CHALLENGES IN WATER RESOURCES FORECASTING AT THE NATIONAL WEATHER SERVICE

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Abstract

The streamflow forecasting mission of NOAA's National Weather Service (NWS) provides social benefits in the form of life and property protection and economic prosperity. Floods, droughts, and provision of potable fresh water are pressing issues throughout the world. Climate change exacerbates these problems and makes hydrologic forecasting more complex and demanding. Improved water quantity and quality forecasts will help water managers and the public deal with the growing challenges.

Hydrologic forecasting within the NWS is carried out through a complex system of hydrometeorological observations and forecasts, hydrologic models, and human interpretation of model results. Additionally, effective forecast services require the quantification of uncertainty, validation and verification of the system performance, and communication of forecast products to the public and decision makers.

These hydrologic forecasting challenges are compounded by the need to rely less on observations of historical series for model calibration, and more on physical characteristics of the watershed, as a way to reduce the cost of implementation and to isolate the problem of model implementation from natural or anthropogenic changes to the watershed, such as those caused by extensive urban development, forest fires, and climate change.

The NWS is actively developing the capability to provide our users with information on the uncertainty of the hydrologic forecasts. We are developing ensemble techniques to cover the effects of the uncertainty in initial conditions, parameters, model structure, and meteorologic forcings (observations and forecasts).

In addition, we are planning on improving low-flow forecast accuracy by using groundwater models coupled with streamflow forecast models. This will reflect the effect of pumping, irrigation, recharge and complex geological conditions not currently represented in our surface hydrology models.

The NWS Office of Hydrologic Development has developed a Strategic Science plan to cover all these topics. This paper will explain the details of the plan, and the challenges we face in its implementation.

INTRODUCTION

The Office of Hydrologic Development (OHD) of the National Weather Service (NWS) prepared a Strategic Science Plan ((“The Plan”, OHD 2009) to set the research directions for hydrology and water resources across NOAA. The goals and challenges NWS faces in improving hydrologic forecasting are covered in considerable detail in the Strategic Science Plan. In this paper, we focus on three topics: hydrologic (surface) modeling, probabilistic modeling, and low-flow modeling geared to streamflow and water resources forecasting.

The Current Hydrologic Forecasting Process

Hydrologic forecasting in the National Weather Service is performed by a complex system of data management tools that combine observations and forecasts of a number of atmospheric processes in order to provide input to a suite of mathematical models of watershed processes, and to a suite of time series and data manipulation techniques that comprise the operations available in the National Weather Service River Forecasting System (NWSRFS, Fread et al. 1995).

Observations used in the forecasting process include precipitation, temperature, snow water equivalent, freezing level and snow cover from a variety of sensors, the details of which are described in the corresponding sections of The Plan, and will not be addressed in this paper. At the heart of the land surface models are two lumped models: the Sacramento Soil Moisture Accounting (SAC-SMA) model, and the snow model known as SNOW 17. There are other models developed and made operational for the land surface process, but those these two models are, by far, the most used by the River Forecast Centers.

National Weather Service operational hydrologic forecasting system accounts for subwatershed heterogeneities via a gridded distributed model that uses SAC-SMA for rainfall-runoff calculations, Snow-17 for snow accumulation and melt, and kinematic overland flow and channel routing (Koren et al, 2004).

The Future Hydrologic Forecasting Process

The future of hydrologic forecasting at the NWS will include:

- A community-based research and operational environment (Community Hydrologic Prediction System CHPS) to replace NWSRFS. CHPS development is currently underway, with four of the thirteen River Forecast Centers conducting parallel operations by using CHPS and NWSRFS.
- Enhanced use of remotely sensed information for a wide range of atmospheric and land-surface characteristics, from both active and passive satellite-based sensors;
- Higher-resolution hydrologic models;
- Explicit consideration of the uncertainty in the forcings and forecasts (an ensemble approach is currently being pursued and will be fully implemented for short-, medium- and long-term forecasting);
- Multi-model ensembles to address the problem of uncertainty in the forecasts arising from structural errors in the models (these ensembles may be formed by combinations of lumped or distributed, conceptual or physically based models);

- Explicit consideration of the errors introduced by sub-optimal parameter values and initial conditions;
- Data assimilation of *in-situ* and remote-sensed state variables; and
- Verification of single-value (deterministic) and ensemble (probabilistic) forecasts.

