Distributed Hydrologic Modeling Operations Concept

Report of the Distributed Hydrologic Modeling Operations Concept Team

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National Oceanic and Atmospheric Administration
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1 Executive Summary

Distributed hydrologic models offer the potential to improve the accuracy of flow forecasts at current gauged river forecast points; enhance the existing Flash Flood Guidance by increasing its spatial resolution; provide additional methods of flash flood forecasting; provide information about flows on ungauged streams or river reaches that are susceptible to flooding; and provide high-resolution information applicable to water resources management, debris flow warning, surface-groundwater interactions and management, and water quality constituents such as temperature, turbidity, contaminant loading, etc.. Implementation of distributed hydrologic modeling for real-time, operational forecasting at National Weather Service (NWS) River Forecast Centers (RFCs) will require changes within existing RFC operations and product dissemination. Distributed hydrologic modeling will bring process changes not only for hydrologic forecasting, but also for procedures such as calibration, verification, and model research. In addition, distributed hydrologic modeling will require the development of new processes to allow offices to introduce new forecast products and services that are only possible through the use of these types of models.

To best understand the types of change in operations and the needed functionality to support distributed hydrologic modeling, this report describes the distributed hydrologic model operations concept developed to identify and describe functional requirements necessary for successful implementation. Within the identified high-level requirements, there is a minimum set of requirements essential for near-term baseline implementation, followed by requirements necessary for successful long-term development. These essential requirements for distributed model operations **must be** addressed first. It is recognized that many of these exist in some form or are currently being addressed. The remaining functional requirements are prioritized in three categories of high, medium, and low within ten basic functional groupings ranked by relative importance as determined for successful long-term implementation and use of operational distributed modeling. These priorities will assist in planning of continued research, development, and operational implementation. The highest ranked functional groupings contain requirements describing needed tools and utilities for data assimilation techniques, data display and analysis, and model calibration.

The functional requirements presented in this report must be integrated with the operational and functional requirements of current and proposed projects (e.g. Community Hydrologic Prediction System (CHPS), Experimental Ensemble Forecast System (XEFS), Data Assimilation, Verification) to facilitate near and long term planning and development for the full implementation of distributed hydrologic modeling at RFCs.

As required by the team charter, this report contains the suggested charter outlining the goals and objectives for the gap analysis project to follow on. In addition, the team recommends that all RFCs start an effort to promote the implementation and application of distributed hydrologic modeling throughout the NWS. This effort would produce a collection of RFC case studies using current distributed hydrologic modeling technology.

The vision for this initiative is to build expertise, interest, and applications for distributed hydrologic modeling in the RFCs now as distributed hydrologic modeling development continues.

2 Introduction and Overview

2.1 Background – What is Distributed Hydrologic Modeling?

Distributed hydrologic models subdivide a watershed into higher resolution distinct modeling elements. These modeling elements can be in the form of regular grids, flowplanes, triangulated irregular networks (TINs), hydrologic response units, or small sub-basins. These subdivisions make it possible to capture the spatial variability of terrain, soils, vegetation, land use, geology, etc. as well as the variability of hydrometeorological forcings such as precipitation, incoming solar radiation, air temperature, wind speed and direction, etc. Distributed hydrologic modeling elements are not restricted to a given size or shape, but often are determined based on either a spatial scale of forecast interest of the spatial resolution or a key input data source, such as precipitation (e.g. the Hydrologic Rainfall Analysis Project (HRAP) grid). Distributed hydrologic models must account for surface and subsurface flow along hydraulic gradients and in open channel elements. Distributed hydrologic models offer the potential to improve the accuracy of flow forecasts at the current river forecasting points, and to provide information about flows on smaller streams that are susceptible to flash flooding.

Researchers worldwide, including those at the National Oceanic and Atmospheric Administration (NOAA), are developing distributed hydrologic modeling approaches that fully exploit data sets that describe the spatial and temporal variability of features such as precipitation, vegetation, soils, terrain, evaporation, temperature, and others. Accounting for the spatial variability of these features marks a considerable advance in the NWS modeling and forecasting capabilities. In addition, it provides the basis to advance into water resource modeling and deliver new types of operational services. Distributed hydrologic models give users the capability to simultaneously simulate basin outlet hydrographs as well as the hydrologic response at points within the basin boundary.

2.2 What is an Operations Concept? Why this Team?

The primary contribution of this report is the description of a future operations concept for NWS distributed hydrologic modeling as well as some analysis of the functional needs necessary to realize that future operations concept. Gary Carter, NOAA's Hydrology Manager, chartered a team (See Appendix A), to "develop an operations concept describing how various users (including researchers) would use a coherent and integrated distributed hydrologic modeling, assimilation and prediction capability, which operates across multiple spatial and temporal scales to support regional and local objectives, ranging from water resources prediction, to river and flood forecasting, to flash flood prediction." The analysis in this report is based on expertise with (a) the current RFC business process, (b) the functionality required to use distributed hydrologic models and (c) service requirements. The clearly defined future operations concept laid out in this report should guide science, software development, and program management for NOAA's Hydrology Program. Specific software requirements, scientific questions, and user requirements should be developed based on the concepts and ideas laid out in this report. In order to fully realize the operations concept defined here, contribution and active collaboration between the various elements of the hydrology program including RFCs, Weather Forecast Offices (WFOs), the Office of Hydrologic Development (OHD), and others will be required.

The distributed hydrologic modeling operations concept impacts large parts of the current operations concept at RFCs. Table 1 summarizes these impacts and explains how they are described in this report.

As part of the normal development of tools and models at OHD to improve field operations, there are other on-going or planned activities, such as CHPS, XEFS, Data Assimilation and Verification. This report focuses on distributed hydrologic modeling and acknowledges the need for coordinating and integrating with those other development activities.

Operational Component	Purpose	Addressed in this report?
Daily Operations	Produce river forecasts at basin outlets	Deterministic only. XEFS will address probabilistic forecast ops. High level functional requirements as related to distributed hydrologic modeling only.
Interior Flow Operations	Produce interior flow forecasts	Functionality and process for manual query. Not the "point and click on the website" access.
Regional Grid Operations	Produce current or forecast high-resolution grids at the Weather Forecast Office (WFO) or RFC scale	Dissemination method not addressed. Dual use of runtime modifications (MODS) functionality described in Section 8.6. Includes inter-RFC mosaic / collaborate capability.
Calibration	Improve model accuracy	Yes
Research	Add or improve modeling techniques	Yes
Short-Term Ensemble Forecasting	Quantify the uncertainty in our short-term forecasts	These topics are not fully addressed in this report. See Section 9: Unaddressed Operational Concepts for more detail.
National Grid Operations	Produce current or forecast grids at the national scale	
Flash Flood Operations	Provide flash flood information	
Verification	Determine forecast accuracy	

Table 1: RFC/OHD Operational Components Impacted By Distributed Hydrologic Models

This report recognizes that the pathway for implementing distributed hydrologic modeling may well be unique at each RFC. Many aspects of the distributed hydrologic model operations concept will be required by all RFCs. Some aspects will be modified or not used at all at some RFCs. The operations concept laid out here is germane to this diversity. RFC-specific development requirements are beyond the scope of this report and will need to be addressed by individual RFCs.

2.3 Customer Requirements for Products and Services

The products and services created through the use of distributed hydrologic models in operations must be tied to customer requirements. The customers of distributed hydrologic models and its capabilities can be divided into two groups: existing customers and potential customers. Table 2 summarizes the existing and potential customers and links to current and future products and services. Distributed hydrologic models offer the potential to improve the accuracy of flow forecasts at the current gauged river forecast points. This capability would benefit the RFC and WFO forecaster as well as any current partners and customers who use existing single-location forecast products. Distributed hydrologic models also offer the capability to provide Flash Flood Guidance at higher spatial and temporal resolution and provide information about flows on smaller streams that are susceptible to flash flooding. This capability benefits the WFO forecaster as well as existing customers and partners who rely on the NWS for critical flash flood watches and warnings.

Customers are currently requesting forecasts at points between official forecast locations. Once distributed models are implemented, those customers will benefit from the by-product information made available by distributed hydrologic models including flow at interior points, gridded water resources information, water temperature and water quality information and groundwater seepage information. Several National Research Council reports support the requirement for much higher resolution water predictions at a wide range of spatial and temporal scales. The 1996 study entitled "Assessment of Hydrologic and Hydrometeorological Operations and Services" calls for the introduction of river models that make use of high-resolution precipitation data and digital elevation data to produce finer spatial resolution forecasts[i]. The report of 2001 entitled "Envisioning the Agenda for Water Resources Research in the Twenty-First Century" describes a wide variety of ways water managers will benefit from enhanced information and predictions[ii]. Agricultural examples include: developing improved crop varieties for use in dry land agriculture; improving the sustainability of irrigated agriculture; and planting crops for more efficient use of water. Environmental water managers need water predictions to support the enhancement and restoration of species diversity and to modify water parameters to maintain and enhance aquatic habitats. In some cases, new science and modeling capabilities can yield new products that existing customers are not yet aware of (e.g. gridded flash flood guidance (GFFG), small-basin non-forecast-point forecasts issued by LMRFC for WFO Nashville) or new customers emerge (e.g. multisensor precipitation data being used by shellfish harvesters and local communities for beach closures). As distributed hydrologic modeling capabilities develop, RFCs will need to reach out to NWS customers and define specific requirements for new products. The usefulness of new products is likely to increase as the science matures and our understanding of accuracies and uncertainties improves.

