7B.3 INTRODUCTION OF NOAA'S COMMUNITY HYDROLOGIC PREDICTION SYSTEM

Jon Roe *
NOAA/NWS Office of Hydrologic Development, Silver Spring, Maryland
Christine Dietz
NOAA/NWS Office of Hydrologic Development, Silver Spring, Maryland
Dr. Pedro Restrepo
NOAA/NWS Office of Hydrologic Development, Silver Spring, Maryland
John Halquist
NOAA/NWS National Operational Hydrologic Remote Sensing Center, Chanhassen, Minnesota
Robert Hartman
NOAA/NWS California-Nevada River Forecast Center, Sacramento, California
Ronald Horwood
NOAA/NWS Northeast River Forecast Center, Taunton, Massachusetts
Billy Olsen
NOAA/NWS Arkansas-Red Basin River Forecast Center, Tulsa, Oklahoma
Harold Opitz
NOAA/NWS Northwest River Forecast Center, Portland, Oregon
Robert Shedd
NOAA/NWS Northeast River Forecast Center, Taunton, Massachusetts
Dr. Edwin Welles
Deltares USA, Inc., Silver Spring, Maryland

1. INTRODUCTION

NOAA's National Weather Service (NWS) is responsible for issuing forecast products for the nation's rivers. The NWS has thirteen (13) River Forecast Centers (RFCs), each of which is associated with at least one major river system. The duties of the RFCs are to provide river and flood forecasts for the protection of lives and property, and to provide basic hydrologic forecast information for the nation's environmental and economic well being.

Forecast information and warnings, are distributed from the RFCs to the public through the 122 NWS Weather Forecast Offices (WFOs). During periods of flooding, the RFCs issue forecasts and coordinate directly with water management agencies to optimize reservoir flood control space. During non-flood periods, the RFCs make daily forecasts for water management and prepare seasonal water supply forecasts; they also provide guidance for a national flash flood program and assist cities in developing local flash flood warning systems. Navigational and recreational forecasts are also produced by some RFCs.

The NWS River Forecast System (NWSRFS) has been the software foundation of forecasting operations employed by the RFCs for over 30 years. While the NWSRFS has served the NWS well, the underlying architecture makes it extremely difficult to adopt and use advances that have emerged in the interactive forecasting and modeling community. In order to remain relevant in the future, the NWS needs a hydrologic modeling infrastructure that can leverage and benefit from models and operational concepts developed across the U.S. and around the world. The concept of a community, with an associated exchange of ideas and products, is the key to the evolution of NOAA's water forecasting capabilities for the benefit of the U.S.

A new software modeling and operational infrastructure, known as the Community Hydrologic Prediction System (CHPS), is expected to be the foundation which will help NOAA meet goals for technology transfer and improved operations and service in the future. CHPS will provide a mechanism that will enable NOAA's water research and development activities and operational service delivery to leverage innovations from other U.S. government water agencies, academia, the private sector, and the international community.

The CHPS implementation project (http://www.weather.gov/oh/hrl/chps/) is currently in its second year of operational development at four "risk-reduction" RFCs; these are the Arkansas-Red Basin RFC, the California-Nevada RFC, the Northeast RFC, and the Northwest RFC. Representatives from these RFCs and the NWS Office of Hydrologic Development (OHD) formed a team known as the CHPS Acceleration Team (CAT), which directs project activities impacting their offices. The remaining nine RFCs (known as the CAT-II RFCs) are about to embark on their own migration during 2010. Project completion, defined as all RFCs generating operational forecasts using CHPS, is targeted for the summer of 2011.