RAINFALL-RUNOFF MODELING

Despite the high-quality of the forecasts produced with lumped conceptual models, a major shortcoming is the need for long time series of high-quality hydrometeorological observations required for parameter calibration, and the high-level of training required to perform a good calibration. Calibration on historical data is problematic for non-stationary conditions such as those induced by climate and land-use/land-cover changes. Furthermore, apart from subdividing watersheds into elevation zones, the lumped models in the NWSRFS do not account for the distribution of forcings, surface properties, and runoff processes within the watershed. The assumption of stationarity has been the cornerstone for the use of long time series in model calibration. However, that assumption may not be valid any longer in a changing climate environment, (Milly *et al*., 2008) and the use of long time series under non-stationary conditions may lead to biases in the parameter estimates. Although the difficulties posed by the model calibration requirement have been somewhat alleviated at the NWS by the development of prior parameter values (Koren *et al.*, 2003) and tools such as the Interactive Calibration Program (ICP), the parameters still need to be fine tuned either by manual or automatic calibration procedures.

Several distributed, physically based models have been developed with the intent of improving the accuracy of hydrologic forecasts, in general, and minimizing the need for model calibration, specifically. Furthermore, it often has been the expectation that those models should be able to adapt their parameters to physical changes in a watershed, such as those resulting from large-scale disturbances to soil and vegetation due to forest fires, without having to resort to recalibration.

By physically based, we mean models for which the parameters can be directly estimated, and the processes closely mimic those occurring within the watershed. Since not all properties of the watershed can be directly observable, it would be necessary for some of those parameters to be estimated by calibration. Similarly, some of the processes may be more efficiently modeled by a conceptual or an empirical approach. Models that blend purely physical parameters and processes with conceptual processes and calibrated parameters may be most appropriate. Example of models in this class are the Sacramento-Heat transfer model (SAC-HT) with *a priori* estimates for some of the original Sacramento model parameters, and a physically based model for the heat-transfer portion (Koren *et al.*, 2007); the Precipitation Runoff Modeling System PRMS (Leavesley et al., 1983); the Hydrograph Model (also known as the Deterministic Hydrologic Modeling System, Vinogradov and Vinogradova, 2008, Semenova and Vinogradova 2009). Nevertheless, even though the *a priori* parameter estimates can produce a satisfactory model performance, there is still the need to refine those parameter values by calibration with historical series.

By distributed models we mean any model that does not consider a watershed as a lumped system. This includes models in which a watershed is divided into regular or irregular grids, sub-

watersheds, hydrologic response units, Representative Elementary Watersheds (REW), representative points, etc.

The Office of Hydrologic Development coordinated two distributed model intercomparison studies (DMIP-1 and DMIP-2) to understand the performance of distributed models under prior (uncalibrated) and calibrated parameter values. DMIP-1 concluded in 2003 (Reed et al, 2004), and DMIP-2 is still underway as of December 2009. A number of studies, including the results of the DMIP-1 and initial results from the DMIP-2 indicate that physically based models have largely fallen short of their goals as operational tools for a number of reasons. Some of the limitations of models that are in particular highly distributed and physically complex are:

- The models are typically based on small-scale hydrologic theory and thereby fail to account for larger-scale processes such as preferential flow paths;
- The data necessary to estimate parameter values are not available at high enough resolution, certainty, or both;
- The data necessary to drive the models are not available at high enough resolution, certainty or both; and
- The computational demands are still a barrier, particularly for performing data assimilation and ensemble modeling in real-time.

