# Hydrological Ensemble Prediction Experiment (HEPEX )
# Workshop March 8-10, 2004
# SUMMARY REPORT

## 1. HEPEX Goal

HEPEX aims to bring the international hydrological and meteorological communities together to demonstrate how to produce reliable hydrological ensemble forecasts that can be used with confidence by the emergency management and water resources sectors to make decisions that have important consequences for the economy, for public health and safety.

## 2. Executive Summary

The main scientific theme of HEPEX will be how hydrologic forecast uncertainty can reliably be quantified at each step of the forecast process and then communicated to, and applied by the end users.

HEPEX is an independent, cooperative international scientific activity that is affiliated with several international organizations and with many other organizations interested in hydrologic ensemble prediction as well. Participation in the HEPEX project will be open to anyone who may wish to contribute to help meet its goal. The project will maintain a list of participants and will keep them informed about HEPEX activities that may be of interest to them. Primary leadership of the HEPEX project is the responsibility of a science steering group that will be composed of representatives of organizations affiliated with the project. A User Council composed of representatives of organizations with a strong interest in using or applying HEPEX results will oversee HEPEX activities.

Many scientific questions need to be addressed for operational hydrological ensemble forecasts to be used to their full potential. Meteorological aspects of ensemble prediction include issues such as:

- What are the requirements of ensemble weather forecasts to support hydrologic prediction?
- Do the existing meteorological forecasts account for important meteorological and climate uncertainties?
- What is the role of operational forecasters?
- What are the scientific questions and issues that need to be addressed to meet requirements?

Hydrologic ensemble prediction involves integrating many sources of uncertain information and accounting for how hydrologic processes would behave in response to this information. Sources of uncertainty include future weather and climate forcing, initial hydrological conditions and uncertainty in model representations of hydrological processes. Because hydrological models are imperfect and because of limitations in representing important sources of uncertainty, the raw ensemble forecasts produced by hydrological ensemble forecast systems may contain complex biases that must be removed to meet user requirements for reliable ensemble forecast information.

Data assimilation is required in hydrological ensemble prediction to process available observations to produce the best possible probabilistic estimates of initial hydrological conditions. These estimates must include ensemble members as well as probabilistic distributions of individual state variables. The ensemble members must represent the appropriate joint variable structure, both among state variables at a given location and spatially, of equally likely possible initial states.

Hydrologic modeling issues that are important to HEPEX include: What are the sources of uncertainty in hydrological models? What are the implications of hydrological models being imperfect representations of real hydrological systems? How can uncertainties in hydrological models, model parameters and hydrological initial conditions be represented in hydrological ensemble prediction?

Verification is essential to HEPEX because we must be able to measure the accuracy and reliability of our results. This is important to our users. It is important to measure progress toward our scientific objectives. And it important to assure that improvements are being made to operational forecast systems.

To address user needs and science issues to meet these needs, HEPEX will organize a set of cooperative activities that include test-beds, inter-comparison experiments as well as scientific workshops and meetings. One objective of the project will be to develop a pilot capability for hydrological ensemble prediction that could be used by hydrological services throughout the world. The results would be demonstrated through test beds, inter-comparison projects and by application by operational hydrological services, water resources agencies and other users.

For HEPEX to achieve its goal it must have strong mutually supportive ties to other international programs. These include programs to: improve weather and climate forecasts; to provide new global sources of data and improve existing sources, especially satellite data and surface observations; to develop improved data assimilation techniques, and to improve hydrological forecasts.

The HEPEX program from its inception must be an evolutionary and adaptive program. The program needs to be responsive to funding opportunities, proactive in fostering collaborative partnerships among academia, operational centers and the private sector (e.g. THORPEX, USWRP, etc.), and aware of relevant breakthroughs and their impact on defining new directions for the program. The foundation of such a program starts with its governance. HEPEX must implement governance that reflects one of a true international effort, with leadership drawn from its global “stakeholders” who are actively involved in hydrometeorological prediction and use of such predictions.

## 3. Statement of Importance and Urgency

Ensemble forecast techniques are beginning to be used for hydrological prediction by operational hydrological services throughout the world. These forecasts are important because they not only offer an estimate of the most probable future state of a system; they also provide an estimate of the range of possible outcomes as well. Indeed, many users are risk-averse. They often are more concerned with having a quantitative estimate of the probability that catastrophic effects may occur than with knowing the most probable future state.

Not only does ensemble prediction in hydrology offer a general approach to probabilistic prediction; it also offers an approach to improve hydrological forecast accuracy as well.

## 4. Introduction

Reliable hydrological ensemble forecasts must account for effects of a wide range of sources of uncertainty. These include uncertainty in precipitation and in other meteorological inputs, uncertainty in initial hydrological conditions and uncertainty in hydrologic forecast model predictions of how meteorological inputs and hydrological initial conditions will be transformed into hydrological outputs.

