Hydrological Ensemble Forecast Service (HEFS)

Development and Operational Implementation
Uncertainties in hydrologic forecasting

- Inherent uncertainty in weather, climate and hydrologic forecast needs to be quantified and communicated to users

- Aids decision-making
  - Forecasters get objective guidance for level of confidence in forecasts
  - End users can decide whether to take action based on their own risk tolerance
Uncertainty estimates needed across all time scales

Forecast Lead Time

Minutes Hours Days Weeks Months Seasons Years

Benefits

Protection of Life & Property Hydropower Recreation Environment Ecosystem State/Local Planning Flood Mitigation & Navigation Agriculture Reservoir Control Health Commerce

Forecast Uncertainty
Need for Uncertainty Estimates Confirmed

• Consistent feedback from customers and research community indicated the need for this uncertainty information
  – 2006 NRC report
  – 2008 CFI survey

• Study by Aptima (human centered engineering) validated the need for uncertainty information for water managers

• Multiple Internal NWS Service Assessments re-affirmed this need:
  – Red River Floods in 1997 and 2009
  – Central U.S. Floods in 2008
  – Nashville Flooding in 2010
Current Ensemble Capabilities (Long Range)

- RFCs use the Ensemble Streamflow Prediction (ESP) component to produce long-term probabilistic forecasts for water supply applications.

- Limitations of existing operational approach
  - Addresses only the uncertainty in future atmospheric conditions using historical observations of temperature and precipitation
  - Produces primarily longer-term probabilistic forecasts
Current Ensemble Products

"click on" tabs for probabilistic forecasts
Short range Ensemble Forecasting underway at most RFCs

**Met-model ensemble forecast system (MMEFS)**  
- OHRFC, SERFC, NERFC, MARFC

**Ensemble Preprocessor (EPP3) based approach (led by OHD)**  
- CNRFC, CBRFC, NWRFC

"HPC QPF" Approach  
- NCRFC, LMRFC, MBRFC, ABRFC
Push for HEFS Operational Implementation

- Well defined need for providing uncertainty estimates
- Limitations of current NWS ensemble forecasting
- HEFS science development maturing
- Prototype ensemble forecasting underway at RFCs
- CHPS implementation completed in 2011
- NYCDEP requirement for hydrologic ensembles
New York Dept. of Environmental Protection (NYDEP) Project

Water Management for part of NYC water supply system

- Will optimize a decision support system based on retrospective simulation using past forecasts
- Avoidance of building expensive water filtration system
- Better management to limit turbidity violations

Requirements include:

- High Priority
  - Daily time-step ensemble streamflow forecasts with two week lead time
  - Forecast updates daily
  - Hindcasts for retrospective period of several decades
  - Strong (but not perfect) consistency in methods between real-time forecasts and retrospective hindcasts

- Lower Priority
  - Forecast lead times out to one year (or at least to June 1)
  - More frequent forecasts (3-hourly) during flooding
  - Additional forecast variables associated with streamflow ensembles to use for water quality prediction, etc.
NYCDEP OST for Operations Support

**RFC Inflow Ensembles**

**Today’s System**
- Reservoir levels
- Infrastructure status
- Water quality

**Inflow Forecasts**
- Probabilistic forecasts at all system nodes
- Reflect variability in historical record
- Account for today’s basin conditions

**Operating Rules**
- Standard long-term rules
- Modified rules to address today’s issues

**Future Status / Performance Measures**
Look ahead over the coming days/weeks/months at the likelihood of:
- System refill
- Available storage for releases
- Drought conditions
- Turbidity levels
- Alum treatment

**Today’s Decision**
- Which operations best balance water supply reliability, water quality, and environmental objectives?
- How much to divert from each reservoir?
- How much to release from each reservoir?
HEFS Service Level Objectives

• Produce ensemble streamflow forecasts:
  • Seamlessly span lead times from one hour to one year
  • Calibrated (unbiased, accurate spread)
  • Spatially and temporally consistent (linkable)
  • Effectively capture the information from current NWS weather to climate forecast systems
  • Consistent with retrospective forecasts
  • Verified

