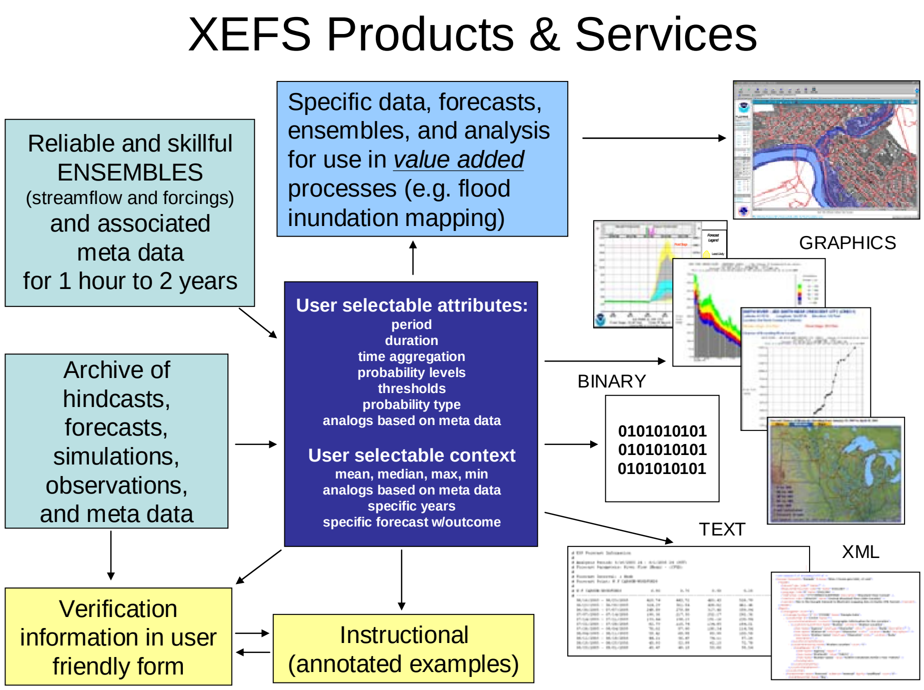
The Experimental Ensemble Forecast System (XEFS) Design and Gap Analysis



Report of the XEFS Design and Gap Analysis Team

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service
Silver Spring, Maryland

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The XEFS Design and Gap Analysis Team

The XEFS Design and Gap Analysis Team was formed in Jan 2007. It was asked to carry out:

1) Design of the Experimental Ensemble Forecast System (XEFS),
2) Gap analysis of existing data, science, techniques, tools, and software, and
3) Planning of development and implementation achievable within 2 years.

The team charter is provided in Appendix A.

The team consists of:

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1 Introduction and Overview

1.1 Background

Ensemble Streamflow Prediction (ESP) has been in operational use by NWS River Forecast Centers (RFC) for over 20 years. The ESP process was designed and implemented within the National Weather Service River Forecast System (NWSRFS) to serve as a long-range probabilistic forecasting tool. Although there are shortcomings, the technique and tools have served the RFCs and their customers quite well.

With the implementation of the Advanced Hydrologic Prediction Service (AHPS), the NWS Hydrology Program has committed to meeting customer requirements for hydrologic forecasts and information, including uncertainty information, at all time scales. Feedback from NWS customers and partners clearly indicates that the provision of reliable uncertainty estimates, particularly at shorter time scales, will dramatically increase the value of forecast services. Additionally, knowledge of forecast uncertainty will provide benefits to the forecast and warning decision processes within the NWS and cost-effective improvement of them.

Implementation of ESP in the short and medium range is considerably different from the long-range application. Long-range uncertainty is dominated by climatic uncertainty. Short- and medium-range ESP must integrate weather forecasts and their uncertainties as well as all significant sources of uncertainty associated with the hydrologic forecasting system and process. Additionally, short- and medium-range uncertainty estimates must be tightly associated with deterministic (i.e. single-value) forecasts issued for the same location and time periods.

Efforts to address the short- and medium-range ESP requirement have been ongoing for several years. Development to date has focused on the generation of reliable forcing ensembles and associated assessment utilities. Four RFCs are currently running prototype software, but the process is not complete or suitable for routine, mainstream operations.

To hasten the pace through which an integrated system of short-, medium-, and long-range ensemble streamflow forecasting capability can be delivered to RFCs, Gary Carter, Director of the Office of Hydrologic Development (OHD), formed and charged the Experimental Ensemble Forecast System (XEFS) Design and Gap Analysis Team in January 2007. The team charter can be found in Appendix A. This report summarizes the findings and recommendations of the Team.

1.2 XEFS Goal

The XEFS team was charged with the design and gap analysis for an integrated short-, medium-, and long-range ensemble streamflow prediction system that can be developed and implemented at RFCs for experimental operation within a 2-year time frame. XEFS is to be viewed as an evolutionary system. While it may not contain all of the desired functionalities, XEFS must be functionally adequate. Additionally, every effort should be made to develop the system and components such that they can be easily transitioned to or compatible with service-oriented architectures (SOA) under consideration by OHD as replacements for NWSRFS.

1.3 XEFS Design

Streamflow prediction and ESP are well developed concepts within the NWS hydrology community. The components of an operational forecast system are relatively easy to identify and diagram. The XEFS team used the system diagram shown in Figure 1.1, developed jointly by OHD and the DOH Science Steering Team (DSST) in 2006 for integrated single-value and ensemble operations, as a basis for the XEFS design.

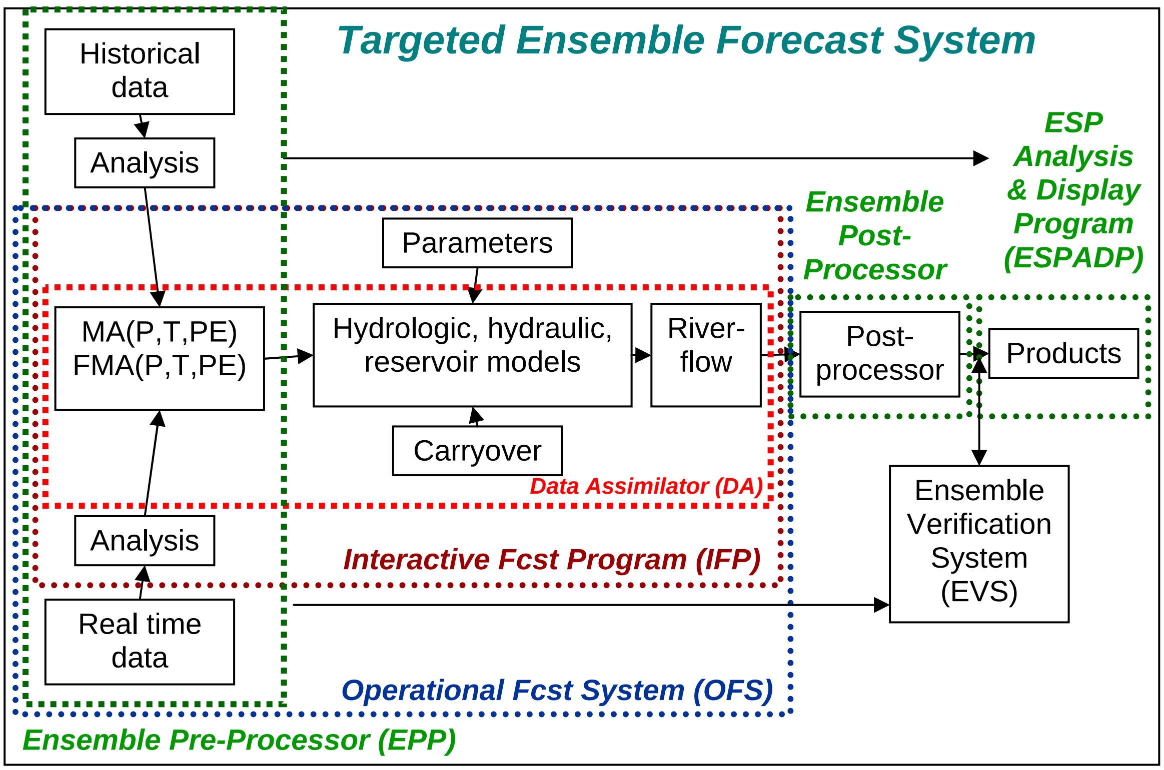


Figure 1.1 XEFS system diagram.

The Team identified the following as the principal components of XEFS:

1) Ensemble Pre-Processor (EPP3)
2) Ensemble Streamflow Prediction System (ESP2)
3) Ensemble Post-Processor (EnsPost)
4) Ensemble Product Generation System (EPG)
5) Ensemble Verification System (EVS)

The version numbers associated with EPP and ESP reflect that operational (experimental or in AWIPS) capabilities currently exist and that new versions are required for XEFS. These components are more easily conceptualized in the workflow diagram shown in Figure 1.2. Throughout this document, gray boxes in workflow diagrams indicate input or output, such as data, parameters, model output or products, to and from operations or applications (white boxes).

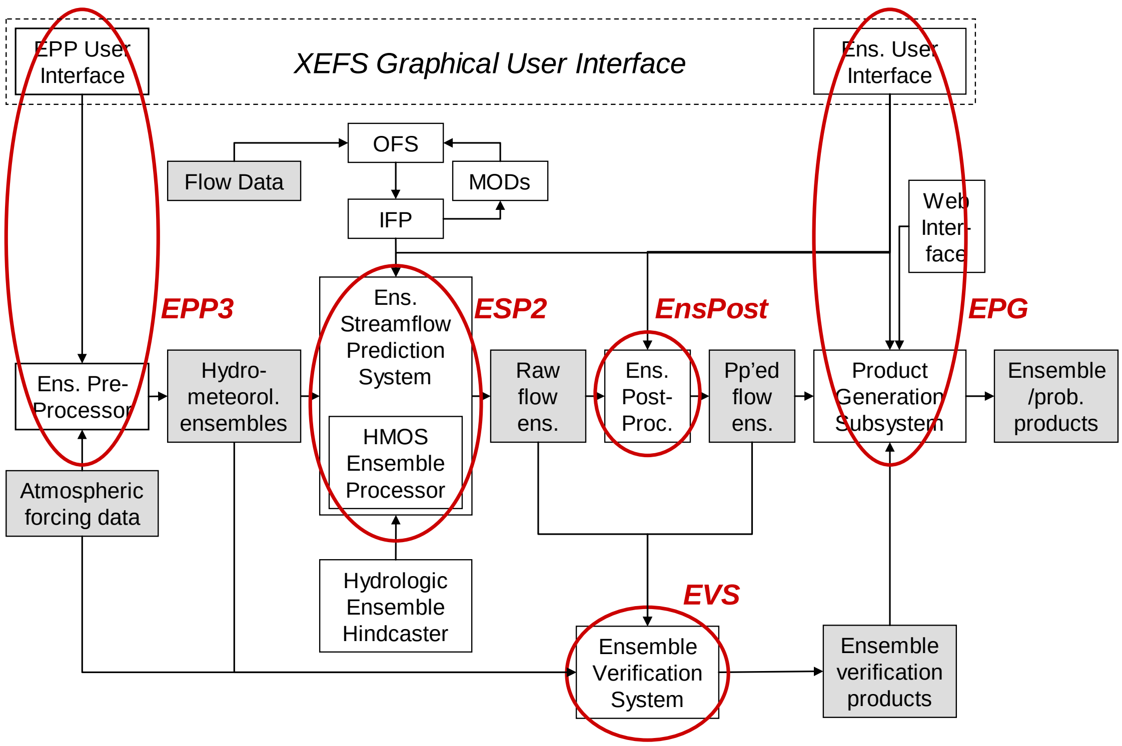


Figure 1.2 XEFS workflow diagram.

1.4 Roadmap for Design and GAP Analysis

The following sections address the design and gap analysis of the five principal components identified above. This includes the baseline functionality, use in operations, identification of current capabilities, identification of science and software gaps, approximate workload, and risks.

As the team worked through and discussed each of the principal components, the notion of Phase I and Phase II developed. In some cases, the team identified capabilities that were important but not essential to an initial (i.e. Phase-I) deployment. In an effort to document and keep track of these features, we also identified Phase-II capabilities for future versions of XEFS.

A key assumption made for Phase I is that the ensemble input and output of XEFS will be stored not in relational database, but as flat files. This is based on the Team's assessment that the current real-time and archive database capabilities are not adequate to handle the volume and traffic of the data involved. As such, it is essential that the formats of all interdependent XEFS input and output files be standardized before multiple teams begin developing the system components.

1.5 XEFS Architecture

XEFS is a large complex system. Advance planning, service-oriented architecture (SOA)-compatible/consistent design of the system, and planned development of integration adaptors are necessary to realize operation-worthy XEFS within two to three years and at the same time enable cost-effective transition to SOA. The Team recognizes that successful evolution of XEFS to a fully operational hydrologic ensemble forecast system (HEFS) will depend critically on the above efforts. To that end, we identified architectural designs of XEFS and its evolutionary end-state HEFS as an essential element of XEFS development. This aspect of Phase I will be critical to cost-effective implementation in the near future of various ensemble data assimilation capabilities under development at OHD and elsewhere.

2 Ensemble Pre-Processor (EPP3)

2.1 Role of EPP3 in XEFS Process

The role of EPP3 is to produce, from all available sources of future forcing information, ensemble forcing forecasts that are reliable, skillful and seamless over the forecast lead time of 1 hour to 2 years and over the spatial scales relevant to the NWS hydrologic services. Figure 2.1 identifies the position of EPP3 in the XEFS workflow diagram. The output from EPP3 serves as the input to ESP2. For Phase I, EPP3 will produce ensemble forecasts of precipitation and temperature only.