Existing meteorological and hydrological ensemble forecast techniques do not reliably account for important uncertainties. Because these techniques rely on imperfect models of the processes they represent, model forecasts (both meteorological and hydrological) contain a complex set of biases that must be removed to meet user requirements. This requires a major scientific effort that can only be accomplished through extensive international cooperation involving the combined efforts of meteorological, hydrological and user communities.

The main scientific theme of HEPEX will be how hydrologic forecast uncertainty can reliably be quantified at each step of the forecast process and then communicated to, and applied by the end users. Reliable quantification of forecast uncertainty is the key science issue that gives the program a unique and important role that at the present is not fulfilled by any existing hydrological prediction related program.

Representatives of operational hydrological services, operational water resources organizations and a wide range of users of the results are expected to participate in helping to define and execute the project. The HEPEX objective can be achieved if the meteorological, hydrological and water resources communities understand the key challenges they face and work together with the user community to couple currently available forecasts tools, to improve the current quality of available systems and to help users to apply probabilistic forecast information.

## 5. Organization of HEPEX

HEPEX is an independent, cooperative international scientific activity that is affiliated with several international organizations and with many other organizations interested in hydrologic ensemble prediction as well. Because of the breadth of the HEPEX goal there is no single international organization that could serve as a single "parent" organization to which HEPEX might report. Therefore, HEPEX will have several international "parents" and will develop appropriate collaborations with them.

### 5.1 Organizational Structure

The organizational structure of the project will include the following:

- General membership
- Affiliations with international organizations (GEWEX,IAHS,WMO, etc.)
- Science Steering Group (SSG) with a chair and co-chair
- User Council with a chair
- HEPEX projects and activities

### 5.2 General Membership

Participation in the HEPEX project will be open to anyone who may wish to contribute to help meet its goal. The project will maintain a list of participants and will keep them informed about HEPEX activities that may be of interest to them.

### 5.3 Organizational Affiliation with HEPEX

Some of the international scientific activities and organizations that have a strong interest in being affiliated with HEPEX include: the GEWEX (Global Energy and Water Cycle Experiment), through its GHP (GEWEX Hydrometeorology Panel) WRAP (Water Resources Application Project); the IAHS (International Association of Hydrological Sciences) through its Prediction for Ungaged Basins (PUB) project; the World Meteorological Organization (WMO) though several of its programs, especially the WMO Hydrology and Water Resources (WMO/HWR) program, the UNESCO International Hydrology Program (IHP) and the World Weather Research Project (WWRP), including its related THORPEX project.

The goal of WRAP is to help GEWEX to meet a goal of demonstrating a capability to apply the results of its research in support of the water resources sector. Indeed the initial impetus for organizing HEPEX developed within the GEWEX the community and was seen as an important activity for WRAP.

The IAHS/PUB project includes a goal to account for and reduce uncertainty in hydrological predictions for ungaged basins. HEPEX will be a working group of the PUB project that will provide an opportunity to integrate some of the activities of other working groups and provide important linkages between PUB and potential users of PUB accomplishments.

Linkages between HEPEX and operational hydrological and water resources organizations could be facilitated by the WMO Hydrology and Water Resources (WMO/HWR) program. WMO/HWR, representing operational hydrological services internationally, could help to define the hydrological requirements (from a user perspective) for what HEPEX might produce, participate in the execution of the project and assist in evaluating the results. Because of the interdisciplinary nature of HEPEX, WMO/HWR could facilitate collaboration between HEPEX and other related WMO activities.

Many other regional, national, local, corporate, scientific or other organizations will be affiliated with HEPEX as well.

### 5.4 Science Steering Group, Chair and Co-Chair

Primary leadership of the HEPEX project is the responsibility of a science steering group that will be composed of representatives of organizations affiliated with the project. It is expected that steering group members will help to lead HEPEX projects and activities and will represent various organizational interests in the execution of the project.

An initial science steering group will be formed by the conveners of the initial HEPEX workshop March 8-10 at ECMWF. The steering group will elect a chair and co-chair. Steering group members will serve for two year terms that may be renewed. Members of the steering group will be appointed by the Chair in consultation with the Co-Chair.

### 5.5 User Council and Chair

A User Council composed of representatives of organizations with a strong interest in using or applying HEPEX results will oversee HEPEX activities. An initial Chair of the User Council will be appointed by the Steering Group. The User Council Chair will appoint members of the User Council who will serve for two year terms that may be renewed. Members of the User Council will elect the User Council Chair. At least two members of the User Council will also serve on the Science Steering Group

### 5.6 Development of HEPEX Projects and Activities

HEPEX projects and activities will be formulated by scientists and users interested in them. Their scope may be local, national, regional or international. They will be conducted with the endoresement of the Science Steering Group. Leaders of these projects and activities will be invited to be members of the Science Steering Group.