• Deliver a wide range of products
Uncertainty in hydrologic forecast

\[ \text{Uncertainty in hydrologic forecast} = \]

\[ \text{“Input Uncertainty”} + \text{“Hydrologic Uncertainty”} \]

precipitation,
temperature,
potential evaporation,
etc.

model initial conditions,
model parameters,
model structure,
anthropogenic impacts
(regulation, diversions, etc.)
No specific uncertainty modeling in HEFSv1
Development and Implementation Plan

- Testing and Implementation at 5 test RFCs
  - Development Release 1 – Completed
    - Workshop: April 2012
    - Beta Test: May - Aug 2012
  - Development Release 2
    - Workshop: Sep 2012
  - Development Release 3
    - Workshop: late March 2013
    - Beta Test: early April 2013 – late July 2013
  - Final HEFSv1
    - Operational Readiness Review – early Nov. ’13

- Operational Implementation at 2-5 RFCs by Dec 31 2013

- Operational Implementation at remaining RFCs – 2014
## Current (Seasonal) Ensemble Streamflow Prediction vs. HEFS

<table>
<thead>
<tr>
<th>Feature</th>
<th>Current ESP</th>
<th>HEFS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Platform</strong></td>
<td>National Weather Service River Forecast System (NWSRFS) (inflexible, outdated)</td>
<td>Community Hydrologic Prediction System (CHPS) (flexible, open architecture)</td>
</tr>
<tr>
<td><strong>Forecast horizon</strong></td>
<td>Weeks to seasons</td>
<td>Hours to years</td>
</tr>
<tr>
<td><strong>Input forecasts</strong></td>
<td>Climate outlook forecasts</td>
<td>Short-, medium- and long-range forecasts (HPC/RFC, GFS/GEFS, CFS/CFSv2)</td>
</tr>
<tr>
<td><strong>Uncertainty modeling</strong></td>
<td>Input uncertainty (propagated to hydrologic outputs)</td>
<td>Input uncertainty and hydrologic uncertainty (but w/ room for improvement)</td>
</tr>
<tr>
<td><strong>Products</strong></td>
<td>Limited number of graphical products</td>
<td>A wide array of data (potential for user-tailored products)</td>
</tr>
</tbody>
</table>
Ensemble Forecasting Challenge

- Mesh ensemble forcings from short, medium, and long range techniques.

- Mesoscale wx models
- Medium range wx models
- Long range global circulation models

- Downscaling
- Downscaling
- Downscaling

- Time
- Variable
- Forecaster skill
- Climate forecasts and indexes
Ensure forecast ensembles maintain spatial and temporal relationships across many scales.

Similarly, ensure consistency between precipitation and temperature is preserved in the forecast ensembles.
Meteorological Ensemble Forecast Processor

- **Short-Range**
  - HPC/RFC forecasts ➔ Ensembles (days 1-5)
- **Medium-Range**
  - GFS/GEFS forecasts ➔ Ensembles (Day 1-14)
  - CFSv1/CFSv2 forecasts ➔ Ensembles (out to 8/9 months)
- **Long-Range**
  - Climatology ➔ Ensembles (out to one year)

**Merging** ➔ Calibrated short- to long-range forcing ensembles
MEFP Methodology

Goal: Produce reliable ensemble forcings that capture the skill and quantify the uncertainty in the source forecasts.

Key Idea: Condition the joint distribution of single-valued forecasts and the corresponding observations using the forecast.

- Use forecasts from multiple models to cover short- to long-range.
- Model the joint probability distribution between the single-valued forecast and the corresponding observation from historical records.
- Sample the conditional probability distribution of the joint distribution given the single-valued forecast.
- Rank ensembles based on the magnitude of the correlation coefficients between forecast and observation for the time scales and associated forecast sources.
- Generate blended ensembles (using Schaake Shuffle) iteratively for all time scales from low correlation to high correlation.
Ensemble Forecast Challenge

- Accurately incorporate the impacts of reservoirs and diversions
  - Reservoir models only approximate the actual operator decisions
  - Reliable information about diversions is rarely available
  - Significant impact on "actual" flows
  - Very important to many user groups
Ensemble Forecasting Challenge

