advances in Water Resources (Yilmaz et al 2008b in review).

d) The Spatial Regularization Approach has been reported in Water Resources Research (Pokhrel et al 2007 in review).

e) The results from the Diagnostic Evaluation Approach and the Spatial Regularization Approach have been submitted to the DMIP-2 experiment organized by Hydrology Laboratory of the NWS.

f) The regionalization work has been reported in Advances in Water Resources and in Water Resources Research (Yadav et al. 2007; Zhang et al. 2008).

g) The use of sensitivity analysis to advance in lumped and distributed hydrological modeling has been reported in Water Resources Research, Geophysical Research Letters and Advances in Water Resources. (Tang et al. 2007a, b; van Werkhoven et al. 2008a, b, c; Wagener et al., 2008).

3. SUMMARY OF BENEFITS AND PROBLEMS ENCOUNTERED

Benefits:

a. UA/PSU researchers are became familiar with the distributed hydrologic model for real time forecasting developed by NWS-HL in an effort to contribute and share new ideas. Students and researchers became familiar with NWS software, methods and procedures.
b. Project provided research topics for two MS theses (Prafulla Pokhrel, Univ. of Arizona & Maitreya Yadav, PSU) and a part of one Ph.D. dissertation (Koray K. Yilmaz, Univ. of Arizona). Aspects of this project were also incorporated into the PhD dissertations of Yong Tang and Katie van Werkhoven (PSU).
c. Fruitful communication between UA/PSU researchers and HL personnel significantly improved the outcome of the project.
d. The project enabled UA researchers to participate actively in the NWS run DMIP and DMIP-2 projects.

Problems encountered:

a. University of Arizona researchers implemented the first version of the HL-DHM (2004), which was not very transparent to the end-users. There was some difficulty in establishing the link between the optimization algorithm and the HL-DHM.
b. When implementing the HL-DHM version at Penn State we found that some adjustments to data structure and code were required for the model to work properly in connection with global sensitivity analysis.

4. OTHER PEOPLES WORK REFERENCED IN THIS REPORT

Koren, V. I., Smith, M., Wang, D. and Zhang, Z. (2000). Use of soil property data in the derivation of conceptual rainfall-runoff model parameters. 15th Conference on Hydrology, Long Beach, American Meteorological Society, Paper 2.16, USA.

Koren, V., Smith, M. and Duan, Q. (2003). Use of a priori estimates in the derivation of spatially consistent parameter sets of rainfall-runoff models. In Duan, Q., Gupta, H.V., Sorooshian, S., Rousseau, A.N. and Turcotte, R. (eds.) *Calibration of* *watershed models*. American Geophysical Union, Water Science and Application, Vol. 6, Washington, pp. 239-254.

Vrugt J. A., H. V. Gupta, L. A. Bastidas, W. Bouten, S. Sorooshian, 2003. Effective and efficient algorithm for multiobjective optimization of hydrologic models, Water Resour. Res., 39 (8), 1214, doi:10.1029/2002WR001746.

5. THESES, PUBLICATIONS AND PRESENTATIONS RESULTING FROM THIS PROJECT

5.1. Graduate Research Theses (4)

Yilmaz, K., K., 2007. Towards improved modeling for hydrologic predictions in poorly gauged basins, Ph.D. Dissertation, Univ. of Arizona.

Pokhrel, P., 2007. Estimation of Spatially Distributed Model Parameters Using A Regularization Approach, M.S. Thesis, Univ. of Arizona.

Yadav, M. 2007. Regionalization of dynamic watershed behavior. M.S. Thesis, Pennsylvania State University.

Van Werkhoven, K.L. 2008. Evaluating model behavior for hydrologic forecasting in gauged and ungauged watersheds. Ph.D. Dissertation, Pennsylvania State University.

5.2. Refereed Journal Articles (13)

Duan, Q., J. Schaake, V. Andreassian, S. Franks, G. Goteti, H.V. Gupta, Y.M. Gusev, F. Habets, A. Hall, L. Hay, T. Hogue, M. Huang, G. Leavesley, X. Liang, O.N. Nasonova, J. Noilhan, L. Oudin, S. Sorooshian, T. Wagener, E.F. Wood, Model Parameter Estimation Experiment (Mopex): An Overview Of Science Strategy And Major Results From The Second And Third Workshops, MOPEX Special Issue of the Journal of Hydrology, 320, pp. 3-17, 2006 (doi:10.1016/j.jhydrol.2005.07.031)

Gupta, H. V., T. Wagener and Y. Liu, Reconciling Theory with Observations: Towards a Diagnostic Approach to Model Evaluation, *Hydrological Processes*, 2008. DOI: 10.1002/hyp.6989.

