HEPEX
Hydrologic Ensemble Prediction EXperiment

Implementation Plan for
The Hydrological Ensemble Prediction Experiment (HEPEX)

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1 Executive Summary

Development of reliable, skillful hydrologic ensemble forecast procedures is a major undertaking that requires global and multidisciplinary collaborations. The Hydrologic Ensemble Prediction EXperiment (HEPEX) is an international project established by the hydrological and meteorological communities to develop advanced probabilistic hydrologic forecast techniques. Following decisions taken during the first and the second HEPEX workshops, held at ECMWF in 2004 and at NOAA in 2005, it has been decided that HEPEX's projects and activities are coordinated by two bodies, the Science Steering Group and the User Committee, and are organized in pilot 'test-beds'.

This document summarizes HEPEX key scientific goals, outlines its key organizational components, and summarizes the test-bed activities that will further advance the HEPEX project towards the development of more valuable hydrological ensemble prediction systems.

2 HEPEX rationale

The Hydrologic Ensemble Prediction EXperiment (HEPEX) (http://hydis8.eng.uci.edu/hepex/) is an international effort that brings together hydrological and meteorological communities to develop advanced probabilistic hydrologic forecast techniques that use emerging weather and climate ensemble forecasts, such as those being developed by GEWEX (http://www.gewex.org/). The overarching goal for HEPEX is "to develop and test procedures to produce reliable hydrological ensemble forecasts, and to demonstrate their utility in decision making related to the water, environmental and emergency management sectors."

Increasingly, users of hydrologic forecasts want quantitative estimates of forecast uncertainty rather than only an approximation of the single most probable scenario. In response, operational agencies are beginning to employ ensemble forecast techniques for hydrologic predictions. Ensemble forecast systems provide an estimate of the most probable future scenario, and also offer a wide range of possible outcomes that account for all sources of forecast uncertainty. These sources include precipitation and other meteorological inputs, estimates of boundary/initial hydrological conditions, the hydrologic forecast models, and model parameters.

HEPEX was launched in March 2004 at a meeting hosted by the European Centre for Medium-Range Weather Forecasts (ECMWF), in Reading, United Kingdom (http://www.ecmwf.int/newsevents/meetings/workshops/2004/HEPEX/). This meeting brought together scientists working in meteorology and hydrology, thus achieving its first aim to foster knowledge sharing and communication between these two communities.

During this 1st workshop, and the 2nd workshop, held at NCAR in 2005, HEPEX participants have been discussing the potential benefits that a probabilistic approach to hydrological prediction could bring to the end users, and have formulated a series of scientific research questions and tasks needed to move HEPEX forward in addressing its overall goal. The scientific questions and objectives are discussed below.

During the 2nd HEPEX workshop, it was decided that one primary mechanism to answer these would be a series of coordinated test-bed demonstration projects. The test beds are collections of data and models for specific basins or sub-basins, where relevant meteorological and hydrological data has been archived. In these test-beds, it is expected that different forecast approaches and tools can be demonstrated and inter-compared. The development of these tools and their demonstration in the test-bed basins are central activities for the implementation phase of HEPEX, along with inter-comparison of various hydrological prediction methods and linkages to users.

HEPEX is an independent, cooperative international scientific activity comprised primarily of researchers, forecasters, water managers, and users. Participation in HEPEX is open to the community and anyone wishing to contribute to its objectives. Scientists and users will formulate projects and activities to assure that user needs, as well as science issues, are addressed. HEPEX activities will include test beds, intercomparison experiments, workshops, and meetings.

At present, HEPEX does not have a dedicated source of funding. Thus, its activities will be planned and carried out by scientists who already have appropriate funding or who might seek funding for their efforts. But it is the hope of the HEPEX community that its efforts will stimulate research-funding agencies to support work related to hydrologic ensemble prediction by formalizing activities around this topic.

3 The four scientific questions that HEPEX aims to address

As stated above, the overarching goal for HEPEX is "to develop and test procedures to produce reliable hydrological ensemble forecasts, and to demonstrate their utility in decision making related to the water, environmental and emergency management sectors." Reliable quantification of hydrologic forecast uncertainty is the key science issue for HEPEX, and the overarching goal has been divided into four key scientific questions:

- What are the adaptations required for meteorological ensemble systems to be coupled with hydrological ensemble systems?
- How should the existing hydrological ensemble prediction systems be modified to account for all sources of uncertainty within a forecast?

- What is best way for the user community to take advantage of ensemble forecasts?
- Can ensemble forecasts be shown to add value to decision making, and can this be quantified?