## 6. Key Scientific Issues

Many scientific questions need to be addressed for operational hydrological ensemble forecasts to be used to their full potential. Examples of important questions include: What are the properties of weather and climate forecasts? How can weather and climate information, including ensemble forecasts, be used reliably? How can the space and time scale properties of weather and climate forcing together with space and time scale properties of hydrological systems be best integrated in a hydrological ensemble prediction system? How does the uncertainty in weather forecasts translate into hydrological uncertainty? How can uncertainties in hydrological models, model parameters and hydrological initial conditions be represented in hydrological ensemble prediction? Can we attribute and quantify the sources of uncertainty? How do we generate consistent ensembles that reflect the total uncertainty of the system, including space-time correlations, and the uncertainty that comes from hydrologic initial states, parameters, and model structure? How do long-range Ocean-Atmosphere phenomena (i.e. El Niño) affect short- medium- and long-range hydrological forecasting? What is the relative role of weather and climate forecasts vs initial hydrological conditions in affecting the skill of hydrological forecasts? How can hydrological ensemble forecasts be verified, and what can be done to gain confidence that a given forecast system is reliable? How do we validate hydrologic ensembles for extreme events? What data could be used to evaluate the limits of predictability? What is the role of a human forecaster? What interface is needed for forecasters to control the operation of a hydrological ensemble forecast system? What is the experience of different groups throughout the world with ensemble hydrological prediction? What are the key science questions that need to be addressed by the HEPEX science plan? These questions need to be expanded and, in some cases, clarified.

### 6.1 Meteorological Aspects of Ensemble Prediction

Meteorological aspects of ensemble prediction include issues such as:

- What are the requirements of ensemble weather forecasts to support hydrologic prediction?
- Do the existing meteorological forecasts account for important meteorological and climate uncertainties?
- What is the role of operational forecasters?
- What are the scientific questions and issues that need to be addressed to meet requirements?

Regarding the first issue, many of the meteorological requirements are relatively straightforward in concept, though in practice they may be difficult to provide. First, consider short-range forecasts for catchments of limited area. The ideal input to a hydrologic ensemble prediction system would be an ensemble of weather and/or climate forecast inputs that have the following qualities:

- Sharpness (to the extent possible, the ensemble has a distribution much different than the climatological distribution).
- Reliability (verified over many cases, probabilities determined from the ensemble match the observed event frequency).
- Accurate spatial variability (e.g., ensemble members forecast more precipitation on the upwind side of a mountain than the downwind side rather than smear the precipitation uniformly over both slopes),

- Accurate temporal variability (i.e., the precipitation trace drawn from ensemble members is statistically indistinguishable from the trace of the measured precipitation);
- Relevant variables. The ensemble data should output the relevant elements needed by the hydrologic prediction model. The most important variable is precipitation amount and type. Most hydrologic models also require a forecast of surface temperature with the freezing level being particularly important in mountainous areas. Some hydrologic models use potential evaporation as an input. Other models account for the energy as well as water budget, requiring information such as radiative fluxes and surface meteorological variables including humidity and wind. Some user applications may need estimates of water demand or electric power demand which require forecasts of surface meteorological variables. Some users, may require a wind forecast (for example, a power generating companies near Niagara Falls required a wind forecast to estimate how much water would be pushed from Lake Erie down the Niagara River).

An important meteorological aspect of ensemble prediction is whether current meteorological forecasts account for all of the important meteorological and climate uncertainties. Existing raw ensemble weather forecasts meet the previously listed requirements only very imperfectly. These ensembles are typically conducted with a reduced-resolution meteorological model, so the ensemble does not provide the required spatial detail. Uncertainty in the initial condition of the atmosphere may not be fully represented. And atmospheric models do not fully resolve all of the physical processes governing the occurrence of precipitation. As a result, the observed weather often does not appear to be a random draw from the ensemble, frequently lying outside the span of the ensemble. Clearly, the weather inputs will need to be improved in order to provide hydrologic models with the data they need. *Research is greatly needed on ways to improve and adjust the operational ensemble weather forecasts.* The appropriate role of operational forecasters in ensemble prediction also needs to be developed.

HEPEX might be able to provide the international advocacy to improve sharing of data. Especially in Europe, river basins often span several countries. Accurate hydrologic forecasts near the mouth of a river, for example, require streamflow and snowfall measurements far upstream, perhaps in a different country.

### 6.2 Hydrological Aspects of Ensemble Prediction

Hydrologic ensemble prediction involves integrating many sources of uncertain information and accounting for how hydrologic processes would behave in response to this information. Sources of uncertainty include future weather and climate forcing, initial hydrological conditions and uncertainty in model representations of hydrological processes. Because hydrological models are imperfect and because of limitations in representing important sources of uncertainty, the raw ensemble forecasts produced by hydrological ensemble forecast systems may contain complex biases that must be removed to meet user requirements for reliable ensemble forecast information.