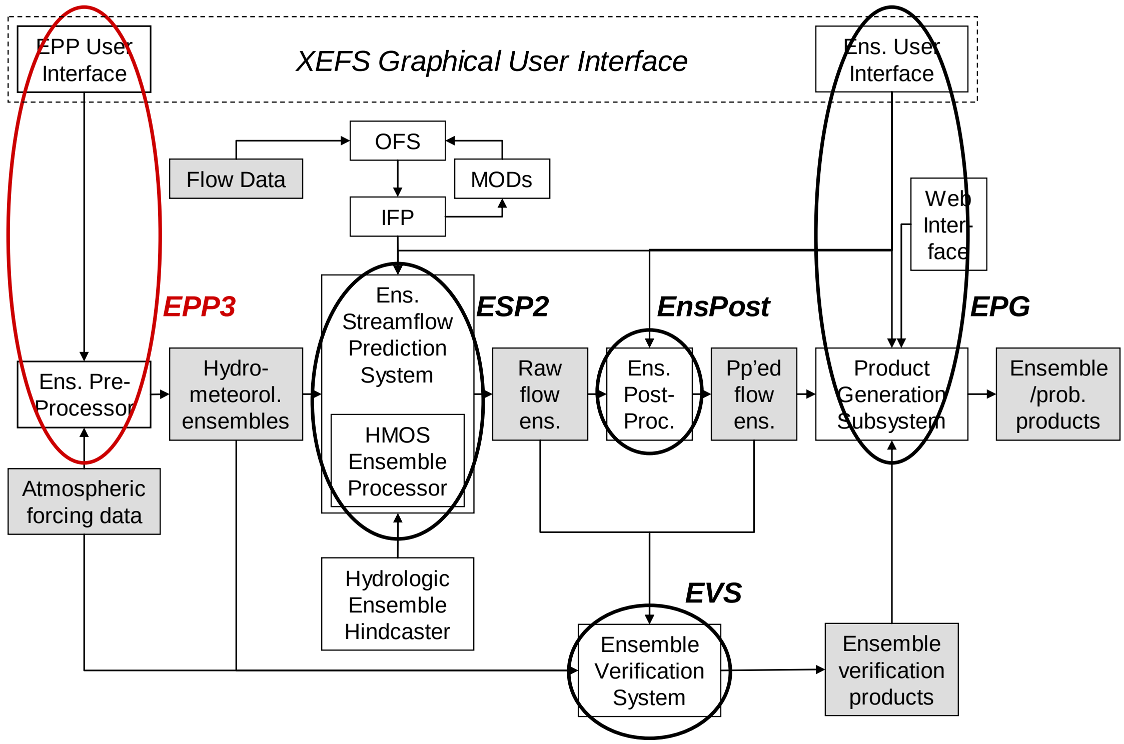


Figure 2.1 Position of EPP3 in the XEFS workflow diagram.

2.2 Functional Requirements

EPP3 has three basic functions:

1) Correct biases in the mean and in the spread so that the resulting ensembles are reliable over the range of space-time scales of interest.
2) Objectively/optimally merge ensembles from multiple sources so that the resulting ensembles are more skillful than the individual ensembles.
3) Seamlessly join/blend short-, medium- and long-range ensembles so that the resulting ensembles are statistically consistent and physically realistic over the forecast lead time of 1 hour to 2 years.

Figure 2.2 shows the workflow diagram for the science algorithm suite of EPP3 in its completed stage (post-Phase I).

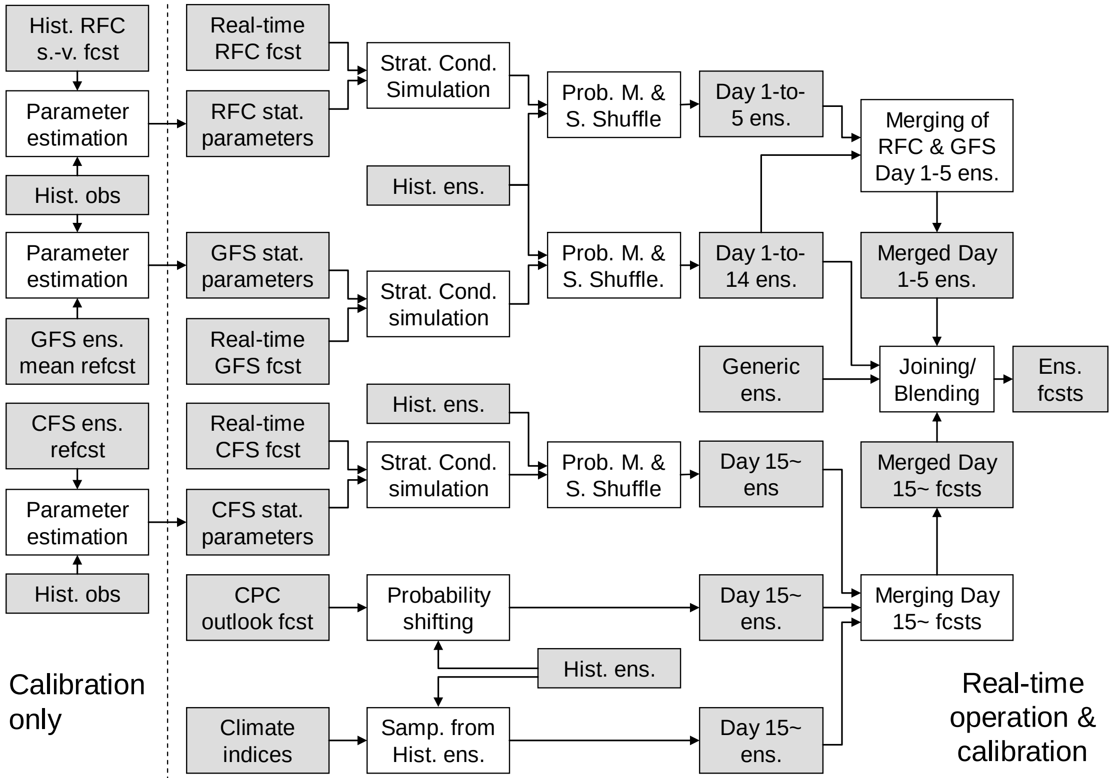


Figure 2.2 EPP3 science algorithm suite workflow diagram.

The basic functional requirements for Phase I are as follows:

1) Generate precipitation and temperature ensembles for lead times of 1 hour to 2 years from HPC/RFC single-value Quantitative Precipitation Forecast (QPF), Model Output Statistics (MOS) T_{min} & T_{max} forecast and NCEP medium- (GFS) and long-range (CFS) ensemble forecasts.
2) Allow ingest of XEFS-formatted ensemble forecasts from other sources, such as the NCEP short-range ensemble forecast (SREF).
3) Allow functionalities for Phase-II integration of NCEP climate outlook forecast.
4) Join/blend short-, medium- and long-range forecasts over the forecast lead time.
5) Operate in both interactive and batch modes.
6) Execute quickly.
7) Operate in both fore- and hindcasting modes.
8) Allow user selection of forcing scenarios, merging, joining, and analysis methods.
9) Allow parameter estimation and calibration.
10) Visualize ensemble traces produced (display capabilities shared with other XEFS sub-components).

Operations Concept

Three types of operations are envisioned for EPP3:

1) Real-time generation of future ensemble forcing,

2) Retrospective generation of ensemble forcing (i.e. hindcasting), and
3) Parameter estimation and calibration.

In fore- or hindcast operation, the forecaster runs EPP3 in a batch or interactive mode through a graphical user interface (GUI). Via this GUI, the forecaster configures the run, selects attributes, executes the run, and monitors the run status. Once the execution is complete, the forecaster displays the precipitation and temperature ensembles, single-value forecasts, ensemble mean, climatology, and verification information. Following review of all available information, the forecaster generates the ensemble forcing fore- or hindcast products.

For parameter estimation and calibration, the forecaster runs the parameter estimation and calibration tools for data processing and analysis, the hindcasting function of EPP3 to generate hindcasts, and EVS for diagnostics. The forecaster may run the parameter estimation and calibration tools interactively or in a batch mode. Through a separate user interface (this might evolve to be integrated into the EPP3 GUI), the forecaster selects attributes for parameter estimation and calibration (e.g. analysis window, choice of techniques), executes and monitors run status, and displays the resulting parameters.

2.3 Current Capabilities

Two prototype applications, the EPP2 RFC Subsystem and the EPP2 GFS Subsystem, currently exist. Both generate short-range precipitation and temperature ensembles from HPC/RFC single-value QPF and MOS forecasts of T_{min} and T_{max}. The GFS Subsystem, in addition, generates medium-range precipitation and temperature ensembles from GFS ensemble mean forecasts of precipitation and temperature out to Day 14. The scientific algorithms used in both subsystems were initially developed by John Schaake and share largely the same methodologies and techniques (Schaake et al. 2007) with the following exceptions. The RFC Subsystem employs different probabilistic and statistical models for the joint relationship between the single-value QPF and the verifying observation to explicitly account for precipitation intermittency and to reduce conditional bias in precipitation ensembles. Prototype parameter estimation programs exist for both RFC and GFS Subsystems.

Currently, no graphical user interface exists for EPP. EPP2 (both the RFC and GFS Subsystems) is interfaced with the user through control files and executed through scripts. The current ESPADP provides ensemble visualization capabilities.

2.4 GAPS

The following gaps have been identified for Phase I:
1) An integrated Ensemble Pre-Processor, EPP3
   - Modular integration of the EPP2 RFC and GFS Subsystems

- Fixed and unified format for precipitation and temperature forecast and observation pairs
- Science enhancements in precipitation ensemble generation to address the conditional bias, intermittency and probability of precipitation (PoP) issues and in temperature ensemble generation to better-resolve diurnal cycle

2) Generation of long-range ensembles from NCEP climate ensemble forecasts
   - Access, ingest and pre-processing of CFS forecast
   - Assessment of skill in CFS forecast
   - Parameter estimation for ensemble generation from CFS forecast
   - Ensemble generation from CFS forecast
3) A graphical user interface, EPP3 GUI
   - To configure the run
   - To select attributes
   - To executes the run
   - To monitor the run status
   - To launch displays
   - To generate products
4) Display capability, EPG
   - To visualize precipitation and temperature ensembles, observations, simulations, single-value forecasts and hindcasts, ensemble mean, climatology, meta data, etc., and verification information
   - To zoom, navigate, perform progressive disclosure, scroll, etc., for review and drill-down examination of short-, medium- and long-range ensemble
5) Parameter estimation and calibration tools
   - To provide assistance for data assemblage, parameter estimation, optimization and diagnostics
   - To configure the parameter estimation and calibration run
   - To select parameter estimation and calibration attributes
   - To executes parameter estimation and calibration
   - To monitor the parameter estimation and calibration run status
   - To launch parameter estimation and calibration displays
6) Training

We envision that the EPP3 User Interface will share a number of functionalities with the Ensemble User Interface, and that the two will need to be merged in Phase II (see also Section 5).

2.5 GAP-Closing Works

The following gap-closing works have been identified:

1) Integration of the RFC and GFS Subsystems into EPP3
   - Integrate selected modules from the RFC Subsystem (parameter optimization, intermittency, ensemble generation) into the GFS Subsystem.
   - OHD (Limin Wu, John Schaake, DJ Seo) to lead, in collaboration with CNRFC (Rob Hartman).

   - OHD, CNRFC and CBRFC to closely coordinate.
2) Development of the EPP3 User Interface
   - CBRFC (Steve Shumate) to lead.
   - CBRFC, OHD and CNRFC to closely coordinate.
3) Integration of climate forecasts
   - OHD (John Schaake, DJ Seo, Satish Regonda, Limin Wu) to lead, in close coordination with CB- and CNRFCs.
4) Development of parameter estimation and calibration tools
   - OHD (Limin Wu, HSEB Team (see Section 7), John Schaake, DJ Seo) to lead, in close collaboration with CB- and CNRFCs.

Development time for EPP3 is estimated at 24 staff-months. EPP3 interacts very closely with ESP2 and shares user interface and graphical display capabilities with other components of XEFS. As such, architectural considerations such as data formats and component interaction processes will have to be established and agreed upon prior to the commencement of work.

2.6 Cross-Cutting Projects

EPP3 cross-cuts with ESP2, EPG and EVS. Development of EPP3 User Interface must be very closely coordinated with development of the Ensemble User Interface for EPG, which will serve as the display tool for EPP3. Ensuring consistency between the single-value forecast and the ensemble forecast is one of the great challenges of XEFS. As such, development of EPP3 must be coordinated with all projects that impact generation of single-value forcing forecasts.

2.7 Risks

EPP3 consists of a large number of input data, and data processing and analysis algorithms. They add to the complexity of the subsystem as a robust integrated suite of data processing and analysis algorithms and as a user-friendly application for routine RFC operations. Use of CFS forecast is a relatively new area of research that may require new thinking, depending on the research findings. Due to the large number of possible scenarios that the forecasters can “build” ensembles from short-, medium- and long-range forecasts, development of a user-friendly user interface will be a large challenge.

2.8 Potential Phase-II Capabilities

The following have been identified for potential Phase-II capabilities:
1) Use of XML (i.e. self-describing) format (rather than, e.g., BFPX).
2) Use of and interface with relational database to extract QPF and observation pairs and temperature forecast and observation pairs, and to output resulting ensembles.
3) Archive capability for long-term ensemble fore- and hindcasts.

4) Development of GUI for parameter estimation and calibration.
5) Use of diurnal cycle-resolving (e.g. hourly) temperature forecast.
6) Incorporation of the NCEP climate outlook forecast.
7) Comparative assessment of skill in CFS and climate outlook forecasts.
8) Objective/optimal merging and joining/blending of short-, medium- and long-range ensembles.
9) Use of PE forecast for generation of PE ensembles.

3 Ensemble Streamflow Prediction System (ESP2)

3.1 Role of ESP2 in XEFS Process

The baseline hydrologic ensemble processor is an essential component of XEFS. This processor fulfills the role of ESP generation. That is, processing the ensemble forcings through the desired hydrologic models in order to produce ensembles of hydrologic parameters such as discharge. Additional considerations are needed to account for the complexities of short-term forecasting and seamless integration of service across time scales. This new tool, or the Next Generation Ensemble Streamflow Prediction Tool, will be referred to as ESP2 in the remainder of this document.

