IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences

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Abstract Drainage basins in many parts of the world are ungauged or poorly gauged, and in some cases existing measurement networks are declining. The problem is compounded by the impacts of human-induced changes to the land surface and climate, occurring at the local, regional and global scales. Predictions of ungauged or poorly gauged basins under these conditions are highly uncertain. The IAHS Decade on Predictions in Ungauged Basins, or PUB, is a new initiative launched by the International Association of Hydrological Sciences (IAHS), aimed at formulating and implementing appropriate science programmes to engage and energize the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make predictions in ungauged basins. The PUB scientific programme focuses on the estimation of predictive uncertainty, and its subsequent reduction, as its central theme. A general hydrological prediction system contains three components: (a) a model that describes the key processes of interest, (b) a set of parameters that represent those landscape properties that govern critical processes, and (c) appropriate

Open for discussion until 1 June 2004

meteorological inputs (where needed) that drive the basin response. Each of these three components of the prediction system, is either not known at all, or at best known imperfectly, due to the inherent multi-scale space–time heterogeneity of the hydrological system, especially in ungauged basins. PUB will therefore include a set of targeted scientific programmes that attempt to make inferences about climatic inputs, parameters and model structures from available but inadequate data and process knowledge, at the basin of interest and/or from other similar basins, with robust measures of the uncertainties involved, and their impacts on predictive uncertainty. Through generation of improved understanding, and methods for the efficient quantification of the underlying multi-scale heterogeneity of the basin and its response, PUB will inexorably lead to new, innovative methods for hydrological predictions in ungauged basins in different parts of the world, combined with significant reductions of predictive uncertainty. In this way, PUB will demonstrate the value of data, as well as provide the information needed to make predictions in ungauged basins, and assist in capacity building in the use of new technologies. This paper presents a summary of the science and implementation plan of PUB, with a call to the hydrological community to participate actively in the realization of these goals.

Key words drainage basins; predictions; uncertainty; heterogeneity; gauging; hydrological models; hydrological theory; field experiments

La décennie de l'AISH sur les prévisions en bassins non jaugés (PBNJ), 2003-2012: émergence d'un futur passionnant pour les sciences hydrologiques

Résumé Les bassins versants de drainage de nombreuses régions du monde sont peu ou pas du tout jaugés, et dans certains cas les réseaux de mesures existants sont en déclin. Le problème est compliqué par les impacts des changements induits par l'homme aux surfaces continentales et au climat, changements qui se produisent au niveau local, régional ou global. Les prévisions pour des bassins peu ou pas jaugés dans ces conditions sont fortement incertaines. La décennie de l'AISH sur les prévisions sur les bassins non jaugés (PBNJ) est une nouvelle initiative lancée par l'Association Internationale des Sciences Hydrologiques. Elle a pour objectif de développer et de mettre en application des programmes scientifiques appropriés pour engager et activer la communauté scientifique, d'une façon coordonnée, vers la réalisation d'avancées majeures dans la capacité de faire des prévisions pour des bassins non jaugés. Le programme scientifique (PBNJ) se concentre principalement sur l'estimation de l'incertitude prédictive, et sur sa réduction subséquente. Un système général de prévision hydrologique comporte trois composantes: (a) un modèle qui décrit les principaux processus d'intérêt, (b) un ensemble de paramètres qui représentent les propriétés du paysage qui régissent les processus cruciaux, et (c) les entrées météorologiques appropriées (là où nécessaire) qui commandent la réponse du bassin. Chacune de ces trois composantes du système de prévision, est soit pas connue du tout, soit dans le meilleur des cas connue imparfaitement, en raison de l'hétérogénéité spacio-temporelle aux différentes échelles du système hydrologique, et ce tout particulièrement pour les bassins non jaugés. Le PBNJ inclura donc un ensemble de programmes scientifiques adéquats pour essayer de faire des inférences sur les entrées climatiques, sur les paramètres et sur les structures de modèle à partir des données et de la connaissance disponibles mais insatisfaisantes, sur le bassin considéré ou sur d'autres bassins semblables, avec des mesures robustes des incertitudes et de leurs impacts sur l'incertitude prédictive. A travers la production de nouveaux éléments de compréhension, et de méthodes de quantification efficace, de l'hétérogénéité multi-échelle du bassin et de sa réponse, PBNJ mènera inexorablement à de nouvelles méthodes innovatrices pour des prévisions hydrologiques dans des bassins non jaugés de différentes régions du monde, associées à des réductions significatives de l'incertitude prédictive. Dans cette manière, le PBNJ démontrera la valeur de données. Egalement il fournira l'information nécessaire pour faire les prévisions en bassins non jaugés, et assistera en création de capabilité sur l'usage de nouvelles technologies. Cet article présente un résumé du contenu scientifique et du plan d'exécution de PBNJ, avec un appel à la communauté hydrologique à participer activement à la réalisation de ces objectifs.

