NWS Hydrologic Model Calibration Research and Development

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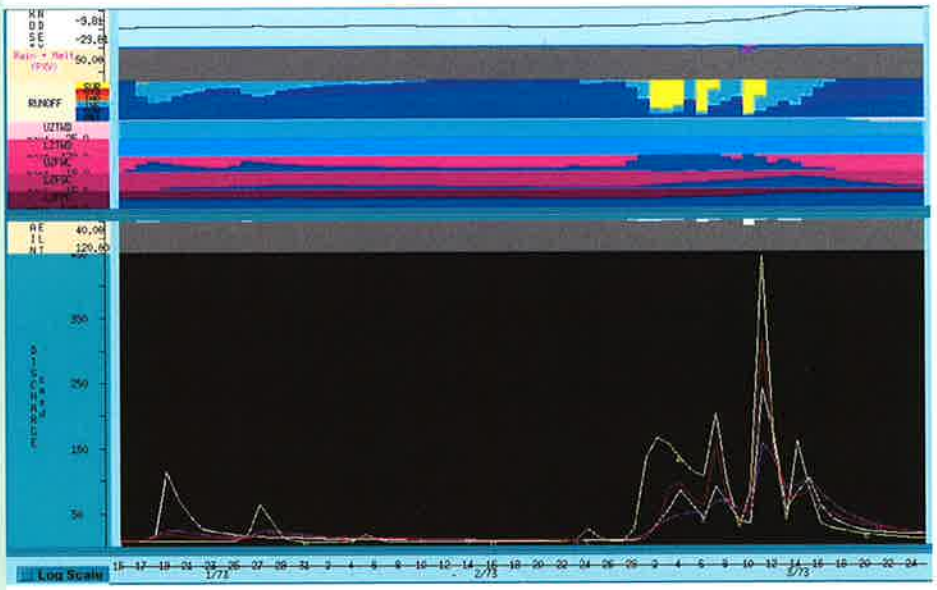

ICP display of simulations from the physically-based frozen ground model

Executive Summary

The National Weather Service Hydrology Laboratory (NWS HL) has a rich history of hydrologic model calibration research. This research program combined extensive in-house efforts with the pioneering work of the University of Arizona. NWS efforts in the calibration arena are well known as evidenced by the recent monogram 'Calibration of Watershed Models' edited by HL employee Qingyun Duan and others.

HL calibration research has led to numerous tools, applications and guidelines. On a regular basis, HL leads calibration workshops for personnel from the River Forecast Centers (RFCs). These are often attended by scientists and students from the University of Arizona, resulting in a fruitful two-way transfer of knowledge and expertise. Examples of this transfer include the development of the Mult-step Automatic Calibration Scheme (MACS) developed by the University of Arizona that uses automatic optimization in three phases to mimic the manual calibration process. Other noteworthy accomplishments are the production of a video series on calibration of the Sacramento Soil Moisture Accounting Model (SAC-SMA), the main rainfall-runoff model used for NWS river forecasting. This video series, created through a collaboration between HL and Konstantine Georgakakos of the Hydrologic Research Center, has been delivered to and used extensively at the RFCs. In addition, this video series has been used internationally in countries that have adopted the NWS River Forecast System (NWSRFS). A significant advance has been the publication of a 340 page manual on all phases of model calibration, from data preparation to implementation of calibration results for operational forecasting.

We believe that manual, guided trial-and-error procedures have a prominent place in the calibration process. However, we are actively engaged in research into automatic methods including single and multi-objective optimization techniques. An active area of work is the development of a local search procedure called Step-wise Line Search (SLS). The use of this procedure and a priori estimates of SAC-SMA parameters results in parameters that are as good as those derived from the well-known global search Shuffled Complex Evolution procedure (SCE). The benefit of the SLS-based procedure is that it requires only a fraction of the number of function evaluations that SCE needs. Thus, this procedure has promise not only for lumped modeling but also for distributed modeling where the number of computational cells would render a procedure like SCE computationally infeasible.

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1. Introduction

Figure 1 shows the domain of each of the 13 River Forecast Centers (RFCs) of the NWS. Within these areas, the NWS generates daily river forecasts at over 4,000 points. Much finer resolution forecasts are provided as required by specific conditions. To provide accurate forecasts, the models that produce these forecasts must be calibrated. The scale of the NWS hydrologic forecasting mission has immense implications for the process of model calibration Gupta et al. (2003). To meet the demands of calibrating nationally-implemented hydrologic models, a comprehensive calibration system has been developed. As shown in Figure 2, the Calibration System (CS) is a major component of the NWSRFS. It contains procedures for data analysis and parameter calibration using manual trial-and-error or automatic calibration methods (Smith et al., 2003).