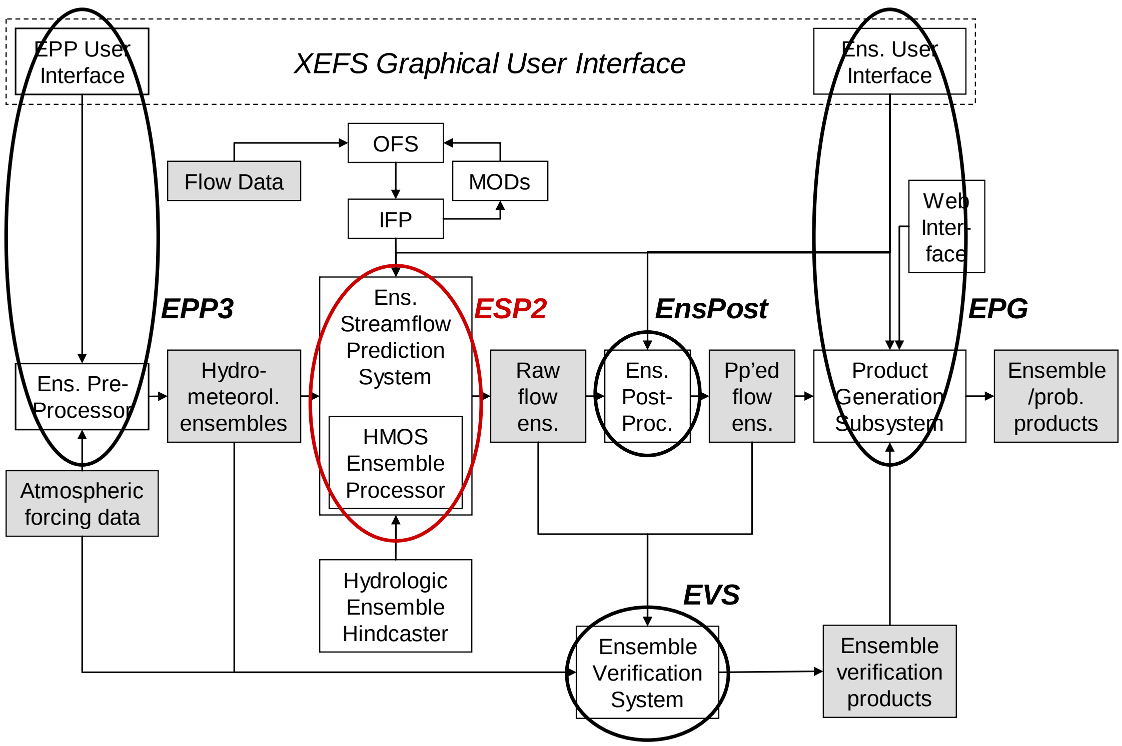


Figure 3.1 Position of ESP2 in the XEFS workflow diagram.

3.2 Functional Requirements

The basic requirements for ESP2 are as follows:

1) Generate hydrologic ensembles from 1 hour to 2 years into the future.
2) Use historical forcings, modified historical forcings, and forcings generated by another system (e.g. EPP3 or numerical weather prediction (NWP) model ensembles).
3) Operate in both fore- and hindcasting modes.
4) Use selected forcing scenarios based on user preference or objective method.
5) Execute quickly in both interactive and batch modes.
6) Execute from a specified carryover dataset.
7) Include the effects of data and state modifications effective between the carryover date/time and the current forecast time.
8) Include the effects of data and state modifications effective in the future.
9) Operate in unison with the interactive forecasting program or equivalent.
10) Emulate all current features of NWSRFS ESP trace generation.

Operations Concept

It's important to visualize how ensemble processing will fit into routine operations, including the flood forecasting process. Given the time frame, the interactive forecast program serves as a reasonable model of work flow in the XEFS era. As now, the forecaster navigates the river topology making appropriate adjustments and modifications which ultimately lead to the issuance of products and services. XEFS simply adds a dimension to the process both in terms of decision support and potential products and information.

As the forecaster views the single-value forecasts, another display will pop-up that provides for analysis and display of the ensembles (both modeling system output as well as forcings). ESP2 resides between the interactive forecast program and the envisioned analysis and display component, the Ensemble Product Generation System (EPG). ESP2 is the ensemble generation engine that uses carryover information (not necessarily the latest, but the set selected by the user of the interactive forecasting system), MODS, and ensembles of future forcings to create ensembles specific to the need identified through the interactive forecast program. In this context, ESP2 can be thought of as an operation, an operation that can be initiated once or more than once per segment. Additionally, there may be times when ensembles are not necessary. At these times, the forecaster will have the option of "switching off" ESP2 and related functions.

Within the analysis and display interface of EPG, the forecaster will be limited to dealing with the element of interest defined by the operation. The operation configuration will provide for defaults which may allow for minimum interaction under most circumstances. Once initiated, the analysis and display function of EPG will provide substantial flexibility in reviewing results and applying various statistical analyses. This includes the ability to look well into the future (i.e. up to two years). ESP2 and the related analysis and display tools of EPG effectively join the single-value forecasting system with the short-, medium-, and long-range probabilistic environment. The impacts of forecasting system changes and modifications on all time domains can be readily assessed and visualized. This function may also allow the user to select optional sources of forcings, weight forcing contributions, and re-run ESP2. Final results from ESP2 will be explicitly available for use in downstream segments.

Additional Modes of Operation

ESP2 must also be capable of batch operation as NWSRFS ESP is today. In this form, ESP2 would use the most recent carryover and apply all effective MODs found in the base set. Controlling configuration would be provided by either control files or through a configuration interface which manages the same.

3.3 Current Capabilities

We currently have at our disposal, NWSRFS. NWSRFS contains ESP. ESP was never designed to work in parallel with OFS and was never intended for short term simulations. While ESP will not meet XEFS requirements, it does provide an established and convenient way of testing XEFS concepts and protocols.

3.4 GAPS

The use of MODs, the fact that carryover can only be stored at 12Z in NWSRFS, and the requirement to operate interactively within an IFP-like environment, renders the existing ESP incompatible with the XEFS vision. Thus, we have a choice. We can adjust expectations or we can develop a new ESP capability that meets the XEFS requirements. All options will be explored.

3.5 GAP-Closing Works

There are essentially four (4) options for developing ensemble generation capability for XEFS. They are:

1) Use the existing ESP capability and reduce expectations.
2) Develop ESP2 as an external operation accessed through IFP using FEWS (a la ResSim).
3) Develop ESP2 as an external operation accessed through IFP directly (a la DHM).
4) Migrate forecasting system to the Community Hydrologic Prediction System (CHPS) and provide ESP2 capability as a feature of this architecture.

Option #1: Reduced Expectations

If one concludes that the cost of developing ESP2 is too high or infeasible, then ESP can be used with significant functional limitations. The most significant limitations relate to carryover and the use of MODs. The only MOD that can be used by ESP is Adjust-Q. When combined with the fact that NWSRFS can only save carryover at 12Z, if may not be possible to maintain coherence between ESP results with the single-value forecast if

MODs are required. This approach would also require addition functional verification to ensure that the current locking mechanisms do not prohibit this approach.

<u>Option #2: Develop ESP2 and access through FEWS (a la ResSim).</u>

This and the following option require the development of a whole new ESP function, essentially from scratch. A significant investment in software closely linked with NWSRFS architecture is probably a poor choice. ESP2 can be developed using a modern language and architecture compatible with envisioned open systems. This is analogous with how ResSim is being linked to NWSRFS. Here, ResSim, a Java application will be adapted to NWSRFS through an operation that interfaces to Delft FEWS. NWSRFS assembles the appropriate information and initiates the external process. It then waits for information to return before proceeding.

Though the investment in ESP2 is quite significant, the use of FEWS makes this approach consistent with our interest in moving toward CHPS. The trick here will be to emulate the FCST program without actually using it. Separation from NWSRFS architecture will avoid problems with file locks, 30 day run length limitations, and the like.

<u>Option #3: Develop ESP2 and access in a custom fashion (a la DHM).</u>

This option shares the requirement of developing ESP2 from scratch (and all of the associated difficulties), but differs in how the application is managed. This approach may be more straightforward, but is less adaptable to the envisioned CHPS environment.

<u>Option #4: Proceed directly to CHPS</u>

For the past 10 years, the NWS has been attempting to move the hydrologic forecasting architecture to a more open system that facilitates cost-effective infusion of new science and technology (i.e. new models, techniques, and data). That effort is now moving ahead in the form of CHPS. Although it is still largely a concept, this strategy is very attractive for XEFS. In a CHPS environment, ESP2 could be developed in a fashion that is (1) unrestricted by traditional NWSRFS constraints (e.g. locks, carryover issues, and 30-day run lengths), and (2) more portable to different computing platforms and environments and amenable to future enhancements.

This option is not a retro-fit of NWSRFS, but instead the creation of XEFS capability in a NWSRFS replacement architecture. In order for RFCs to operationally use XEFS in this environment, they must migrate at least a portion of their operations to CHPS. At this time, OHD is evaluating Delft FEWS as the architecture for CHPS. FEWS already has some ensemble capability, although it has not been fully evaluated. Since the FEWS architecture is open and portable, enhancements to meet XEFS requirements will be less of a problem than in NWSRFS.

Recommended Option: #4

The interaction of ESP with NWSRFS components is very complex and may be problematic in short-term operations. It's entirely possible that a development path including NWSRFS would be abandoned after significant investment if an unanticipated dilemma arises. While much is yet unknown, it seems clear that the NWS will need to move its operations to a more modern and open architecture (e.g. Delft FEWS). An investment in that domain should (1) be adaptable to other SOA forecasting systems, and (2) provides a substantial incentive for RFCs to make the transition. Assuming that a new forecasting system provides for all common operational models (eliminates need to recalibrate) and that short-, medium-, and long-range probabilistic forecasts are supported, the RFCs will aggressively make the transition.

Pending further assessment, refinement and enhancement of existing Delft FEWS ensemble capabilities needed to meet XEFS requirements should take less than 1 year. This development will require key skills and feedback from those involved in ensemble operations. The NCRFC will act as the focal point for guiding this development activity and providing feedback to developers.

3.6 Cross-Cutting Projects

If Option #4 is chosen, ESP2 is fully consistent with all development efforts and energy directed toward CHPS.

3.7 Risks

This component has the following risks:

1) Development of ESP2 that interacts with NWSRFS data, parametric, and model resources will not function properly due to complexities of NWSRFS that no one really fully understands.
2) CHPS is delayed to the point where XEFS cannot be fielded in a reasonable time period.
3) The complexities of enhancing and developing ESP2 capability within the CHPS environment turns out to be as or more complicated than doing the work associated with the NWSRFS architecture.
4) ESP2 within the CHPS environment works fine, but RFCs cannot move to CHPS for other reasons.

3.8 Potential Phase-II Capabilities

If we get Phase I complete under any scenario other than Option #1, it will be a major accomplishment.

Phase I of XEFS only addresses the uncertainty in precipitation and temperature forcings. Uncertainty arises from many other sources, including model structure, parameters and states as well as flow regulations that are not adequately accounted for. HMOS may provide a glimpse of the total uncertainty. Some of these uncertainties may be approximated through the use of EnsPost. Nonetheless, explicit accounting of individual uncertainties will provide the greatest insight into where in the forecasting system and process future investments may result in the biggest benefit. Toward that end, Phase II should include explicit accounting and rigorous reduction of these other uncertainties to the greatest feasible extent and degree. The candidates include, but are not limited to:

1) ensemble data assimilation (DA) to reduce uncertainty in the initial conditions and to keep track of growth (due to accumulation of errors in time and/or through the forecast system) and reduction (due to newly available observations) of uncertainty,
2) the parametric uncertainty processor to reduce and to explicitly account for uncertainty associated with model calibration,
3) multimodel ensemble to reduce the effects of and to account for structural errors in our models, and
4) new techniques for modeling of flow regulations and accounting of uncertainties associated with them.

3.9 Hydrologic Model Output Statistics (HMOS) Ensemble Processor

The ensemble forecasting paradigm that XEFS embraces is to decompose the forcing and hydrologic uncertainties, model them and account for them separately, and combine them later in the processing stream via a numerical application of the total probability law. While the uncertainty decomposition allows accounting of the total uncertainty at all forecast lead times (i.e. from 1 hour to 2 years) and hence the primary methodology of choice for XEFS, this paradigm requires separate modeling of both forcing and hydrologic uncertainties. The Team recognizes that, for short-range streamflow ensembles, a simpler, MOS-like approach may be possible that directly accounts for total uncertainty by developing statistical relationships between the forecast flow and the verifying observed flow. From the statistical relationships that are derived specifically for each forecast lead time, short-range streamflow ensembles may be generated that correct systematic biases in the single-value flow forecast and capture the skill and total uncertainty therein. This simpler methodology is herein referred to as the HMOS Ensemble Processor, or HMOS for short. Strictly speaking, HMOS is more than the conventional MOS in that it also uses the most recently available flow observations analogously to the Adjust-Q operation. As such, it may be seen as a combination of MOS and a statistical Adjust-Q technique. As is with any MOS-type techniques, HMOS is applicable only at those service locations where “long-term” archive of model stage/flow forecast and verifying observations is available.

3.9.1 Role of HMOS in XEFS Process

HMOS is an alternative short-range flow ensemble generator that is a part of ESP2. Accordingly, it is controlled and interfaced with other components of XEFS by and alongside the ESP2 process, respectively. Figure 3.2 shows the position of HMOS in the XEFS workflow diagram.