- Maintain coherence between deterministic and ensemble forecasts
Ensemble Forecasting Challenges

• There are many other technical ensemble forecasting challenges – that’s another talk

• Some are specific to NWS operations

• Many technical challenges have been solved
Ensemble Forecast Challenge of a different kind

- Provide uncertainty information in a form and context that is **useful to our customers**
  - Education and training
  - Context, validation and verification
  - Compatibility with decision support tools
- Realizing the full utility of this information

*Internal NWS customers (WFOs)*

*External partners and customers (Water Managers, USACE, EMs, local communities, public)*
Forecast Dissemination Process at Short Range

RFC
Flood Forecasts

WFO
Product Generation
Software
* WARNGEN
* RIVERPRO

Users
outlook and/or a watch. When issuing hydrologic products, the use of confidence levels should be similar to those used in other NWS Outlook/Watch/Warning products. The following are guidelines to assist the forecaster in the decision making process:

- Include flood potential information in the Hazardous Weather Outlook (HWO) for 30% or greater chance of hazardous flooding in the 1 to 7-day time frame.
- Issue a Hydrologic Outlook for a 30%-50% chance of flooding and/or where more detail is deemed necessary than what is stated in the HWO. The ESF is not mandatory if the information is adequately presented in the HWO.
- Issue a Flood Watch for a 50-80% chance of flooding.
- Issue a Flood or Flash Flood Warning for an 80% or greater chance of flooding that is expected to reach warning criteria (e.g., flood stage or fast-flowing water at least six inches in depth).
- Issue a Flood Advisory for an 80% or greater chance of flooding that is not expected to reach warning criteria but could cause significant inconvenience, and if caution is not exercised, could lead to situations that may threaten life and/or property.
What is needed for partners?

• Proving the skill/value in these forecasts
  • Verification Information
  • Event specific

• Communicating effectively (understandable, formats, etc)

• Commitment to overcoming hurdles (policy, legislative mandates, bureaucracy, process, education, etc)

• Silver Jackets part of solution?
  • Local knowledge
  • Closer to specific issues/hurdles
Final Comments

• NWS has an established practice of probabilistic forecasting at the long range
  • Producing forecasts, AND
  • Communicating forecasts

• At the short range, NWS RFCs are bringing out ensemble forecasts, but...

• The communication and process challenges may be as difficult as the technical challenges.
Nashville, TN, Apr 30, 2010
MMEFS system OHRFC

GEFSA-based Stage Simulations Expected Value Plot
Cumberland River at Nashville, TN
Forecast for the period 4/30/2010 18h - 5/8/2010 12h Z
This is a conditional simulation based on the current conditions as of 4/30/2010

River Flow
(CFS)

Major Flooding
Moderate Flooding
Flood Discharge

Forecast Window (12 Members)
Forecast Cycle: 20100501 00 UTC
Critical efforts & Challenges

• Primary efforts
  ▪ Ensemble bias-correction: new forecast sources, additional info (ens. spread, atm. indices), other techniques (DA), and forecaster guidance of hydrologic model operation
  ▪ Long-term ensemble reforecasting (~30 years) and verification
    ➢ Collaboration between atmospheric and hydrologic communities

• Challenges
  ▪ Provide uncertainty information useful to users
    ➢ Testing/training and outreach w/ forecasters and users
  ▪ Reduce cone of uncertainty for improved decision support
  ▪ Improve uncertainty modeling of rare events
Ensemble Forecasting Challenge

- Need to maintain *temporal* consistency (for all time steps) and *spatial* consistency (from upstream to downstream basins) across many scales and many forecast variables

![National Map]

![Major River System]

![High Resolution Flash Flood Basins]

- Downstream forecast point
- Precipitation
- Snow Water Equivalent
- Evaporation
- Temperature
New York City Water Supply System

- 3 systems – Delaware, Catskill, and Croton
- 19 reservoirs & 3 controlled lakes
- 2,000 square mile watershed in parts of 8 upstate counties
- Serves 9 million people (1/2 of population of New York State)
- Delivers ~ 1.1 billion gal per day
- Unfiltered supply (Cat/Del)
Operational Issues