Existing Customer	**Improved Product/Service or Future Product**
RFC and WFO	Improved forecast accuracy to existing forecast guidance
WFO (implicitly means Emergency Management Agencies (EMAs) and public or customer)	Improved Flash Flood Guidance (FFG) as requested by WFOs
WFO, EMA, Public Interests	Flow at Interior Points (future product)
Potential Customer	**Future Product/Service**
Forecasters and researchers for model diagnostics, Agricultural / Land Users	Flow at Interior Points
Water Resource Managers, Agricultural / Land Users, Construction, Military, Environmental Modelers (e.g. for model initialization for the National Centers for Environmental Prediction (NCEP)), Weather Services Industry, Researchers	Grids: * Soil Moisture at various depths (e.g. 10cm, 30cm, 100cm) * Frost Depth / Soil Temperature * Snow Water Equivalent
Water Resource Managers, Ecosystem Managers, environmental users, recreational users, researchers, coastal modelers	River/Lake Water Turbidity and Temperature and Other Water Quality
Water Resource Managers, Agricultural / Land Users , Ecosystem Managers, environmental users, researchers, coastal modelers, cold regions streamflow forecasting operations	Groundwater/surface water interaction (i.e. streamflow gain/loss information within aquifer recharge zones

Table 2: Existing and future customers and the distributed hydrologic modeling products and services they may benefit from.

2.4 Report Organization

The operations concept for distributed hydrologic modeling is presented in sections 3-7. These sections detail current and future operations for gauged locations (section 3), ungauged locations (section 4), gridded forecasts (section 5), calibration (section 6), and research (section 7). Each operations concept is detailed in three sections:

1. Introduction and background
2. Current operations concept – how it's done now, using what tools
3. Future operations concept – how the team anticipates using the new tools to meet operational needs and deliver products and services in the future.

Section 8 defines the high level functional changes required to realize the operations concept laid out in this report. It is subdivided into categories which were prioritized for future development.

Section 9 lists aspects of the operations concept which, for various reasons, were unaddressed in sections 3-7.

Section 10 defines a pathway forward through the formation of a follow-on team to prioritize development and prototype applications, and a national RFC effort to promote continued and NWS-wide field testing and application.

3 Producing Forecasts at Gauged Locations

3.1 Definition, Purpose

RFC operations have and in the foreseeable future will always focus on the production of forecasts at gauged locations. Currently RFCs issue deterministic forecasts to support short-term public forecasts (typically 0-5 days), and probabilistic forecasts to support longer-range guidance. The following analysis does not address issues related to the production and dissemination of short-term probabilistic forecasts (see Section 9.1)

3.2 Current Operations Process

The hydrologic forecaster works with the Hydrometeorological Analysis and Support (HAS) forecaster to prepare a single set of deterministic forcings including past precipitation (quantitative precipitation estimates, or QPE), future precipitation (quantitative precipitation forecasts, or QPF), temperature, and potential evapotranspiration (PET). The HAS forecaster uses various forecast tools (NAWIPS Meteorological Analysis Package (NMAP), Multisensor Precipitation Estimator (MPE)) to create and modify grids of these forcing data. These grids are on the HRAP polar stereographic projection at a roughly 4x4 km scale. For "lumped model operations" the grids are averaged to produce a single value for a larger computational area (i.e. a river basin).

RFCs use the National Weather Service River Forecast System (NWSRFS) for hydrologic modeling. NWSRFS consists of three major systems, the Calibration System, the Operational Forecast System (OFS) and the Ensemble Streamflow Prediction System. OFS uses calibrated parameter values to generate short-term river and flood forecasts and maintain model state variables. OFS executes batch model runs on a segment-by-segment basis from upstream to downstream basins. The Interactive Forecast Program (IFP) is a graphical user interface that allows the forecaster to interact with the hydrologic physical processing model of OFS. IFP provides the forecaster with information needed to make decisions about the correctness of data or model results, aids in the creation and management of run-time modifications, allows the forecaster to perform what-if scenarios, and provides the capability to easily and quickly put those decisions into action to produce forecasts reflecting their best judgment about current and future hydrometeorological conditions.

The hydrologic forecaster interacts with the calibrated (see Section 6) model simulations by making MODS to the OFS models and operations. The hydrologic forecaster makes adjustments to improve model performance – that is, agreement with observed river and reservoir levels, snow pack, etc. – over observed periods. MODS can alter almost every part of the simulation process including model states, routing speed, rating curve shifts and reservoir operations. The assumption is made that hydrologically sound adjustments to the model states that improve model performance in the past will in turn improve model forecasts at future time steps.

The forecaster also performs quality control to mitigate poor quality data. Quality control operations include ignoring the rating curve, removing bad stages from the database or readjusting the QPE as new data are reported.

Once the simulations data are deemed "forecast ready" the forecaster prepares and disseminates the river forecast products.

3.3 Future Operations Concept

There are several reasons why the current operations concept will need to change with distributed hydrologic models:

- Local biases or other errors in the gridded forcing fields can be masked out when the pre-processors create mean areal values. As we move to harness the full resolution of the data, quality control will become much more important.
- Hydrologic forecasters can manually create scientifically valid runtime manual modifications for lumped models; this is demonstrated at all RFCs. However, with a dramatic increase in computational elements, it will be infeasible to interact manually with distributed hydrologic models as forecasters have interacted with lumped models.
- In many places the RFCs may use lumped models jointly with distributed hydrologic models, using runtime MODS as they traditionally have.
- Forecasters may choose to blend aspects of their lumped and distributed hydrologic models. For example, they may want to couple or otherwise blend simulations to create a single forecast.
- Modeling resolution, both spatial and temporal, will need to vary to allow RFCs to use distributed hydrologic models in wide-ranging applications.

Future operations may consist — broadly — of the following steps:

(1) Hydrologic forecasters and HAS review and analyze all inputs for quality assurance and completeness utilizing geographic information system (GIS)-based analysis tools combined with remotely sensed or in situ data sources, such as soil moisture and independent evapotranspiration estimates. The quality control process will need to be more conscious (than today) of gaps or problems in the gridded data that

could result in gross errors in areas of the simulation, such as poor radar coverage, bad rain gauges, etc.

(2) Run models.

(3) Run Data Assimilation (DA) processes.

(4) Forecaster selects a river system and reviews the multiple model simulations, each with an ensemble of forcings. Forecaster uses advanced analysis and display tools to assess the reasonableness and accuracy of all simulations. This includes graphical views of historical model bias from past verification analysis.

(5) Forecaster may choose to adjust the DA parameters (weights, objective function) and rerun DA.

(6) If the simulation is still not considered "product ready" the forecaster may choose to manually modify the simulation (i.e. make runtime MODS).

(7) Forecasters choose which simulation or combination of inputs and simulations to use.

(8) Forecaster generates and disseminates products.

(9) Automatic data archiving and verification processes run.

(10) Verification results analyzed. Model states analyzed.

4 Producing Forecasts at Ungauged (Interior) Locations

4.1 Definition, Purpose

Typically, RFCs only produce forecasts at pre-determined (i.e. lumped) basin outlets. Customers are unable to get information for smaller streams and tributaries, or flow at intermediate places along the reach of the river. Several methods should be available for forecasting at ungauged locations.

Because stage-flow relationships have little meaning beyond the gauged / measured location, interior location forecasts will likely be flow only. In addition, probabilistic / ensemble forecast information will be needed to account for the higher degree of uncertainty in the forecast and the inability to provide comprehensive verification. The operations concept for short-term probabilistic forecasting will be addressed by the XEFS team.

4.2 Current Operations Process

RFCs regularly issue hydrologic forecasts at ungauged lumped basin outlets. (The site may have had a gauge, or may have wire-weight readings only). If the lumped basin is modeled with hydraulic models, forecasters have the ability to issue quantitative estimates of both flow and water surface elevation at locations interior to the basin. Otherwise, RFCs rarely provide "official" forecasts at locations inside lumped basins. Forecasters occasionally do prepare subjective forecasts by qualitatively comparing to a gauged location (interior and/or basin outlet).

4.3 Future Operations Concept

The steps required to produce forecasts at ungauged (interior) locations will be similar to the steps required to produce forecasts at gauged locations. The hydrologic forecaster makes DA and other modifications needed per Section 3.3.

For pre-selected points the RFC sets up an automatic process that creates the flow data and coordinates the data exchange. If desired (and feasible within the modeling limitations), stage information is provided as well.

For real-time selection of locations, a customer may call requesting information at a specific point. The forecaster queries the distributed hydrologic model ensemble forecast and provides probabilistic flow information at the finest spatial resolution possible. Flow information provided should be accompanied or based on statistical flood frequency or recurrence interval data. If desired, and feasible within the modeling limitations, stage information is provided as well. Deterministic forecasts are done the same way, but with a single ensemble member.