2. Purpose and scope.

The purpose of this document is to provide an overview of the research and development of hydrologic model calibration, including parameter estimation. Such models as the NWS operational snow model (Snow-17), the Sacramento Soil Moisture Accounting model (SAC-SMA), and hydrologic routing components are included here. Also, this document overlaps the calibration of kinematic wave channel routing parameters for distributed modeling. However, this document does not cover the calibration of NWS dynamic wave channel routing models.

While past efforts regarding hydrologic model calibration will be discussed, the emphasis of this document is on current and future activities and strategies.

3. Relevant web sites

The reader is directed toward items on the following web page for additional information.

http://www.nws.noaa.gov/oh/hrl/calb/calbmain.htm

4. R&D strategy

Figure 3 presents the strategy for hydrologic model calibration R&D. As with other areas of research, HL places high value on a combination of internal and extramural research. Indeed, a long collaborative research relationship between HL and the University of Arizona has resulted in a successful two-way exchange of knowledge and experience. On the one hand, the University of Arizona developed the SCE method (Duan et al., 1993), and then the developer himself was employed in HL for 12 years. SCE is perhaps the most widely used of the automatic optimization procedures available in the NWSRFS Calibration System. On the other hand, understanding of the NWS manual calibration procedures led to the development of the Multi-step Automatic Calibration Scheme (MACS) (Hogue et al., 2003). Significant internal efforts have been aimed at

the development of manual and automatic calibration procedures and tools. Moreover, HL scientists devote considerable time to developing calibration techniques for any new models.

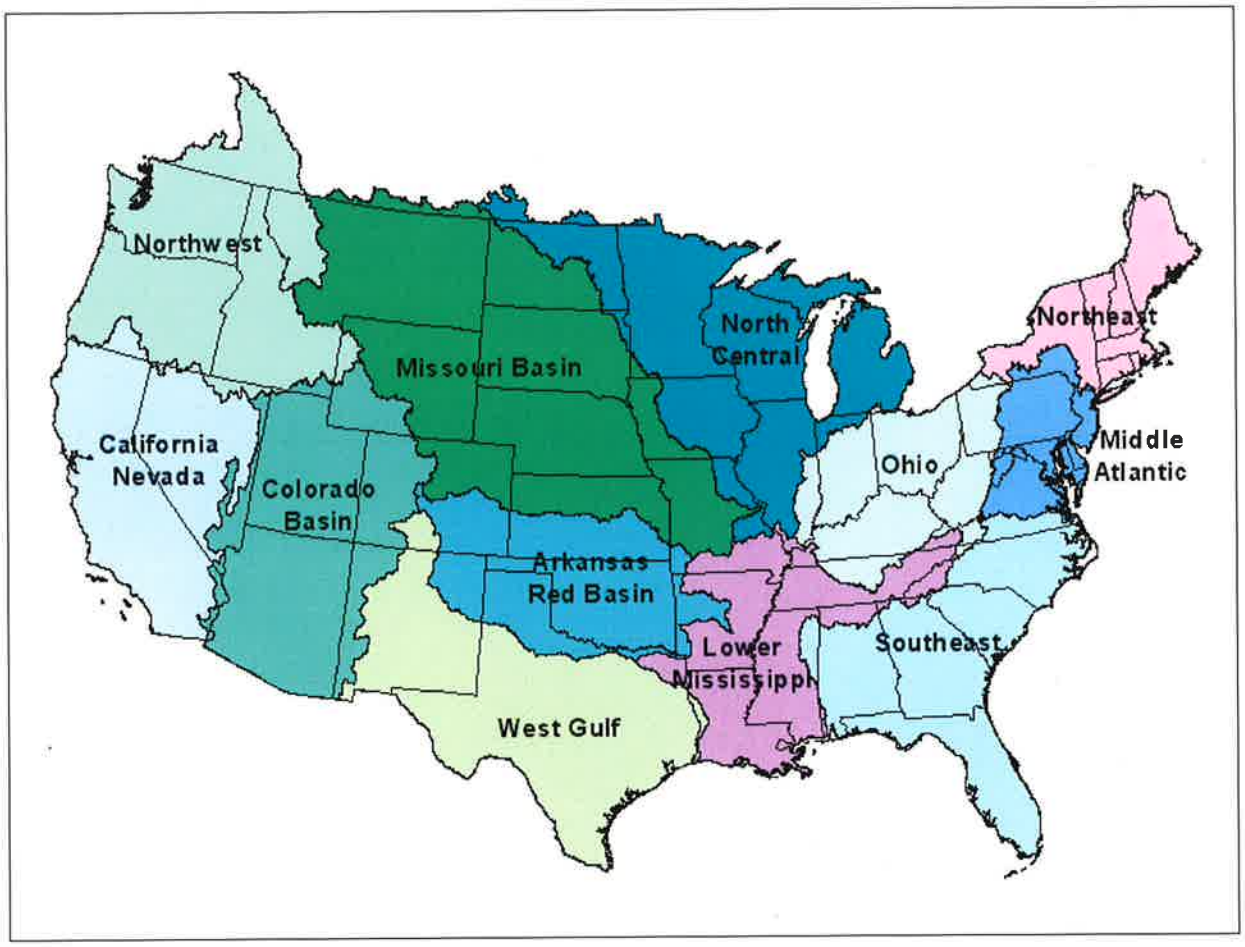

Figure 1. Boundaries of NWS River Forecast Center domains (Alaska Pacific RFC not shown)