It should be pointed out (though not described in detail in this paper) that CHPS will be integrated, as a key national baseline component, into NOAA's Advanced Weather Interactive Processing System (AWIPS) just as the NWSRFS has been a key part of AWIPS since its inception in the mid-1990s. Care must and will be taken to integrate CHPS into AWIPS in such a way as to make CHPS available to non-NWS users (e.g., universities and foreign weather and water services) who do not need all of the other capabilities of AWIPS or have their own capabilities similar to AWIPS. That is, CHPS must be able to be configured so that its data inputs and data outputs can be provided by other avenues than those provided by AWIPS. There are several examples of foreign weather and water services using NWSRFS today who will want to convert to CHPS soon after the NWS RFCs complete their conversion. AWIPS is the overarching hardware and software system employed by NOAA at all NWS forecast offices (i.e., RFCs, WFOs, and National Centers); CHPS is planned to be one of the earliest infusions of new technology into a modernized AWIPS. For further detail on technology infusion into AWIPS refer to Henry (2009).

Although the CHPS project is still in implementation, it has already generated lessons learned that are worthy of presentation to a broader audience. The remaining sections of this paper provide the reader with a brief description of the architectural foundation and implementation concepts of CHPS, an insight into some of the challenges that have been encountered while beginning the transition path to operational use of the new system, and the expected and partially realized benefits to NOAA in future years.

2. WHAT IS CHPS?

CHPS is both a concept and a system. The community concept of CHPS reflects a desire on the part of NOAA to reach out to the broader hydrologic community. CHPS is also an open forecasting system designed to be modular in nature, and built upon standard software packages, modern protocols, and open data modeling standards. CHPS will provide the basis by which new and existing hydraulic and hydrologic models and data can be shared within the community. The new system will be deployed at all NWS RFCs.

CHPS uses the Delft Flood Early Warning System (FEWS)* (http://www.wldelft.nl/soft/fews/int/index.html) as the core of its infrastructure combined with NWS and U.S. Army Corps of Engineers (USACE) hydrologic and hydraulic models. FEWS provides data import, storage and display and some basic hydrologic calculations. The hydrologic modeling occurs in the user supplied models. Figure 1 is a diagram of the relationship between CHPS and FEWS.

* FEWS is developed and distributed by Deltares and Deltares USA, Inc.