The operations and research communities are steadily making progress towards resolving the above limitations. Nevertheless, one thing is clear: the most highly resolved and most physically complex models are not necessarily the most appropriate for operational hydrologic forecasting for the foreseeable future. At the same time, the anticipated benefits of models that are more highly resolved and more physically based than the lumped conceptual models that have been the mainstay of hydrological forecasting for the last several decades should be investigated further. Continued research and development along these lines offers the potential for:

- More accurate forecasts in ungauged and poorly gauged basins;
- More accurate forecasts after changes in land use and land cover, such as forest fires and other large-scale disturbances to soil and vegetation;
- More accurate forecasts under non-stationary climate conditions;
- Modeling of interior states and fluxes, which are critical for forecasts of water quality, soil moisture, land slides, groundwater levels, low flows, etc.; and
- The ability to couple hydrologic forecasting models with those for weather and climate forecasting.

The benefits of more highly resolved and physically based models are discussed in Appendix B of The Plan. How these advances will be utilized and furthered by NWS is a major thrust of the Plan. It is recognized that distributed, physically based modeling is not an end itself, but rather must be evaluated in recognition of operational requirements, capacities, and cost effectiveness. Accordingly, NWS will focus on models that:

- Make use of the prior estimation of parameter values from existing distributed datasets;

- Have parameter sets that can be initially observed and then adjusted to account for changes in watersheds and stream channels in a computationally efficient, physically meaningful and robust manner. Models with directly observable or inferable parameters, and do not require further adjustment to produce reliable streamflow and soil moisture simulations, will be emphasized;
- Are amenable to the assimilation and forecasting of both streamflow and internal watershed states (e.g., soil moisture and groundwater levels);
- Are appropriate for the resolution and certainty of both the observed and forecasted atmospheric forcings;
- Are appropriate for hydrologic forecasting across a range of space and time scales;
- Are amenable to real-time forecasting at NWS field offices given realistic levels of computer resources, personnel and training, and
- Work within the Community Hydrologic Prediction System.

It is very likely that no single model will be capable of meeting all of the above requirements, and so the plan envisions a suite of models, including distributed and lumped models, that will be integral components of the hydrologic forecasting system for the foreseeable future.

In evaluating any new technology—hydrologic or otherwise—against a well-established one, it is critical to recognize that there is almost always an unavoidable period of maturation before the new technology reaches its full potential. This process in the context of paradigm shifts in hydrologic forecast systems is illustrated in Figure 1**,** which is modified from a figure in the National Research Council (NRC) Report of a Workshop on Predictability and Limits-to-Prediction in Hydrologic Systems (NRC, 2002).

Comparing its forecast skill to a system based on a better-established paradigm with a new approach will likely provide an unfairly pessimistic view of the ultimate potential of the new system (see the NRC, 2002 report for details). Therefore, transferring from the existing paradigm once it reaches or approaches maturity, to a new paradigm, may result in a temporary decrease in skill. However, once the new system matures, its forecast skill should overpass that of the existing one. Some examples of new paradigms in hydrologic forecasting that are showing promise of following this trajectory include: multi-model ensemble forecasts, multivariate and distributed parameter calibration, and assimilation of distributed and multivariate data.

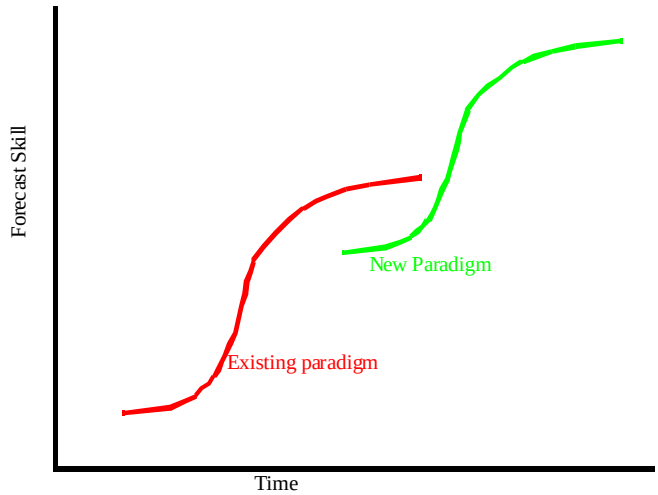

Figure 1. Conceptual figure demonstrating how advances in predictability science transition to improved operational predictions. Adapted from NRC (2002).