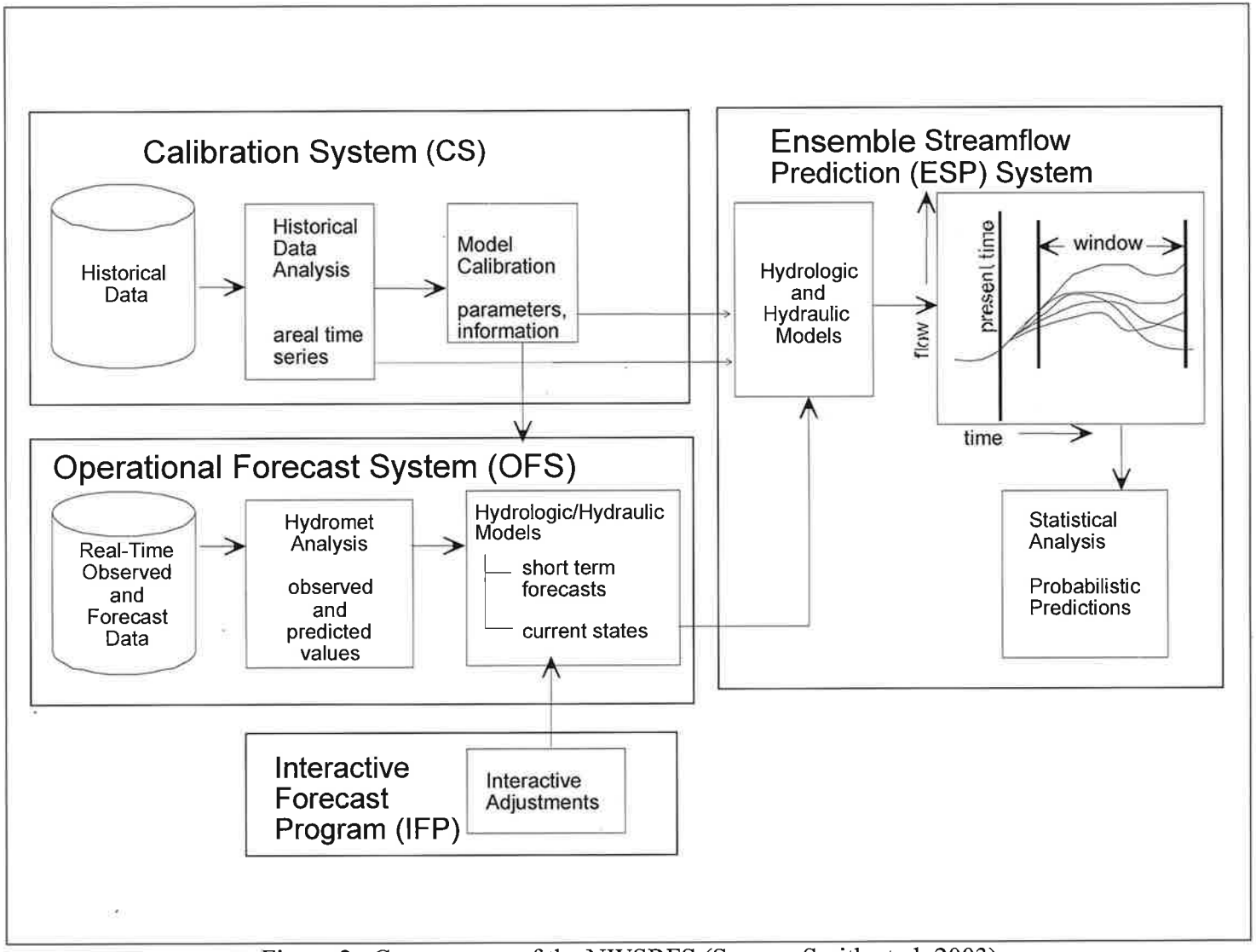

Figure 2. Components of the NWSRFS (Source: Smith et al. 2003)