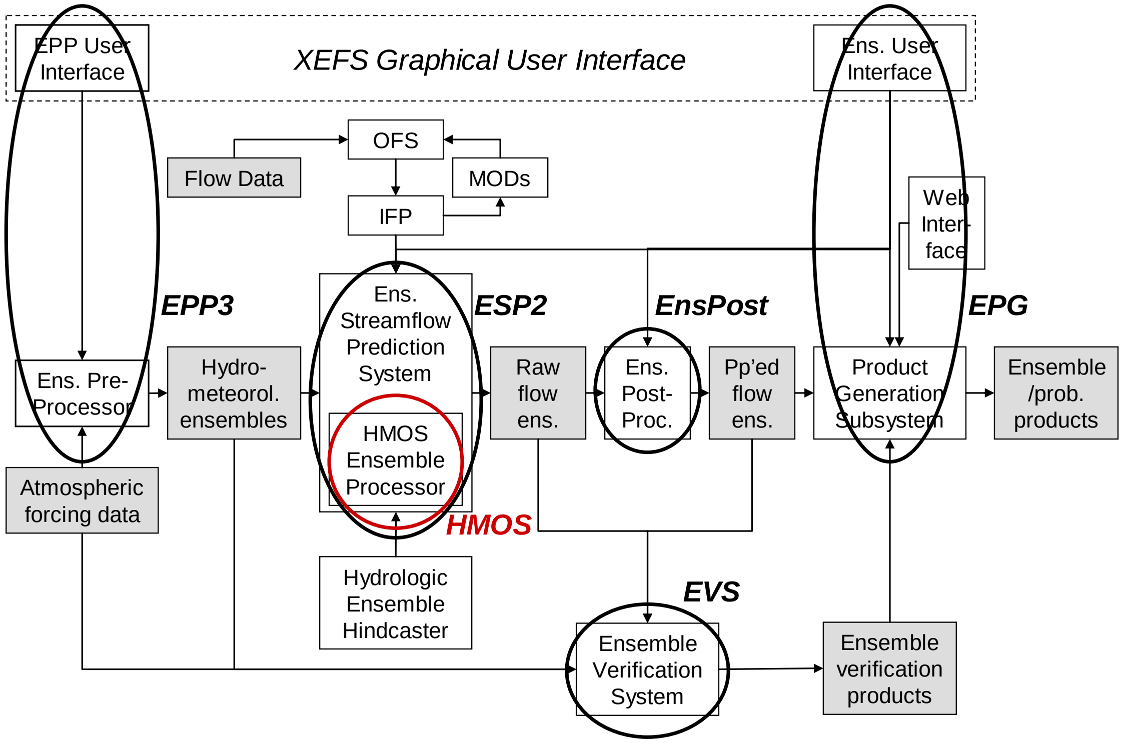


Figure 3.2 Position of HMOS is the XEFS workflow diagram.

Development of ESP2 that seamlessly interfaces with the single-value forecast process, including accounting of all MODs, is a large challenge. HMOS may be viewed as an ESP2 stopgap for short-range ensemble streamflow forecasting in that the statistical relationships for HMOS already reflect the final single-value flow forecast that incorporates all MODs (but only for locations with available archive of forecasts and observations).

3.9.2 Functional Requirements

Figure 3.3 shows the HMOS workflow diagram. As will be seen, HMOS shares a number of functionalities with EnsPost (cf Figure 4.2), an aspect that will be exploited for rapid development from the existing prototype EnsPost.

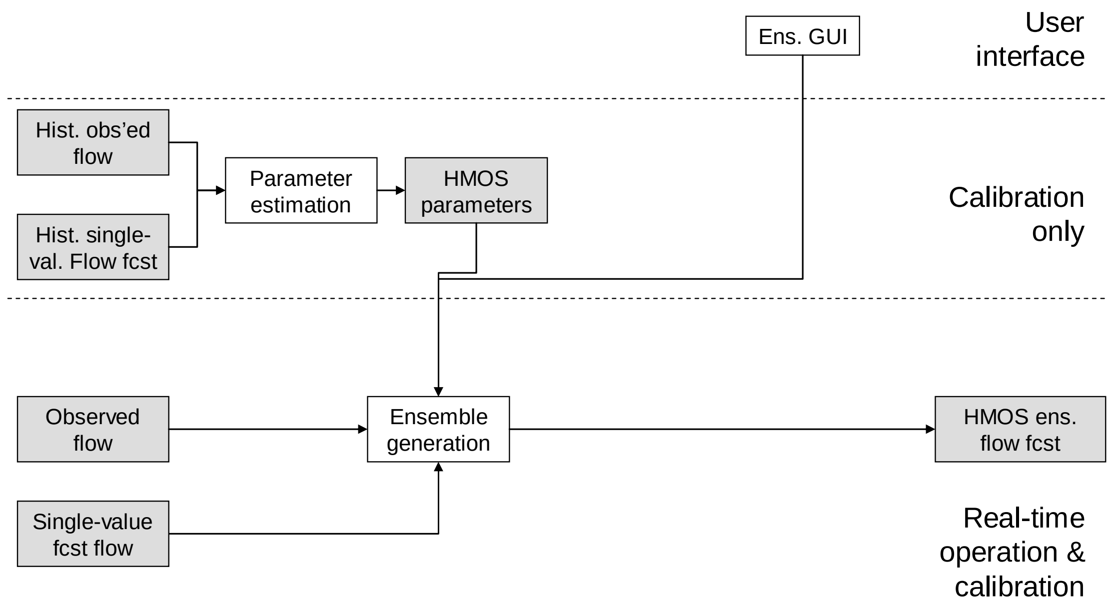


Figure 3.3 HMOS workflow diagram.

The basic functional requirements for HMOS are as follows:

1) For calibration
   - Ingest historical observed and forecast flows for each forecast lead time.
   - Perform statistical analysis, parameter estimation and calibration.
   - Output statistics and calibrated HMOS parameters.
2) For real-time operation
   - Ingest the most recent flow observations and the single-value flow forecast out to the user-specified short-range forecast lead time.
   - Ingest the pre-calculated statistics and calibration parameters.
   - Generate flow ensemble traces via conditional simulation.
   - Allow the user to specify ensemble generation attributes.
   - Allow the user to view and examine the resulting ensembles, single-value forecast and observed flow.

<u>Operations Concept</u>

The same operations concept as ESP2's applies; HMOS operates as an additional option or alternative for generating short-range flow ensembles in ESP2.

3.9.3 Current Capabilities

Currently, there is no HMOS capability, operational or developmental. A number of potentially shareable modules, however, exist in the current prototype EnsPost and the EPP2 RFC Subsystem.

3.9.4 GAPS

1) Tools for parameter estimation and calibration.
2) HMOS ensemble processor for real-time operation,
3) User interface and display capabilities.
4) Training.

3.9.5 GAP-Closing Works

1) Tools for parameter estimation and calibration
   - OHD (Satish Regonda, DJ Seo) to develop a prototype in collaboration with ABRFC (Bill Lawrence)
2) HMOS ensemble processor for real-time operation
   - OHD (Satish Regonda, DJ Seo) to develop a prototype
   - ABRFC to develop prototype data ingest and output capability
3) User interface and display capabilities
   - To be carried out as part of development of the Ensemble User Interface for EPG, which also serves as the display tool for HMOS

Development time for HMOS-specific Phase-I capabilities is estimated at 12 staff-months.

3.9.6 Cross-Cutting Projects

Being a part of ESP2, development of HMOS must be connected to the overall development of ESP2, including the user interface and display capabilities.

3.9.7 Risks

The quality of HMOS ensembles will depend largely on the data availability for parameter estimation and calibration. Availability of historical archive of flow forecast and verifying observations varies greatly from RFC to RFC and among different RFC forecast points. Applicability of HMOS at the national scale in this regard is not yet clear. In areas where rapid snowmelt is important, additional stratification of the data will be necessary, which would require a significantly larger data set.

3.9.8 Potential Phase-II Capabilities

The following have been identified for potential Phase-II capabilities:
1) Scientific and functional improvements to parameter estimation and calibration, ensemble generation, user interface and display.
2) Joining/blending of HMOS ensembles with the observed traces.

4 Ensemble Post-Processor (EnsPost)

4.1 Role of EnsPost in XEFS Process

The raw streamflow ensembles from ESP2 are usually biased in the mean and in the spread due to hydrologic uncertainties from various sources. The role of EnsPost is to render the raw flow ensembles reliable by correcting these biases. Figure 4.1 shows the position of EnsPost in the XEFS workflow diagram.

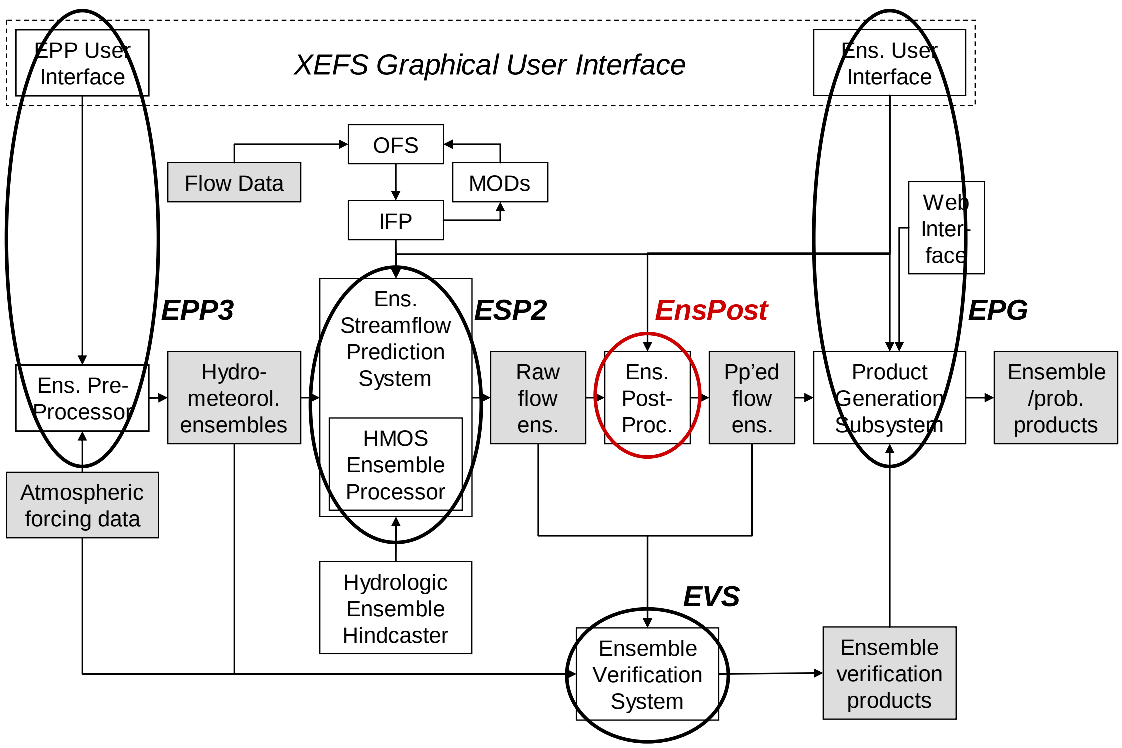


Figure 4.1 Position of EnsPost in the XEFS workflow diagram.

4.2 Functional Requirements

Figure 4.2 shows the workflow diagram for EnsPost.

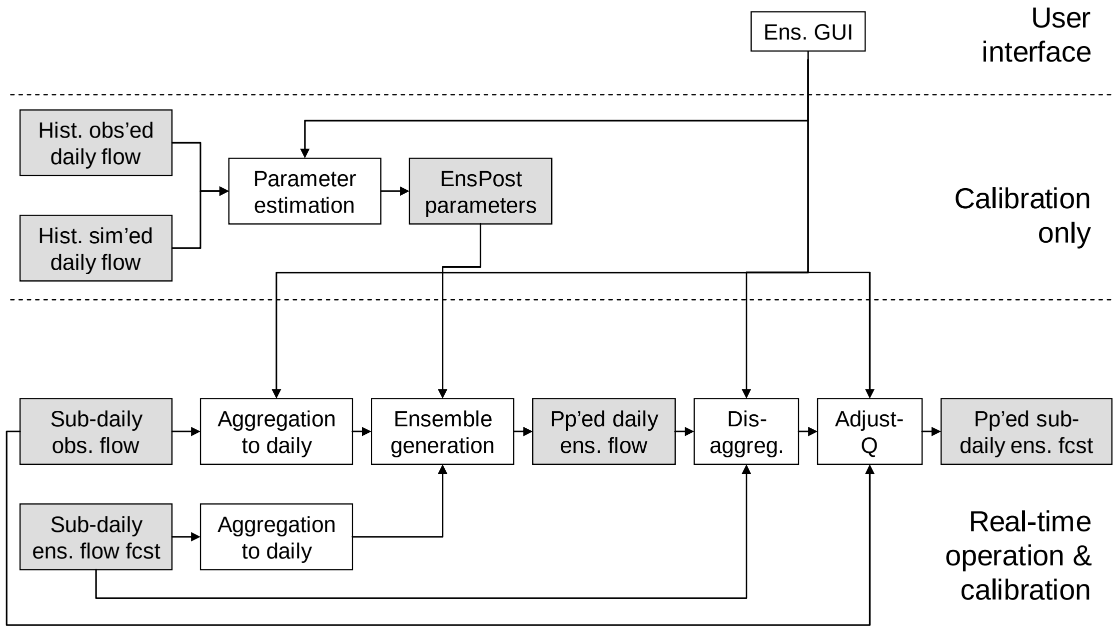


Figure 4.2 EnsPost workflow diagram.

The basic functional requirements for Phase I are as follows.

For calibration:
1) Ingest historical observed and model-simulated flows.
2) Estimate statistics and optimize parameters for the statistical prediction model.
3) Output the statistics and optimized parameters.
4) Visualize the calibration results.
5) Repeat 2) through 4) if necessary.

For real-time operation:
1) Visualize the raw ensemble forecast and observed flow.
2) If the raw ensemble forecast is deemed to be of high quality, skip post-processing.
3) If not, post-process as below.
4) Ingest statistics and parameters from calibration, raw ensembles of forecast flow from ESP2, and observed flow.
5) Aggregate the sub-daily flows to mean daily.
6) Select the type of post processing: deterministic or stochastic.
7) Perform post processing.
8) Disaggregate the daily flows to sub-daily and perform Adjust-Q if desired.
9) Output and visualize the post-processed flow ensembles.

<u>**Operations Concept**</u>

1) Parameter estimation and calibration

Similarly to traditional model calibration, the forecaster performs, through user interface and display tools, estimation of the statistics necessary and calibration of the parameters of the statistical prediction model. The forecaster reviews the results, and terminates or performs additional calibration.

2) Real-time operation

The forecaster may keep EnsPost turned on as a default, or turn it on interactively only for specific forecast points and for specific conditions where, based on review of the raw flow ensembles and verification information, the forecaster judges that EnsPost may improve reliability of the raw flow ensemble forecast.