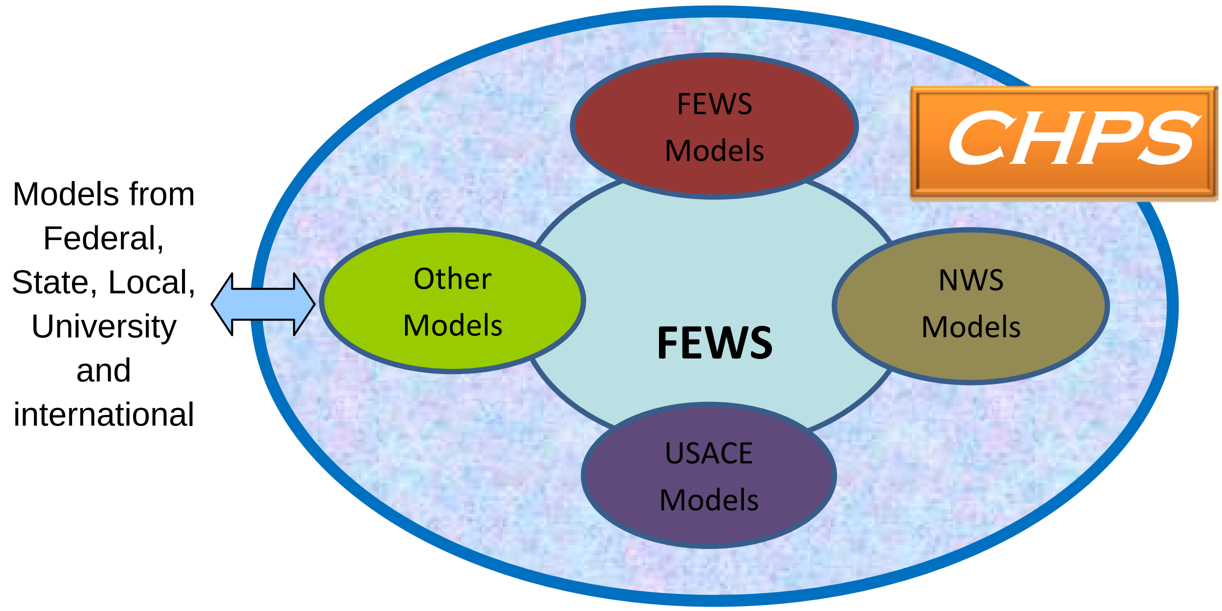

Figure 1 Relationship between CHPS and FEWS.

The initial deployment of CHPS will include the same models (labeled "NWS models" in Figure 1) that are currently available in NWSRFS, except the hydraulic routing models. The NWS models include: the Anderson Snow model (Snow 17); the Sacramento soil moisture and Continuous Antecedent Precipitation Index runoff models; a Unit Hydrograph model; Lag and K, Tatum, Layered Coefficient, and Muskingum routing models; two NWS developed reservoir models; an NWS developed agricultural consumptive use model; an NWS developed glacial melt model; an NWS developed Rain/Snow Elevation model; and NWS developed models for in channel baseflow and losses. The NWS FLDWAV and DWOPER hydraulic models will not be ported to CHPS. The (USACE) HEC-RAS will be used for hydraulic routing by the NWS RFCs in their operational forecasting environment for the first time. To add a third option for reservoir modeling to the RFC repertoire, an implementation of the USACE's ResSim model is also to be included with the CHPS distribution.

OHD isolated the model algorithms from the NWSRFS computational infrastructure and either rewrote the model into new software code or wrapped the existing software code to create independent stand alone models. It is straightforward to connect any model to FEWS via a simple software adapter which routes FEWS provided time series, parameters and states to the models. Every adapter has two elements: a FEWS component called the FEWS General Adapter and a Model Adapter which is associated with an individual model. The FEWS General Adapter is a standard component of FEWS which can be configured by the user to deliver time series, parameter sets and model states from the FEWS database to the model. The configuration is done with an XML file. The FEWS General Adapter is the same for all models. The Model Adapter takes the FEWS provided data and executes the model, reformatting the FEWS provided data if necessary. After the model has completed, the Model Adapter collects the model output and hands it back to FEWS. Model Adapters can be built for any model a user wishes to run with FEWS. A diagram of this "open model" concept is captured in Gijsbers (2009). The FEWS General Adapter – Model Adapter combination is the software architecture building block key to establishing the functional agility needed for CHPS.

All FEWS functions are highly configurable. Data ingest, model connectivity, and the displays can all be constructed to meet the unique needs of local forecasters. As noted above, model access is also configured so any model can be used in conjunction with FEWS. The flexible configuration of FEWS is one of the elements that make it very attractive to the NWS users as they need to forecast within the variety of hydrologic regimes found across the nation.

The NWS river forecasting process is well defined. Forecasters are able to make manual modifications of the model inputs, states, or outputs in order to keep the models performing properly. This manual modification function was not available in FEWS and therefore it was added to FEWS to support the NWS implementation.

This new development is called the Interactive Forecast Display (IFD). Figure 2 is an image of the IFD time series display and Figure 3 is an image of the IFD modifiers display.