ENSEMBLE MODELING

The needs for reliable and skillful ensemble and probabilistic hydrology and water resources forecasts have grown considerably in recent years as more users practice risk-based decision making. The range of spatio-temporal scale for which such probabilistic forecast information is needed is very large. **Figure 2** depicts the overarching service goal for the Advanced Hydrologic Prediction Service (AHPS; McEnery *et al.*, 2005), and shows the range of forecast lead-time for which reliable and skillful ensemble and probabilistic information must be produced to meet the needs of the multitude of customers and users.

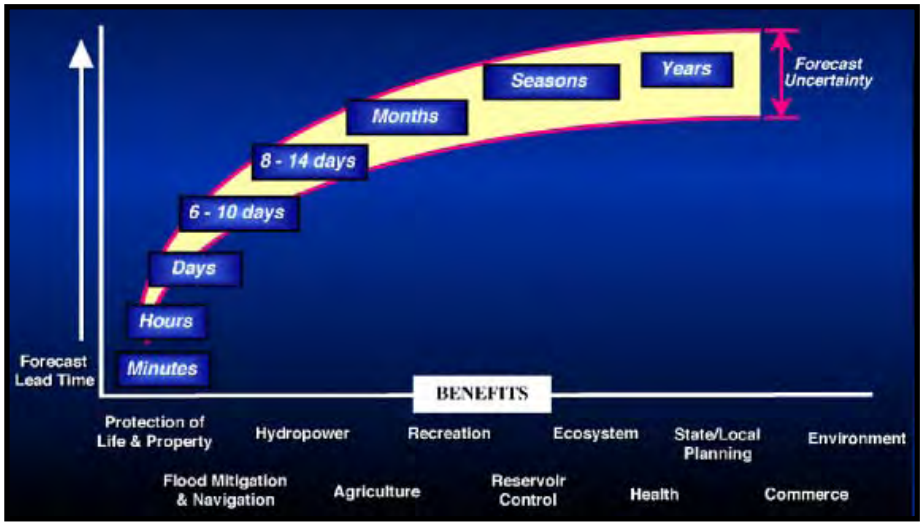

Figure 2. Uncertainty in hydrologic forecasts as a function of forecast horizon

Operational hydrologic ensemble forecasting has two overarching science goals. The first is to accurately quantify the integrative predictive uncertainty associated with the principal forecast elements in hydrology and water resources products, such as streamflow and soil moisture. The

second is to minimize the constitutive uncertainties cost-effectively. The left-hand side of Figure 3 shows the major sources of error in hydrologic forecasting, and illustrates qualitatively how the uncertainty may increase as the forecast lead-time increases. The right-hand side of the figure identifies the components of the hydrologic ensemble forecast system (see below) that address reduction and quantification of the uncertainties.