4 HEPEX Organization

HEPEX activities can be structured in two ways: either by 'test-bed' or by 'topic' (Fig. 1). In other words, HEPEX activities can be organized/managed either by test-bed, with each test-bed reporting to a 'Test-bed Leader' (red boxes T1, T2 in Fig. 3), or by topic, with each topical area of research lead by a 'Topic Leader' (blue boxes in Fig. 1). All activities are coordinated by two bodies, the User Committee and the Scientific Steering Committee: their members represent a mixture of areas of expertise, geographical regions, and institutional capabilities, and will include the Test-bed Leaders, the Topic Leaders and key figures. Each committee will have two co-chair-persons. Appointments to the committees will be revisited and revised at least every 2 years, most likely at HEPEX workshops (the next, 3rd HEPEX Meeting is planned for June, 2007). Sections 6 will provide a list of possible research topics, and section 7 will list the test-beds proposed and established during the 2nd HEPEX workshop.

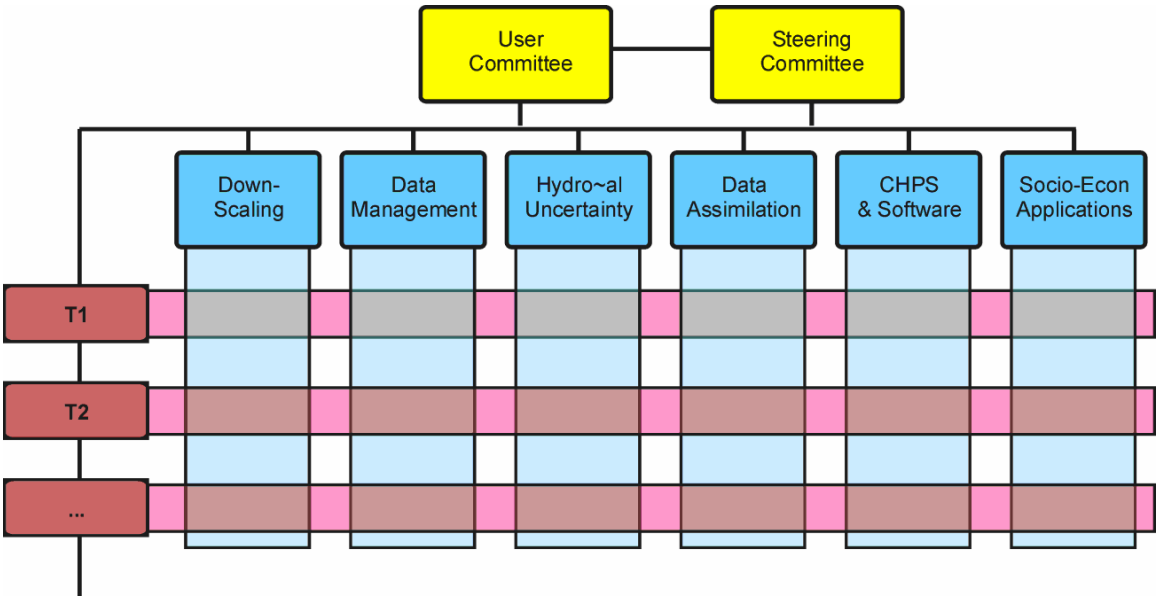

Figure 1. *HEPEX organizational structure. The User Committee and the Scientific Steering Committee (yeloow boxes) coordinate all HEPEX activities, which are structured in a matrix-like form and are managed by 'Test-bed Leaders' (red boxed, T1, T2, ..) and by 'Topic Leaders' (blue boxes).*

The terms of reference for the Scientific Steering Group are:

- To formulate, together with the Users Group, the program for HEPEX
- To provide scientific guidance for the conduct of HEPEX, in collaboration with the Users Group, using advice from individual experts or expert groups, as necessary
- To formulate and execute test bed projects with possible support from national and international organizations
- To use existing or, where necessary, propose new mechanisms for assuring the exchange and analysis of HEPEX data and the dissemination of scientific results
- To establish scientific liaison with relevant organizations and existing programs, as appropriate

Since HEPEX aims to have an impact on real-time operational activities, one of the first necessary steps is to identify scientific questions relevant to address users' needs. Users of hydrological forecasts may include reservoir and city water-supply managers, emergency management professionals, and environmental scientists concerned about water quality or fisheries. Agriculture, insurance, navigation, and power-generation industries may want such products, as well as recreational scientists, and many others. For each, HEPEX will seek to determine how the data can most effectively be presented in order to aid in their decision-making process. On the other hand, many customers may not be familiar with how they can optimize their decisions based on probabilistic information, so the process will work both ways, and HEPEX will collaborate with users to adapt their existing practices. The Users Committee will help to steer research projects towards addressing questions such as:

- Who are the primary customers and potential customers of hydrological forecasts?
- How can we improve communication of scientific discoveries to the customers, and how can we tailor hydrological systems to meet their requirements?