Therefore, hydrologic ensemble forecast systems must include the following basic components:

- Meteorological ensemble preprocessor to remove biases in meteorological forecasts and downscale the information to provide precipitation and other forcing variables at the space and time scales required by hydrological forecast models. Because hydrological processes are sensitive to space-time variability of precipitation and other forcing variables, it is essential that the space-time structure of the meteorological ensembles have members that give a consistent representation of the space-time structure of the events that might occur. This includes representing the space-time dependence in forecast skill. It is not possible to predict exactly when and where very large precipitation events will occur over very small hydrological basin areas. But forecast skill increases over larger time intervals and special areas.
- Data assimilator to process observations (precipitation, snow cover, streamflow, remote sensing information, etc.) to update initial hydrological conditions and to produce ensemble members that represent the uncertainty in the initial conditions. Initial condition ensemble members must be consistent with corresponding meteorological forcing ensemble members.
- Hydrological forecast models that can account for model uncertainty in how natural hydrological processes would respond to prescribed initial conditions and input forcing.
- Hydrologic post-processing and product generation procedures to remove complex biases from raw hydrological ensemble forecasts and to produce probabilistic forecast products required by users.
- Forecast verification component to assess the accuracy and reliability of raw and adjusted hydrological ensemble forecasts and to monitor the accuracy and reliability of raw and downscaled/adjusted meteorological forecast inputs. Because large sample sizes are required for verification of probabilistic forecasts and because most users are interested in forecasts for specific physical locations, a retrospective forecast simulation capability must be included.

A key factor driving uncertainty in initial hydrological conditions is uncertainty in the precipitation estimates used to estimate the initial conditions. A major scientific effort is needed to develop Ensemble Quantitative Precipitation Estimation (EQPE) techniques, including multi-sensor EQPE techniques that account for uncertainties associated with use of rain gages, radars, satellites, etc in precipitation estimation over a wide range of space and time scales.

Another great challenge is to account for uncertainty in hydrological forecast models. This uncertainty occurs because hydrologic models are imperfect. Model structure is a simplified representation of the aggregate behavior very complex, highly variable natural processes. In addition, hydrologic model parameters are selected to give a good fit of how the model represents observed events. But there is no “best” way to make this fit so there is no unique set of model parameters that will always be “best’ to use for every forecast situation.

Uncertainty in updated hydrological initial conditions depends on:

- Uncertainty in previous initial conditions
- Uncertainty in model forcing
- Hydrological model uncertainty

It is a major challenge for hydrological research for the foreseeable future to account for this uncertainty and to demonstrate that this uncertainty can be represented accurately and reliably.

Uncertainty for rare (record) flood and drought events is especially important for practical applications. Demonstrating that this uncertainty can reliably be estimated is a special challenge because this can only be done on a regional, as opposed to local, basis in order to get large enough sample sizes.

One approach to improving both the accuracy of forecasts and the reliability of uncertainty estimates is through multi-model ensemble forecasting. This can include use of different models and use of multiple parameter sets for the same model. Multi-model ensemble techniques can be used both to produce meteorological ensemble forcing as well as hydrological ensemble forecasts.

### 6.3 Data Assimilation

The role of data assimilation in hydrological ensemble prediction is to process available observations to produce the best possible probabilistic estimates of initial hydrological conditions. These estimates must include ensemble members as well as probabilistic distributions of individual state variables. The ensemble members must represent the appropriate joint variable structure and spatial pattern structure of equally likely possible initial states.

Available observations include in situ measurements of variables such as precipitation, streamflow, snow water equivalent, soil moisture, air temperature, etc. They may include remotely sensed observations from radar or satellites. One of the challenges for HEPEX is to develop data assimilation techniques to use all of the available data and especially to process potential new satellite observations for improved hydrologic ensemble prediction, especially in data sparse areas. One example of this challenge is the case of precipitation estimation. It is well known that there usually is a great deal of uncertainty in these estimates, especially satellite-based estimates. If they are to be used for ensemble prediction, uncertainty in precipitation estimates must be quantified and an ensemble approach to satellite precipitation estimation must be developed. Similar approaches are needed for assimilating other data sources.

The weather and climate forecast communities have led the way in developing and applying environmental data assimilation techniques. HEPEX should address the commonalities and differences of these techniques with those needed by HEPEX and should build on this experience.