For automatic forecast point selection, a tool alerts the forecaster which locations have met which predetermined critical threshold(s). The forecaster takes appropriate steps based on the forecast information. If data quality is the cause of a “false alarm”, the forecaster fixes the appropriate input and reruns the simulation.

5 Producing Gridded Forecasts

5.1 Definition, Purpose

The ability to produce gridded datasets is one of the key benefits to the use of distributed hydrologic modeling techniques. A wide array of physical elements can be extracted and presented in a way that can be used by a variety and diverse group of customers.

5.2 Current Operations Process

Currently most RFCs do not provide “official” gridded products other than QPE and QPF. Southern region offices currently use the Hydrology Laboratory – Research Distributed Hydrologic Model (HL-RDHM) to produce official gridded flash flood guidance (FFG). Their method is similar to the creation of standard FFG information – once the simulation is determined to be “product ready” the forecaster runs the FFG program.

5.3 Future Operations Concept

The steps required to produce gridded forecasts will be similar to the steps required to produce forecasts at gauged locations. The forecaster makes DA and other modifications needed per Section 3.3. (Depending on the RFC, this step may be partially or completely done as part of the “daily river forecast operations”.) Once the modeled states are considered “forecast-ready” the hydrologic forecaster runs grid generation program to generate the gridded forecasts. RFCs will need to coordinate gridded products to ensure consistency. After coordination the hydrologic forecaster releases the final products.

6 Calibration

6.1 Definition, Purpose

Calibration is the process of adjusting model parameters such that simulated variables sufficiently agree with observed values of the same variables, and parameters properly represent the processes they are intended to model. Ideally, models for which parameters could be derived without calibration would be used for river forecasting. However, the current state of the science is such that existing approaches to model watershed processes without calibration are inadequate for river forecast operations. Therefore, any feasible solution for NWS hydrologic modeling will continue to require model calibration. The greatest challenge with calibrating distributed hydrologic models is their very large number of parameters, and the subsequent complications that poses to manual and automatic parameter calibration. Another challenge is determining the appropriate resolution needed for any particular input parameter data set. In other words, not all data sets will necessarily require the same spatial or temporal scale resolution to achieve optimal/desired results. Errors in the input data create localized simulation errors which can grow and propagate through the entire simulation as shown in Figure 1. This "cascading error" effect can wipe out any expected gains from finer scale modeling, and may lead to even worse results than lumped modeling.

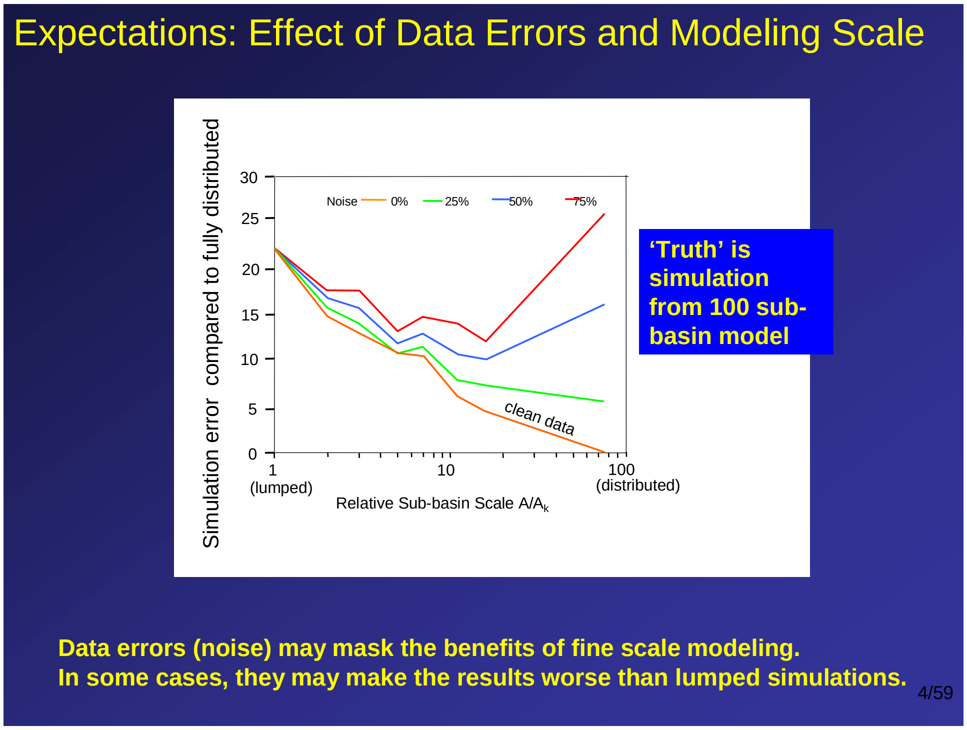

Figure 1. Effect of data errors on the simulation accuracy. In this numerical experiment, the addition of errors to the data (shown in the top three traces), may wipe out any expected gains from finer scale modeling, and may lead to even worse results than lumped modeling. [iii]

As model scale resolution increases, so does the number of parameters in need of potential adjustment, as well as the data “noise” affecting model error. With the current state of technology, automatic calibration and parameter estimation techniques are valuable tools, but are not complete solutions or replacement for manual expert calibration. These techniques can introduce complications when parameter values are adjusted beyond the realm of physical meaning. During the process of (manual or automatic) calibration, it is important that parameters maintain a reasonable physical representation.

6.2 Current Operations Process

The calibration process will vary based on the specific models used. The lumped hydrologic model calibration process is reasonably well established. For the distributed hydrologic models currently in use at River Forecast Centers, an initial process has been established.

6.2.1 Current Lumped Hydrologic Model Calibration[iv]

Several tools are currently available for calibration.

- “MCP3” is an NWSRFS program that ingests historic data to create model time series that are compared to observations for calibration.
- RFCs use the Interactive Calibration Program (ICP) to run MCP3.
- The Calibration Assistance Program (CAP) uses GIS data to assist in deriving parameters for lumped Sacramento and Snow models.
- Interactive Double Mass Analysis (IDMA) is used primarily to quality control lumped precipitation data.
- “STAT-QME” is an NWSRFS tool that gives the calibration process basic statistical analyses of the calibration.
- “STAT-Q” is a standalone statistical analysis program. It provides more advanced statistical analyses and functionality as compared to STAT-QME but is not integrated with ICP/MCP3.
- “XDMS” is similar to the X-Window Navigation Animation and Visualization (XNAV) program. XDMS was written to support an early prototype distributed hydrologic model, and is still used today as a visualization tool.

A calibration process should approach this process from a large area (entire river basin) perspective rather than from single headwater perspective. This is much more efficient for data access and analysis and calibration consistency.

1. Gather information and data
2. Assess spatial variability of hydrologic factors
3. Select flow-points and period of record for calibration
4. Analyze historical data and put in form needed by models
5. Calibrate hydrologic models (snow, soil moisture, river, and reservoir)
6. Implement calibration results for operational use

6.2.2 Current Distributed Hydrologic Model Calibration

The tasks for parameterizing and calibrating the current NWS distributed hydrologic model are similar in concept to those for lumped model calibration. This is the current calibration process for HL-RDHM (using the gridded Sacramento Soil Moisture Accounting (SAC-SMA) model and SNOW-17 models with kinematic wave routing):

1. Decide if distributed hydrologic modeling can be appropriately applied in a given area.
2. Derive a priori parameters for SAC-SMA and Snow-17 (or obtain pre-computed grids provided by OHD).
3. Obtain 1-hour calibrated lumped parameters for the basin if available.
4. Analyze historical forcing data (precipitation, temperature, evapotranspiration) for consistency and quality.
5. Obtain hourly flow data, if available.
6. Derive a priori routing parameter grids using HL-developed scripts and programs.
7. Assign appropriate basin outlet grid cell and add to connectivity file. Due to limitations of the connectivity file actually representing true conditions, the outlet grid may need to be adjusted slightly if an extra "feeder stream" connects just above or below the gage location and it is not correctly depicted in the connectivity file.
8. Adjust pixel areas.
9. Prepare HL-RDHM input file (deck).
10. Run HL-RDHM.
11. Identify events which should be excluded from calibration due to bad data.
12. Iteratively adjust scale factors for selected parameters to meet calibration objectives. Use manual methods or automatic calibration methods.
13. Plot mean precipitation, simulated and observed flow and runoff time series to assist with parameter adjustments (e.g., using ICP).
14. Examine simulation statistics using STAT-QME and or STAT-Q programs.
15. Visually examine the spatial patterns of inputs, parameters, and model results using "XDMS" and or GIS software.

6.3 Future Operations Concept

We envision several new tools to help the hydrologist calibrate a distributed hydrologic model. These tools (detailed in Section 8.4) will facilitate more advanced analyses such as:

(1) The calibration process assembles the required information – the current lumped or distributed calibration, an understanding of the geophysical nature of the basin (land use, soil types, terrain, etc.) and historical data (precipitation, temperature, potential evapotranspiration, soil moisture, stages/flows).

(2) The calibration process performs quality control of the forcing data (including numerical weather prediction (NWP) model re-analyses and Next Generation Doppler Radar (NEXRAD) data where available), interpreting statistical analysis of a priori grids over selected basin to detect outlier data. The calibration process

uses grid editing and data analysis utilities to make necessary input grid data changes.