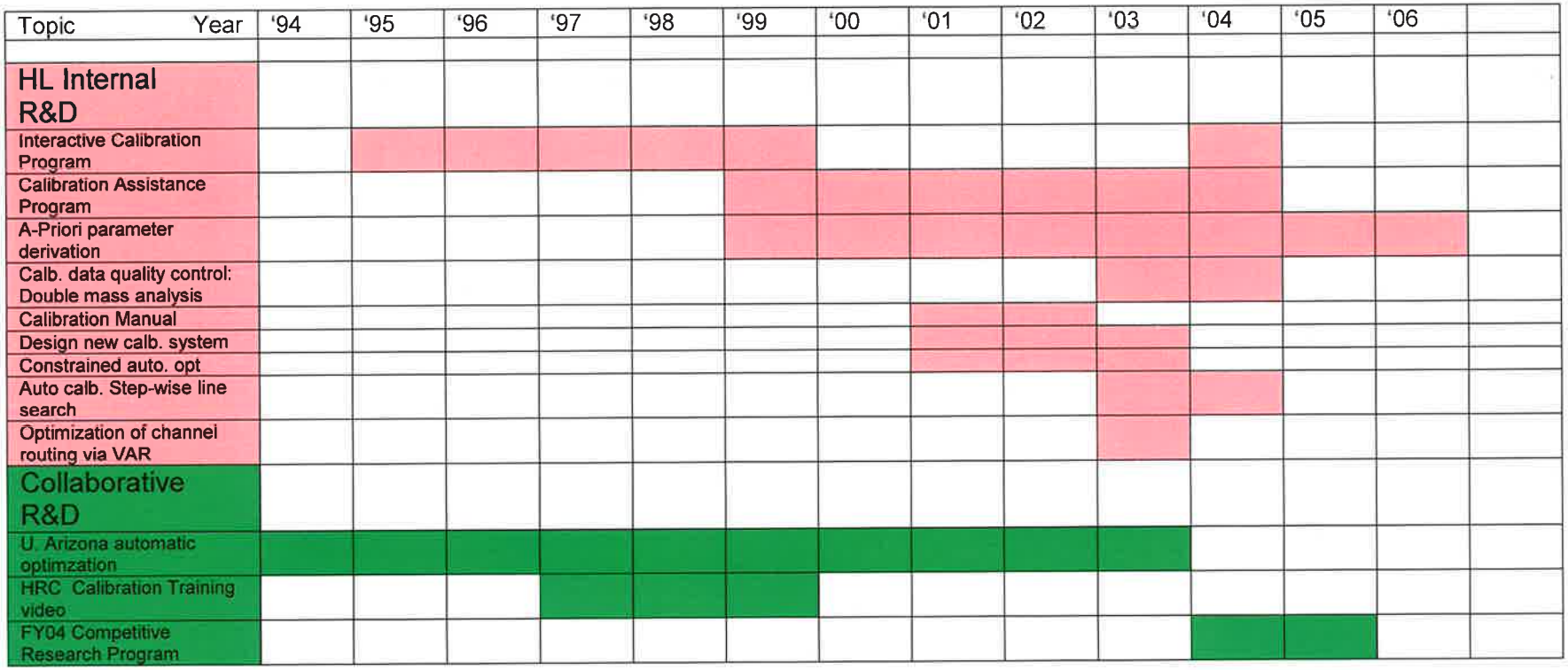

Figure 3. Major plan elements for hydrologic model calibration research and development

5. HL Internal Research and Development

Manual-Expert Calibration

Gupta et al. (2003) provide an excellent overview of the history of automatic calibration procedures. Moreover, they also clearly discuss their deficiencies, stating that:

'.... research conducted during the past two and a half decades has revealed that the traditional automatic calibration methods suffer from a number of serious conceptual and practical weaknesses'.

Indeed, Schaake (2003) states the widely recognized fact that automatic calibration using a single objective function (as in most available automatic calibration schemes) does not adequately measure the ways in which a model fails to fit the real data. In light of these current deficiencies, we maintain that manual trial-and-error (hereafter called Manual-Expert calibration after Gupta et al. (2003)) approaches embody the preferred strategy for model calibration in the NWS. Moreover, many RFCs advocate for Manual-Expert calibration, believing that this process is a very beneficial experience in the development of a hydrologic forecaster (Smith et al., 2003).

To support Manual-Expert calibration, HL has developed a number of visualization tools. A major advance in manual calibration was the development of the Interactive Calibration Program (ICP) in the mid 1990's shown in Figure 4. Smith et al. (2003) present an overview of the capabilities of ICP. ICP is extremely powerful, able to display multiple time series of input forcings, model states, and output values. Various analysis tools are also in ICP to aid the calibration process. ICP is also heavily used in many other areas of HL research and development: snow, frozen ground, and distributed modeling. Indeed, ICP was the main tool to display simulations at the August, 2002 meeting of the participants of the international Distributed Model Intercomparison Project (DMIP) (Smith et al., 2004).

Unfortunately, ICP development has largely stagnated as a result of the untimely death of the main developer in 1999. After this, ICP enhancements have been identified (Anderson, 2003; http://www.nws.noaa.gov/oh/hrl/calb/ICP_Recom/index.htm) but have never received a high enough priority in the HL work queue to be implemented. A very modest effort has been started in FY04 to define the functional requirements of ICP in order to perform a re-software engineering of the entire code. Depending on the availability of funding, the re-engineering process will be initiated so that ICP is updated.