Over the past several years the importance of land data assimilation to produce initial conditions of the land surface for weather and climate forecasting has been recognized and collaborative scientific Land Data Assimilation System (LDAS) projects have been nurtured by GEWEX. These include the U.S. National-LDAS project, a European LDAS project and a Global LDAS project. To date these projects have focused on processing precipitation and other land surface forcing variables to produce single-value estimates of initial conditions. They are beginning to focus on estimates of uncertainty in these initial conditions and on using observations related to endogenous LDAS variables to update the initial forward estimates. HEPEX should collaborate with these LDAS projects.

### 6.4 Hydrological Modeling

Hydrologic modeling issues that are important to HEPEX include: What are the sources of uncertainty in hydrological models? What are the implications of hydrological models being imperfect representations of real hydrological systems? How can hydrologic uncertainty be quantified? How can uncertainties in hydrological models, model parameters and hydrological initial conditions be represented in hydrological ensemble prediction?

Hydrologic model "structures" in practical use vary considerably with place and lead-time. The role that different models might play in ensemble prediction needs to be investigated.

Some specific suggestions for HEPEX to consider are:

- Since HEPEX will involve participants from numerous diverse fields, it would be very helpful to have some energy devoted to clarifying the current confusion of terminology between (and within) fields – for example, the words uncertainty, parameter etc., are used with different meanings by atmospheric scientists and hydrologic scisntists.
- There is a real need for better data related to extreme hydrologic events.
- To improve hydrologic model development and evaluation, there is a need to push models in the direction of simulating/predicting variables that can actually be "observed". For example, many of the state variables of hydrologic models do not necessarily directly correspond to observable quantities (e.g., "soil moisture").
- The project should consider if there is a need for a "common" model framework for hydrology (based perhaps on a true object oriented strategy)? It was recognized however, that this may be more useful for science discussions than for operations / applications. But this is an important issue for the CHPS project to consider.
- It was strongly felt that each participating modeling group should be encouraged to consider how their model predictions can be made to reflect the inherent model uncertainty (structures, parameters).

- It would be helpful to have available and use data on internal variables for calibration.

### 6.5 Verification

Verification is essential to HEPEX because we must be able to measure the accuracy and reliability of our results. This is important to our users. It is important to measure progress toward our scientific objectives. And it important to assure that improvements are being made to operational forecast systems.

Development of verification techniques for use in hydrological ensemble forecasting is a challenge for HEPEX for several reasons:

- Verification of hydrological forecasts, even single-value forecasts is not well developed. One manifestation of this is that there is that there is very little discussion of verification in the latest WMO Manual of Practice for hydrology. There are few references to hydrologic verification in the scientific literature.
- Techniques for verification of probabilistic forecasts are in their infancy.
- Very little attention has been paid to measuring space-time scale dependent properties of ensemble forecasts that are critical to the success of distributed hydrological forecast models and to the success of long-range ensemble hydrological predictions .

Another challenge for HEPEX is that verification of probabilistic forecasts requires large sample sizes to limit effects of random sampling variability on the results. Users are generally interested in the accuracy and reliability of forecasts for specific locations. This depends on hydrologic conditions at these specific locations. Results for other locations may not be representative of the specific locations of interest to a given user. Therefore, retrospective approaches to verification must be developed. These will require retrospective procedures to represent ensemble forecasts of weather and climate forcing. It also will require retrospective approaches to the operation of data assimilation procedures that may use observations that did not exist in the past.

Verification of probabilistic forecasts of rare events is an especially difficult problem that cannot be solved by local retrospective forecasting alone but will require a regional approach to retrospective forecasting.

Verification procedures need to be applied at many stages of ensemble hydrological prediction, not just to the final outputs prepared for users. This is important to understand what is happening in the hydrological forecast process, to diagnose opportunities for improvement and to assess the limits of predictability.

## 7. Scientific Components of HEPEX

To address user needs and science issues to meet these needs, HEPEX will organize a set of cooperative activities that include test-beds, inter-comparison experiments as well as scientific workshops and meetings. One objective of the project will be to develop a pilot capability for hydrological ensemble prediction that could be used by hydrological services throughout the world. The results would be demonstrated through test beds, inter-comparison projects and by application by operational hydrological services, water resources agencies and other users.

HEPEX does not have a dedicated source of funding. HEPEX activities will be planned and carried out by scientists that already have appropriate funding or who might seek funding for their efforts. The HEPEX science plan (that will be developed) will define the scientific agenda for HEPEX, give legitimacy to the need for general areas of research, stimulate scientists to undertake the research, avoid duplication of efforts, stimulate international research cooperation and stimulate research funding agencies to support the work needed for HEPEX to succeed. It also is expected that scientists participating in HEPEX will organize special sessions at scientific meetings and publish their results in peer-reviewed scientific journals including occasional special issues.

## 7.1 User Roles and Perspectives

HEPEX is both a user-driven as well as science-driven activity. Users will be actively involved both as participants and leaders, through the User Council, of HEPEX activities. A fundamental guiding principle of HEPEX is the premise that "people support what they help to create". So it is essential to the success and sustainability of HEPEX that users be involved in most aspects of the project.