4.3 Current Capabilities

A prototype ensemble post-processor currently exists (Seo et al. 2006). An earlier version of the processor was implemented in AWIPS several years ago to support (long-term) ESP. It is known, however, that the AWIPS version of the calibration component of EnsPost does not produce the same results as the research version. The current version of EnsPost supports only a daily timestep, rather than sub-daily, due to general lack of availability of sub-daily historical data necessary for calibration.

4.4 GAPS

The following gaps have been identified for Phase I:
1) Adjust-Q capability
2) Development of guidance for use with Adjust-Q and/or MODs
3) Improved bias and uncertainty correction
4) Disaggregation of daily to sub-daily flow
5) Assessment of sample size requirement (i.e. number of ensemble members needed)
6) User interface and display tools for parameter estimation and calibration
7) Training

4.5 GAP-Closing Works

1) Enhancement of the existing prototypes for calibration and real-time operation
   - OHD (Satish Regonda, DJ Seo, HSEB Team) to lead in coordination with ABRFC (Bill Lawrence)
2) User interface and display tools
   - To share with the Ensemble User Interface for EPG, which also serves as the display tool for EnsPost

Development time for EnsPost-specific capabilities is estimated at 12 staff-months.

4.6 Cross-Cutting Projects

EnsPost cross-cuts with ESP2, EPG and EVS, and may share common modules with HMOS. Calibration of EnsPost amounts to statistical calibration of the hydrologic models and hence should be considered as an extension of the traditional hydrologic model calibration process. As such, development of EnsPost needs to be coordinated with enhancement projects for traditional calibration tools.

4.7 Risks

As with HMOS, the potency of EnsPost depends largely on the availability of long-term observed and model-simulated flows, and the degree to which the assumption of stationarity in the streamflow climatology holds over a multi-decadal period. Similarly, in areas where snowmelt is important (e.g. rain on snow), additional stratification of the available data will be necessary, which would require a significantly larger data set for parameter estimation and calibration.

4.8 Potential of Phase-II Capabilities

In Phase I, EnsPost will be based on statistical modeling of daily flow only. For areas where observed and model-simulated flow data are available at sub-daily scales (6-hourly or hourly), direct modeling of the sub-daily flow will be necessary in Phase II for improved performance.

An ideal situation for EnsPost is that hydrologic uncertainties are dealt with to a sufficient degree by a combination of automatic data assimilation (post-Phase I) and manual forecaster MODs in the forecast process so that the errors in the raw flow ensembles are largely uncorrelated in time (i.e. “white”). In such a case, the role of EnsPost would simply be to inject additional noise into the raw flow ensembles to account for the unexplained/unexplainable uncertainty. As such, unlike the other components in XEFS, improvement in the forecast process is expected to reduce complexity of EnsPost over time.

5 Ensemble Product Generation System (EPG)

5.1 Role of Product Generation in XEFS Process

The generation of products and the delivery of service is an essential component of XEFS. The requirements for this component were developed by the team up front to ensure that the other components satisfy the requirements for product generation and delivery and information content therein. The Ensemble Product Generation System (EPG) fulfills several important roles:

1) Performs statistical analysis of ensembles.
2) Generates products and information for customers and partners.
3) Generates information and visualization for internal decision support including flood forecasting.
4) Integrates with verification system to provide context information such as reliability relative to the specific product requested/generated.

The EPG is composed of the Product Generation Subsystem, the Ensemble User Interface which provides convenient selection of product attributes and analysis techniques, and the web interface which provides the NOAA customers and partners with access to the Product Generation Subsystem for flexible generation of acceptable user-specified products. The Ensemble User Interface is an internal asset.

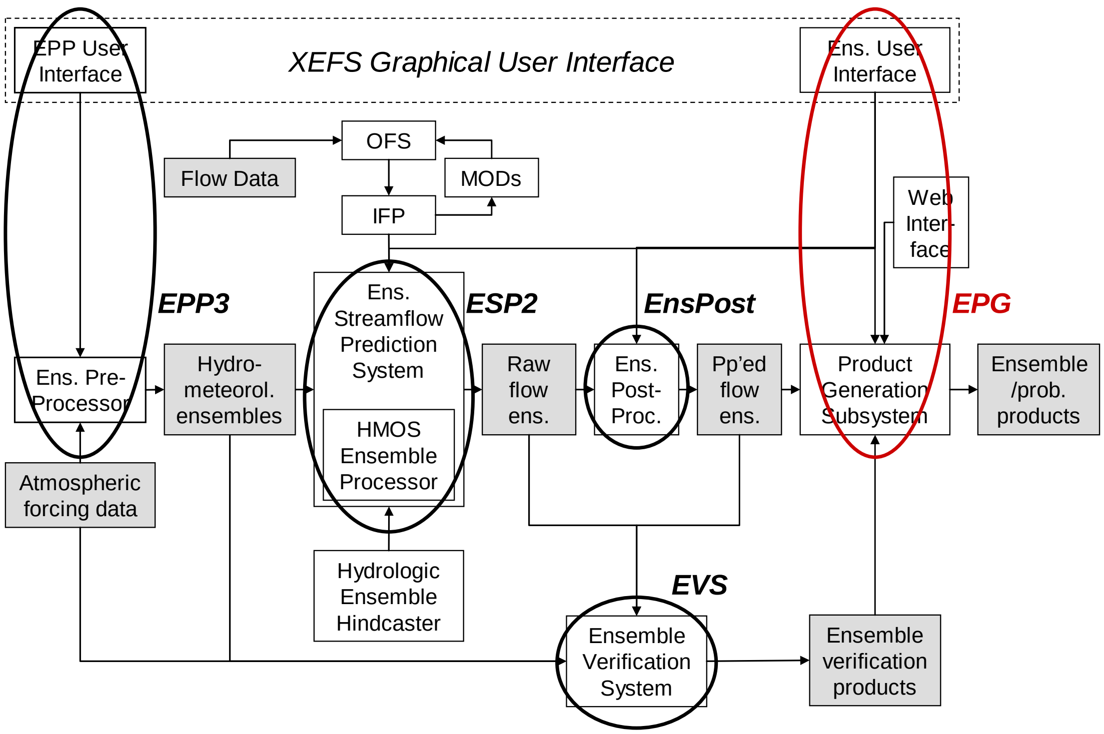


Figure 5.1 Position of the Product Generation System in the XEFS workflow diagram.

5.2 Functional Requirements

<u>**Supporting Information**</u>

EPG relies upon and assumes the existence of:

1) reliable and skillful ensembles of streamflow and forcings and associated meta data for 1 hour to 2 years into the future, and
2) an archive of hindcasts, forecasts, simulations, observations, and meta data.

Neither of these data resources is simple to generate, organize, or maintain. The details of the data resources architecture is a cross-cutting activity for the XEFS design. Additionally, reliable and skillful ensembles will, in most cases, require some sort of post-processing actions to ensure that the statistical character of the information is appropriate. The EPG must be capable of tracking and noting post-processing techniques when developing products and information (i.e. preserving meta data).

Generalized Schematic

Figure 5.2 shows a generalized schematic of the XEFS Ensemble Product Generation System (EPG).

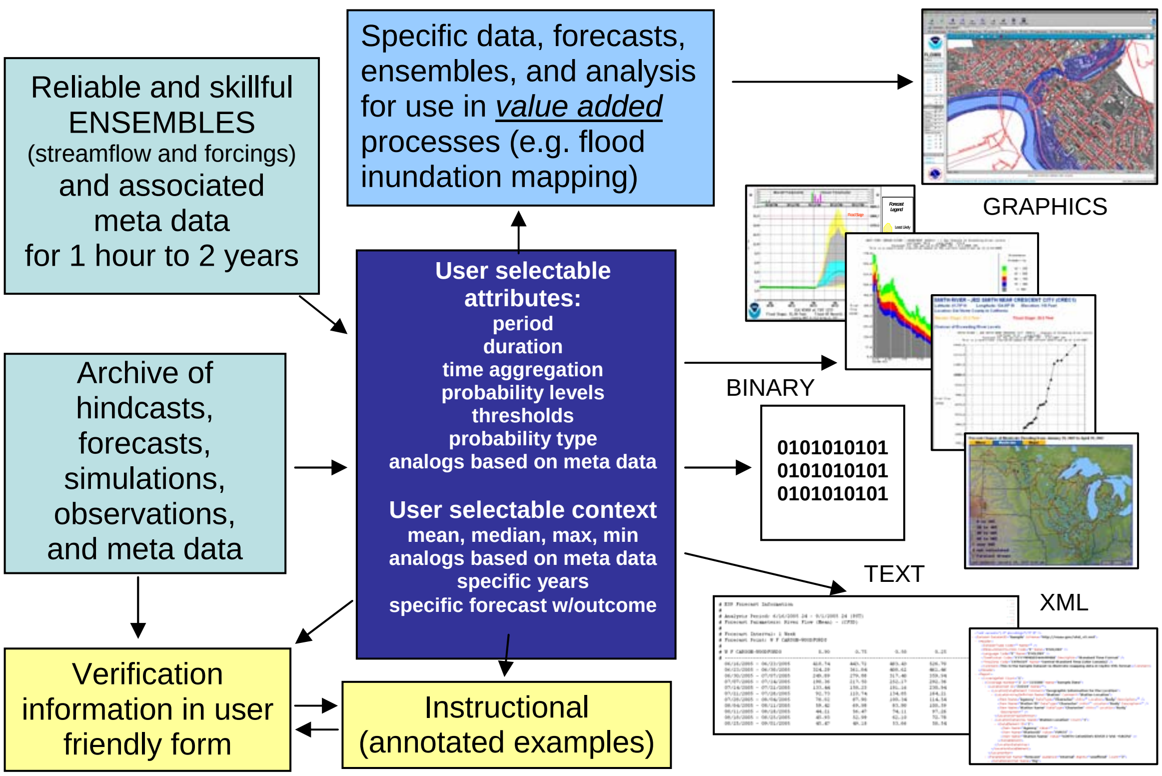


Figure 5.2 Generalized schematic of Ensemble Product Generation System (EPG).

Modes of operation

The EPG must be capable of multiple modes of operation. It must serve as a resource to forecasters and developers as well as NWS customers through web service interfaces. Components of EPG will also function within the operational forecasting environment to provide decision support to forecasters. EPG must be accessible then through at least three types of interfaces:

1) Batch operation

   The sheer volume of products associated with AHPS requires the mass production of many products. Operations in the XEFS environment will have similar requirements.

2) An interactive GUI (Ensemble User Interface)

   Internal interaction with EPG will be provided through the Ensemble User Interface. Interaction with operational staff is envisioned in at least two forms. First, EPG will behave similarly to ESPADP with navigation to various observed and simulated time series. The analysis and display options will be dramatically expanded based on the stated requirements. This process can be used for review or specialized product generation.

   Second, EPG must provide interactive support to the interactive forecast program. In this case, the Ensemble User Interface will pop-up for the defined time series, instruct the Product Generation Subsystem to perform the configured analysis, and display the configured plot. By default, plots will show observed and forecast values within the time domain of the interactive forecast program. Reviewable time series will be limited to those relevant to the segment. Time scales will be viewable through the end of the ensembles generated by ESP2 (i.e. 2 years). This capability will allow forecasters to (1) see the probability associated with their single-value forecast and (2) see and understand the impacts of forecast system changes (i.e. MODs) on the ensembles and XEFS products.

3) Web-based services

   It is critical that we provide our knowledgeable customers with access to flexible product generation. The EPG is ideally suited to meet our customer's requirements. The Product Generation Subsystem of EPG will need to be accessible through NWS web pages in order to properly support customer needs for probabilistic flood and water resources information. The Ensemble User Interface for external customers will be a webpage that allows for configuration and display of specific products. Available options and combinations will be limited to those that make sense.

EPG products themselves will not be subject to modification through the provided interfaces. Modification of products must be done through reselection of product attributes and context.

User Selectable Attributes

The power of ensemble analysis lays in the flexibility to assess information and develop analyses in a multitude of fashions. Users must be given full flexibility to develop products and information important to them. Time aggregation, period, and duration should be flexible to the extent of the original ensembles. Users should also have the ability to assess low flows, peaks, and measures relative to critical thresholds. Analysis attributes relative to probability distribution selection, probability levels, and ensemble selection and weighting based on choice or meta data should be available. The team also agreed that the selection of some analysis attributes may lead toward misleading or questionable products. As such, user selectable analysis attributes for external customers would be limited to those known to produce reliable products and information.

User Selectable Context

Context is something that tends to be missing from many hydrologic products but has the potential to vastly improve the value and assist in the interpretation of our information. Context may come in the form of statistical moments, analogs, or comparison with specific years of interest. Context may also be provided by validation results of a specific event or forecast that includes forecast(s) and realized observations.

The application of context will be product- and format-specific, but in all cases should be a selectable option by the user if appropriate and available.

Types of Output

The EPG must be capable of producing text, binary, graphical, and XML output. Sample products can be seen in Figure 5.2. They are by no means comprehensive but representative. In addition, the EPG must be capable of accessing and integrating verification information in an understandable context related to the specific product generated. Annotated examples from EPG will serve as aids in training for both staff and customers and partners.

It should be noted that the generation of probabilistic flood inundation maps is considered beyond the scope of the Phase-I XEFS design. XEFS will provide ensembles which may be used by other value-added processes to develop this type of information.

5.3 Current Capabilities

Current capabilities consist of the ESP Analysis and Display Program (ESPADP), and a variety of locally developed software running at several RFCs. ESPADP has been an extremely successful and useful tool for RFCs and for AHPS. ESPADP delivered the ability to generated products and visualize ensemble information in a very effective fashion. Many features of ESPADP will be useful in the design and development of the EPG.

Locally developed RFC product development software provides insight into and examples of products we may want to consider delivering as a part of XEFS. In particular, the ability to optionally include context information when viewing single-value forecasts and model results, a capability desired for EPG, is seen in Figure 5.3 below.