Pokhrel, P., H.V. Gupta, and T. Wagener, A Spatial Regularization Approach to Parameter Estimation for a Distributed Watershed Model, *Water Resources Research*, in 2nd review 2008.

Tang, Y., Reed, P., Van Werkhoven, K. and Wagener, T. 2007. Advancing the identification and evaluation of distributed rainfall-runoff models using global sensitivity analysis. *Water Resources Research*, 43, doi:10.1029/2006WR005813.

Tang, Y., Reed, P., Wagener, T. and Van Werkhoven, K. 2007. Comparing sensitivity analysis methods to advance lumped watershed model identification and evaluation. *Hydrology and Earth System Sciences*, 11, 793-817.

Van Werkhoven, K., Wagener, T., Reed, P. and Tang, Y. 2008. Rainfall characteristics define the value of streamflow observations for distributed watershed model

identification. *Geophysical Research Letters*, 35, L11403, doi:10.1029/2008GL034162.

Van Werkhoven, K., Wagener, T., Reed, P. and Tang, Y. 2008. Characterization of watershed model behavior across a hydroclimatic gradient. *Water Resources Research*, 44, doi:10.1029/2007WR006271.

Van Werkhoven, K., Wagener, T., Tang, Y., and Reed, P. 2008. Complexity reduction in multiobjective watershed model calibration. *Advances in Water Resources*, (In Review).

Wagener, T., Reed, P., Van Werkhoven, K., Tang, Y. and Zhang, Z. Advances in the identification and evaluation of complex environmental system models. *Journal of Hydroinformatics*, Invited Paper. (In Review)

Yadav, M., T. Wagener, and H.V. Gupta, 2007. Regionalization Of Constraints On Expected Watershed Response Behavior For Improved Predictions In Ungauged Basins, *Advances in Water Resources*, *Advances in Water Resources*, 30(8) pp. 1756-1774, doi:10.1016/j.advwatres.2007.01.005

Yilmaz, K. K., H.V. Gupta, and T. Wagener, A Process-Based Diagnostic Approach to Model Evaluation: Application to the NWS Distributed Hydrologic Model, *Water Resources Research*, In press 2008a.

Yilmaz, K., Gupta, H.V. and T. Wagener, Evaluating the A Priori Parameters of the HL-DHM Model using a Multi-criteria Penalty Function Approach, *Advances in Water Resources*, in review 2008b.

Zhang, Z., Wagener, T., Reed, P. and Bhushan, R. 2008. Ensemble streamflow predictions in ungauged basins combining regionalized streamflow indices and multiobjective optimization. *Water Resources Research*. (In Press)

5.3. Book Chapters (2)

Wagener, T., T.S. Hogue, J. Schaake, Q. Duan, H.V. Gupta, V. Andressian, A. Hall & G. Leavesley, The Model Parameter Estimation Experiment (MOPEX): Its Structure, Connection to Other International Initiatives, and Future Directions, in V. Andréassian, N. Chahinian, A. Hall, C. Perrin & J. Schaake (Editors), Large Sample Basin Experiments for Hydrological Model Parameterisation: Results of the MOdel Parameter Experiment (MOPEX) Paris (2004) and Foz de Iguaçu (2005) workshops, IAHS Publication 307, 339-346, 2006.

Yadav, M., T. Wagener, and H.V. Gupta, Regionalization of Dynamic Watershed Response Behavior, in V. Andréassian, N. Chahinian, A. Hall, C. Perrin & J. Schaake (Editors), Large sample basin experiments for hydrological model parameterisation: Results of the MOdel Parameter Experiment (MOPEX) Paris (2004) and Foz de Iguaçu (2005) workshops, IAHS Redbook Publ. no. 307, 220-229, 2006.

5.4. Keynote Lectures and Invited Presentations (14)

Gupta, H.V., Reconciling Theory with Observations: Elements of a Diagnostic Approach to Model Evaluation, Presentation (Invited) at Imperial College, London, UK, Feb 7, 2008.

Gupta, H.V., Reconciling Theory with Observations: Elements of a Diagnostic Approach to Model Evaluation, Presentation (Invited) at Department of Hydrology and Water resources, The University of Arizona, Apr 2, 2008.

Gupta, H.V., Reconciling Theory with Observations: Elements of a Diagnostic Approach to Model Evaluation, Presentation (Invited) at Penn State University, State College, Pennsylvania, Feb 14, 2007.