Users hope HEPEX will provide information from the meteorological and hydrological communities on the models used and assumptions. Users also hope that forecast system improvements will be designed with their involvement to meet their needs. Users must ultimately decide if their needs are being met or if improvements are actually being made. "Reliability measures" are needed so that the accuracy of the uncertainty is understood.

## 7.2 Outreach, Education and Product Development

A major step is to make sure that potential users know what HEPEX can do for them. New technologies are rapidly adopted if they are incremental improvements over the old way of doing things. Technology transfer has a difficult time when a radical departure from past practice is the goal – particularly if the benefits are not immediately clear and there is increased risk of going wrong. HEPEX is an opportunity for making more than an incremental improvement. It involves new concepts, new information and requires users to develop new ways of using information to make decisions.

Therefore, HEPEX should develop a plan for outreach and education of the users, resource managers, and decision makers. While the meteorology and hydrologic research communities readily understand the value of probabilistic forecasts, the end users are not uniformly aware how their decision making ability might be improved with this new information. As well, the meteorology and hydrologic communities may not be providing the most relevant products to the end users, and this outreach may direct us to developing more user-relevant forecast products.

An aggressive campaign is needed to promote HEPEX. This should be based on an understanding of customers, their requirements, their capabilities, and limitations for absorbing the results. The customers include the Cities and Towns affected by flood plain zoning as well as the agencies and consultants that define the zones.

HEPEX should motivate "value added" vendors and consultants to promote HEPEX concepts and products. The User Group concept, with conference sponsorship for the first few years by EPA, was a major factor in the success of the Storm Water Management Model SWMM replacing the Rational Method in the design of urban drainage systems.

It is important to include environmental and regulatory agencies in HEPEX – they can help to create a paradigm shift towards more realistic understanding of the environment and more enforceable regulations. Water quality issues are inherently probabilistic and are a natural arena for promoting HEPEX.

Use the web as a demonstration site to market successful applications. Provide a demonstration toolbox for training and testing the effectiveness of ensemble forecasts.

To be sure that HEPEX results are likely to be useful it should make a survey to locate instances where existing hydrologic forecasting procedures appeared to be deficient and where the infrastructure (data, people, and budgets) is in place to accept HEPEX. Then, focus initial development for implementation into practice on those specific situations where HEPEX can be shown to be useful almost immediately.

To help users to use probabilistic forecasts HEPEX should

- Sponsor and support educational activities, aimed at hydro-met agencies and regulators
- Education of staff, e.g. of water authorities, the Corps of Engineers
- Develop demonstration toolbox, e.g. for post-processing ensembles
- Create simple probabilistic measures, e.g. probability of exceeding thresholds
- Create game-type examples, e.g. based on gambling
- Include social science expertise to facilitate meetings and supporting materials for decision makers that are the ultimate users of the forecasts.

To facilitate product development HEPEX should:

- Clarity of objectives. HEPEX is for Users, not for "developer delight".
- Define the users and garner their active support – forecasters, water managers, regulatory agencies.
- Create customer demand through e.g. legislation, demonstration of net economic benefit, environmental protection, and social welfare (the BIG THREE public accounts)
- Help prospective users and regulatory authorities understand that it's a viable technology
- Facilitate making the technology and data readily available, including obviously usable computer outputs and documentation.
- Look to the future computer and data systems that will be available when the products roll out. While going ahead now with development and demonstration of probabilistic products don't be constrained by currently available run times, memory, storage, or internet capabilities.
- Generate "excitement" in academia – seek financial support for projects that develop or depend on ensemble forecasts

HEPEX needs to focus on the total package that users will require. This should include a replacement for water management simulation and optimization methods that deal with a single hydrologic trace at a time. Users need today's best SINGLE recommendation from the ensemble of information

### 7.3 Community Hydrolologic Prediction System (CHPS)

The over-arching goal of CHPS is to develop an environment that would facilitate collaborative advancement of hydrologic ensemble prediction capability. What should be done to achieve this goal needs to be developed. If it to succeed at integrating the many complex scientific components that are required and if it is to succeed at reducing the time required for infusing science into hydrological forecast operations, CHPS must be much more than a discussion group. On the other hand CHPS must support testing of a wide range of new approaches so it cannot be only a single, "best" approach. It must be a research system that easily supports introduction of alternative procedures. It cannot be a fully operational system dependent on specific data system protocols. But it must be reasonably compatible with them.

CHPS could be a methodology for testing and evaluating the efficiency of HEPS (Hydrological Ensemble prediction systems), a common database on which each proposed HEPS should be tested, a computational library or frame for research software.