• **Complex and aging system**
  – 19 reservoirs
  – Design allows flexibility
  – Infrastructure service
  – New infrastructure
  – Complex rules (DE basin)

• **Multiple Objectives**
  – Water supply reliability
  – Highest quality water
  – Environmental benefits
  – Economic benefits
  – Spill mitigation

*Improved operations by using RFC probabilistic forecasts*
Hydrologic Forecast Needs

Quantify forecast uncertainty for

• Short-range (hours to days)
  ▪ Flood watch and warning program.
  ▪ Local emergency management.
  ▪ Flood control system management.
  ▪ Reservoir management.

• Medium-range (days to weeks)
  ▪ Local emergency management preparedness.
  ▪ Reservoir management.
  ▪ Snowmelt runoff management.

• Long-range (weeks to months)
  ▪ Water supply planning.
  ▪ Reservoir management.
Modeling uncertainty sources in hydrologic forecasting

- Traditional NWS ESP approach for long-term forecasting accounts for the forcing uncertainty *only* based on *climatology*:
  - it uses historical forcing inputs as climatology-based ensembles with current hydrologic initial conditions to propagate input uncertainty into hydro models and generate flow ensemble forecasts

- Needs to be improved to
  - account for forcing *and* hydrologic uncertainty sources -> improve total uncertainty modeling
  - integrate additional forcing input forecasts -> reduce forcing input bias and improve uncertainty estimates
Hydrologic Ensemble Post-Processor: strategy

• Current prototypes for short range (days 1-5)
  – **Probability matching combined w/ auto-regression** (Seo et al. 2006) to process each ensemble trace
  – **Hydrologic Model Output Statistics** approach to process single-valued flow forecasts

• Future approach
  – Other statistical post-processing techniques
    • HEPEX post-processing testbed and workshop (June 2011)
  – Data assimilation (DA) techniques to improve initial condition uncertainty modeling
  – Parametric uncertainty processor, multi-model hydrologic ensembles
MEFP Summary

MEFP aims to produce short- to long-range forcing ensembles at basin scale that are reliable and skillful for hydrological ensemble forecasts.

- Use single-valued/ensemble mean forecasts from *multiple* NWP models (RFC/HPC, GFS/GEFS, CFSv1/v2) to cover short- to long-range lead times.
- Use multiple aggregated events (from 6-hr to 3-month) to capture forecast skill at multiple temporal scales.
- Maintain spatial and temporal correlations in the forcing ensembles across large areas, for all time steps, and for both precipitation and temperature, based on climatological realizations of the variables.
Forcing uncertainty modeling for lumped hydrologic models

- Current approach for meteorological post-processing of HEFSv1 using multiple forecast models
Methodology: Schaake Shuffle

- The spatial variability between two neighboring basins is preserved (in terms of rank correlation) in the forecast ensembles.

For a given time step

<table>
<thead>
<tr>
<th>Year</th>
<th>Basin A Historical ensemble</th>
<th>Basin A Forecast ensemble</th>
<th>Basin B Historical ensemble</th>
<th>Basin B Forecast ensemble</th>
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<tbody>
<tr>
<td>1958</td>
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- Similarly, co-variability between precipitation and temperature is preserved (in terms of rank correlation) in the forecast ensembles.
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Irrational outcomes
NWS Ensemble Forecasting Challenge #5

- Include forecaster guidance of hydrologic model operation

- Hydrologic models require on-going tuning

- Forecasters commonly adjust or influence raw model output
Hydrologic Forecasting Uses

- **Short-range** (hours to days)
  - Watch and warning program
  - Local emergency management activities
  - Reservoir and flood control system management
    *(all deterministic)*

- **Medium-range** (days to weeks)
  - Reservoir management
  - Local emergency management preparedness
  - Snowmelt runoff management
    *(partly deterministic, partly probabilistic)*

- **Long-range** (weeks to months)
  - Water supply planning
  - Reservoir management
    *(mostly probabilistic)*
The need for forecast verification

• All forecasts are imperfect -> need to evaluate the forecast quality and to communicate information to forecast users