(3) The calibration process uses a series of statistical measures to evaluate goodness of fit between simulated and observed variables such as discharge, volumetric soil moisture versus content, snow water equivalent, snow covered area, time series of top layer soil moisture evolution, etc.

(4) The calibration process has the ability to look at spatial data such as static parametric data, time series of spatial variables such as model states, observations, and forcings.

(5) The calibration process uses GIS-based examination techniques to assess variables over a large area and determine parameter consistency and reasonableness.

(6) The calibration process uses a combination of expert-manual methods and automatic calibration algorithms to minimize selected objective function(s) at various stages in the calibration process.

(7) The calibration process will be able to select parameter sets from a Pareto front in order to balance various trade-offs. (See the Glossary for additional explanation.)

7 Research

7.1 Definition, Purpose

OHD primarily performs applied research and development, both in-house and in collaboration with other entities. The overarching goal of research and development in OHD is to provide new tools for RFC and WFO field operations. However, the capability must exist within RFCs and collaborating researchers to implement additional distributed hydrologic models. This capability is needed in an operational setting to test new distributed hydrologic models and to apply additional models in a multi-model hydrologic ensemble operational context. Hardware resources to run additional distributed hydrologic models, especially as multi-model ensembles, will be very significant.

7.2 How it's done now and why it will need to change

In a sense, the lumped modeling research and development (R&D) environment needs to expand to include distributed hydrologic modeling, as both will continue to be needed in the future. Basically, analysis and display tools need to be developed so that the researcher can analyze and use spatially variable data in addition to point time series data. An important requirement has been that the research work be performed in an environment as close to the NWSRFS as possible to maintain an efficient research-to-operations path. In this regard, much of the lumped and distributed hydrologic modeling research done to date has been connected to the NWSRFS Calibration system as shown in Figure 2 below.

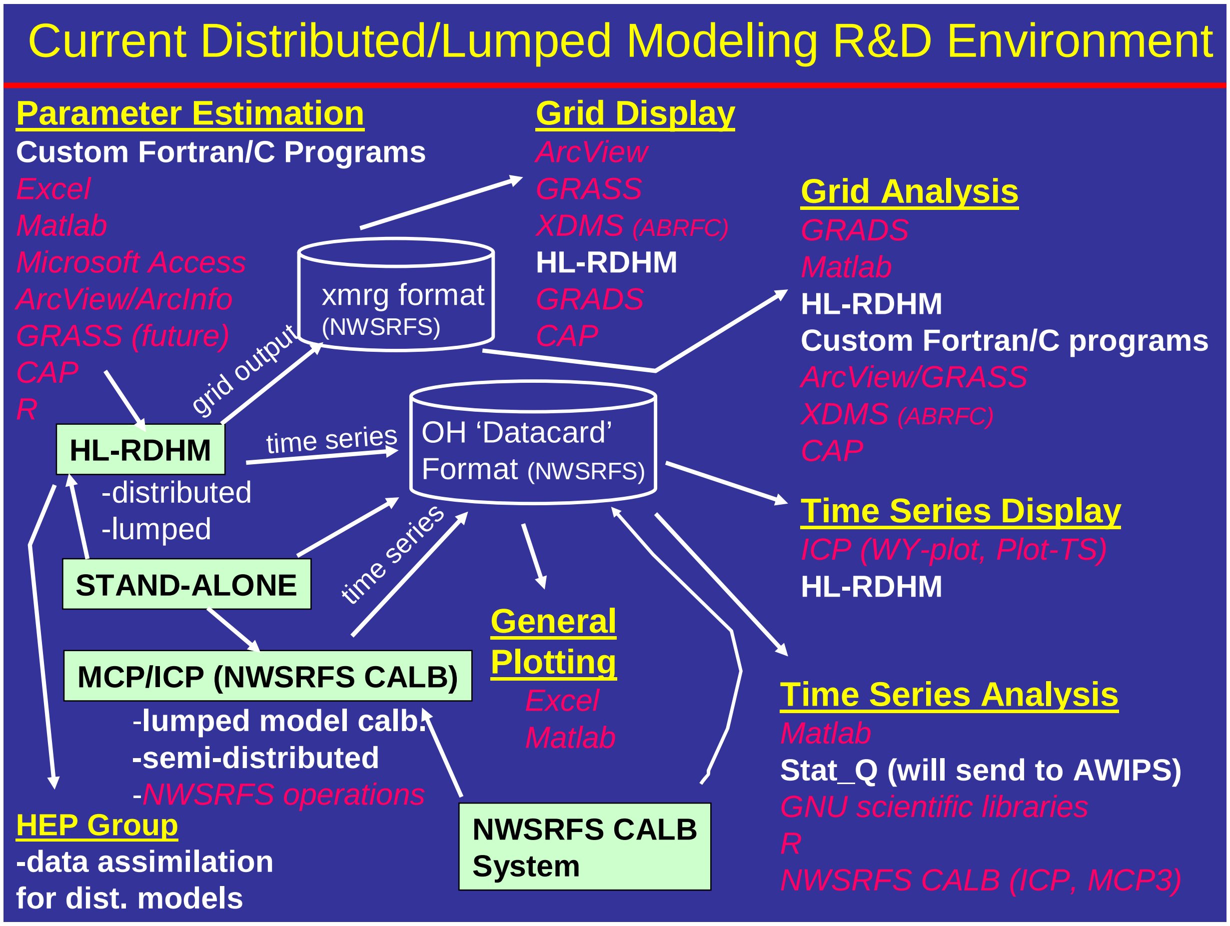

Figure 2: The current R&D environment for hydrologic modeling within the Hydrologic Modeling Group. Items in red (italic) are COTS software or code developed by others. Items in white (bold) under the yellow (underline) headings are custom codes. Note that there are specific links to NWSRFS systems as well as the use of NWSRFS time series and gridded data formats.

A primary goal of the environment for current distributed hydrologic R&D is to maximize similarity to the NWSRFS operational system in order to streamline the research to operations path. As seen in the figure above, this includes the use of the NWSRFS Calibration system, the MCP/ICP programs, and the XMRG and OHD datacard formats for gridded and time series data, respectively. Another important emphasis is to utilize commercial off-the-shelf (COTS) and software developed / supported by NWSRFS and others as much as possible to streamline the research-to-operations process. As seen in the figure above, nearly 85% of all the tools used in R&D are COTS software (e.g. Matlab, Arcview, GRASS, R, etc.) or code developed by other RFCs and offices. These programs are shown in red (*italic*) above.

7.3 How it will be done in the future

We envision an environment such as the one in Figure 3 which shows a more streamlined approach to research-to-operations and includes partner collaboration. The main requirement is that hydrologic research and development will be performed in a managed environment within CHPS. This will enable distributed hydrologic modeling to seamlessly interface with the XEFS architecture (for assimilation and ensembles) and code for R&D since distributed hydrologic modeling will just be another model under the XEFS paradigm. As is the current case, the primary goal of this environment is to perform R&D in an environment that is as close to the operational system as possible in order to streamline the research-to-operations path.

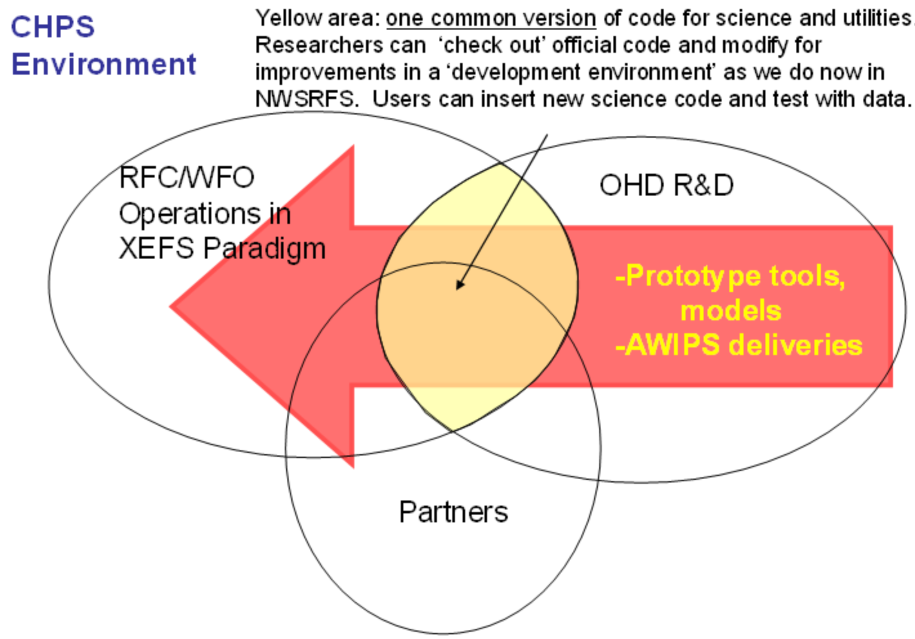

Figure 3: Streamlining Research to Operations

<u>Future R&D</u>

In the future, hydrologic modeling R&D will take advantage of the CHPS architecture, enabling researchers to focus on developing, modifying, and inserting scientific models and algorithms into a research environment and Research-to-Operations path with far less demand for writing 'overhead' code to handle data. Certainly distributed hydrologic modeling will be included in this new approach to R&D. One of the major changes required is that we must consider questions such as the following:

(1) Determining the optimal size of the computational element to achieve a desired objective. This was not really needed in the lumped modeling case in which the only product was basically a forecast at a point.
(2) Propagation of input data errors through a distributed hydrologic model. This is related to the previous item. Given a certain level of data errors, modeling a basin at the finest scale might produce worse results than a lumped model due to error propagation.
(3) Evaluation of new sources of information from which to derive model parameters for the individual computational elements.
(4) High performance computing platforms are necessary to perform model calibrations.
(5) Research will need spatial display and analysis procedures

8 Functional Needs

The current lumped basin modeling system contains several functional capabilities. These, and other capabilities, will be required to implement spatially gridded distributed hydrologic modeling. Section 8.1 describes the minimum operational capabilities to run a distributed hydrologic model in operations mode with the ability to make official forecasts. Sections 8.2 to 8.12 identify the enhancements necessary to realize the full potential of distributed hydrologic models.