Gupta., H.V., Reconciling Theory with Observations: Elements of a Diagnostic Approach to Model Evaluation, Presentation (Invited), University of Nevada, Reno, Nevada, Mar 30, 2007.

Gupta., H.V., and Y. Liu, Reconciling Theory with Observations: Towards a Diagnostic Approach to Model Evaluation, Keynote Presentation at PUB USA Meeting, Corvallis, OR, Oct 16-19, 2006.

Gupta, H.V., Wagener, T., Yilmaz, K. and Yadav, M. Improved Distributed Watershed Modeling in Gauged and Ungauged Basins using the HL-RMS System, National Weather Service - Hydrology Laboratory, Washington D.C., USA. Feb 2006

Wagener, T. 2008. Catchment similarity and its utility for scientific investigation and operational predictions. UNESCO Workshop on Comparative analysis of floods and droughts - Catchment and aquifer typology, 20-23rd April 2008, Smolenice near Bratislava, Slovakia. (Invited Talk)

Wagener, T., Sivapalan, M., Troch, P. and Woods, R. 2008. Searching for a catchment classification system for hydrology. 2008 Assembly of the European Geosciences Union (EGU), 13-18th April 2008, Vienna, Austria. (Invited Talk)

Wagener, T., Reed, P., Werkhoven, K. van and Tang, Y. 2007. Identification and evaluation of complex environmental systems models using global sensitivity analysis and evolutionary multiobjective optimization. International Workshop on Advances in Hydroinformatics (HIW07), Niagara Falls, Canada, June 4-7th 2007. (Invited Keynote)

Wagener, T. 2006. Catchment classification and hydrologic similarity. Hydroecological Landscapes and Processes (HELP) Workshop – "Expert Workshop on Watershed Characterization Schemes for Canadian Forests", 9-11th November 2006, The University of Western Ontario, London, Ontario, CA. (Invited Plenary Speaker)

Wagener, T. 2006. Towards an uncertainty framework for PUB. USA PUB Workshop, 16-19th October 2006, Oregon State University, Corvallis, Oregon, USA. (Invited Talk)

Wagener, T., Yadav, M., and Gupta, H.V. Hydrologic ensemble predictions in ungaged basins. Invited Talk at the 2nd International Symposium on Quantitative Precipitation Forecasting and Hydrology, 4th-8th June, 2006, Boulder, CO. 2006.

Wagener, T., Yadav, M. and Gupta, H.V., Hydrologic ensemble predictions in ungauged basins. 2nd International Symposium on Quantitative Precipitation Forecasting and Hydrology, Boulder, CO, 4-8 June, 2006.

Yilmaz, K., Wagener, T. and Gupta, H.V., Integrated Strategy for Identification of Distributed Watershed Models using the HL-DHM System, National Weather Service - Hydrology Laboratory, Washington D.C., USA. Feb 2005.

5.5. Presentations (36)

Gupta, H.V., T. Wagener, K. Yilmaz, P. Pokhrel, H. Kling, Parameterization And Parameter Estimation Of Distributed Models For Flash Flood And River Prediction. Presentation at the NWS Office of Hydrology, Feb 28, 2008.

Kling, H., K. Yilmaz and H.V. Gupta, Diagnostic Evaluation of a Distributed Precipitation-Runoff Model for Snow Dominated Basins, presented at the American Geophysical Union: Joint Assembly, 27th to 30th May 2008, Fort Lauderdale, FL, USA, 2008.

Kling, H., and H. V. Gupta, Relationship between spatial discretization and the parameters and model performance of precipitation-runoff and water balance models, Presented at the Fall Meeting of the American Geophysical Union, H18: Parameter Estimation in Hydrology: Theoretical Developments and Applications, San Francisco, CA, USA, Dec 10-17, 2007.

Pokhrel, P., H.V. Gupta, H.V., and Wagener, T., Distributed Parameter Estimation Using a Regularization Approach, presented at El Dia Del Agua, Department of Hydrology & Water Resources, The University of Arizona, Tucson, Arizona, Mar 6, 2008.

Pokhrel, P., and H.V. Gupta, Estimation of Spatially Distributed Model Parameters Using a Regularization Approach, presented at El Dia Del Agua, Department of Hydrology & Water Resources, The University of Arizona, Tucson, Arizona, Mar 1 (oral), 2007.