• Forecast verification helps answer key questions such as:
  – How good are the forecasts for a given application (e.g. bias, skill compared to a reference forecast system)?
  – What are the strengths and weaknesses of the forecasts (e.g. quality for high flow vs. average flow)?
  – What are the main sources of uncertainty and error in the forecasts (e.g. forcing inputs vs. model states)?
  – How are new science and technology improving the forecasts (e.g. comparing forecasts produced by 2 different systems for same events)?
  – What should be done to improve the forecasts (e.g. target improvements of system components w/ the most expected gain in forecast quality)?
The goals of forecast verification

• Ultimate goal of forecast verification: to provide useful verification information to
  – modelers and forecasters to guide improvements of forecasting system
  – users to maximize utility of forecasts in their decisions

• Verification is useful if the information generated leads to decisions about the forecast/system being verified
  – forecast verification can be developer-oriented or application/user-oriented
Key requirement of forecast verification

- Need to compare observed events with corresponding forecasts for a *large sample*
  - requires *hindcasting* to retroactively produce forecasts from a *fixed* forecast system for multiple years
  - especially true for
    - *new* forecast system (e.g. no existing archive of HEFS forecasts)
    - *ensemble* forecast: probability forecasts are “information rich” and therefore require more data
Additional requirements of forecast verification

• A *variety* of verification metrics should be used to describe the different aspects of forecast quality
  – bias, skill compared to reference, reliability, event discrimination, sharpness (*see COMET module: Introduction to Verification of Hydrologic Forecasts*)

• Quality usually depends on forecast situation/conditions
  – analyze different subsets of events (e.g., above flooding level, below freezing level, by season)

• Quality usually varies strongly with
  - lead time, temporal scale (e.g., 6-hr flow vs. monthly volume), spatial scale (e.g., flash flood basin vs. major river system) -> verification needed for different forecast products
Summary

• Hydrologic ensemble forecasting aims to generate a number of *equally likely traces* of future hydrologic time series to quantify the *inherent forecast uncertainty* and therefore aid decision making.

• Hydrologic ensemble forecasts should quantify both *forcing uncertainty* and *hydrologic uncertainty*.

• Modeling specific uncertainty sources should improve the quantification of the total uncertainty in flow forecasts; therefore HEFSv1 includes:
  – meteorological post-processing (to model *forcing uncertainty*).
  – propagation of forcing uncertainty through hydrologic models.
  – hydrologic post-processing (to model *all hydrologic uncertainty*).

• Forecast verification provides useful verification information to guide system improvements and maximize forecast utility in user applications.

• Forecast verification requires *multi-year ensemble hindcasting* and involves the use of various verification metrics and space-time scales.
HEFS Components
What are they (very briefly)?

- Meteorological Ens. Forecasts Processor (MEFP, formerly EPP3)
  - Generates calibrated precipitation and temperature ensembles that reflect the forcing uncertainty using multiple forecast sources

- MEFP Parameter Estimator & EnsPost Parameter Estimator
  - GUI calibration tools to estimate parameters for MEFP and EnsPost

- Ensemble Post-processor (EnsPost)
  - Produces ensemble streamflow forecasts that reflect the hydrologic uncertainty and have reduced hydrologic model biases

- Ensemble Verification System (EVS)
  - Verification tool for ensemble time series forecasts (e.g. flow, temp., precip.)

- Graphics Generator
  - Creates products for output or analysis
HEFSv1 Limitations

- Limited quality control procedures and tools quickly QCing each component and the final outputs (forecasts)

- Doesn’t account for all sources of uncertainty (e.g. initial conditions – no Data Assimilator)

- Doesn’t account for complex hydrologic conditions, e.g. river regulation and flow timing errors
  - Only as good as the underlying models

- Limited products – We need to gradually build these capabilities for products into defaults for Graphics Generator
HEFSv1 Limitations

- Limited input data sources – RFC, GEFS/GFS, and CFS, with significant work to include more models, such as SREF

- Limited flexibility of the science algorithms

- Limitations of the hydrologic models, e.g. Lag/K routing

- Limited conditions under which the HEFS has been tested
  - Delivered with defaults
  - Diagnostics needed to optimize for different conditions