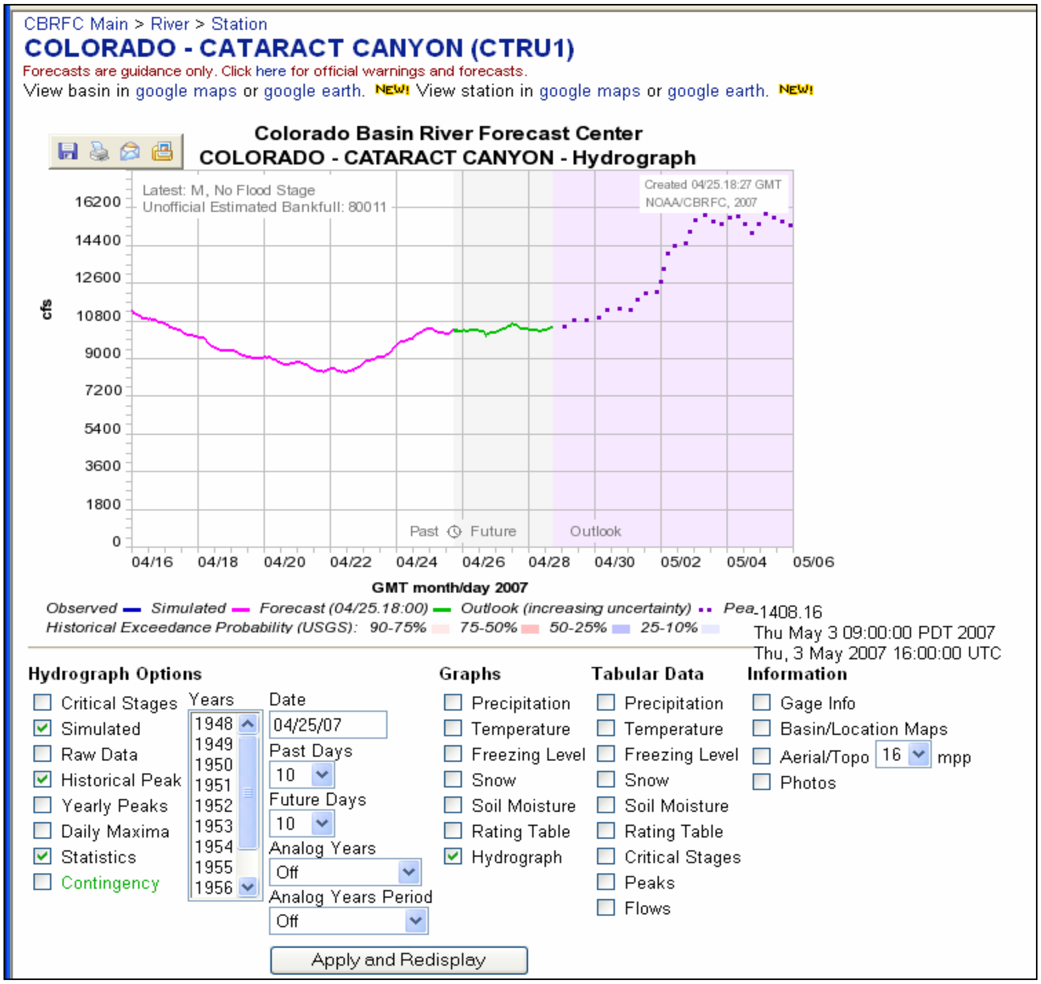


Figure 5.3 An example of providing context information alongside the single-value forecast.

Allowing customers to configure ESP products and information is a key component of delivering XEFS service. Several RFCs currently allow customers to configure their ESP products in a limited way through web interfaces such as shown in Figure 5.4. This sort of capability assumes that the EPG is accessible in some fashion via the Internet and that needed data resources are also available in that environment.

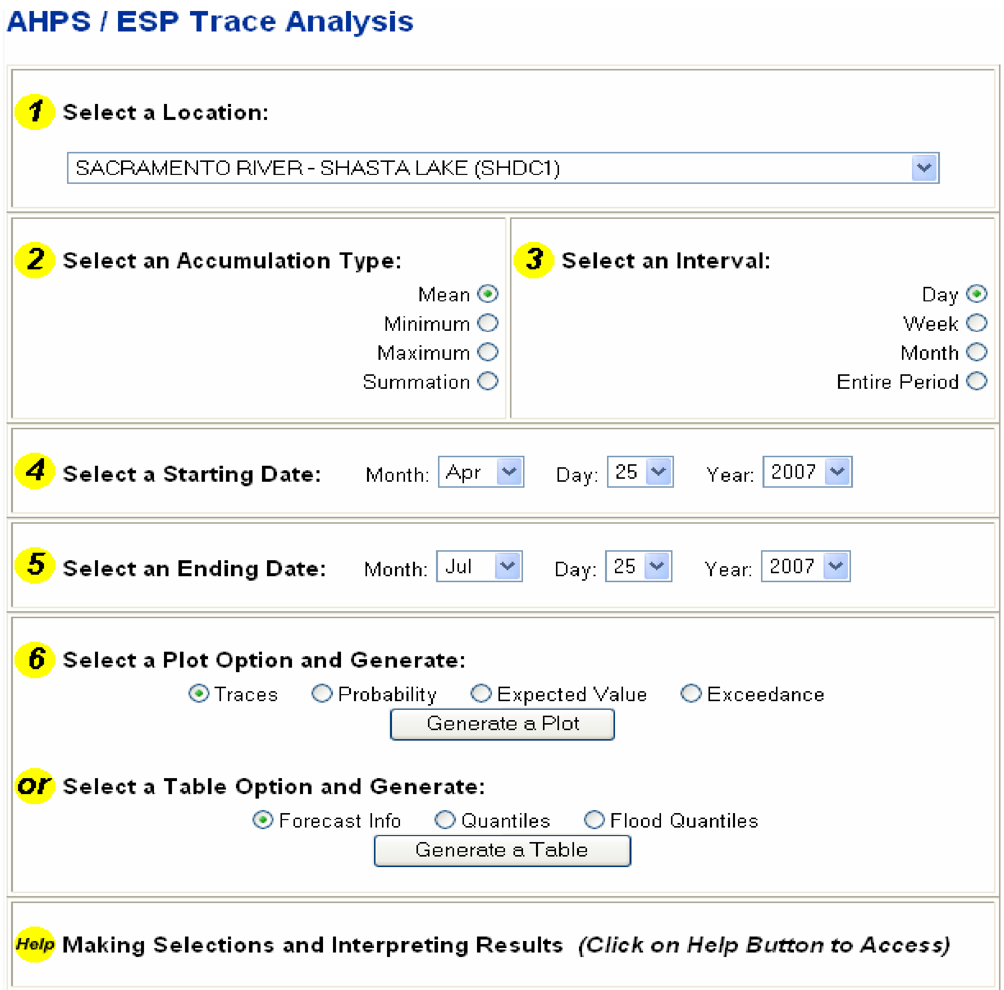


Figure 5.4 An example of current web interface for customer-configured ensemble product generation.

Several RFCs are experimenting with contingency and/or “poor man’s” ensemble products. While these do not meet the full requirements of XEFS, they do provide insight into the types of products that can be delivered to customers as seen in Figure 5.5. The team recognizes that probability information as show in this figure can be easily misinterpreted and that enhancement will be necessary for clarity.

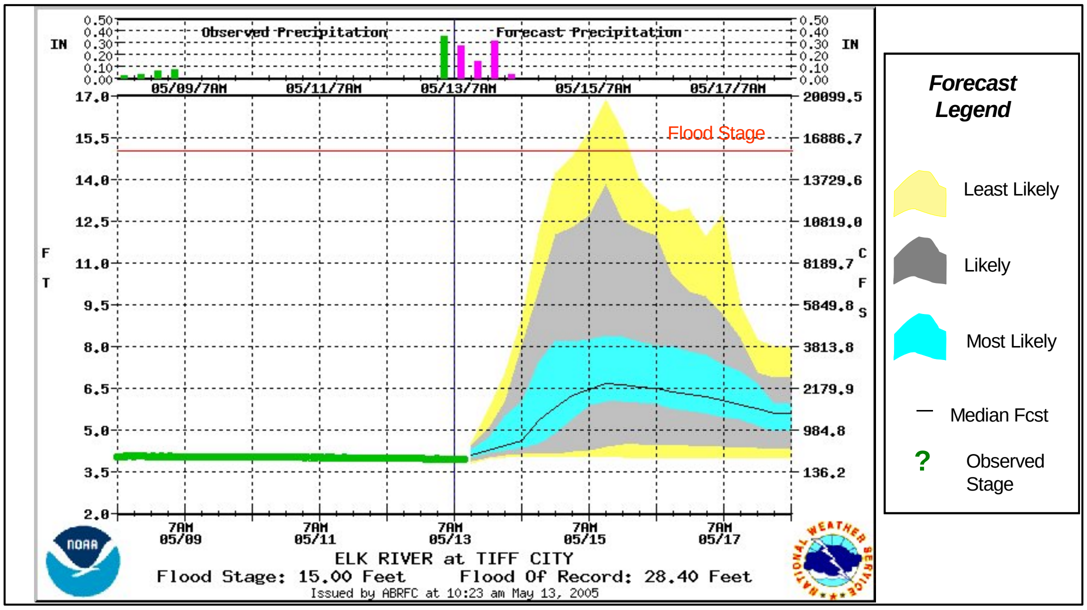


Figure 5.5 An example of envisioned ensemble/probabilistic forecast product.

The need for spatial products exists that describe the probability of reaching critical stages across areas ranging from portions of states to the entire country. Several RFCs are already doing this as AHPS supports this sort of spatial display. An example of this type of product is shown in Figure 5.6.

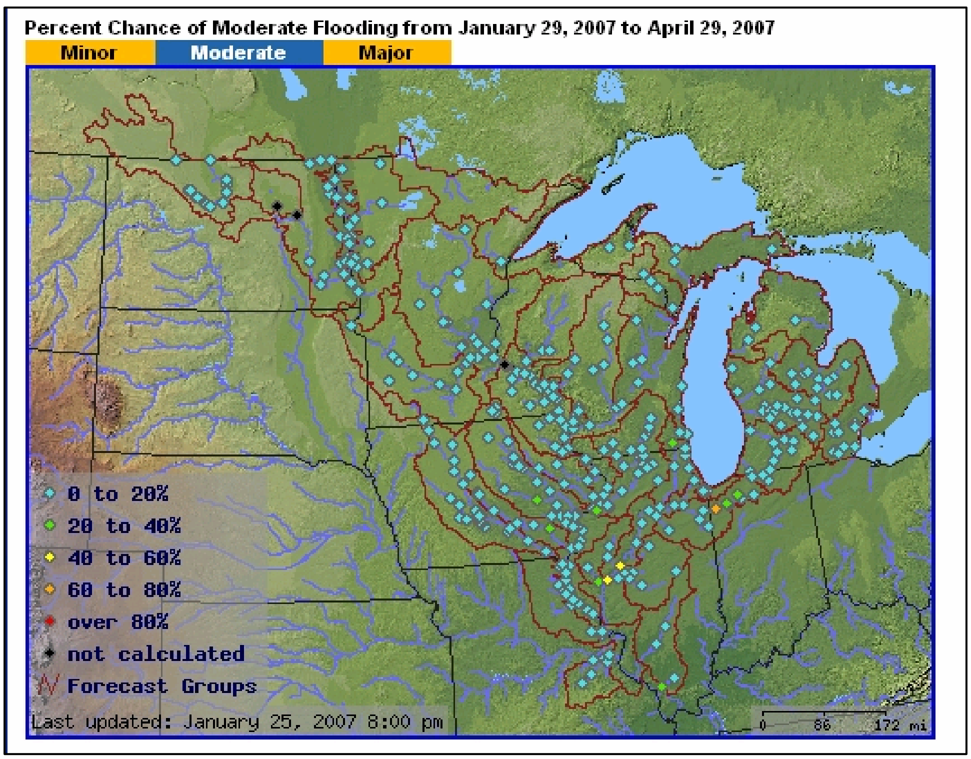


Figure 5.6 Example of spatial probability product.

5.4 GAPS

The GAPS for the EPG are substantial. Although we have a reasonable feel for what needs to be delivered in the form of products and services, the complexities of interaction between the generated ensembles, the HMOS ensemble processor, the ensemble post-processor, the ensemble verification system, databases, the Interactive Forecast Program (IFP), and web interfaces are immense. The ESPADP program is over 10 years old and, while very useful and flexible, was not designed to operate in all of these new roles. Thus the GAP for EPG is an operationally viable system that meets the requirements identified in Subsection 5.2 above. No currently available software or system can reasonably fill this requirement as a placeholder.

Additionally, the Team noted that the EPG will not necessarily allow full flexibility to customer interface because some potential products may be misleading. A GAP exists to establish the suite of acceptable customer products and services as well as the combination of options used to generate them.

5.5 GAP-Closing Works

The development of the EPG is a significant software project that will require a high level of programming expertise, scientific expertise (hydrology and statistics), and the ability to integrate and accommodate interaction with verification, forecasting, and web interfaces.

EPG should be developed in a fashion that will lend itself toward migration to CHPS. Coding, data transfer and format and component interaction standards should be developed up front. Many fundamental capabilities can be modeled after ESPADP with extensions to meet expanded requirements.

As envisioned, the software work for EPG can be broken into three components, the Ensemble User Interface, the Product Generation Subsystem and the web interface. The Ensemble User Interface and the web interface may be developed using a combination of OHD and RFC staff resources. The Product Generation Subsystem will likely require contractor support. In addition, this work requires a special collaborative development environment with a very high frequency-feedback loop. The CNRFC will serve as the focal point for guidance and feedback related to EPG development with substantial support from the CBRFC.

Development time for EPG is estimated at 24 staff-months. The extremely high level of interaction with other XEFS components requires that architectural considerations such as data formats and component interaction processes be established and agreed upon prior to the commencement of work.

5.6 Cross-Cutting Projects

The EPG is a massive information and analysis integration project. As such, it is cross-cutting with all components of XEFS as well as OHD investigations related to the use of weather and climate ensembles and the use of alternative modeling techniques and models in ensemble operations.

The EPP3 interface and the Ensemble User Interface share a great deal of commonality. Phase II should certainly consider merging these into a single application interface (see Figure 5.1). It is also possible that merging may be achievable in Phase I.