Several key issues were identified and need to be individually noted:

- The development of CHPS is sensitive in the operational context of Europe. The system should not be used to develop forecast information that conflicts or competes with official sources of information.

- The development of CHPS will have to address institutional issues. CHPS must have a clear benefit for all those who choose to participate. Many modeling systems are proprietary. A researcher may be hesitant to include their models or approaches if their funding may be negatively impacted.

- The CHPS conceptual framework should allow for the coupling of weather and hydrologic models. Coupling need not be required at the beginning, but the framework should not preclude it. Some felt that coupling would prevent CHPS from becoming obsolete. Coupling also encourages scientific collaboration between meteorologists and hydrologists.

- The CHPS framework should include downscaling techniques.

- CHPS should allow for the demonstration of capability. Demonstrations need not include all the details of operational use to be beneficial. The demonstration of operational capability facilitates the acquisition of funding. Techniques that address operational issues (i.e. missing/late data, human error, etc.) are needed.

The development of CHPS in the form of a system that can demonstrate capability, identify needed elements, and evaluate various components and techniques has tremendous potential and utility to all sectors interested in hydrologic ensemble prediction. Many institutional obstacles exits, but can be navigated. Leadership and investment will be required to move forward.

### 7.4 Test Beds and Inter-comparison Projects

Development of reliable hydrological ensemble forecasts will be nurtured though activities such as inter-comparison projects and "hydrologic ensemble test beds." Test beds would facilitate the rapid development of a high-quality hydrologic ensemble prediction techniques. The test bed concept would work in concert with the development of CHPS, the Community Hydrologic Ensemble Prediction System.

What is this test bed? We envision that a test bed would include a data base with a readily accessible collection of meteorological ensemble forecasts, associated weather observations, land-surface analyses, streamflow measurements, and information on the uncertainty of the measurements. Most likely, there would be several test beds spanning a diverse range of geographic regions. The regions would be selected for their general interest and data availability; weather and streamflow measurements should have been plentiful in test bed regions over a long period of time, so hydrologic models could be tested on weather scenarios spanning a number of years. Operational and experimental ensemble weather forecasts (before and after calibration) would be posted to the test bed data base. Individual researchers and groups could download the relevant forecast and observed data, run their hydrologic models, and validate their hydrologic forecasts. We envision that some facility would host this test bed and would provide an easy way for the community to get free, rapid access to all of the data. In practice, of course, it may prove difficult to supply the test bed with a large dataset of retrospective ensemble forecasts from a consistent model, especially one that is used operationally. The weather services do not yet routinely run such re-forecasts.

A test bed would permit the examination of some crucial questions. What are the relative sensitivities to weather forecast uncertainty vs. land surface/snow cover uncertainties? What is the relative value of raw ensemble forecasts vs. those corrected to provide unbiased information. Is one proposed hydrologic modeling system better than another?

Inter-comparison experiments should be designed to include:

- Methodology of ensemble generation, including the representation different types of uncertainty (input, initial conditions, model etc),
- Ensemble processing that includes downscaling and bias corrections, and
- Development of ensemble-based forecasts in hydrologic models

Hydrological forecast model activities might include

- Inter-comparison of Distributed vs. lumped models. Questions to be investigated in such a model inter-comparisons include:
    a. What level of discretization is required? Space/time scale?
    b. How can we propagate uncertainty through highly nonlinear hydrologic models?
    **c.** How can we explain and correct for lack-of-fit of models (both lumped and distributed) that occurs because models are imperfect?
    d. What kinds of diagnostic tools are required/useful?

- Creation of a common/benchmark data set (high resolution rainfall, spatial data, nested runoff, etc.)

- Some mechanism to discuss and test how to adapt the modeling strategy to take advantage of relative strengths of hydrologic and meteorological models (spatial representation, stochastic approaches, dynamical representation). One important mechanism may be to define an interface/information exchange protocol for passing hydrological & meteorological models between models.
- Integrate with/take advantage of MOPEX, PUB, DMIP, etc.
- Promote common level of modeling expectation within the HEPEX community

### 7.5 Meetings, Workshops and Publications

HEPEX will foster scientific collaboration and exchange through special sessions at national and international scientific meetings, special focused workshops and publication of papers in peer reviewed journals, including special issues growing out of special sessions and workshops.

### 7.6 Science and Implementation Strategy Document

A Science and Implementation Strategy Document will be prepared by the Science

Steering Group with assistance from the user Council.

## 8. International Linkages

For HEPEX to achieve its goal it must have strong mutually supportive ties to other international programs. These include programs to: improve weather and climate forecasts; to provide new global sources of data and improve existing sources, especially satellite data and surface observations; to develop improved data assimilation techniques, and to improve hydrological forecasts. Many of these programs have goals that include producing results that are beneficial to water management or that reduce the effects of natural hazards such as floods and droughts. Therefore, HEPEX offers an important opportunity to help these programs to demonstrate that they are meeting their goals.