Pokhrel, P., and H. V. Gupta and T. Wagener, Distributed Parameter Estimation Using a Regularization Approach, Presented at the Fall Meeting of the American Geophysical Union, H18: Parameter Estimation in Hydrology: Theoretical Developments and Applications, San Francisco, CA, USA, Dec 10-17, 2007.

Pokhrel, P., and H.V. Gupta, Estimation of Spatially Distributed Model Parameters Using a Regularization Approach, Presented at the Fall Meeting of the American Geophysical Union, Session H45 on Optimization and Sensitivity Analysis for Parameter Estimation, Forecasting and Management with Complex Models, San Francisco, CA, USA, Dec 11-15, 2006.

Pokhrel, P., and H.V. Gupta, Distributed Parameter Estimation for Flash Flood and River Prediction, poster presented at El Dia Del Agua, Department of Hydrology & Water Resources, The University of Arizona, Tucson, Arizona, March, 2006.

Reed, P.M., Tang, Y., *Van Werkhoven, K. and Wagener, T. 2007. Using global sensitivity analysis to better understand how real-time observations influence operational flood forecasts in the Susquehanna River Basin. Association of Environmental Engineering and Science Professors, Blacksburg, Virginia July 2007.

Rosero, E., Gulden, L.E., Yang, Z.-L., Gochis, D.J., Wagener, T. and Niu, G.-Y. 2008. Identifying a good LSM: Use of a new, ensemble-based framework to evaluate enhanced hydrological representations in the NOAH land surface model. AGU Joint Assembly, 27-30th May 2008, Fort Lauderdale, Florida, USA.

Tang, Y., Reed, P., *Van Werkhoven, K. and Wagener, T. 2008. Comparison of parameter sensitivity analysis methods for lumped watershed models. World

Environmental & Water Resources Congress - American Society of Civil Engineers EWRI Section, 12-16th May 2008, Hawaii, USA.

Van Werkhoven, K. and Wagener, T. 2008. Reducing uncertainty in hydrologic predictions in data sparse regions: A case study in southern Africa. 88th American Meteorological Society Annual Meeting, 20-24th January 2008, New Orleans, USA.

Van Werkhoeven, K., Wagener, T., Reed, P. and Tang, Y. 2007. Sensitivity analysis of a distributed hydrologic model for uncertainty reduction and identification of dominant model controls. 14th IUGG General Assembly, Perugia, Italy, 2-13th July 2007.

Van Werkhoven, K., Wagener, T., Reed, P. and Tang, Y. 2007. Characterization of watershed model behavior and sensitivity-guided parameter optimization across a hydroclimatic gradient. AGU Fall Meeting, 10-14th December 2007, San Francisco, USA.

Van Werkhoven, K. and Wagener, T. 2007. Reducing uncertainty in hydrologic predictions for ungauged basins in southern Africa. American Water Resources Association, Albuquerque, New Mexico, USA, 12-15th November 2007.

Van Werkhoeven, K., Wagener, T., Reed, P. and Tang, Y. 2007. Sensitivity analysis of a distributed hydrologic model for uncertainty reduction and identification of dominant model controls. SAHRA 7th Annual Meeting, 10-12th October 2007, Tucson, AZ.

Wagener, T., Gupta, H.V., Yilmaz, K., and Yadav, M. Evaluation of Hydrologic Models in Ungauged Basins using Regionalized Watershed Response Characteristics. Presented at session HW2004: Towards Improved Evaluation of Hydrological Models: The Need to Understand and Characterize Uncertainties in the Modelling Process, 4th IUGG General Assembly, Perugia, Italy, 2-13 July 2007.

Wagener, T., R. Bhushan, P. Reed, H. V. Gupta, M. Yadav, and Z. Zhang, A new approach to the calibration of complex watershed models in ungauged basins using regionalized hydrologic indices. Presented at the Fall Meeting of the American Geophysical Union, H18: Parameter Estimation in Hydrology: Theoretical Developments and Applications, San Francisco, CA, USA, Dec 10-17, 2007.

Yadav, M., Wagener, T. and Gupta, H.V., Watershed Classification based on hydrologic response behavior, AGU Fall Meeting, San Francisco, USA, (Poster), December 2005.

Yadav, M., Wagener, T. and Gupta, H.V., Regionalization of dynamic watershed response behavior, SAHRA Annual Meeting, Tucson, USA, (Poster), October 2005.

Yadav. M, T. Wagener, and H.V. Gupta, Regionalization of Constraints on Hydrologic Response Behavior, Session H20 on Surface Water Hydrology & Water Resources Posters. Presented at the Spring Meeting of the American Geophysical Union, Baltimore, MD, USA, May 23-27, 2006.