Calibration Assistance Program

The HL-developed Calibration Assistance Program (CAP) (see Reed, 2002; and http://www.nws.noaa.gov/oh/hrl/calb/esrihtmlfinal/p1082.htm) contains data sets and tools that are primarily used for the analysis of mountainous areas. CAP is a *national* ArcView GIS-based suite of tools that facilitates the derivation of basin sub-divisions, model parameters, potential evaporation estimates, and mean areal estimates of precipitation and temperature. Moreover, CAP also contains satellite snow cover maps that can be used in conjunction with observed streamflow hydrographs and area elevation curves to identify different regimes that

occur over the watershed. CAP also contains national vegetation maps to help identify such regimes. Appendix 3 provides more details about the functions available in CAP.

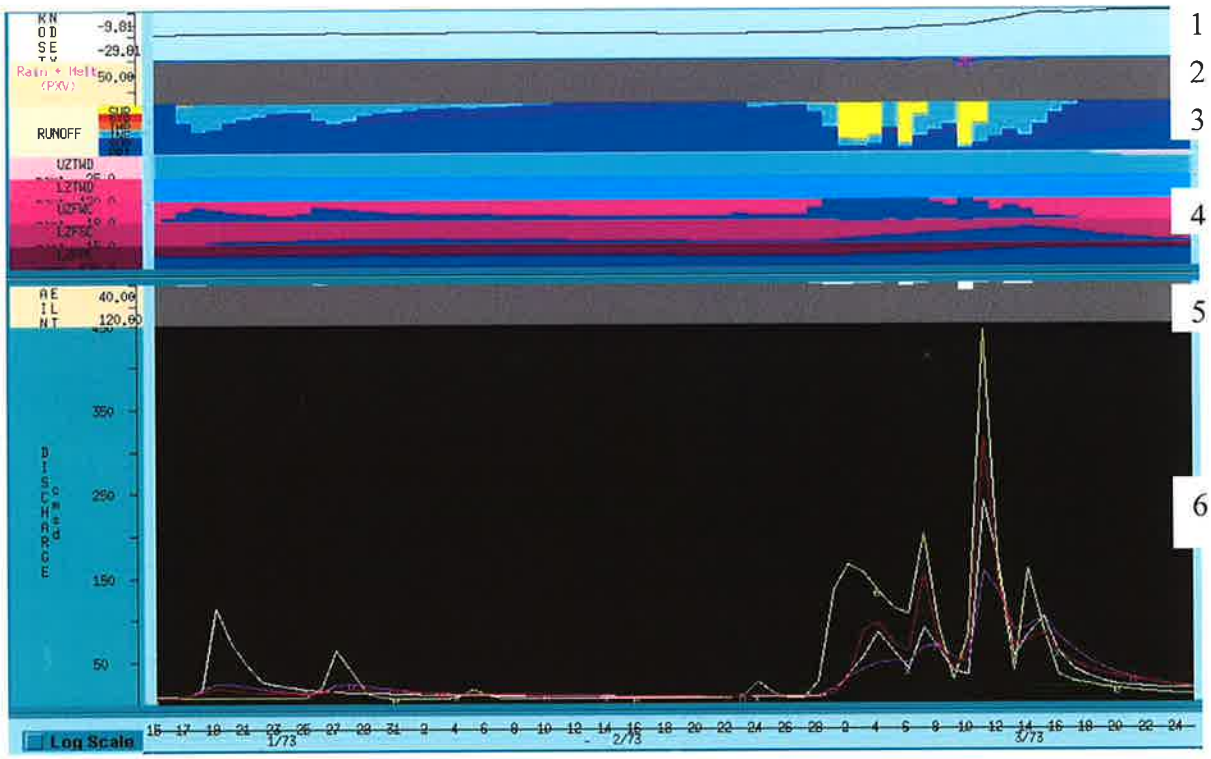

Figure 4. Main ICP display. Pane 1 shows the computed frost index for frozen ground computations. Pane 2 shows the rain and snow melt timeseries. Pane 3 displays the runoff components generated by the SAC-SMA model. Pane 4 shows the states of the 5 main storage reservoirs. Pane 5 shows the incoming rain-plus-snowmelt each time step. Pane 6 shows hydrograph plots for the period from January, 1973 to March, 1973.