The requirements are grouped together based on common functionality. The team recommends that once a basic CHPS-based distributed hydrologic modeling capability is in place, "Data Assimilation" should be the first item worked on, followed by "Analysis and Display Tools", "Calibration", etc. (Note, "Basic Capability" was automatically considered top priority. "Research", although listed last, was not formally ranked by the team. OHD will use their discretion to rank the functional needs for research against other functional needs.)

The functional needs within the groupings were ranked "High", "Medium" and "Low". These rankings are relative to other items in the functional grouping (i.e. an item ranked "High" in 8.3 is not necessarily more important than one ranked "Medium" in 8.6).

These lists only show those areas of functionality that relate to an assessment of a future operations concept. Capabilities related to rainfall-runoff, snow, reservoir and routing models are discussed in the OHD Strategic Science Plan[v] and are not in this report. Likewise, as RFCs work more with this model and science and technology advances, new functionally will likely be identified and will need to be considered.

The functionalities described below will likely require several OHD projects and teams. The team recommends the follow-on Gap Analysis project maps these requirements to new or existing Hydrologic Operations and Service Improvement Process (HOSIP) projects. The priorities below should be considered by the follow-on (and OHD in general) when allocating resources for science and software development.

8.1 Basic Distributed Hydrologic Modeling Capability

The most basic functional need is for a distributed hydrologic modeling capability that can run in operations mode with the ability to make official forecasts. This must include:

- Ability to ingest current forcings such as QPE, QPF and temperature. **(Must Have)**
- Ability to choose and run one or more hydrologic models (distributed or lumped). **(Must Have)**
- Snow / energy models to model snowmelt and frozen ground. **(Must Have)**
- A rainfall-runoff model that supports multiple resolutions and ingests atmospheric forcings to produce soil moisture states and local flow. **(Must Have)**
- A routing capability to connect computational areas. **(Must Have)**
- Ability to choose and run one or more reservoir simulation models (e.g. the joint reservoir model (RES-J), etc.) **(Must Have)**

- Ability to produce a river flow forecast time series (variable time step at least down to one hour) at pre-determined locations (e.g. basin outlets / forecast points). **(Must Have)**
- Ability to compute grid operations and display results in a timely enough manner to support real-time operations. **(Must Have)**
- Multi-model quantitative forecast verification - ability to quantify the differences between model performance in order to make decisions about which system to use at different points. **(Must Have)**
- Ability to interface with operational ensemble, flash flood guidance, data assimilation and verification capabilities. **(Must Have)**
- Current Hydrometeorological Forcings – Observed and forecast precipitation and temperature, at their current resolution and quality, which are consistent between calibration and real time operations so as not to introduce biases into the forecasting process. **(Must Have)**
- Gridded precipitation archive of sufficient length to calibrate model and with an analysis scheme consistent with real time analysis scheme. **(Must Have)**
- Gridded temperature archive of sufficient length to calibrate model and with an analysis scheme consistent with real time analysis scheme. **(Must Have)**
- Basic Potential Evapotranspiration – Ability to generate potential evapotranspiration using computed values. **(Must Have)**
- River, Reservoir and Stage Information – includes the ability to adjust (i.e. through a rating curve or reservoir routine) flow, stage and storage time series based on these data. **(Must Have)**
- Basic Analysis and Display (spatial and temporal) – Ability to view flow and stage output time series at a basin outlet / forecast point. Ability to view inputs and state variables (e.g. SAC-SMA bucket contents) for each computational area. **(Must Have)**
- Ability to view multiple forecasts including multiple lumped and multiple distributed hydrologic models. **(Must Have)**
- Precipitation Processing Analysis and Displays - Ability to view, analyze, and manipulate spatial displays of precipitation observations from in situ gauge, satellite, and radar (as well as merged products). **(Must Have)**
- Observation Quality Control tools – Ability to add, modify or delete observations at the judgment of the RFC forecaster. This includes an ability to identify and fill in missing data and estimates obtained through a variety of estimation techniques. **(Must Have)**
- Allow production of temporary MODS that, for the current simulation only, overrides model simulations. (Analogous to the current “time series change” (TSCHNG) MODS.) **(Must Have)**
- Ability to choose a single official forecast from an ensemble of forecasts (i.e. if there are multiple models running, choose one). **(Must Have)**
- Basic Calibration Assistance Program (CAP) – Ability to derive parameter values from physical characteristics of the watershed. **(Must Have)**
- Ability to use manual and automatic calibration techniques described in the HL-RDHM User Manual 2.0. This includes a basin averaged parameter multiplier

capability, a multiple time-scale objective function, and an automatic calibration algorithm to refine parameter multipliers. **(Must Have)**

8.2 Data Assimilation

Data assimilation (DA) in hydrologic forecasting operations is an optimization process that makes corrections to model state variables and forcing data based on real-time observations of hydrological variables such that the model states and forcing data reflect and represent better the observed reality in a dynamically consistent way with the model. DA derives an optimal set of initial conditions, observed precipitation and PET so that the model-simulated flow is sufficiently close to the observed.

Data assimilation has the potential to transform the forecaster role. Instead of spending time creating MODS, forecasters will be able to interact with the DA parameters and objective functions to prioritize and bound input or model variables using forecaster skill to minimize forecast errors. The DA process results in an optimized and prepackaged suite of MODS to correct model bias. The DA process should result in increased forecast accuracy and a nationally consistent, rational approach to model modifications and adjustments.

This approach has both pros and cons. The primary pro is that, in a shorter time, DA can adequately modify the model simulation in a dynamically consistent way with the model by harnessing the computational power of modern computers. The primary cons are the additional computational requirements that DA impose on the system, and the possibility to have to resort to manual MODS in case the DA results are not acceptable.

- Implement Data Assimilation techniques for distributed (and lumped) model operations. **(High)**
- Allow for real-time interactions with and control over DA parameters. For example, set different limits (upper and lower bounds) on precipitation and PET based on forecaster judgment, adjust relative weights on the sources of error in the assimilation equations, and rerun the assimilation. **(High)**
- Enhance DA to assimilate and optimize across multiple observation-simulation comparisons (i.e. where available multiple gauging points, not just basin outlet, or observations of other variables such as soil moisture). **(Medium)**

8.3 Analysis and Display Tools

As direct forecaster interaction with models becomes more demanding due to their physical scope and complexity, data analysis and subsequent quality control takes on even greater importance. New tools are needed to display and analyze both gridded and time series data. These tools should be robust, expandable, easy to interpret, but yet sophisticated enough to address the needs of forecasters, researchers, and users alike.

For operations, these tools must provide the functionality to visualize, analyze and validate / quality control the tremendous volume of spatial and temporal inputs and model components. For research and calibration this is a fundamental requirement as gridded and time series data are intrinsic to distributed hydrologic modeling.

- Unified analysis, display and modification – within the forecasting environment. Currently, time series displays are part of IFP, precipitation and state variable displays are part of standalone applications such as XNAV and XDMS, and modification capabilities are in all of the above. These tools need to be consolidated for optimal use in distributed hydrologic modeling. Tools should be combined with utilities to allow grid editing of selected areas or individual cell values in question. (Interdependent functional requirements should co-exist in the same utility.) **(High)**
- Spatial and temporal display (including spatial animation), analysis and manipulation of: forcing information (such as soil moisture, soil temperature, air temperature, solar radiation, etc.); state variables; forecasts. Ability to compute statistics of data such as temporal consistency, departures from normal, variability versus elevation or exposure, etc. **(High)**
- Numerical Weather Prediction - Ability to view spatial displays of numerical weather model output. **(Low)**
- Advanced Statistical Analysis – A broad variety of statistical analysis tools should be included. This is particularly useful for calibration and research, but also necessary for analysis of system performance during operations. **(Low)**

8.4 Calibration

Calibration of distributed hydrologic models will be much more complex than lumped model calibration. The data volume and corresponding need for quality control will increase dramatically. The degrees of freedom increase exponentially as lumped basins are broken into smaller computational areas. The objective functions to measure calibration improvements will become much more complex as well, as we work towards simultaneous calibration using multiple streamflow gauges and additional data types.