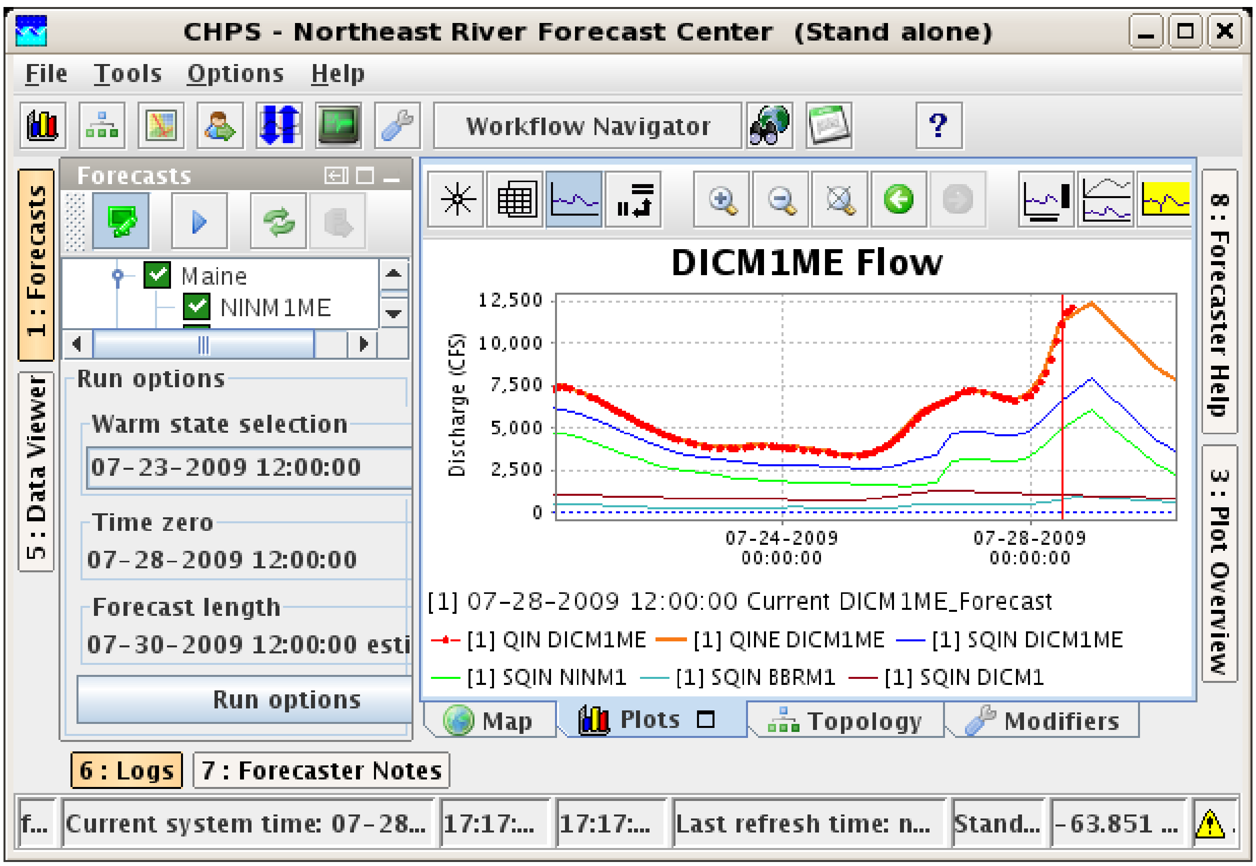

Figure 2 The Interactive Forecast Display time series display.