- No MODS available
Schedule – High Level

- Prior to 2014,
  - HEFS will be provided to just the 5 HEFS test RFCs
  - HEFS will remain outside the CHPS baseline
- Allowances for improving performance
  - Deltares FEWS optimization – funding reduced
  - HW upgrades - no funding from OHD, except for need to support NYCDEP project
    - CHPS to AWIPS move in 2013 - will include HEFS load for HW
- Development Releases on ~6 month schedule
  - Large planned changes in early releases
  - Feedback from testing and RFC into later releases
- HEFSv1 final release to test RFCs – late CY 2013
- Each release
  - Release notes, user’s manuals, & training
- Implementation to all RFCs in 2014
Schedule – cont’d

- **HEFSv1** – no major enhancements after Dev. Rel 3
  - **Operational Readiness Review** – early Nov. ’13

- **HEFS** release to other RFCs & include in CHPS baseline – 2014
  - Workshop for remaining RFCs – date tbd
HEFS implementation: proposed schedule
NYCDEP funding to accelerate HEFS implementation efforts

- July 2011: complete preliminary software design
- **July 2011: provide climatology-based (ESP) reforecasts**
- July 2011 – March 2012: development release 1
  - Detailed design
  - Coding, internal testing, documentation
  - Field testing (**starting in March 2012**) and feedback
- **July 2012: provide experimental ensemble reforecasts**
- April 2012 – June 2013: development releases 2 - N
  - Detailed design
  - Coding, internal testing, documentation
  - Field testing (with each new release) and feedback
- July 2013 – September 2013: **beta test, no major enhancements**
- **September 2013: provide final ensemble reforecasts**
- October 2013 – December 2013: **operational test, only fixes**
- January 2014: **full operations**
New York City Water Supply Issues

- Turbidity issues
- Drought issues
GFS and CFSv1 Forecast Skill

Correlation Coefficient of Forecast and Observation

GFS Precipitation Forecast

CFSv1 Precipitation Forecast

Potential skill of GFS and CFSv1 precipitation forecast for NFDC1 in CNRFC
Uncertainty estimates needed across all time scales

- Uncertainty often increases with increasing lead time
- Uncertainty varies with situation (e.g., weather/climate conditions, hydrologic response of basins) and location
- Necessary to provide forecast uncertainty estimates across all time scales to support various user applications (e.g., protection for flash flooding, reservoir
Short range Ensemble Forecasting underway at most RFCs

Met-model ensemble forecast system (MMEFS)
- OHRFC, SERFC, NERFC, MARFC

Ensemble Preprocessor (EPP3) based approach (led by OHD)
- CNRFC, CBRFC, NWRFC

“HPC QPF” Approach
- NCRFC, LMRFC, MBRFC, ABRFC
Overview

Given the *inherent uncertainty* in weather, climate and hydrologic forecasts, hydrologic ensemble forecasting aims to generate a number of *equally likely traces* of future hydrologic time series to quantify the forecast uncertainty.

This basic theory module is designed to introduce the processes associated with hydrologic ensemble prediction.

Topics include:

I. Motivations for hydrologic ensemble prediction
II. Modeling uncertainty with probability models
III. Quantifying uncertainty sources
IV. Hindcasting and verification
Uncertainty estimates via hydrologic ensemble forecasting

• Ensemble forecasting aims to generate a number of *equally likely* traces of future hydrologic time series
  - these traces can be used as input to a user’s decision support system
  - these traces can be used to make probabilistic statements about the occurrence of future hydrologic events (e.g., probability of flow > flood level)

• Ensemble forecasting relies on probability modeling
  - probability: a measure of the *chance* of an event
HEFS System Architecture

Weather/climate forecasts

Meteorological Ensemble forecast processor

Forcing input ensembles

Verification system (EVS)

Verification products

Input flow data

Streamflow

Hydrologic Ensemble Processor (models)

“Raw” flow ensembles

Post-processed

Product generation system

Ensemble products

No specific uncertainty modeling in HEFSv1

Initial conditions and model parameters (e.g. DA)

Hydrologic Ensemble Post-processor