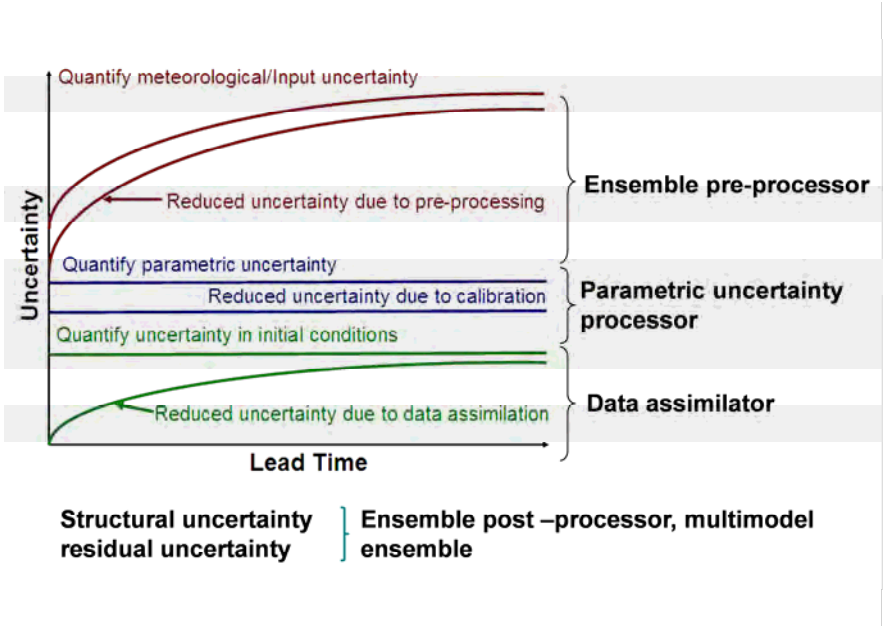

Figure 3. Uncertainties in Hydrologic Forecasting

In an effort to produce uncertainty information for short-term forecasts, NWS initiated development of prototype capabilities for short-term ensemble forecasting in the late 1990s through early 2000s. They include the Ensemble Pre-Processor (EPP) for generation of ensembles of future precipitation and temperature from single-value quantitative precipitation and temperature forecasts (QPF, QTF; Clark *et al.*, 2004; Schaake *et al.*, 2007), the Ensemble Post-Processor for accounting of hydrologic uncertainties (Seo *et al.*, 2006), the Hydrologic Ensemble Hindcaster (HEH) for hindcasting and large-sample verification of streamflow ensembles (Demargne *et al.*, 2007), and the Ensemble Verification System (EVS) for verification of precipitation, temperature and streamflow ensembles (Demargne *et al.*, 2007). Since the mid-2000's, NWS has expanded the capability of EPP to generate mid-range (from Day 1 through Day 14) precipitation and temperature ensembles from the mean of the ensemble forecasts from the National Centers for Environmental Prediction's (NCEP) Global Forecast System (GFS) (Schaake *et al.*, 2007). Work is ongoing to generate long-range ensemble forecasts of precipitation and temperature from the NCEP's Climate Forecast System (CFS). A number of RFCs have been operating these prototype tools experimentally (Figure 4). In that figure, the acronyms represent the names of the River Forecast Centers (RFC), as follows: Northwest (NW), Missouri Basin (MB), North Central (NC), Northeast (NE), California-Nevada (CN), Colorado Basin (CB), West Gulf (WG), Arkansas-Red River Basin (AB), Lower Mississippi (LM), Ohio (OH) Southeast (SE) and Middle Atlantic (MA).

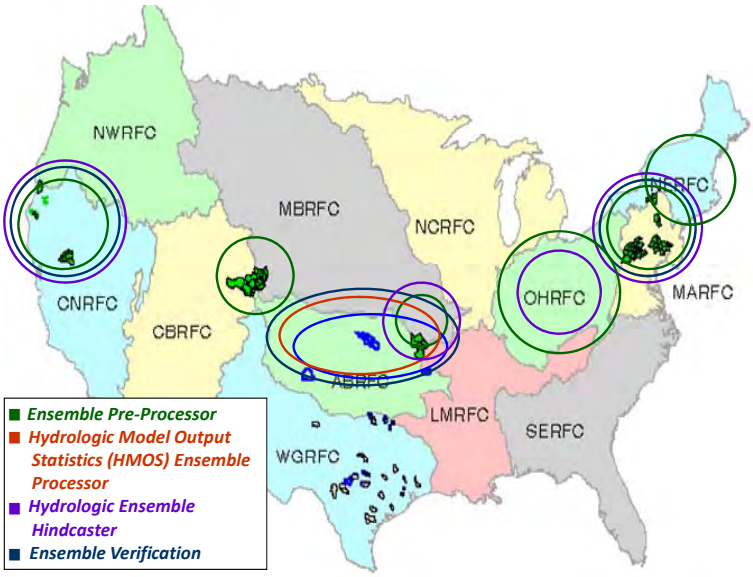

Figure 4. Current Experimental Operations of Short-Term Ensemble Forecasting Tools

The vision is to be able to produce reliable and skillful ensembles for a wide spectrum of hydrology and water resources services (see Figure 2 and Figure 3*)* from minutes to years into the future and over a range of spatial scales where the service needs exist. The envisioned hydrologic ensemble forecast system must be able not only to capture the *integrative predictive* uncertainty associated with the hydrology and water resources variables over this range of spatio-temporal scale, but also to *reduce* the various uncertainties in the forecast process (Figure **3**) through pre-processing, data assimilation, and post-processing.