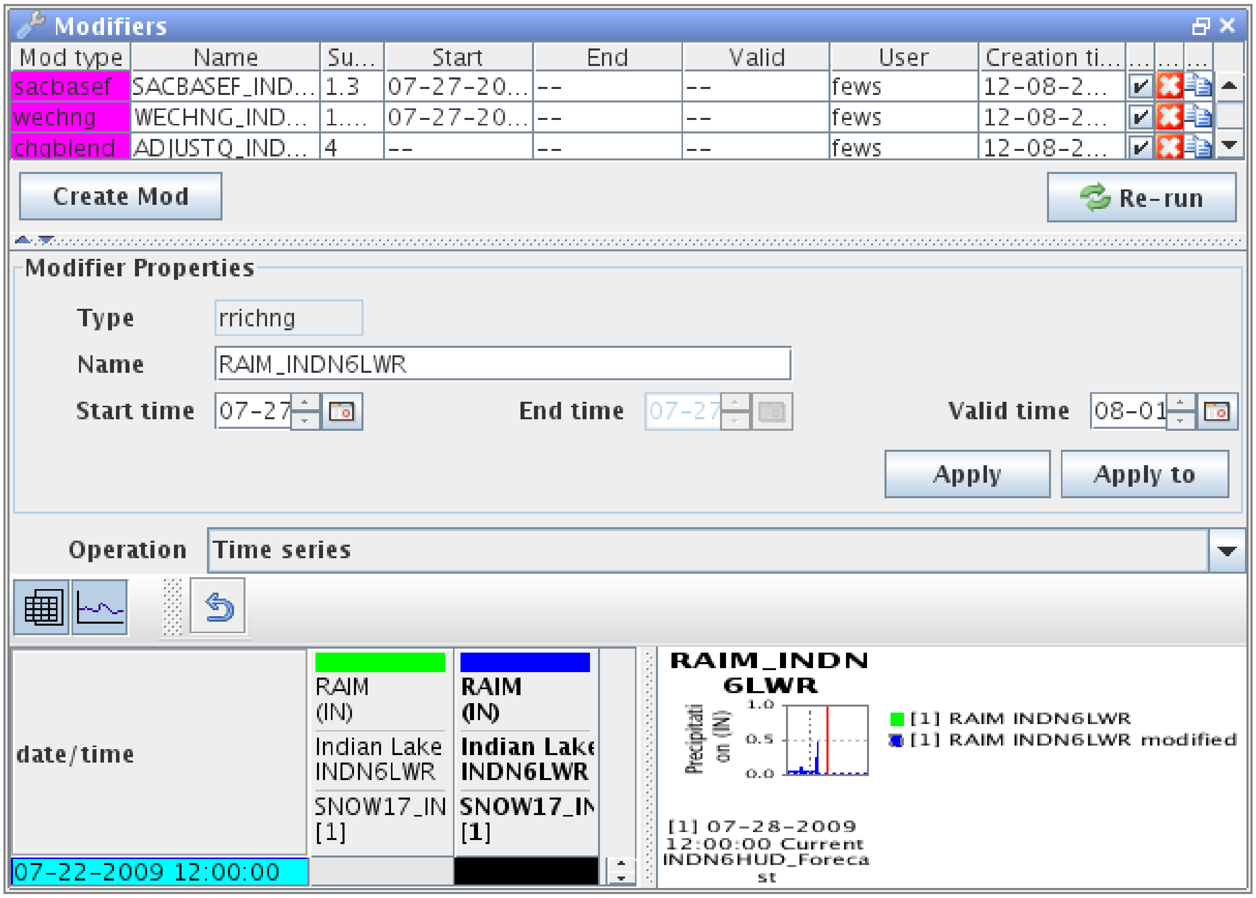

Figure 3 The Interactive Forecast Display modifier display.

The IFD allows the user to make an initial assessment of the forecast performance across all the basins of interest through its view only mode. Forecasts computed without any modifications are pushed to the user's computer for review via pre-configured displays. Regions where the models are not performing as well as required can then be reviewed in depth by the forecasters. Model states and input time series can be manually adjusted to improve model performance.

One area of active research for CHPS is automated model updating. The NWS anticipates being able to collaborate with the international forecasting community via FEWS to develop operationally feasible updating techniques. This ability to collaborate with the broader forecasting community is one of the benefits the NWS expects to achieve from the CHPS implementation.

3. TRANSITION CHALLENGES

NOAA expects to derive numerous benefits by implementing CHPS, comparable to the effort expended to deploy the system. The transition from NWRFS to CHPS will affect the entire NWS hydrology program and it must be completed in such a way the forecast users are not disrupted. There are technical and cultural challenges the NWS must overcome to succeed. The technical challenge of moving the existing model parameters into the new system is a detailed problem being addressed by Deltares and NWS software programmers.