As already mentioned, HEPEX is an open group comprised primarily of researchers, forecasters, water managers, and users. Scientists and users who are not yet part of HEPEX and who want to help forward its goals are encouraged to contact the HEPEX co-chairs (John Schaake at NOAA, John.Schaake@noaa.gov, and Roberto Buizza at ECMWF, Roberto.Buizza@ecmwf.int).

HEPEX is a global project affiliated with several international organizations. The initial impetus for HEPEX grew out of a need to help the World Climate Research Program's (WCRP) Global Water and Energy Cycle Experiment (GEWEX) meet its water-resource applications objectives. The World Meteorological Organization's Hydrology and Water Resources Program (HWRP) is assisting HEPEX meet the needs of National Hydrological Services who will use HEPEX products. HEPEX expects the International Association of Hydrological Sciences (IAHS) Predictions for Ungaged Basins (PUB)

initiative will contribute both new science and data sets, and will participate in some of the test bed projects. Ensemble atmospheric forecasts are expected to be available for HEPEX applications from a number of models participating in the World Weather Research Project's (WWRP) THORPEX Interactive Grand Global Ensemble Experiment (TIGGE). Finally, HEPEX is assisting the inter-governmental *Group on Earth Observations* (GEO) to demonstrate how observations from a Global Earth Observation System of Systems (GEOSS) could contribute to improved hydrological ensemble prediction products. HEPEX is one of the GEO Projects (WA-06-02, http://www.earthobservations.org/doc_library/workplan_docs.html).

5 A framework for a hydrological ensemble prediction system

HEPEX aims to develop the key components of a hydrological ensemble prediction system (Fig. 2), including:

- A Land Data Assimilator,
- An Atmospheric Ensemble Pre-Processor,
- A Hydrologic Ensemble Processor, and
- A Product Generator

In this schematic, the Land-Data and the Atmospheric Ensemble Pre-Processor create the initial condition for the Hydrological Ensemble Processor, taking into consideration the climatology of hydrological land surface condition (provided, e.g., by a historical offline simulation or by a more complex, real-time analysis system) and climatological atmospheric conditions, and using a range of hydrological models that take into account also regulatory elements (e.g. water management regulations).