- Advanced Calibration Assistance Program. Statistically analyze a priori parameter grids across a basin or other designated area and display results in various conventional tabular and graphical formats (e.g. box plots to detect extreme outliers) for forecaster interpretation. Quality control analysis tools should be combined with utilities to allow grid editing of selected areas or individual cell values in question. **(High)**
- Interactive Calibration Program (ICP) for Distributed Hydrologic Modeling – ability to fine tune parameter values based on comparisons of historical observations to model simulations. **(High)**
- Ability to run sections separately. **(High)**

- Ability to derive and then graphically change connectivity information. **(High)**
- Enhanced flowchart for calibration to complement the existing lumped model calibration process steps. **(High)**
- Ability to select / group computational areas by common spatial and temporal resolution. **(Medium)**

- Advanced objective functions (multiple temporal scales, multiple stations, multiple data types), multi-step calibration procedures, and efficient search algorithms. **(Medium)**
- Ability to use pattern / shape matching algorithms so that spatial fields of hydrologic variables can be calibrated to observed spatial fields. **(Medium)**
- Ability to simultaneously use ensemble and data assimilation for calibration purposes. **(Low)**

8.5 Atmospheric Data Forcings

Atmospheric forcing data will continue to be one of the most important components of hydrologic modeling. The availability and quality of model input data become even more important as distributed hydrologic modeling requires higher resolution data, both spatially and temporally. In addition, as hydrologic models become more sophisticated in their formulation and execution, atmospheric variables (e.g. solar radiation, wind, relative humidity) will be required beyond those traditionally used in NWS hydrologic modeling.

- Improved Precipitation Estimates – Higher quality, finer scale, gridded precipitation estimates are vital to this effort. This includes algorithms which temporally disaggregate long duration time series data and intelligently combine precipitation estimates from gauges, radars, satellites, numerical weather prediction analyses, and spatial climatology. **(High)**
- Improved gridded precipitation archive – more years, higher quality, higher resolution where needed. **(High)**
- Improved Quantitative Precipitation Forecasts - Distributed hydrologic models in forecast mode require forecasts of precipitation at the same temporal and spatial resolution as the model. Current work with Warn-on-Forecast concept may yield high resolution short-term QPF that bridges the gap between qualitative and quantitative flash flood forecasting. **(Medium)**
- Advanced Potential Evapotranspiration – High-quality, fine-scale, gridded estimates and forecasts of potential evapotranspiration (PET) which are consistent between calibration and real time operations so as not to introduce biases into the forecasting process. **(Medium)**
- Snow data – Improved-resolution snow data. (e.g. remotely sensed, algorithm based gridded data from the National Operational Hydrologic Remote Sensing Center (NOHRSC)) **(Medium)**
- Ensemble forcings – Ensemble forcing information is required for all forecast and analysis forcings to fully account for the uncertainty in the forecast process. **(Low)**
- Linkages to NWP models – NWP models provide an additional information source for atmospheric water vapor, the surface water budget terms, and the surface energy budget terms. While NWP data are derived from assimilated observations, it contains information potentially useful to distributed hydrologic model calibration. **(Low)**

8.6 Forecaster Interaction with Runtime Modifications

Forecaster interaction for the purpose of gridded product production will depend on the mode of operation needed or desired by a RFC at a given time. If the lumped model is the primary tool used to produce river forecasts, the interaction will be relatively independent of the lumped model operation. And even if the distributed hydrologic model is used to produce river forecasts, additional effort will be required to prepare the model for producing gridded products.

The combination of data assimilation and runtime modifications discussed in Section 3.3 can be used to adjust / improve the simulation for both river flow (at specified locations) and gridded products (for selected regions). Although the mechanism will be the same, the interaction may be more related to compensating for localized biases / errors in the forcings. In addition, RFCs may need to collaborate with neighboring RFCs to ensure consistent mosaicked gridded products.

- Allow production of scalar MODS using multiple computational area groupings, including basin, grid and elevation. **(High)**
- MOD History – can be used for bias identification. Once an extensive collection of MODS are available these data can also be used as a neural network feedback mechanism. **(Medium)**

8.7 Interior Location Selection

One advantage of distributed hydrologic modeling is the ability to simulate flow at any location within the model grid. New tools are needed to both display and analyze flow at interior locations.

- Allow selection of pre-defined locations. **(High)**
- Allow selection of all locations. **(Medium)**
- Allow interactive real-time selection of locations. **(Medium)**
- Allow real-time selection of locations through some batch selection process. **(Medium)**
- Create an automatic system / tool that selects points using critical thresholds, such as bankfull or other critical elevation, flow frequency, rainfall intensity. **(Low)**

8.8 Model and Operate at Multiple Spatial and Temporal Resolutions

The spatial and temporal variability of data in gridded formats makes it desirable to utilize that data as model forcings without the requirement to adjust the resolution. In addition, distributed hydrologic modeling on a region scale can potentially provide adequate boundary conditions for much finer, local scale modeling. With these possibilities and considerations, the distributed hydrologic modeling system should be flexible to utilize multiple spatial and temporal resolutions.

- Ability to transform gridded forcing data to the computational map. **(High)**
- Ability to transform gridded forcing data to multiple output grids. **(High)**
- Ability to run simulations at multiple time scales. **(High)**

- Ability to have multiple computational area shapes – grids of multiple sizes, sub-basins, TINs, etc. **(Medium)**
- Ability to select and run certain sections of the computational area at finer spatial and temporal scale while maintaining continuity of model states over the entire area. For example, if multiple areas are calibrated for a 1-km, 15-minute model, and the concern is flash flooding in one area, then only that area is run every 15 minutes. **(Medium)**
- Ability to run models with variable resolutions in the vertical dimension (i.e. different resolutions for surface, sub-surface, and groundwater components). **(Low)**

8.9 Surface and Subsurface Data

Similar to atmospheric data forcings, the availability and quality of surface and subsurface data are important to the continued improvement of hydrologic simulations.

- Interior Gauges – Streamflow gauges exist that are not currently modeled by RFCs. Many of these gauges lack long records and/or rating curves. However, information from these gauges may be useful for distributed hydrologic model calibration. **(High)**
- Soil Moisture - Surface and subsurface moisture states and subsurface transport. **(Medium)**
- Vegetation data - Remotely sensed or model vegetation for its effects on hydrology. **(Medium)**
- Soil Temperature **(Medium)**

8.10 Coordinating Multiple Models

As more modeling tools become available to RFCs for use in operational forecasting, it is important to appropriately utilize and apply each model for its known strengths and weaknesses. For some forecast points, use of a deterministic distributed hydrologic model will improve on a lumped model for most storm events. At other forecast points, a distributed hydrologic model may show benefits for only certain types of events or no benefits over a lumped model. For forecast points containing many segments, it may be optimal to model some segments with a distributed hydrologic model and some with a lumped model. Making a prudent choice among these modeling options requires an integrated modeling system that allows generating forecasts with multiple model combinations. To narrow down the many possible combinations to be considered, additional research should be done to provide guidance on where certain rainfall-runoff, hydrologic, and hydraulic routing models should be implemented. When more than one model is capable of providing useful and complementary information, use of an ensemble approach to model analysis and forecasting is recommended. In the beginning, simply combining the simulations of multiple models within one display is sufficient. However, long term development will include more advanced comparison and coupling of models for probabilistic or confidence interval forecasting.

- Ability to blend ensemble of simulations to create a single official forecast. **(Medium)**

- Ability to create hybrid / coupled models when creating "official" prediction, e.g. distributed local flow with hydrologic routed flow. **(Medium)**
- Ability to analyze and review historical analog events to assess model biases and river behavior. **(Low)**

8.11 RFC Mosaic

Although every RFC has unique challenges and customer products, there will be users who will want gridded information containing data from multiple RFCs. For most products at the WFO, state or national scale, consistent mosaic procedures and tools will be needed.

- Allow grid mosaic across RFC boundaries. **(Medium)**
- Allow review of the mosaic at each participating office. **(Low)**
- Allow update of the mosaic at each participating office. **(Low)**

8.12 Research

The team considered the need for specific functionalities to support research in a distributed hydrologic model environment. All these topics are “Must Have” priority.

- Ability to perform R&D in the same environment as the operational forecast system to streamline the research-to-operations path.
- Ability to perform R&D in the in the same environment as other research groups in OHD.
- Research on distributed modeling, as well as research on other topics at OHD and at field offices, may require enhancement to CHPS functionality beyond the development of the standard data and model adaptors. Because the primary responsibility for CHPS enhancements will lay with Deltares/Delft Hydraulics and/or Raytheon, OHD will need to define the mechanism by which OHD will make it possible to proceed with urgent requests not immediately addressable by Deltares/Delft Hydraulics or Raytheon.
- Ability to use non-’CHPS’ tools like Matlab, S-Plus, R, etc.
- Ability to use all tools and utilities, such as Calibration, ESP, etc.
- Ability to have partners interact with the ‘CHPS’ model code and with OHD research model code.
- Graphics to support R&D
- Detailed Functional Requirements from the joint HSEB/HSMB/RFC DMS 1.0 project.