The more complex cultural issues are being addressed by a core NWS leadership team. Those challenges include retraining the forecasters so they can operate the new system as effectively as they did the old. The headquarters staff, both programmers and scientists, will also need to re-orient themselves to the newer more flexible environment. Further, the NWS must develop new support paradigms to accommodate the change from in-house developed software to externally provided software. Even though one of the benefits of using FEWS is the international community of users, it is also one of the challenges the NWS faces as they will no longer dictate all of the development as they have in the past.

3.1 *CHPS Project Leadership Team*

The NWS OHD has overall responsibility for executing the CHPS project; hence project leadership was assigned to OHD's Hydrologic Software Engineering Branch (HSEB). However, the scope of the CHPS project was broader than most software development projects previously tackled by the HSEB, requiring some skills not usually found within its portfolio.

The formation of a leadership team in late 2007 which included Deltares, the CAT members, and several NWS headquarters participants including the HSEB, was an unusual step for the OHD. There was some initial concern that representation from four RFCs could hinder the decision making process, and two or three RFCs would be preferable; but four turned out to be very feasible. Although it took several months for the CHPS leadership team to function effectively, the strategy ultimately paid off as all members learned to build consensus and make compromises while remaining committed to the primary goal. Meanwhile the headquarters staff learned to take on more of a monitoring and supervisory role in place of the more traditional project leadership one. One substantial benefit to the NWS of the distributed leadership has been the commitment from the CAT RFCs to deploy the system despite the hard work required of them.

Very early in the project the CAT recognized that this new system had the potential to completely change the nature of operational river forecasting at RFCs. Therefore in 2008 the CHPS leadership team engaged a representative from the NWS Employees Organization (NWSEO) who could provide input and feedback on activities which would directly impact the day-to-day activities of the forecasters.

Once the decision to go with FEWS as the underlying infrastructure was made, the CAT members committed to making CHPS their highest priority. This might mean delaying other activities in favor of CHPS, such as delaying river forecast model calibrations until after CHPS is deployed. Also vital to the project's success was a conviction on the part of every team member that this very challenging project would succeed. Frequent interactions between all team members have been essential. Quarterly face-to-face meetings have been held during the life of the project to make important design and implementation decisions; weekly conference calls are also conducted to report on progress and discuss key issues.

3.2 *The First Four RFCs*

The project plan for CHPS, when first proposed by Deltares, was clearly a daunting endeavor with an aggressive schedule. It was considered too high a risk to transition all 13 RFCs at the same time; therefore the CAT volunteered to forge a path by transitioning to the new system ahead of the other RFCs as a project risk reduction measure. The goal was to create and validate a transition path for the nine CAT-II RFCs based on the CAT RFC experiences; the CAT-II RFCs would begin transition (i.e., "migration") in February 2010, one year after the CAT members began theirs. To help bring the CAT-II RFCs up to speed the CAT members also agreed to provide a "buddy" support system, whereby each CAT RFC was partnered with two or three CAT-II sites based loosely upon location. The goal of this support system was to build upon the growing expertise of the CAT RFC staff by providing peer-level answers to initial questions from the CAT-II RFC staff as they began their journey. An intense series of "buddy visits" during the summer of 2009 launched the support system.

Complicating the project is the operational distinctiveness of individual RFCs, each of which must tailor its deliverables to meet the needs of a broad and diverse customer and partner base in a location-specific hydrologic and weather regime. Thus the majority (though not all) of the functional requirements were outlined by the CAT subset of the RFCs; requirements for the remaining offices were subsequently defined one year later. Key to the initial requirements definition was the recognition by the CAT that the scope must remain realistic and limited to “baseline” operational capabilities (named BOC). The CAT subsequently led the requirements definition for the CAT-II, resulting in a BOC-II requirements document produced in April 2009. The latter document forms the basis for the initial release of an operational CHPS at all RFCs.