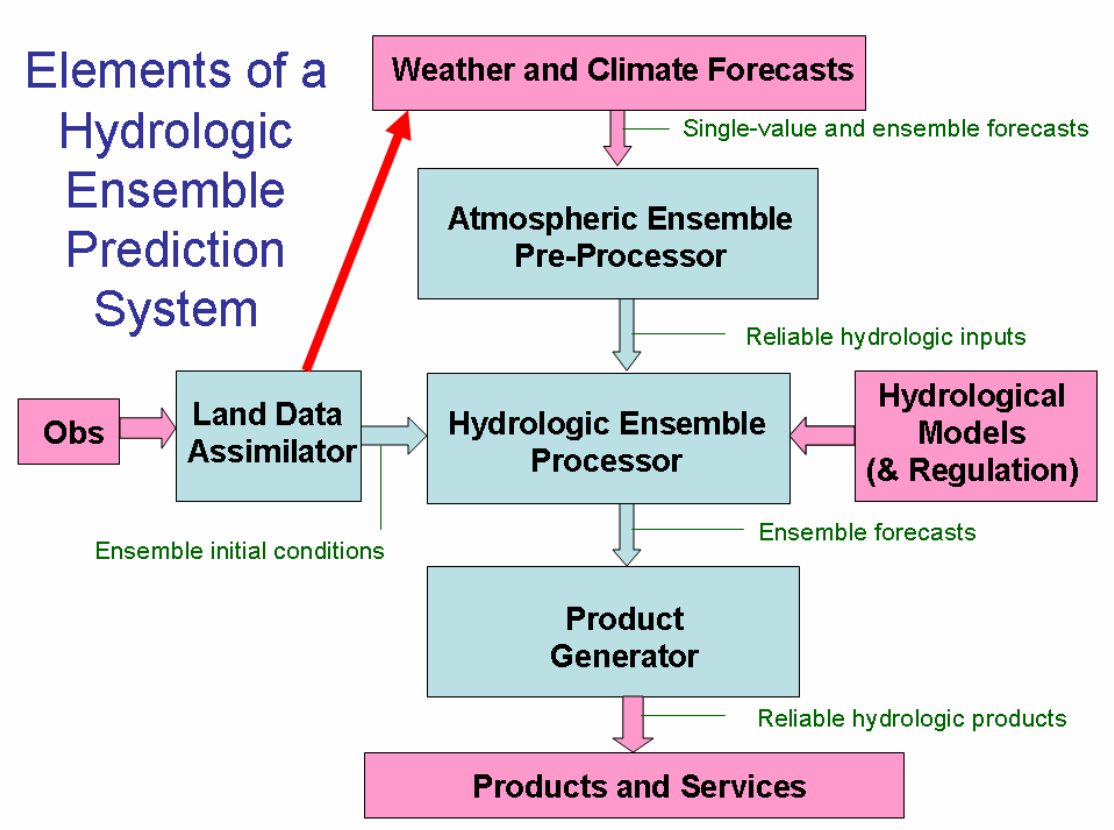

Figure 2. *A framework for a hydrologic ensemble prediction system.*

Understanding the uncertainties associated with each component and their impact on each forecast product is one of HEPEX's goals. To achieve this goal, HEPEX aims to develop an Atmospheric Ensemble Pre-Processors capable of using the prediction of forecast uncertainties in weather variables to estimate the uncertainties of hydrological predictions. For example, one of the areas of research will be in Ensemble Quantitative Precipitation Estimation (EQPE) techniques. HEPEX aims also to develop a Land-Data Assimilator capable of estimating and reducing the uncertainty of initial/boundary conditions estimates. Other areas of investigations will be the role of model approximations, and the use of parameter estimation techniques to improve hydrological models.

The appropriate way to represent hydrologic forecast uncertainty and convey that information to forecast users is not well understood. Therefore, product development is an essential component of the HEPEX research agenda. HEPEX plans to promote the operational application of hydrologic ensemble forecasts by developing more user-friendly products that convey hydrological forecast uncertainty in an immediate and

intelligible way. Finally, research and developments in forecast verification methods will be promoted to supply users with all the information required to be able to use hydrological forecasts in decision-making procedures.

6 Examples of HEPEX research topics

Hereafter, few areas of topical research that HEPEX will promote are briefly discussed.

6.1 Sources of hydrological prediction errors

By their nature, predictions will always contain uncertainties. The sources of uncertainties in hydrological forecast can be grouped in three major classes: uncertainties due to initial condition errors (e.g. in the land surface initial conditions or in the atmospheric weather parameters), model approximations (both in the atmospheric and in the hydrological models) and product generation. For example, the uncertainties in the initial conditions may be reduced by having more accurate observations and better data assimilation methods. Data assimilation approaches will be developed for better estimation of initial conditions, especially for short-term hydrologic forecasts. Uncertainties due to model approximations may be reduced by further improving the state-of-the-art atmospheric and hydrological ensemble prediction systems.

6.2 Multi-model ensemble approaches

A multi-model approach to ensemble prediction may be able to reduce prediction errors. Most models are developed and calibrated independently; therefore, it is likely that each model and its corresponding forecasts will have identifiable strengths over other forecasts. Statistical approaches are needed to merge multiple model forecasts so that all pieces of useful information can be used and the strengths can be combined. In the future, multiple hydrological forecasts might be available from different research groups: the design of optimal methods to merge these hydrologic forecasts is thus an essential component.

6.3 Bias correction and spatial and temporal downscaling approaches

Hydrological prediction needs input of surface meteorology, including precipitation, air temperature and other forcing variables. If the atmospheric forcing are from a regional or climate model forecast, they are very likely to be biased. Although the ability of regional and global atmospheric models to simulate the atmosphere has been improving, the

climatology of climate models is likely to be different from what is in the real world. Such biases in precipitation, air temperature and other variables will have noticeable influence on the hydrologic predictions, since hydrological models are calibrated with observed atmospheric forcing and observed streamflow. Bias correction methods are required to remove these biases.