## 9. Future Activities

The HEPEX program from its inception must be an evolutionary and adaptive program. The program needs to be responsive to funding opportunities, proactive in fostering collaborative partnerships among academia, operational centers and the private sector (e.g. THORPEX, USWRP, etc.), and aware of relevant breakthroughs and their impact on defining new directions for the program. The foundation of such a program starts with its governance. HEPEX must implement governance that reflects one of a true international effort, with leadership drawn from its global "stakeholders" who are actively involved in hydrometeorological prediction and use of such predictions.

An early goal of HEPEX must be determining and prioritizing the needs of the program. Once the forecast parameters and the precision requirements of end users are determined, the data needs and goals of requisite meteorology and hydrology can be defined more precisely. To achieve this goal, the program must be designed to reach across the historic boundaries that have separated the disciplines of meteorology and hydrology from the end users; seamless communication between camps is essential for success of the program. Of course, the ultimate goal for HEPEX is proving that hydrological forecasts have "value" for hydrological parameters of interest to the end user. Documenting of value includes showing how such forecasts can aid decision-making, then creating of intuitive "decision tools" to aid users.

User requirements, in conjunction with the inherent difficulty of the atmospheric-hydrologic prediction problem, mandate development of a hierarchy models. Nowcasts (0 to 6 h) and short-range forecasts (6 h to 2-3 days) imply an important role for limited-area, regional mesoscale meteorological ensembles that are coupled with fine scale distributed runoff models. Requisite hydrological scales for precipitation are a 4 km (or finer) grid mesh and a 30 minute (or shorter) accumulation interval. This requirement, especially for ensembles, imposes major communication and data archiving considerations on the program. The medium-range (2-3 days to 2 weeks) forecast requires global ensembles to drive runoff models. Since output from atmospheric global models is much coarser than what is required by hydrological runoff models, downscaling is required. Downscaling could be accomplished through embedding regional atmospheric models within global models, statistical procedures, or a combination. Seasonal forecasts (30-90 days) will require a combination of coupled atmospheric-ocean-land models and statistical forecasts. Downscaling is also required for the output from the seasonal forecasts.

A valuable role for HEPEX would be determining a “consensus” set of specific meteorological products that are needed by hydrologists. This includes use of verification measures and spatial-temporal filtering for meteorological fields that are relevant to hydrology and end users. Because fields from meteorological ensemble forecasts contain errors, their accuracy can be improved significantly by statistical post-processing.

Calibration of ensembles poses a host of challenges beyond those for deterministic forecasts because of the dimensionality of the output and the need for properly conditioned multivariate fields that are physically consistent (e.g. small dew point depressions during rain events). The requirement of physical consistency implies multivariate post-processing. Consistent atmospheric fields also are required for input to drive hydrological models that, traditionally, have not been verified, much less calibrated. Thus, close collaboration between meteorologists and hydrologists is needed for calibration of meteorological forecast fields for input into hydrological models.
The selection of “test beds” should be a community effort among HEPEX scientists, participating operational forecast centers, and collaborating end users. Joint selection will ensure that results are relevant to hydrology and of value to end users. It will also promote collaborations and reduce redundancies. Test beds are required for different global sites and for different time-space scales, and must include both regulated and unregulated basins. HEPEX should “go to the where data and instruments are”; that is the program should take full advantage of existing sites where long records exist for “fully” instrumented catchments.

Use of historical data sets implies that critical commitments are needed from the operational forecast centers to provide access to archives of ensemble forecasts. This requires that HEPEX work with operational centers to encourage “ensemble re-forecasting” projects that can provide access to state-of-the-art forecast information for test beds with long records. Long archives will be necessary for the hierarchy of models: short-range limited-area mesoscale, medium-range global and coupled atmospheric-ocean models. In fact, it is essential that operational centers become engaged in HEPEX in order to have the robust sample sizes that are mandatory for evaluating events ranging from extreme short-range flash flooding forecasts to longer-range seasonal hydrological forecasts.

Data assimilation for ensemble hydrological forecasts poses it own unique set of challenges. Particular attention must be paid to the land surface, improvement of land-surface models, acquisition of observations (especially relevant below surface measurements), and the generation of perturbations that are physically consistent with the attendant meteorological fields. Uncertainties in key input parameters for the land-surface, such as antecedent precipitation that are not yet quantified but are believed to be large, should be included.

HEPEX should work to make available the beginnings of a Community Hydrological Prediction System (CPHS) to the community. This will require commitments and yet identified resources to re-engineer software to make hydrological models "user friendly", but its availability would serve to "jump start" research on coupled ensemble prediction systems. For this reason, HEPEX should plan a workshop to start the immediate development of a CHPS to be released to the community as soon as feasible.