It is well known that structural errors in hydrology and water resources (in particular, rainfall-runoff) models are a major source of uncertainty. The multimodel ensemble approach (Georgakakos *et al.*, 2004) provides a framework in which the major sources of uncertainty (Figure 3) may be quantified and reduced while maintaining dynamic and statistical consistency of the processes modeled and the products generated. Given the wide range of spatio-temporal scales over which ensemble and probabilistic information must be produced, the space-time scale at which the hydrology and water resources models can operate cost-effectively must vary (e.g., at time steps of hourly, 6-hourly, etc. and at spatial scales of, e.g., HRAP, MAP, etc.). As such, the ensemble forecasting framework must be flexible enough to allow operation of hydrology and water resources models at different space-time scales, and the science capabilities need to be developed to produce ensemble and probabilistic information from multiscale models that is statistically consistent across scale. Figure 5 depicts this envisioned multi-model ensemble framework through which each of the major sources of uncertainty Figure 3) may be accounted for, propagated and integrated.

For accurate and space-time-specific monitoring and prediction of water resources, hazards, and quality, comprehensive and integrated modeling of water flow, storage, and quality from hillslope to ocean is necessary. Such modeling should be comprehensive and multi-scaled to close the water budget from local to national scales, and integrated across all natural and man-made hydrologic, hydraulic, limnological, and estuarine processes and systems that impact availability,

quality, supply, and demand of water. Modeling of such processes and systems should include all science elements of storage and flow as well as a number of other elements. The time scales associated with these processes and systems range from minutes to years and beyond. To integrate these diverse models with dynamical and statistical consistency over a wide range of scale, wide-ranging interdisciplinary science and systems expertise are required. Of particular challenge is to couple the water resources models with the decision support systems under the ensemble paradigm for uncertainty-based prediction and decision-making. Hence, closer and expanded partnerships and collaborations with the research and the user communities are essential.
The rationale for an uncoupled, rather than coupled, hydrologic/land surface model, as depicted in Figure 5, is based on the assessment that, within the planning horizon conceived for the Strategic Science Plan, only the uncoupled framework is likely to provide the flexibility and modularity necessary to meet the NWS service goals. The advantages of an uncoupled hydrologic/land surface model include full utilization of the expanded ensemble forcing, broadening of the forcing sources, and easier correction of model biases, increase in model resolution, support to RFC operations, and development and implementation of multi-model ensemble methodologies.