Using atmospheric forcing from regional and global climate models will also require proper approaches for spatial and temporal downscaling. The typical spatial resolution of forecast products from global models is still coarse for hydrological applications. The seasonal climate model forecast normally only provides monthly mean values, and they need to be disaggregated to daily or sub-daily time series. The disparities in spatial and temporal resolutions between information provided and needed for hydrological prediction grant the researches on downscaling methods. Different research groups have developed different downscaling approaches, including statistical and dynamical downscaling. HEPEX will encourage the sharing and intercomparison of these different methods.

6.4 Shared data sets (GFS/CFS/ECMWF verifications seasonal forecasts)

Although these are more technical rather than purely scientific issues, it is of the foremost importance that data sets are generated using a common and agreed upon format, and are shared among the HEPEX participants. In fact, experiences show that researchers spend much of their time on obtaining, processing and organizing data, and some of the work was carried out repeatedly by different groups because of poor communication among groups or unwillingness to share data. The HEPEX community will try to solve this problem by having a central data repository along with the toolbox repository. Sharing commonly used datasets such as the GFS/CFS/ECMWF forecasts will help to save resources as all the research activities are not officially funded by any agencies. It can also help to improve the quality of the data sets.

6.5 Development of Forecasting Tools (shared tool box repository, development of protocols for tool interfaces)

One of the central activities of HEPEX is to develop, test, intercompare and share forecasting tools. These tools are expected to be modularized as much as possible so that they can be easily ported and used by other developers. Each tool is expected to handle one or more tasks in the forecasting process. This may include bias correction, spatial and temporal downscaling, data assimilation approach for creating initial conditions, forecast verification, etc. A protocol is necessary to standardize these tools so that different tools with the same functionality but contributed by different developers can be easily interchanged. Such a modular structure (or plug-and-play structure) enables

intercomparisons between different forecast methods. A shared tool repository therefore is needed to distribute and track these tools.

6.6 Verification tools

A set of standard forecast verification tools are needed to evaluate different forecast approaches. Simple metrics such as root mean square error, Brier score and skill score, ranked probability score and skill score, relative operating characteristic curves and many other measures that have been used operationally will be considered. These standard verification tools will be shared among different groups based on possible protocols on forecast output format.

7 Test-bed sites

A HEPEX Test Bed is a setting for HEPEX-community experiments. A test bed could be a single basin (and its sub-basins), a region containing multiple basins, or possibly a global collection of basins that facilitate experiments addressing questions over a range of scales and climates. Regardless of geographical domain, test beds focus on one or more clearly defined HEPEX scientific topic, have the potential to develop data resources needed for community experiments to address the questions, and are expected to include active user participation.

Proposals for eight test bed projects were presented at the 2nd HEPEX workshop. Six of them represent a variety of basins or sub-basins with different terrain, different climatologies, different hydrological issues, different data densities, and differences in the amount of regulation of stream flows in the basin. The remaining two test beds are focused on development and intercomparison of procedures that cross-cut the other six test beds. Figure 3 shows the global distribution of the test beds.