3.3 *Parallel Execution*

The RFCs have experienced multiple major operational system transitions over the years, including the introduction of the NWSRFS itself. The transition to CHPS introduces a new computing technology that is in stark contrast with the decades old technology of the NWSRFS. What complicates transitions at operational forecast offices is the need to implement changes without interrupting or degrading existing operations. Based on their experience with a similar project for the U.K. Environment Agency, Deltares proposed a parallel execution period for the NWS during which the RFCs would run the NWSRFS and CHPS side by side until each office is certain they can rely on CHPS for their operational forecasting. OHD further committed to purchasing interim hardware for each RFC on which to execute CHPS, so that the NWSRFS performance would not be impacted. The additional hardware in place at RFCs now provides the NWS with a valuable tool to validate computer resource requirements for CHPS.

3.4 *Recommendations*

While there will assuredly be more challenges before the project is complete, the lessons learned to date have highlighted some key strategies for successful execution of the CHPS project:

- A diverse project management team with strong user focus (in this case the CAT working with NWS headquarters).
- A project management team answering directly to senior authority (the CHPS team reports to the NOAA Integrated Water Forecasting Program Manager).
- Field representatives on the management team with authority to make decisions for their offices (e.g., Hydrologists-In-Charge).
- Complete commitment from user representatives on the management team to make the work for their staffs a top priority including attendance at all project workshops.
- An aggressive schedule designed so the second set of operational offices retains interest and is not left waiting too long.
- A multi-year budget to make it all happen.
- A contractor having solid experience with operational system transitions and a demonstrated track record of success (such as Deltares).

4. BENEFITS TO NOAA OPERATIONS

4.1 *Modern Computing Technology*

There are many classic benefits of modernizing a legacy software system and the benefits become more pronounced as the system ages. The NWS OHD started pursuing efforts to modernize the legacy NWSRFS in the latter 1990s in an effort to provide more flexibility to address upcoming major service requirements and to simplify and lower the cost for performing maintenance and small enhancements. As the upcoming service enhancements (e.g., gridded modeling, short term ensemble forecasting, water resources forecasting, water quality forecasting, etc.) came into clearer view in the early 2000s, OHD realized it would not be possible to modify NWSRFS to provide these new capabilities because of its monolithic nature and commensurate lack of flexibility.

One step OHD took was to develop an architectural view of a modular and loosely coupled software system to replace NWSRFS yet preserve existing hydrologic science models and their calibrations. In 2005 OHD concluded work on defining this architectural vision, and began conducting due diligence on existing products before setting out to develop a new system from the ground up. OHD identified the basic architectural features of the modeling framework they had envisioned in the FEWS product from Deltares. One of the key features of FEWS is the ability to adapt numerical models and other science algorithms to the underlying infrastructure in a very straightforward and repeatable fashion. This not only allowed OHD to migrate its legacy science models from NWSRFS to CHPS but also opened up a significant ability to share science models with the rest of the hydrologic community via the FEWS adapter mechanism. There are three clear benefits to NOAA: the ability to use models from other hydrologic partners; a much faster path to incorporate new science models and algorithms into operations; and the transfer of hundreds of thousands of lines of infrastructure code from NWSRFS to the COTS product FEWS. This last benefit liberates NOAA hydrology software development personnel to pursue hydrologic value-add software rather than non-scientific infrastructure software. As one measure of the simplification of software maintenance, OHD will be able to retire over 350,000 lines of NWSRFS source code resulting primarily from the accommodation of computational infrastructure in FEWS.

4.2 *Community Partnerships*

An incentive for the development of a community system is the need to transition research into operations. One example of a successful community partnership is the Weather Research and Forecasting model (http://www.wrf-model.org/index.php), which has enabled the weather forecasting community to contribute to different portions of the model by using a common framework.