5.7 Risks

EPG is a non-optional component of XEFS. Obvious risks are as follows:

1) The design requirement presented here cannot be achieved within a reasonable period of time.
2) Components which must interact with EPG fail to adhere to data and interface standards.
3) Security policy prevents customer interaction with EPG through NOAA web pages.
4) The proposed NOAA/NWS web architecture is not capable of supporting the data and interface requirements of EPG.
5) Training is inadequate for both NWS staff and NWS customers and partners.
6) RFCs are unable to gather and process the information needed to provide appropriate context.

5.8 Potential Phase-II Capabilities

It is likely that some number of envisioned Phase-I capabilities will need to be relegated to Phase II. These might include for example, the ability to weight trace years objectively in light of climatic indexes or dominant weather patterns. Also, if not realized in Phase I, merging the EPP3 interface and the Ensemble User Interface into as single application interface will need to be carried out in Phase II.

6 Ensemble Verification System (EVS)

6.1 Role of Component in XEFS Process

EVS provides the forecasters and the end users with verification information associated with ensemble fore- or hindcast products generated from the XEFS process. The verification information from EVS addresses questions such as “Should I use or not use the product?”, “How reliable and skillful are the XEFS products and services?”, “How good are we?” and “How and where can we improve forecast quality?” It also provides skill assessment in both calibration and real-time operations processes. Figure 6.1 shows the position of EVS in the XEFS workflow diagram.

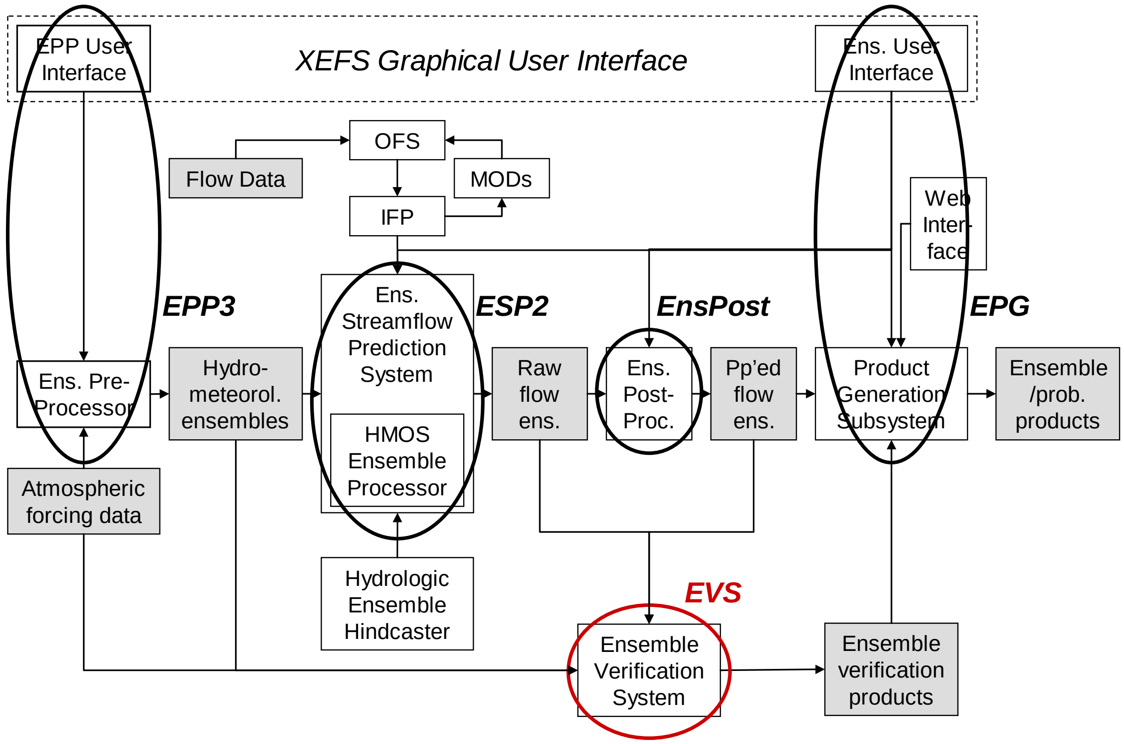


Figure 6.1 Position of EVS in the XEFS workflow diagram.

6.2 Functional Requirements

Figure 6.2 shows the workflow diagram for EVS, which may be divided into four areas: user interface, pairing of the fore- or hindcasts and verifying observations, calculation of the statistics, and graphical display of the results.

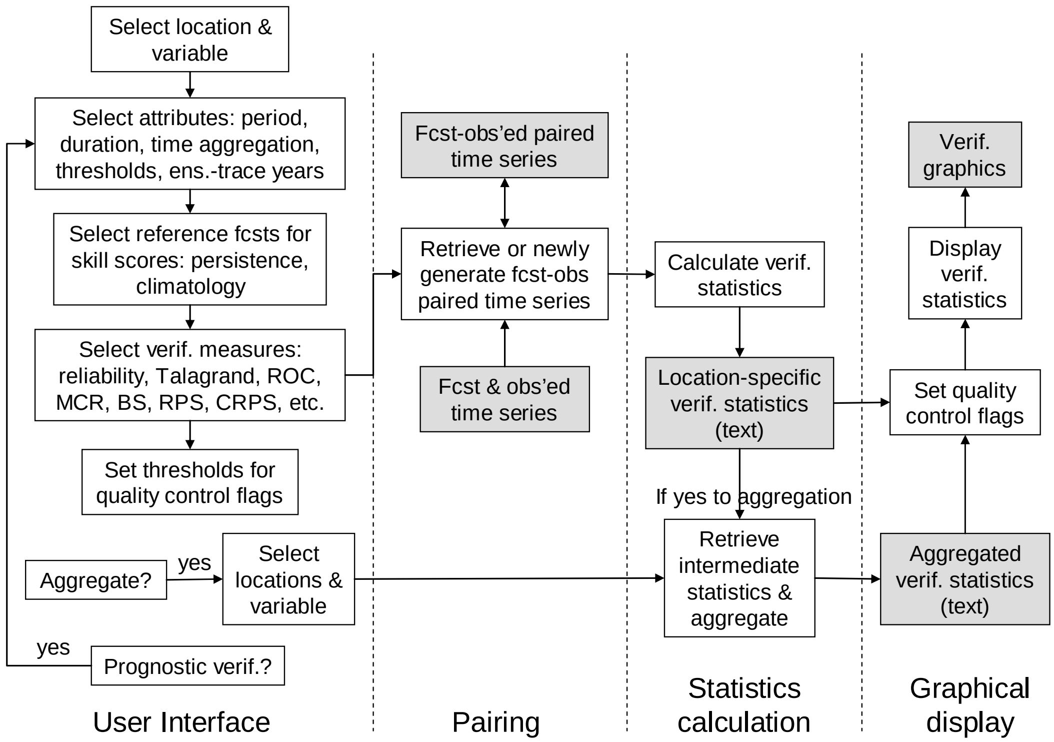


Figure 6.2 EVS workflow diagram.

The basic functional requirements for Phase I are as follows:

1) Runs in both batch and interactive modes.
2) Ingests fore- or hindcasts and verifying observations and pairs them.
3) Allows the user to specify verification attributes, including period, duration, time aggregation, thresholds, and ensemble-trace years.
4) Processes the paired data according to the verification attributes.
5) Allows the user to specify reference forecasts, verification measures, and options for aggregation and prognostic verification.
6) Generate the verification statistics.
7) Display the verification statistics.

<u>Operations Concept</u>

Multiple scenarios are possible. Here we describe an example. The forecaster runs EVS in a batch mode to pair fore- or hindcasts and verifying observations. The forecaster selects verification attributes and options, and generates, displays and reviews the verification statistics. The forecast iterates the process until the desired information content is obtained. Given the selected set of attributes and options, the forecast runs EVS in a batch mode to generate verification results and graphics for multiple forecast points. The forecaster reviews the graphics and, if necessary, runs EVS interactively for additional drill-down verification. Both the text and graphical results are stored and available to EPG and EPP3.

For prognostic verification, the following scenario is envisioned. The forecaster is reviewing a current, potentially high-impact ensemble/probabilistic forecast, and is not sure how much confidence he/she may place in it. The forecaster runs EVS interactively and selects a set of attributes to generate verification information for similar, historical events. The forecaster displays the ensemble forecasts for the past events and the verifying observations to aid real-time decision making.

6.3 Current Capabilities

A prototype EVS currently exists consisting of 3 components:

1) Graphical User Interface (Java)
    - User control
        - User interactions controlled by GUI
        - Statistics and plotting engines called by GUI
    - Staged working environment
        - Tabs (high level), windows, panels (low level)
        - Navigate using tabs and Next/Back
        - Administrative functions always visible
    - Three stages (as ‘tabs’)
        - Verification of one variable on one segment
        - Aggregation of statistics across segments
        - Display of original or aggregated statistics
2) Statistics engine (FORTRAN)
    - Verification statistics
    - Aggregation of statistics
    - Driven by command files (written by GUI)
3) Plotting engine (R)
    - R statistics and graphics (www.r-project.org)
    - R plotting scripts written by GUI.

6.4 GAPS

The following gaps have been identified for Phase I:

1) Processing of raw ensembles and verifying observations according to the user-specified verification attributes.
2) Verification of river stage.
3) Addition of other verification statistics (rank histogram, discrimination measures, continuous RPS, etc.).
4) Direct ingest of binary ensemble forecast files (.CS) from ESP.
5) Visualization of ensemble, single-value and reference forecasts and observations.
6) Handling of time offsets between forecast values and observations.

7) A single Java program for graphical user interface, data processing and calculation of verification of statistics.
8) Improved GUI for easier use.
9) Training.

6.5 GAP-Closing Works

1) EVS enhancement to address the Phase-I gaps
   - OHD (James Brown, Julie Demargne, DJ Seo) to lead, in collaboration with MARFC (Joe Ostrowski)
   - OHD and MARFC to closely coordinate with CN-, CB- and AB- and NCRFCs.

Development time for Phase-I EVS is estimated at 18 staff-months.

6.6 Cross-Cutting Projects

EVS receives input from EPP3, ESP2 and EnsPost, and produces input to EPG. Extremely close coordination with development of EPG and the ensemble user interface will be necessary to ensure seamless transfer of verification information within and out of XEFS.

6.7 Risks

Reliable calculation of ensemble verification statistics requires large amounts of data, for which extensive hindcasting may be necessary (i.e. if the input data are available and can be easily processed). Long-term hindcasting for many forecast points requires large data processing and computing power, which may not be readily available at the RFCs in the Phase-I timeframe.

6.8 Potential Phase-II Capabilities

The following have been identified as potential Phase-II capabilities:

1) Interface with relational database.
2) Develop easy-to-understand verification statistics for operational hydrology that can be easily and clearly communicated to the customers and users.
3) Compute confidence intervals for verification statistics.

7 Summary and Recommendations

It is essential that the NWS develop the ability to generate reliable hydrologic ensembles for lead times of 1 hour to two years. The products and services available through this capability are fundamental to AHPS and will help us achieve our goals in the emergency service and environmental stewardship program areas.

The Team's principal summary and recommendation are as follows:

The scientific gaps associated with baseline Phase-I capability are significant but bridgeable at the current pace of investment. The software and systems gaps are considerable and additional investment is necessary. The value delivered to our customers, however, far outweighs the investment. The time is right to move forward decisively and aggressively.

The Team makes the following general recommendations:

1) Resources should be allocated to achieve baseline phase-I capability within two to three years.

2) A combination of OHD, RFC, and contractor staff should be used to develop phase-I capabilities. Each component of XEFS should have at least one RFC partner who will provide critical feedback, testing, and evaluation. RFCs with adequate programming skills may contribute directly to selected components. A development team should be formed for each component. The development team will be responsible for expanding and executing the project plan which includes collaborating with other XEFS teams.

3) Data and data formats are fundamental to the development and efficient operation of all components. Standard data formats must be established and strictly adhered to by all component developers.

4) Component development must be tightly coordinated. An oversight team, co-led by field and OHD staff should be formed to ensure that activities and decisions that affect multiple components are effectively coordinated, resources are made available, and that development is on track.

5) All components of XEFS should be developed in a fashion that is modular and compatible with service-oriented architecture.

6) Given the complexities of ESP2, the XEFS functionality should be targeted for the CHPS environment rather than retrofitted into the existing NWSRFS. This will require an integration of the CHPS and XEFS development projects.

7.1 Workload Summary

There is a fair amount of uncertainty associated with the total amount of time each component will require. Some of this is related to the process and some to the fact that RFC developers and collaborators will be unavailable during significant events. The total time is also a function of the number of people working on the project. A 24-staff-month task can take 24 months for 1 individual or perhaps 6 months if 4 staff members are dedicated to it.

It should be noted that the estimated workload requirements are for Phase-I capability only. Should additional or Phase-II capability become a requirement, the workload may increase.

1) EPP3 – Ensemble Pre-Processor

The effort is estimated at 24 staff-months. OHD resources consist of DJ Seo, Limin Wu, Satish Regonda, and John Schaake. RFC collaborators will be CNRFC and CBRFC. The CBRFC will work on the development of the EPP3 interface with assistance from the HSEB Team (see below). Total calendar time to delivery of tested Phase-I capability is 15 months. DJ Seo will act as the leader for this component.

2) ESP2 – Ensemble Generator

This effort includes two components, ESP and HMOS. The ESP2 development effort is closely linked with CHPS development and is therefore both cross-cutting and less certain. OHD resources consist of the members of the HSEB Team. The RFC collaborator for ESP2 will be the NCRFC. Significant contractor support will be required for development of this component. A member of the HSEB Team will act as the leader for this component. The ESP2-specific development requirement can be worked into the CHPS plan and should take about 12 staff-months.

The development of operation-worthy HMOS capability is estimated at 12 staff-months but must be fully coordinated with the ESP2 development work. OHD resources consist of Satish Regonda, DJ Seo and the HSEB Team. Total calendar time to delivery of tested Phase-I capability is 15 months. DJ Seo will act as the leader for this component. The RFC collaborator for HMOS will be the ABRFC.

3) Ensemble Post-Processor

This effort is estimated at 12 staff-months. OHD resources consist of Satish Regonda, DJ Seo, and the HSEB Team. The RFC collaborator will be the ABRFC. DJ Seo will act as the leader for this component. Total calendar time for this component is estimated at 15 months.