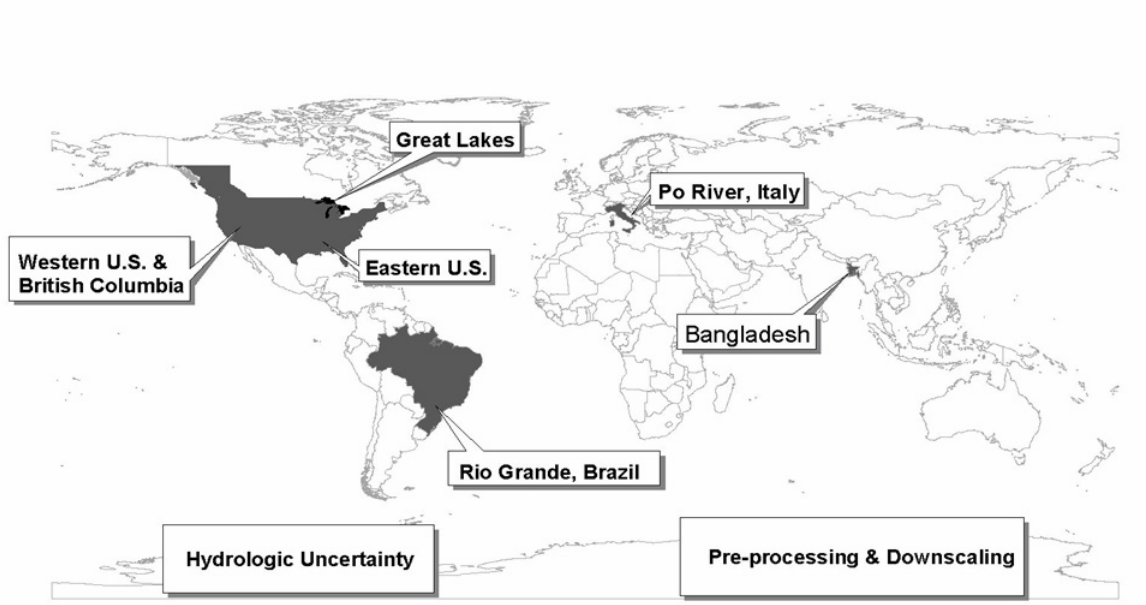

***Figure 3**: Locations of HEPEX test bed projects. The test beds "Hydrological Uncertainty" and "Pre-processing and Downscaling" have a global scope and scientifically cross-cut the other test beds.*

These test beds and the outstanding research objectives for each test beds are as follows:

- **T1 Great Lakes, Canada/US** - To demonstrate the importance of relatively detailed atmospheric and hydrologic modeling for medium-range atmospheric and hydrologic forecasting on large basins.
- **T2 Bangladesh** - To provide operational real-time forecasts of river discharge into Bangladesh at daily, weekly, monthly, and seasonal time-scales.
- **T3 Rio Grande** - To explore the use of ensembles produced by the CPTEC model of global climate, the use of forecasts produced by RAMS for lead times extending up to a month and longer, and the use of short-term rainfall forecast from the operational ETA model of CPTEC.
- **T4 Po Basin, Italy** - To test simplistic routines for bias removal in an area, such as Northern Italy, that is dominated by important orography (Alps), and to test methods for flood forecasting based on threshold exceedances.
- **T5 Western Basins, US/B.C. Canada** - To develop hydrologic ensemble forecasting techniques that are particular to the orographically complex, snowmelt-driven basins of the Western US and British Columbia with a focus on monthly to seasonal lead-times.

- **T6 Southeast Basins (US)** - To address the following HEPEX science questions: How do we generate skillful and reliable meteorological forcing for seasonal hydrologic forecasting? How do we generate the hydrologic ensembles that reflect the total uncertainties? How can climate information, such as climate model forecasts or teleconnections, be used reliably in seasonal hydrologic forecasting? How do we validate hydrologic ensembles for extreme events?
- **T7 Statistical downscaling** - To identify the space-time scales for which forecast skill is present for different variables and develop methods to extract and combine information at different space-time scales; to identify the GFS output variables that can be used to provide sub-grid information for use in a statistical model to replicate precipitation processes; to identify the sample size required to reliably forecast precipitation, temperature, and streamflow for different thresholds.
- **T8 Hydrological uncertainties** - To investigate the relative merit of the different sources of prediction uncertainties including: model inputs, model parameters, and model structure; leading to uncertainties in model states and fluxes. To address questions such as: what are the advantages and limitations of different methods for characterizing and reducing uncertainty in hydrologic model simulations?

8 HEPEX activities

The development of a hydrological ensemble prediction system (as discussed in section 5), via the establishment and completion of test-beds (section 7) that focus on key scientific topics (section 6) is the main HEPEX activity. HEPEX workshops (the 3rd one is planned for June 2007) will be organized to discuss progress and plans for future development. Furthermore, HEPEX participants will help to convene special sessions on aspects of hydrologic ensemble prediction at professional society meetings (EGU, AGU, AMS, IAHS, etc.). These may lead to special publications or special issues of society journals.

9 HEPEX deliverables

HEPEX deliverables will include:

- Testbed Projects - Annual testbed project reports, additional testbed projects, including some in developing nations.
- Shared Datasets - Shared datasets from initial testbed projects, report on historical atmospheric forecast archive data requirements, hydrologic assessment of THORPEX/TIGGE ensemble forecast products.

- Forecast Tools (CHPS components) - Forecast tools from initial testbed projects; generic operations concept document for hydrologic ensemble forecasting (possibly in collaboration with WMO Hydrology and Water Resources Programme); synthesis report on ensemble forecast verification and relationships between ensemble and single-value forecasts; progress report on bias correction and statistical down-scaling techniques; progress report on multi-model applications; progress report on data assimilation techniques.
- Scientific Meetings and Publications - Periodic HEPEX workshops; special issue on ensemble prediction of EGU HESS Journal; AGU Chapman Conference on Hydrologic Uncertainty and Ensemble Prediction.
- User Support - Report on what users can expect to gain from ensemble forecasts and limitations of the forecasts; inventory of user applications.