Derivation of A Priori Hydrologic Model Parameters

We believe that research into the derivation of a priori estimates of parameters for hydrologic models is an integral part of the calibration process. Meaningful initial estimates of model parameters simplify the Manual-Expert calibration process. Traditionally, hydrograph analysis techniques have been used to derive initial estimates of some model parameters. Pioneering research by Koren et al. (2000) resulted in promising estimates of all the parameters for the Sacramento Soil Moisture Accounting model (SAC-SMA). This method used the state-wide coarse resolution soils information (STATSGO) available from the National Resources Conservation Service (NRCS). The parameters of Koren et al. (2000) have been made available to all the RFCs via the CAP. Duan et al. (2001) used these parameters for land surface models. Recent work by Anderson et al. (2003) investigates the utility of NRCS fine-scale county level soils data (SSURGO) in the derivation of SAC-SMA parameters. This research should tell us whether fine-scale soils information is needed or not. Complimenting the work with the SAC-SMA model parameters, Moreda et al. (2003) developed procedures to derive a priori estimates of parameters for a continuous antecedent precipitation index model (API) being used in a distributed format.

Significant effort has been directed at the derivation and calibration of channel routing parameters for the kinematic wave component of the distributed model developed by HL (Reed et al., 2002; see also PowerPoint file: AGU_spring_2002_Reed). The premise of this research is that basin-outlet channel geometry information and outlet discharge measurements can be combined with stream channel morphological relationships to estimate routing parameters at grid cell locations in the basin.

Quality Control of Calibration Data: Consistency Corrections

Smith et al. (2003) outline the reasons for quality control of the data used for model calibration. As shown in Figure 3, we are analyzing the effects of performing and not performing one of the recommended quality control procedures called double mass analysis of data consistency (Linsley et al., 1982; see page 70). This study should help us determine the sensitivity of hydrologic simulations and forecasts to errors in calibration data.

Calibration Manual

While not strictly a research effort, a major accomplishment in 2002 was the development and publication of a comprehensive manual covering all phases of model calibration. (Anderson, 2002). (see http://www.nws.noaa.gov/oh/hrl/calb/calibration1102/main.htm. Topics covered in this 350 page compendium range from analysis of historical data to the incorporation of calibration results into the NWS operational system. Also discussed is the very important yet often neglected concept of examining and maintaining consistency between the historical data used for model calibration and the real-time observed data used for operational forecasting. Such analyses are critical in that studies have shown that a bias of as little as 3°F can have major effects on the timing of the onset of snowmelt (Anderson, 2002). This manual has been made available online and was also delivered to the University of Arizona.

Design of Enhanced Calibration System

As shown in Figure 2, the Calibration System represents about one-third of the functionality of the entire NWSRFS. It was designed to provide a seamless progression from model calibration to use of the model for operational forecasting. In addition, it was designed as an R&D environment for new NWSRFS models and components. In spite of its overall importance, very few enhancements have been made to the Calibration System. The preeminent need according to Smith et al. (2003) is to more efficiently link the functions performed by the various disparate programs in the Calibration System. To this end, a list of functional requirements has been prepared (Anderson, 2003b) (document available online at http://www.nws.noaa.gov/oh/hrl/calb/EnhancedCalb/index.htm). However, as with ICP, the effort to enhance the Calibration System has never achieved high enough priority to have resources directed to this task.

Automatic Calibration

As stated earlier, HL is actively engaged in automatic optimization research. Recent efforts have focused on two areas. First, a procedure has been developed to utilize a priori estimates of the SAC-SMA model to constrain the automatic optimization process when calibrating a number of neighboring basins (Koren et al., 2003). The idea here is that the a priori estimates can be used to guide the optimization process so that the final model parameters have a logical spatial consistency. This work is continuing in the sense that research into a priori estimates of model parameters is ongoing as discussed above.

HL and the NWS field offices have used SCE since its development. Recently, research was initiated to develop a new procedure to search the error surface for minima (Kuzmin et al. 2004; see also file: Kuzmin_presentation_04.ppt). This procedure is called the Step-wise Line Search (SLS) method. The premise of this effort is that given reasonable estimates of the initial parameters of a model, a global search procedure is not needed. Rather, it is sufficient to have a local search procedure. Research to date has shown the SLS method used with the a priori parameters of Koren et al. (2002) achieves parameters that are equivalent to those derived using the SCE approach. However, the SLS method requires only a small fraction of the number of function evaluations required by SCE. Given this success, we see the greatest utility of the SLS approach being the calibration of a distributed model. The use of a global search algorithm such as SCE for distributed modeling applications is computationally infeasible.

As part of this work, HL is investigating new objective functions for use with automatic optimization. A multi-scale objective function evaluating monthly, weekly, daily, and hourly flow errors is being tested. Results to date indicate that a smoother objective function surface is produced.

6. Collaborative Research and Development

As shown in Figure 3, HL has a long and productive history of collaboration with leading institutions. For many years, HL has supported automatic optimization research at the University of Arizona. A significant two-way exchange of knowledge has occurred during this period. HL

adopted the SCE algorithm and even employed its developer for over 12 years. On the other hand, the MACs procedure discussed earlier was developed in part from U. of Arizona's participation in HL's calibration training workshops conducted at RFCs. Further evidence of this transfer can be seen in the references to HL Manual-Expert calibration techniques in several peer-reviewed papers authored by U. of Arizona scientists (e.g., Gupta et al., 2003; Boyle et al., 2000). HL has also supported the research into the calibration of semi-distributed models (e.g., Boyle et al., 2001; Khodatalab et al., 2004).