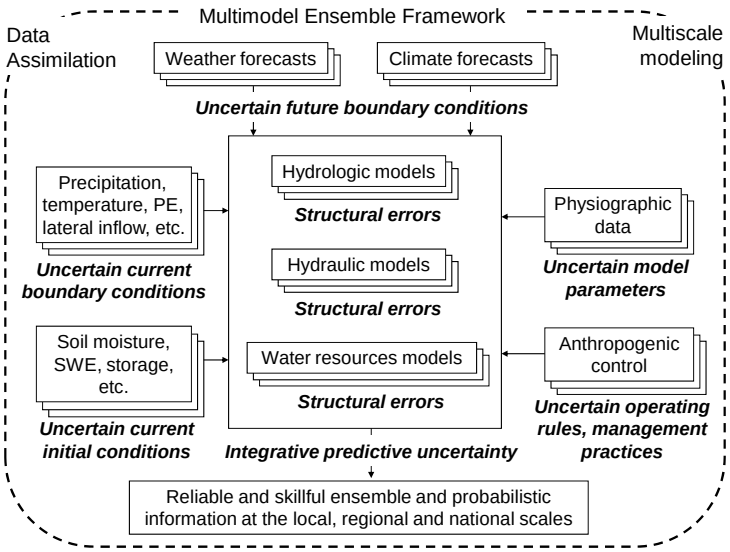

Figure 5. Multi-model Ensemble Framework

LOW FLOW FORECASTING

Historically, the focus of NWS streamflow forecasts has been primarily on high flows for flood forecasting nation-wide and for water supply in the west. Therefore, detailed knowledge/modeling of groundwater has not been necessary, given its negligible contribution to the hydrograph during high flows. However, with the new emphasis on low flow forecasting for drought and water resources services, the groundwater contribution to streamflow becomes substantial. It follows then that improving NWS ability to forecast low flows depends on the quality of groundwater models we use.

The hydrologic forecast operations by the National Weather Service do not currently include explicit groundwater hydrology models. Only the base flow components of the two hydrologic models (Sacramento and Continuous API) provide some degree of information about groundwa-

ter conditions. Ongoing collaboration between OHD and the University of California at Irvine is investigating the linkage of sub-surface flow paths amongst the grids modeled using HL-RDHM. Additional work which we will be investigating includes the work at the USGS by Markstrom *et al.* (2008) who finished coupling the Precipitation Runoff Modeling System (PRMS), a distributed rainfall-runoff model, with the U. S. Geological Survey Modular Ground-Water Model (MODFLOW) under the name, Groundwater/Surface-Water Flow (GSFLOW) Model. MODFLOW has also been coupled with Hydrological Simulation Program - FORTRAN (HSPF) at the University of South Florida (Said *et al.*, 2005). At the University of Texas/Austin, a groundwater component and Topmodel approach to runoff has been added to the Noah LSM, in partnership with NCEP/EMC.

NWS should be in a position to provide reliable forecasts of groundwater contribution to stream flow, critical for effective low-flow forecasting, especially during drought conditions, by using two- or three-dimensional groundwater models in conjunction with other surface and hydraulic routing models. Furthermore, NWS should make use of the wealth of information on groundwater levels provided by observations wells (as of November 2007, the USGS obtains real-time data (5 – 60 minutes) at 1,035 sites, and daily data at 4,953 sites.) Use of these data would provide information for model calibration, verification, and data assimilation. However obtaining estimates of groundwater pumping in rural areas will be a major challenge. Those records are not available in real-time, although the slow-responding times of groundwater systems make the availability of real-time information less critical.

Verification of the performance of the groundwater models requires observations of the water table elevation. Although new remote-sensing techniques, based on the NASA/ GeoForschungsZentrum (GFZ) Gravity Recovery and Climate Experiment (GRACE) satellite system are now being developed, those observations have a very high vertical resolution, (of the order of cm), but a horizontal resolution of the order of about 80 km, much too coarse for practical NWS hydrologic forecasting applications. Furthermore, GRACE observations measure total change in water (including snow, soil moisture and groundwater). It is, therefore, a challenge to estimate how changes are distributed among the components.

The modeling of karstic and fractured aquifers is particularly challenging. Obtaining geologic information and calibration of groundwater models for such aquifer is the main difficulty.

Finally, Operational use of coupled groundwater and surface-water models will require additional training by NWS forecasters.

In collaboration with the USGS and other agencies, OHD should research the issues of coupling surface and groundwater forecasting models, specifically how to consider flow in the unsaturated zone, how to couple the one-dimensional soil moisture accounting models with two- and three-dimensional groundwater models; and how to deal with widely different response times.

Once the issues have been identified, OHD will produce prototypes to be field-tested in those RFCs that have watersheds in which low flows and water extraction for irrigation and water supply are important.

CONCLUSIONS

The National Weather Service prepared a Strategic Science Plan to guide the hydrologic science research and transition to operations for the next 5 – 10 years. This paper summarizes three aspects of the research plan, namely the directions of distributed hydrologic modeling, probabilistic forecasting, and coupled groundwater-surface water modeling considerations for low-flow forecasting.

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