9 Unaddressed Operational Concepts

9.1 Short-Term Probabilistic Information

Of particular concern is how RFC operations will need to change to produce short-term (i.e. 0-5 days) probabilistic products such as daily or high-water river flood forecasts. The Experimental Ensemble Forecast System (XEFS) project will provide operational concept details. This section discusses the functional requirements specifically related to the use of distributed hydrologic models in the production of probabilistic information.

- Provide (and later, verify) uncertainty information for all forecasts of all predictants.
- Maintain ensemble metadata throughout the forecast process (what's inside the trace).
- Provide a statistical post-analysis of grid ensembles (e.g. quartiles, median, mode, etc.)
- Provide (and later, verify) uncertainty information for both grid cells and specific points
- Utilize uncertainty information to generate ensembles accounting for each error source (input, calibration, initial state, modeling). Some of the information needs to be provided as "forcing metadata", but some of the information will need to be generated by the distributed hydrologic model system.

9.2 National Grid Operations

As indicated in Table 1, national grid operations were outside the scope of this team's charter and were not addressed in detail. However, the team does recognize that there is an increasing demand from customers and partners for national scale gridded hydrologic information. It was determined that the overriding questions of how this information would be produced, where these products will be produced and the content of these products would fall within the objective of a future team. The current team recognizes the need for RFCs to produce and mosaic consistently formatted gridded products, as many customers (WFOs, municipalities, etc.) receive forecast guidance from multiple RFCs.

9.3 Flash Flood Operations

Currently WFO forecasters have two primary tools to assist in the issuing of localized flash flood watches and warnings to the public in a timely manner with the largest possible lead time and accuracy. The decision assistance tools are Flash Flood Monitoring and Prediction (FFMP) and the Site Specific Hydrologic Predictor (SSHP). FFMP provides a visual comparison of observed and forecast meteorological and hydrologic information over a small basin scale to assess the threat of flash flooding. The meteorological information is currently radar data and is being enhanced to included gridded radar mosaics of QPE and 1-hour QPF. Hydrologic information is the Flash Flood Guidance provided by RFC. SSHP provides a selection of rainfall-runoff models that operate on smaller basins with one-hour time steps allowing the WFO staff to provide more timely and specific stream-based forecasts and warnings to the public.

Flash Flood Operations may dramatically improve with the finer spatial and temporal resolution of distributed hydrologic modeling. The Research Distributed Hydrologic Model is being used operationally in Southern Region RFCs to provide a finer spatial and temporal resolution Flash Flood Guidance to WFOs. This method uses soil moisture estimates from the research distributed hydrologic model to estimate a dynamic Natural Resources Conservation Service (NRCS) Curve Number. The Curve Number is used with the variable threshold runoff (computed from NRCS unit hydrograph and design storms) to compute flash flood guidance on a 4x4 km scale. A limitation of this method is the difficulty in modeling threshold runoff consistently and accurately for interior points. The threshold runoff technique has been developed for a regional scale application, and may not be easily interpolated to interior points due to a lack of field measurements, geomorphologic heterogeneity, and generalization of risk to life and property.

Enhancements beyond generating higher resolution FFG are also being developed. The Distributed Hydrologic Model – Threshold Frequency (DHM-TF) concept offers the ability to produce flow frequency forecasts at all grid points in a model. Forecasters will be able to compare modeled frequencies with locally defined threshold frequencies to determine when warnings are warranted. Local threshold frequency grids may be derived from numerous sources such as known flood frequencies at nearby forecast points, geomorphological surveys, and local engineering design standards. Reed at al. (2007) showed that the threshold frequency approach can inherently correct for model bias and can provide benefits without extensive model calibration[vi]. Also, the DHM-TF method can include cell-to-cell routing to allow creation of flood threat information at scales ranging from one model cell to the RFC basin scale. For implementation, the DHM-TF method will most likely be included in the suite of rainfall-runoff models currently referred to as the WFO SSHP. We can also consider ingesting DHM-TF-based grids into FFMP.

Flash flood operations ultimately require a hydrologic model at the same temporal frequency and spatial resolution as the rainfall estimation available to the WFO. Flash floods can occur very quickly and even today, WFO forecasters rely on the rapid updating of precipitation estimation processes to help determine which areas to warn for. Currently NEXRAD precipitation estimations are made every 5-6 minutes. New data sets will provide 1x1 km resolution precipitation information. To fully support the flash flood program and to accurately reflect the rapid response nature of the flash flood phenomena, distributed hydrologic modeling needs to be conducted at the same scales as the precipitation estimation.

9.4 Verification

The requirements related to verification at gauged forecast locations will not change dramatically as we implement distributed hydrologic models. By definition it is impossible to verify forecasts at ungauged locations. New procedures will be developed to verify new physical elements (e.g. soil moisture, temperature). The Verification Project will provide operational concept details. This section discusses the functional requirements specifically related to verification of distributed hydrologic model information.

- Verify all forecast physical elements (e.g. soil moisture).
- Verify all gauged river locations, not just the ones where forecasts were issued.
- Provide a basis for comparing and verifying "soft data" such as observer-reported storm data or watershed conditions.
- Assess the sources of error, not just an end-result root-mean-square (RMS) error.
- Provide statistics / input for use in calibration process.
- Provide verification statistics that allow model-by-model performance comparison (e.g. "Did lumped model or distributed hydrologic model perform better here last month?").

9.5 Other Operational Details

9.5.1 Hardware and Communication

Proper use of distributed hydrologic modeling requires infrastructure considerations that are beyond the ability of this team's expertise to scope. These include data storage, computer processing power, internal bandwidth, communication security, etc. These requirements must be considered by the follow-on teams that will implement the functionality detailed in this document.

9.5.2 Output Formats and Web Infrastructure

OHD must consider how the end users will receive and use the new products and services that will come from the use of distributed hydrologic models. It may be necessary to interface with the National Digital Forecast Database (NDFD), or create a standalone NDFD-like web service. Infrastructure considerations must be a forethought rather than an afterthought.

10 Follow-On Teams – Charters

This team recommends the formation of two follow-on projects. A gap analysis and implementation project will systematically document gaps between the operations concept laid out here and the current operations in the NWS. In addition, we recommend the formation of a second team centered on the RFCs to promote the actual use of distributed hydrologic modeling in the NWS. This team would produce a collection of RFC case studies using current distributed hydrologic modeling technology. It is important to build expertise, interest, and applications for distributed hydrologic modeling in the RFCs now as distributed hydrologic modeling development continues in OHD.

10.1 "Distributed Hydrologic Modeling Gap Analysis and Implementation Strategy"

Objective:

- Combine new requirements from the Distributed Hydrologic Model Operations Concept Team and existing requirements from the DHM project to create Hydrologic Operations & Service Improvement Process (HOSIP) Gate 2 materials for a CHPS-based Distributed Hydrologic Modeling System.
- Map other requirements from the Distributed Hydrologic Model Operations Concept Team to new or existing HOSIP projects.
- Assess hardware, communication, required to implement distributed hydrologic forecasting at RFCs.
- Assess output formats and web infrastructure required to provide new services based on distributed hydrologic forecasts.
- Develop a road map stating what should be done and in what order. Since resources are unknown, dates are not necessary.

As the baseline system, the distributed hydrologic modeling system should be one that:

- Works in tandem with the CHPS-based lumped modeling system
- Contain / combine the best science existing in NWSRFS-DHM and HL-RHDM
- Be usable to create / derive deterministic forecasts, interior flow forecasts and gridded products
- Work seamlessly with other critical OHD projects such as the Data Assimilator and the Experimental Ensemble Forecast System (XEFS).

The gap analysis should include identification and assessment of existing capabilities, identification of the needs to realize distributed hydrologic modeling, identification and prioritization of the gaps, assessment of current resources available for gap-closing and approximate cost of additional gap-closing measures.

It is understood that the process of developing DHM will be evolutionary and that the project plan must have the flexibility to identify new requirements and shift emphasis and workload as deemed appropriate.

Scope and Authority:

- Recommendations must be readily actionable by OHD and the participating RFCs, leading to formation of the joint development team and kick-off of its activities immediately following this team's activities.
- Analysis must be objective.
- Basis for decisions will be decided on by the team.
- Staff time is expected to be approximately 1 day per week.
- Travel expenses, if needed, will be covered by OHD.

Schedule: The team will complete assigned tasks within 6 months of its inception.

Success Criteria: Successful passage of HOSIP Gate 2 for a CHPS-based Distributed Hydrologic Modeling System, and other related projects, new or existing.

Team Membership:

HSEB (Team Leader)
HSMB
Pedro Restrepo
Other Field or OCWWS/HSD Personnel as needed

Additional personnel from the RFCs, NWS Regions or Headquarters may participate as consultants. The team mentor will be Gary Carter.

10.2 "Distributed Hydrologic Model Case Study" Effort

Vision: River Forecast Center (RFC) forecasters will gain experience with the Office of Hydrologic Development (OHD) distributed hydrologic model (DHM) or research distributed hydrologic model (HL-RDHM). This experience will include setting up the model, calibrating, and running the model. Experience in region specific applications of a distributed hydrologic model gained through this effort will (1) build hydrology expertise in the National Weather Service (NWS), (2) contribute to the longer range intelligent implementation of distributed hydrologic modeling in NWS operations, and (3) improve field collaboration with OHD.