A practical yet significant achievement was the development of a calibration training video through a collaboration between the Hydrologic Research Center (HRC, 1999) and HL. This effort was sponsored and funded by the World Meteorological Organization (WMO). This video series covers in great depth the calibration of the SAC-SMA model, which is the primary rainfall-runoff model used at NWS RFCs. This video series has been delivered to all NWS RFC offices and has been used in many institutions internationally.

7. Tools, procedures, and guidelines delivered to RFCs.

HL's combined internal and collaborative R&D efforts have resulted in significant and practical tools, procedures and guidelines delivered to the RFCs. Table 1 presents the major items that have been delivered.

Table 1. Summary of major tools, procedures, and guidelines delivered to NWS RFCs.

Name	Description	Status
Interactive Calibration Program (ICP)	Powerful GUI with many display and analysis features	Enhancements designed, held up by low priority
Calibration Training Video	4-part video series on calibration of SAC-SMA model.	Delivered to all RFCs; distributed internationally
Calibration Assistance Program (CAP)	ArcView-based system providing numerous	Available at all 13 River Forecast Centers
MACS procedure	Multi-step automatic calibration Scheme by U. Arizona	Presented at calibration workshops. Part of collaborative work between CBRFC and U. AZ
Interactive Double Mass Analysis Technique (IDMA)	GUI tool for quality control of calibration data.	Delivered to all RFCs and officially supported.
Calibration Training Manual	350-page comprehensive guide to all phases of model calibration	Available on line; delivered to all RFCs and U. of Arizona.

8. Recommendations

Given the scope of the NWS forecasting mission and the subsequent immense implications for hydrologic model calibration as part of the AHPS initiative, we recommend that funding be allocated so that that the Calibration System (especially ICP) can be upgraded (Smith et al, 2003). More efficient links between the many disparate programs in the Calibration System are needed. This can be most effectively achieved through a re-design of the entire system. Such a re-designed system would also be easily enhanced as new procedures are developed.

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Koren, V.I., Smith, M., and Duan, Q.-Y, 2003. Use of a priori parameter estimates in the derivation of spatially consistent parameter sets of rainfall-runoff models. In: Duan, Q., Gupta, H.V., Sorooshian, S., Rousseau, A.N., Turcotte, R., (Editors.) Calibration of Watershed Models, Water Science and Application 6, American Geophysical Union, Wash. D.C., 239-254

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Smith, M.B., Laurine, D.P., Koren, V.I., Reed, S.M., and Zhang, Z., 2003. Hydrologic Model Calibration in the National Weather Service. In: Duan, Q., Gupta, H.V., Sorooshian, S., Rousseau, A.N., Turcotte, R., (Editors.) Calibration of Watershed Models, Water Science and Application 6, American Geophysical Union, Wash. D.C., 133-152.

Appendix 1

Papers and Publications from Hydrologic Model Calibration Research

Peer-Reviewed Papers in Scientific Journals (HL scientists in bold)

Duan, Q.-Y, 2003. Global optimization for watershed model calibration. In: Duan, Q., Gupta, H.V., Sorooshian, S., Rousseau, A.N., Turcotte, R., (Editors.) Calibration of Watershed Models, Water Science and Application 6, American Geophysical Union, Wash. D.C., 89-112.

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Kuzmin, V., Koren, V.I., and Seo, D.-J., 2004. Calibration of the Sacramento model: Stepwise line search. In preparation.

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Seo, D.-J, Koren, V., and Reed, S., 2003. Improving a priori estimates of hydraulic parameters in a distributed routing model via Variational assimilation of long-term streamflow data. Weather Radar Information and Distributed Hydrological Modeling, IAHS Publication no. 282., Eds.: Tachikawa et al., proceedings of Symposium HS03 held during the IUGG 2003, Sapporo, Japan, June 30-July 11, 109-113.

Smith, M.B., Laurine, D.P., Koren, V.I., Reed, S.M., and Zhang, Z., 2003. Hydrologic Model Calibration in the National Weather Service. In: Duan, Q., Gupta, H.V., Sorooshian, S., Rousseau, A.N., Turcotte, R., (Editors.) Calibration of Watershed Models, Water Science and Application 6, American Geophysical Union, Wash. D.C., 133-152.

Presentations at conferences

1. **Reed, S.M, King, S., Koren, V., Smith, M., Zhang, Z., and Wang, D**., 2001. Parameterization Assistance for NWS Hydrology Models Using ArcView. ESRI Users Conference.

Appendix 2

What will Speed Up the Calibration Process?

Mike Smith and Janice Sylvestre
August 27, 2003

A. Scope: Calibration of Hydrologic Models. Calibration of dynamic wave channel routing models is covered in another document.