Our vision for CHPS is precisely the same, that is, to allow researchers from within NOAA, other Federal agencies, universities, and the international community to be able to contribute to the development of hydrologic forecasting models and techniques. The adapter-based open CHPS environment facilitates access to the information researchers and developers need to develop, test, and deploy hydrologic forecasting applications thereby expediting the transition from research into NWS hydrologic forecast operations at the RFCs. Of course CHPS also allows the hydrologic community outside of NOAA to benefit from the NWS's river forecasting models, which will be shared via the FEWS adapter concept. The NWS is identifying mechanisms to facilitate an exchange of models and techniques.

4.3 *Enhanced Forecast Operations*

The implementation of FEWS within CHPS offers the NWS an opportunity to modify its river forecasting process. The NWSRFS generates displays in a fixed order with no opportunity for modifying that order while forecasting. The displays are integrated into the process to perform model computations. The FEWS infrastructure, on the other hand, separates the data display and the model computations used to generate the data. By separating the two functions, the forecasters now have an opportunity to review displays for an entire basin and pinpoint the models which require attention. This will allow them to spend more time reviewing model outputs for those basins where the models may not be performing as well as needed. Additionally, forecasters will be able to peer more deeply into the model results yielding a better understanding of behavior during unusual situations. Again, this is expected to yield improved forecasts.

The forecasters will also have access to a computational library allowing them to create a greater variety of calculations. Although not implemented yet, the forecasters are already beginning to experiment with run-time metrics to indicate model simulation quality helping them to pinpoint basins in need of attention. FEWS also offers a suite of verification metrics that can be used to monitor the longer term quality of numerous forecast locations.

In addition, functions which are now incorporated into the forecasting process via separate standalone applications can be viewed as integrated displays within the FEWS environment. Examples of these functions include displays of gridded data or displays of peak to peak correlations between nearby river forecast locations. By bringing the key river forecasting functions into a single integrated application interface, forecasters can take advantage of more information in the process and thereby improve their forecasts.

4.4 *Global User Community*

FEWS is currently used as a river forecasting infrastructure across Europe and in Asia. Verwey (2007), for example, describe the application of FEWS in the Mae Nam Mun and Chi river basin in Thailand and the potential to couple the system with an extended flood forecasting system for the Mekong Basin to provide longer forecast lead times and higher reliability of forecasts in Laos, Cambodia and Vietnam. With the addition of the United States, the user community spans an even greater portion of the globe. One purpose of the FEWS software is to create an exchange of ideas by incorporating them into the software. The NWS development of the IFD is an example of just such an exchange. The versions of FEWS, distributed to the entire user community, now include the NWS-required development for the IFD. The NWS approach to river forecasting, as it is incorporated into the IFD, is a new vision for other forecasting agencies. Most other forecasting agencies follow the meteorological approach of letting the models run with some automated data assimilation. The ability to modify the model behavior during the simulation is very attractive to other FEWS users. The new capabilities in FEWS will allow other forecasting agencies to review the NWS approach and to propose improvements which can in turn be used by the NWS.

The exchange of ideas has also occurred with the NWS benefiting from the development for other forecasting agencies. The U.K. Environment Agency implemented FEWS within its National Flood Forecasting System for England and Wales. This implementation required new functions be integrated into the baseline FEWS such as the displays of forecast skill scores and hydraulic profiles. These are new functions for the NWS to explore. With numerous agencies now using FEWS, a large number of forecasting models have been adapted by their creators and are ready for use by the hydrologic community.

5. SUMMARY

The CHPS implementation is a significant investment for the NOAA Integrated Water Forecasting Program. The success to date with the implementation can be largely attributed to the integrated management team who has guided the project. The project is expected to return benefits to NOAA in terms of reduced overall maintenance costs and a greater ability to collaborate with the water science community. NOAA considers this investment very timely as the demands for weather and water services are increasing. We look forward to working with many in the future to make the hydrologic prediction system implemented by NOAA a Community Hydrologic Prediction System.

6. REFERENCES

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