Yadav, M, Wagener, T. and Gupta, H.V., Regionalization of dynamic watershed response behavior. *Eos Trans. AGU, 87*(36), Jt. Assem. Suppl., Abstract H23D-15. (Poster) 2006.

Yilmaz, K.K., Gupta, H.V., Wagener, T., 2008: Evaluating the utility of satellite-based precipitation estimates for flood forecasting in ungauged basins, Poster presented at Seventh Annual AMS Student Conference, 19-20 January, New Orleans, LA, 2008

Yilmaz, K.K., Gupta, H.V., Wagener, T., A Signature Index Approach To Diagnostic Evaluation And Parameter Estimation Of Watershed Models, presentation at HydroPredict 2008 conference, Prague, Czech Republic, Sept 15-18, 2008.

Yilmaz, K.K., and H.V. Gupta, Towards Improved Hydrologic Predictions in Ungaged / Poorly Gauged Basins, Departments of Geological Engineering & Civil Engineering, Middle East Technical University, Ankara, Turkey, June 29, 2007.

Yilmaz, K.K., H.V. Gupta, and T. Wagener, Diagnostic Evaluation of a Distributed Watershed Model: A Process-based Approach, Presented at session HW2005: From Measurements and Calibration to Understanding and Predictions, 4th IUGG General Assembly, Perugia, Italy, 2-13 July 2007.

Yilmaz, K.K., H.V. Gupta, and T. Wagener, A signature index approach to diagnostic evaluation and parameter estimation of watershed models, Poster Presented at the Fall Meeting of the American Geophysical Union, H18: Parameter Estimation in Hydrology: Theoretical Developments and Applications, San Francisco, CA, USA, Dec 10-17, 2007.

Yilmaz, K., H.V. Gupta and T. Wagener, Diagnostic Evaluation of a Distributed Watershed Modeling Approach, Session H45 on Optimization and Sensitivity Analysis for Parameter Estimation, Forecasting and Management with Complex Models, Presented at the Fall Meeting of the American Geophysical Union, Baltimore, MD, USA, May 23-27, 2006. San Francisco, CA, USA, Dec 11-15, 2006.

Yilmaz, K., H.V. Gupta and T. Wagener, Diagnostic Evaluation of a Distributed Watershed Modeling Approach, Presented at the PUB USA Meeting, Corvallis, OR, USA,. San Francisco, CA, USA, Oct 16-19, 2006.

Yilmaz, K., H.V. Gupta and T. Wagener, Diagnostic Evaluation of a Distributed Watershed Modeling Approach, Presented at the SAHRA Annual Meeting, Scottsdale, AZ, USA, Oct 11-13, 2006.

Yilmaz, K., H.V. Gupta and T. Wagener, Estimating Parameters of a Distributed Hydrologic Model using Catchment Characteristics and Input-Output Data, Session H20 on Surface Water Hydrology & Water Resources Posters. Presented at the Spring Meeting of the American Geophysical Union, Baltimore, MD, USA, May 23-27, 2006.

Yilmaz, K., H.V. Gupta and T. Wagener, Constraining Parameters of a Distributed Hydrologic Model Using Both Apriori Information and Optimization, presented at El Dia Del Agua, Department of Hydrology & Water Resources, The University of Arizona, Tucson, Arizona, March, 2006.

Yilmaz, K., H.V. Gupta and T. Wagener, Estimating Parameters of a Distributed Hydrologic Model using Catchment Characteristics and Input-Output Data, Session H20 on Surface Water Hydrology & Water Resources Posters. Presented at the Spring Meeting of the American Geophysical Union, Baltimore, MD, USA, May 23-27, 2006.

Yilmaz, K., & H.V. Gupta and T. Wagener, Constraining Parameters of a Distributed Hydrologic Model Using Both Apriori Information and Optimization, Session H47 on the Calibration and Uncertainty Estimation of Spatially Distributed Hydrologic Models, Presented at the Fall Meeting of the American Geophysical Union, San Francisco, CA, USA, December 5-9, 2005.

Yilmaz, K., H.V. Gupta, T. Wagener, Incorporating A-priori Information to Constrain Parameters of a Distributed Hydrologic Model, NSF-STC SAHRA Annual Meeting, Tucson, AZ, (Poster Presentation), 26-28 October 2005

Yilmaz, K.K., Jongyoun, K., Wagener, T., Hogue, T., and H.V. Gupta (2004), "Modeling ungauged basins with the Sacramento Model", presentation made at 4th International MOPEX Workshop, Paris, France.