Statement of the Problem: Currently distributed hydrologic modeling is used only in a limited manner for NWS operations. Much of the work done in the research community has focused around distributed hydrologic models for many years. The advent of the nationwide Next Generation Doppler Radar (NEXRAD) platforms and the availability of high-resolution topographic, soil type and land use information has allowed the NWS to move distributed hydrologic modeling from the research environment to the operational environment. While a large amount of research and development work still needs to be done to deliver a model to meet the NWS needs, field expertise is needed now to facilitate implementation of a distributed hydrologic model.

Mission: To build field-level expertise in distributed hydrologic modeling. This will be done through a case study methodology. Each River Forecast Center will perform a case study using one of the OHD distributed hydrologic models to address an issue of local importance. Additionally, by prototyping some of the new products enabled by distributed hydrologic model use, field personnel will build and strengthen ties within the community that will form the basis for future collaboration.

Success Criteria: The initiative will be successful when one representative from each RFC presents a case study to the team and contributes to a report summarizing the results of the case studies.

Scope of Authority / Limitations: The team will formally meet monthly via teleconference and continue informal discussion related to distributed hydrologic modeling via the NWS list server. Team members will be expected to attend any NWS distributed hydrologic model workshop that might be organized to support this effort. Team members will develop expertise with the current distributed hydrologic models supported by OHD.

Membership:
1 member per RFC
Advisors from OHD
Other reps as required

Schedule:
TBD

Appendix A

Distributed Hydrologic Modeling Operations Concept Team Charter

Overview / Background: It is recognized that spatially distributed hydrologic models, in general, may improve upon current hydrologic forecasting capabilities in many situations and are essential to meet new and emerging requirements for water resources prediction. During the past several years, the NWS has been developing hydrologic and computer science capabilities associated with distributed hydrologic modeling and data assimilation. Research and operational prototypes of both distributed conceptual models and distributed physical models have been tested within the organization. Moreover, a wide variety of distributed hydrologic modeling capabilities exist externally.

Objective:

- Develop an operations concept describing how various users (including researchers) would use a coherent and integrated distributed hydrologic modeling, assimilation and prediction capability, which operates across multiple spatial and temporal scales to support regional and local objectives, ranging from water resources prediction, to river and flood forecasting, to flash flood prediction.
- Prioritize the business requirements that are derived from the Operations Concept for this system. Business Requirements describe in business terms what must be delivered or accomplished to provide value. The reason to prioritize the requirements is to create groupings of functionality that can be combined and implemented as discrete units.
- Produce a charter document for a subsequent "Distributed Hydrologic Modeling Capability Gap Analysis and Implementation Strategy" team to be formed upon acceptance of this team's deliverables.

Additional Team Requirements:

- Recommendations must support both the NOAA and NWS mission.
- Recommendations must support the Hydrology Program's goal of integrated water resource services.
- Recommendations must be consistent with OHD's plans for a Community Hydrologic Prediction System (CHPS) infrastructure.
- Analysis will focus on business requirements rather than software design or technical specifications.
- Analysis will focus on how best to implement the science of distributed hydrologic modeling into the existing NWS organizational structure.

Authority:

- Basis for decisions will be decided by simple majority of the team members. Minority opinions may be included in the report at the discretion of the dissenting member or members.
- Staff time is expected to be up to 1 day per week.

- The majority of meetings will be held via teleconference. At least one face-to-face meeting is anticipated.
- Travel expenses, if needed, will be covered by a combination of OHD and the team member's organization.

Termination Date: The team will be formed and commence activities in August 2007. The team shall present a reviewed and approved final report no later than December 15, 2007.

Success Criteria: Presentation to the OHD Director of a field-reviewed and agreed-to concept of operations, prioritization of business requirements for distributed hydrologic modeling, and a charter document for a "Distributed Hydrologic Modeling Capability Gap Analysis and Implementation Strategy" team that will follow up on this team's findings.

Membership: The team will be made of the following individuals. Additional personnel from the RFCs, NWS Regions or Headquarters may participate as consultants.

Team Members	
Pedro Restrepo (Leader)	OHD
Ken Pavelle (Coordinator)	OHD
Kris Lander	CRH
Kevin Werner	WRH
Paul McKee	WGRFC
Dave Streubel	APRFC
Ed Clark	CBRFC
Paula Cognitore	MARFC
Eric Jones	LMRFC
Tom Adams	OHRFC
Mike Smith	OHD/HSMB
Mary Mullusky	OCWWS/HSD

Consultants to the Team	
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Geoff Bonnin	OHD/HSMB
DJ Seo	OHD/HSMB
Seann Reed	OHD/HSMB
Victor Koren	OHD/HSMB
Deb Atkins	OHD/HSEB
Diane Cooper	SRH
Don Cline	NOHRSC

Team Mentor	
Gary Carter	OHD

Responsibilities

Team Members

- Actively participate in all team activities, including teleconference and face-to-face meetings, interim and final document preparation and review
- Vote on decisions that impact the team's process and/or results.
- Solicit and coordinate input from their NWS region
- Report on progress (status, issues) to the Team Leader

Team Leader

- Is also a Team Member
- Lead all team activities
- Report on progress (status, issues) to the Team Mentor

Team Coordinator

- Is also a Team Member
- Schedule all team meetings, conference calls, etc.
- Distribute all materials to team members
- Coordinate preparation and delivery of final documents

Team Mentor

- Provide guidance and direction on the team's purpose
- Solicit input from external reviewers, e.g. Hydrologists-In-Charge
- Accept and approve findings

Consultants

- Provide additional input and guidance as needed
- Actively participate in the review of final deliverables

Appendix B

Acronyms and Glossary

ABRFC	Arkansas-Red Basin River Forecast Center
Calibration	A process of refining model parameters based on observations
CAP	Calibration Assistance Program
CBRFC	Colorado Basin River Forecast Center
CHPS	Community Hydrologic Prediction System
COTS	Commercial Off-The-Shelf Software
DA	Data Assimilation
DHM	Distributed Hydrologic Modeling System
DHM-TF	Distributed Hydrologic Model – Threshold Frequency
EMA	Emergency Management Agency
FFG	Flash Flood Guidance
FFMP	Flash Flood Monitoring and Prediction
GFFG	Gridded Flash Flood Guidance
GIS	Geographic Information System
HAS	Hydrometeorological Analysis and Support
HL	Hydrology Laboratory (part of the Office of Hydrologic Development)
HL-RDHM	Hydrology Laboratory Research Distributed Hydrologic Modeling System
HOSIP	Hydrologic Operations & Service Improvement Process
HRAP	Hydrologic Rainfall Analysis Project
HSEB	Hydrologic Software Engineering Branch
HSMB	Hydrologic Science & Modeling Branch
ICP	Interactive Calibration Program
IDMA	Interactive Double Mass Analysis

IFP	Interactive Forecast Program
LMRFC	Lower Mississippi River Forecast Center
MCP/MCP3	Manual Calibration Program
MODS	Run-Time Modifications to the hydrologic model simulation
MPE	Multisensor Precipitation Estimator
NCEP	National Centers for Environmental Prediction
NDFD	National Digital Forecast Database
NEXRAD	Next Generation Doppler Radar
NMAP	NAWIPS Meteorological Analysis Package
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRCS	Natural Resources Conservation Service
NWP	Numerical Weather Prediction Models
NWRFC	Northwest River Forecast Center
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast Center
OFS	Operational Forecast System
OHD	Office of Hydrologic Development
Pareto Front	Given a set of calibration parameters, an adjustment that can improve at least one part of the calibration without making any other parts worse off is called a Pareto improvement. A calibration is Pareto efficient or Pareto optimal when no further Pareto improvements can be made. A Pareto front or Pareto set is the set of parameterizations (allocations) that are all Pareto efficient.
PET	Potential Evapotranspiration
QPE	Quantitative Precipitation Estimate
QPF	Quantitative Precipitation Forecast

QTE	Quantitative Temperature Estimate
R&D	Research and Development
RES-J	NWSRFS Joint Reservoir Model
RFC	River Forecast Center
RMS	Root-Mean-Square Error
SAC-SMA	Sacramento Soil Moisture Accounting Model
SNOW-17	NWSRFS Snow Model
SSHP	Site Specific Hydrologic Predictor
SOA	Service-Oriented Architecture
STAT-QME	Multiyear Statistical Summary Operation, run in MCP
STAT-Q	Statistical Operation, run in MCP
TIN	Triangulated Irregular Networks
TSCHNG	Time Series Change, a runtime modification
WFO	Weather Forecast Office
WGRFC	West Gulf River Forecast Center
XDMS	A visualization program built specifically for the prototype NWSRFS distributed hydrologic modeling system
XEFS	Experimental Ensemble Forecast System
XMRG	A binary data card format used by NWSRFS for gridded data
XNAV	X-Windows Navigation Animation and Visualization Program

Appendix C

Business Process Diagrams for “Current” and “Future” Processes

[PLACEHOLDER]

Appendix D

References

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