B. Hydrologic Model Calibration

B.1. Upgraded Calibration System

Perhaps the most effective changes can be achieved by upgrading the Calibration System (Smith et al. 2003). As an example of the dramatic increases in process efficiency that can be realized, several years ago Heather Friedeman, JJ Pan, and Mike Smith developed the Interactive Double Mass Analysis (IDMA). This was a GUI tool that replaced the manually intensive graphical procedure for performing a data quality control procedure called >double mass analysis=. This procedure is a standard and widely accepted step in hydrologic data analysis and is performed on gage observations of rainfall, temperature, potential evaporation, and streamflow (Linsely et al. 1982). (It is analogous to the need for an MPE Re-analysis of the historical Nexrad radar products). After this tool was delivered to the field, Geoff Bonnin commented that one or more RFCs reported that this part of the quality control process for model calibration was reduced from >months to weeks=. While IDMA was somewhat of a crude combination of existing programs, it nonetheless provided dramatic improvements.

Eric Anderson has completed the definition of the Functional Requirements for an enhanced Calibration System. Such a system would more effectively tie together all the >legacy= programs and procedures that were developed on the NAS 9000 and simply ported to the HP workstations. New tools would also be added, such as the data mining tools developed at the University of Arizona and U. of California at Berkeley. The new system would combine the functions and data now present in:

Calibration Assistance Program (CAP)
Interactive Calibration Program (ICP)
Interactive Double Mass Analysis Program (IDMA)
Calibration programs MAP, MAT, PXPP, TAPLOT, MAPE, and MAPX
Archives of RFC data (critical for FloodWave Calibration)
New versions of Data (e.g., potentially John Schaake=s data)
Automatic calibration procedures.

As new models are developed, it is critical that a commensurate calibration system is developed for field implementation.

B.2. Continued Research

This item primarily addresses the need for continued long term research and development into automatic optimization methods for model parameter calibration. It is the opinion of Victor Koren, Eric Anderson, Mike Smith, and the University of Arizona that the current single objective optimization procedures developed to date cannot duplicate the quality of manual calibration (Schaake, 2003). However, there is great potential in multi-objective automatic optimization and its derivatives to provide efficiency in the calibration process while achieving the quality and spatial consistency achieved through manual calibration. This is a very active area of research, and the University of Arizona is perhaps the leader in this area. Also, Vadim Kuzmin is looking at the automatic calibration process from a new perspective. In addition, he is developing a procedure to evaluate the goodness of the parameters derived by automatic calibration (his so-called F-Robustness approach).

Research is also needed on the derivation of initial (*a priori*) values of model parameters, both for lumped and distributed models. Victor Koren pioneered the derivation of SAC-SMA parameters from NRCS course resolution soils information and delivered these to the RFCs via CAP. Experience with these parameters has shown the need for further work. Richard Anderson has adapted Victor=s theory to derive SAC-SMA parameters from high resolution NRCS soils information. In some cases simulation improvements have been seen compared to those derived from coarse resolution soils data.

B.3. RFC Implementation

Efficient model calibration is dependent on the RFC organization as well. Smith et al. (2003) described the well-organized approach at the NWRFC. Such well-organized approaches have led to the completion of model calibration at NWRFC, CBRFC, and CNRFC, with the additional benefit that forecasters are better trained (Don Laurine, personal communication). Mike Smith and Eric Anderson have advocated such organized approaches at every calibration workshop for the last 10 years. However, it is up to the individual RFC leadership to stress the importance of such an approach.

References

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Appendix 3

Calibration Assistance Program
Summary of Capabilities and Data Sets
http://www.nws.noaa.gov/oh/hrl/calb/esrihtmlfinal/p1082.htm

A. Capabilities

The CAP is an Arc/View application. Its capabilities include the following.

1. Derive area-elevation curves
2. Sub-divide basins based on elevation zones
3. Derive elevation-precipitation plots
4. Display defined zones on top of other data layers (e.g. precipitation, elevation)
5. Compute basin mean, max, and min values of: (may also compute for each elevation zone defined within a basin)
    - 5.1 precipitation (monthly, annual, and seasonal)
    - 5.2 potential evaporation (monthly, annual, and seasonal)
    - 5.3 potential evaporation adjustment factors
    - 5.4 percent forest
    - 5.5 percent of each forest type
    - 5.6 soil-based estimates for 11 SAC-SMA parameters
6. Display selected NOHRSC historical snow images from (1990-1995)

2. Data Sets

1. Digital Elevation Model (DEM) 4km resolution
2. Percent of forest cover on 1km grid
3. Forest type on 1km grid
4. PRISM annual and monthly precipitation grids.
5. Annual and monthly potential evaporation grids
6. Soil type, depth, and texture for 11 layers
7. Snow cover grids for 1990-1995
8. State boundaries
9. EPA River Reach Files (RF1)
10. SAC-SMA parameter grids (1km x 1km)