4) EPG – Ensemble Product Generation System

This effort consists of three parts, the Product Generation Subsystem, the Ensemble User Interface and the Web Interface. The effort for the Product Generation Subsystem is estimated at 12 staff-months. NWS resources to accomplish this task are very limited. Heavy use of skilled contractors will be required to deliver this capability. The RFC collaborator will be the CNRFC. The OCWWS collaborator will be Mary Mullusky. Rob Hartman will act as the leader for this effort with assistance from OHD/HSEB for contracting and contract management support.

The effort for the Ensemble User Interface and the Web Interface is estimated at 12 staff-months. The CB- and CNRFCs will be the lead developers of this capability with assistance from the HSEB Team. The CBRFC's lead role in development of the Ensemble User Interface and the EPP3 User Interface will greatly help realize the same look and feel of the overall user interface and graphical display as well as programming and architectural consistency necessary for cost-effective merging of the two interfaces in Phase II.

5) EVS – Ensemble Verification System

This effort is estimated at 18 staff-months. OHD resources consist of James Brown, Julie Demargne, and DJ Seo. The RFC collaborator will be the MARFC. James Brown will act as the leader for this component. Total calendar time to delivery of tested Phase-I capability is 15 months.

Work is already underway in certain areas of XEFS. The coordinated development effort is expected to begin by mid-July 2007. Phase-I capability should therefore be available for demonstration as early as January 2009.

7.2 Development Coordination and Management

The five components of XEFS are highly interdependent. A high level of coordination will therefore be necessary across all XEFS development activities that will be taking place simultaneously. Closely-coordinated project planning for individual components as part of the HOSIP process, and the data and data format standards will help achieve this.

For closely coordinated development, interconnected management and end-to-end oversight of all XEFS development activities at RFCs, OHD/HSMB and OHD/HSEB while keeping the management overhead lean, the Team recommends the following Phase-I leadership team:

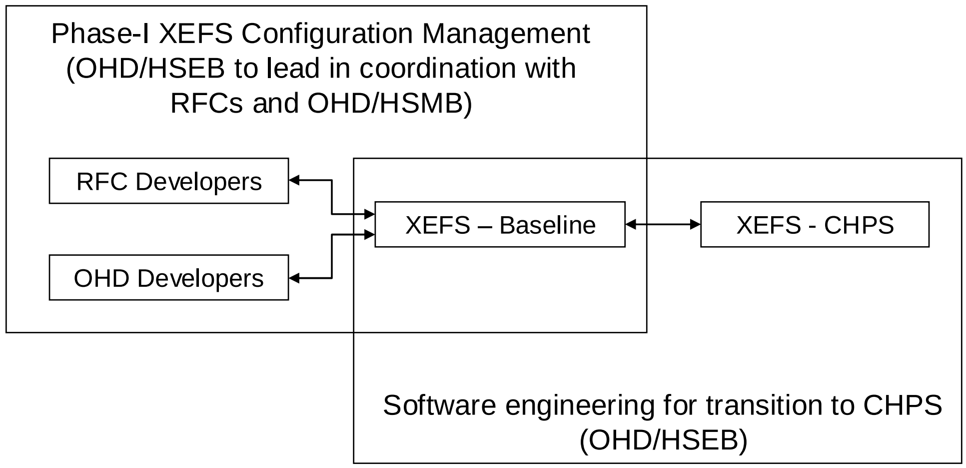
Role	Name
Overall RFC development leader	Rob Hartman (HIC, CNRFC)
Overall research & prototype development leader	DJ Seo (HEP GL, OHD/HSMB)
Overall software engineering leader	Chris Dietz (PAL, OHD/HSEB)

The overall leaders will develop, in collaboration with development leaders, component-specific projects and development teams, which are proposed below. Depending on the need for additional expertise and skills and availability of their time, the development teams may recruit other NWS staff at the RFCs or Regions.

<table>
<tr><th rowspan="2">System Component</th><th rowspan="2">Sub-components</th><th colspan="2">Development Team</th><th rowspan="2">Development Leader</th><th rowspan="2">Develop-ment outcome</th></tr>
<tr><th>OHD, OCWWS</th><th>RFC</th></tr>
<tr><td>Architecture</td><td></td><td>HSEB Team</td><td></td><td>HSEB</td><td>SOA-compatible XEFS</td></tr>
<tr><td rowspan="2">EPP3</td><td>Ensemble Pre-Processor</td><td>Limin Wu, John Schaake, DJ Seo, Satish Regonda</td><td>Rob Hartman</td><td>DJ Seo</td><td rowspan="2">EPP3 w/ GUI</td></tr>
<tr><td>User Interface</td><td>HSEB Contractor #1</td><td>Steve Shumate</td><td>Steve Shumate</td></tr>
<tr><td rowspan="2">ESP2</td><td></td><td>HSEB Team, HSEB Contractor #2</td><td>John Halquist</td><td>HSEB</td><td rowspan="2">ESP2</td></tr>
<tr><td>HMOS</td><td rowspan="2">Satish Regonda, DJ Seo, HSEB Team</td><td rowspan="2">Bill Lawrence</td><td rowspan="2">DJ Seo</td></tr>
<tr><td>EnsPost</td><td></td><td>EnsPost</td></tr>
<tr><td rowspan="3">EPG</td><td>Product Generation Subsystem</td><td rowspan="3">Mary Mullusky, HSEB Team</td><td>CNRFC Contractor #1</td><td>Rob Hartman</td><td rowspan="3">EPG w/ GUI and Web Interface</td></tr>
<tr><td>Ensemble User Interface</td><td>Steve Shumate</td><td>Steve Shumate</td></tr>
<tr><td>Web Interface</td><td>CNRFC</td><td>Rob Hartman</td></tr>
<tr><td>EVS</td><td></td><td>James Brown, Julie Demargne, DJ Seo</td><td>Joe Ostrowski</td><td>James Brown</td><td>EVS</td></tr>
</table>

The HSEB Team includes Chris Dietz, Sudha Rangan, Hank Herr, and an existing contractor. Phase-I software engineering represented in the above table may include integration of readily available and XEFS-applicable ensemble capabilities, if exists, developed by Delft.

Given the large number of development teams involved, ensuring similar look and feel and architectural consistency across all components of the baseline XEFS and seamless integration of them is a large challenge. Also, the baseline system will have to be compatible with the service-oriented architecture of CHPS. Toward these goals, we propose the following two-step development process.



The first step administers configuration management (CM) of all components of the baseline XEFS that are developed at RFCs and OHD. OHD/HSEB will maintain version-controlled copy of the baseline XEFS, from which the RFC and OHD developers can check out and check in the modules that are being worked on. The CM protocol will be determined jointly by the RFCs and OHD. It should be flexible and, if necessary, updated during the course of the development. At certain points in the development phase, the baseline XEFS will have to be unit- (as individual components) and integration-tested (as an integrated system).

The second step is envisioned to be mostly an HSEB activity, in which the version-controlled baseline XEFS is mapped and configured into the CHPS architecture and environment. Findings from this step are expected to propagate back to the RFC and OHD developers so that the baseline XEFS from Phase I is as SOA-compatible as possible. Once common development protocol and environment are established as above, high-level applications or development environment may also be considered for prototyping activities.

7.3 Training and RFC Implementation

Throughout the team discussions that lead to this document, training was a central theme. NWS staff will need both systems and science training in order to understand and effectively use the XEFS capability. In addition, NWS customers will need to be trained on access, generation, and interpretation of XEFS products and services. Component development plans should integrate training requirements and materials. In Phase I, Julie Demargne of OHD/HMSB will serve as the coordinator for integrated development of ensemble science training materials.

Prior to any serious RFC deployment, OHD and OCWWS/HSD will need to schedule and execute a significant training program for NWS staff. This will need to include not only RFC staff, but WFO staff who need to generate and interpret probabilistic products and services for customers.

If the recommendation to align development of ESP2 with CHPS is accepted, the implementation of XEFS will accompany CHPS at the RFCs. This complicates the CHPS implementation, but it also provides a great deal of incentive for RFCs to make the transition. Without knowing the CHPS implementation schedule, we estimate that it may be possible to begin deployment of XEFS within CHPS as soon as in the summer of 2009.

8 References

Schaake J., J. Demargne, M. Mullusky, E. Welles, L. Wu, H. Herr, X. Fan, and D.-J. Seo, 2007. Precipitation and temperature ensemble forecasts from single-value forecasts, Hydrol. Earth Syst. Sci. Discuss., 4, 1812-2116.

Seo, D.-J., H. Herr and J. Schaake, 2006. A statistical post-processor for accounting of hydrologic uncertainty in short-range ensemble streamflow prediction, Hydrol. Earth Syst. Sci. Discuss., 3, 1987-2035.

Appendix A

Team Charter for Experimental Ensemble Forecast System (XEFS) Design and Gap Analysis

Objective: Carry out:

- Design of the Experimental Ensemble Forecast System (XEFS),
- Gap analysis of existing data, science, techniques, tools, and software, and
- Planning of development and implementation achievable within 2 years.

As the baseline prototype system, XEFS should:

- Operationally serve the RFCs as an interim ensemble forecasting capability,
- Provide an ensemble forecasting infrastructure common to both OHD and RFCs to develop requirements and operations concepts, identify areas of need and potential science enhancements, and assess value and performance of additional capabilities and features, and
- Expedite maturation of system components that can be readily transitioned to operations within 2 years of implementation of the Service Oriented Architecture.

While XEFS is not expected to comprise all major functionalities desirable in a hydrologic ensemble forecast system in order to fast-track development and implementation, it should be extensible to allow data assimilation, distributed modeling and other capabilities as future enhancements. For flexibility and transparency necessary for efficient joint development by OHD and RFCs, XEFS should be open and modular. While the primary thrust of XEFS is on providing ensemble forecasting capability for daily short-term (Day 1~14) forecasting operations at the RFCs using lumped models, as an integrated ensemble forecast system XEFS should also be able to support seamlessly long-term (~1yr) ensemble forecasting and appropriately leverage climate forecast information. The gap analysis should include identification and assessment of existing capabilities, identification of the needs to realize XEFS, identification and prioritization of the gaps, assessment of current resources available for gap-closing, and approximate cost of additional gap-closing measures.

The team will:

- Design XEFS, based on the short-term ensemble CONOPS developed jointly by DSST and OHD, and expert knowledge and opinions of the team members,
- Carry out gap analysis for development and implementation of XEFS,
- Recommend specific gap-closing measures, and
- Develop project plan for XEFS development and implementation achievable within 2 years.

It is understood that the process of developing the XEFS 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, may be covered by a combination of OHD and the team member's organization.

Termination Date: The team will be formed and commence activities in late Dec 2006 and remain in place for a period of up to 3 months.

Success Criteria: An agreed-to design and development plan for XEFS that provides a clear pathway for the implementation within 2 years.

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

Team Members:

Robert Hartman	CNRFC	Team Co-Leader
Dong-Jun Seo	OHD/HSMB	Team Co-Leader
Bill Lawrence	ABRFC	Team Member
Steve Shumate	CBRFC	Team Member
Joe Ostrowski	MARFC	Team Member
John Halquist	NCRFC	Team Member
Chris Dietz	OHD/HSEB	Team Member
Mary Mullusky	OCWWS/HSD	Team Member

Appendix B

Acronyms and Glossary

Adjust-Q	Technique that blends observed and simulated discharges over time
AHPS	Advance Hydrologic Prediction Service
AWIPS	Advanced Weather Interactive Processing System
BFPX	A data format used by the current Ensemble Pre-Processor
BS	Brier Score
Calibration	A process of refining model parameters based on observations
CFS	Climate Forecast System
CHPS	Community Hydrologic Prediction System
CM	Configuration Management
CRPS	Continuous Ranked Probability Score
CS	Conditional Simulation
DA	Data Assimilation
Delft FEWS	WL Delft Hydraulics – Forecast Early Warning System
DHM	Distributed Hydrologic Modeling System
DOH	Development and Operations Hydrologist (RFC position)
DSST	DOH Science Steering Team
Ensemble	A collection of potential outcomes
EnsPost	Ensemble Post-Processor
EPG	Ensemble Product Generation System
EPP	Ensemble Pre-Processor

EPP3	Next Generation EPP that combines best features of EPP2 and GFS Subsystems
EnsPost	Ensemble Post-Processor
EPG	Ensemble Product Generation System
ESP	Ensemble Streamflow Prediction
ESP2	Next Generation ESP Technique
ESPADP	ESP Analysis and Display Program
EVS	Ensemble Verification System
FCST	Forecast executable (component of NWSRFS)
Forecast	A model run that uses states based on observations and future forcings for the current date
GFS	Global Forecast System
GUI	Graphical User Interface
Hindcast	A model run made subsequently with states based on observations and forecast forcings for a date in the past
HMOS	Hydrologic Model Output Statistics Ensemble Processor
HPC	Hydrometeorological Prediction Center of the National Centers for Environmental Prediction (NCEP)
HSD	Hydrologic Services Division
HSEB	Hydrologic Software Engineering Branch
HSMB	Hydrologic Science and Modeling Branch
IFP	Interactive Forecast Program (component of NWSRFS)
MAP	Mean Areal Precipitation
MAT	Mean Areal (air) Temperature
MCR	Mean Capture Rate

Meta Data	Data that describes the nature and or context of other data
MOD	Run-time Modification to NWSRFS
MOS	Model Output Statistics
NCEP	National Centers for Environmental Prediction
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
OCWWS	Office of Climate, Weather, and Water Services
OFS	Operational Forecasting System (component of NWSRFS)
OHD	NWS Office of Hydrologic Development
PE	Potential Evapotranspiration
PoP	Probability of Precipitation
QPE	Quantitative Precipitation Estimate
QPF	Quantitative Precipitation Forecast
RFC	River Forecast Center
ROC	Relative Operating Characteristic
RPS	Ranked Probability Score
Simulation	A model run that utilizes observations for forcings
SOA	Service Oriented Architecture
SREF	Short-Range Ensemble Forecast
XEFS	Experimental Ensemble Forecast System
XML	Extensible Markup Language