Mots clefs bassins versants; prévisions; incertitude; hétérogénéité; jaugeage; modélisation hydrologique; theorie hydrologique; hydrologie experimentale

INTRODUCTION

Across the globe, water resources and the water environment are under threat as never before. In river basins everywhere, human activities have disrupted the natural hydrological and ecological regimes. Water supplies are not secure for billions of people worldwide, flood risk is increasing, and biodiversity is steadily decreasing due to the ongoing destruction of riparian ecosystems. The impacts of human activities on the land surface are felt not only locally, but are transmitted through land surface–atmospheric feedbacks to disturb the climate itself, leading to changes in the magnitudes and frequency of floods and droughts at even remote locations.

The challenge for the hydrological community is to identify appropriate responses to these threats. Sustainable management policies are needed to provide water not only for life, health and development, but to prevent further ecosystem degradation and hopefully to reduce the severity, frequency and impacts of natural hazards and disasters. Wise stewardship of water and the environment requires a variety of predictive tools that can generate predictions of hydrological responses over a range of space–time scales and climates, to underpin sustainable management of river basins, integrating economic, social and environmental perspectives. Accurate and reliable predictions are becoming extremely important to civic society, with local and regional communities increasingly being asked to make independent judgments about actions required to prevent and manage natural disasters, and manage the natural environment around them and their water resources in a sustainable manner. These decisions can only be made with the widest possible information being made available based on accurate and reliable predictions.

Over the years, hydrologists have developed numerous predictive tools (e.g. empirical models, lumped models, distributed models, statistical regionalizations) that allow objective and quantitative decision-making with respect to water resources and water quality management, as well as natural hazard assessments. The most widely used tools, such as unit hydrographs, flood frequency curves, flow duration curves, etc., are essentially data driven, and are estimated from hydrometric (gauged) data at drainage basin scales. Application of these tools for prediction in other basins is based on the premise that: (a) the past is a reasonable guide to the future, and (b) that data from any one basin, and models derived therefrom, are useful guides to estimating hydrological responses at another basin. Over the past three decades, there have been attempts to make some of these tools more rigorous and more realistic representations of environmental processes, through incorporation of spatial and mechanistic details. However, the resulting, more sophisticated models continue to suffer from similar restrictive assumptions, especially when developed and/or parameterized through calibration with historical data from gauged basins. Whatever models are used, in view of the tremendous spatio-temporal heterogeneity of climatic and landscape properties, extrapolation of information, or knowledge, from gauged to ungauged basins remains fraught with considerable difficulties and uncertainties, especially in the light of the generally poor understanding of where water goes when it rains, what flow path it takes to the stream, and the age of the water that emerges in the channel.

Meanwhile, new knowledge and new technological advances are becoming available to the hydrological community, in the form of increased process understanding, more advanced theories (e.g. scaling theories), new measurement technologies such as satellites and environmental tracers, and advanced data processing, data archiving and visualization technologies. They point to exciting new opportunities for advancing the science of hydrology that are unimaginable at the present time, and for improved predictions for the benefit of mankind.

IAHS PUB INITIATIVE ON PREDICTIONS IN UNGAUGED BASINS

The IAHS Decade on Predictions in Ungauged Basins (PUB) is an initiative of the International Association of Hydrological Sciences (IAHS). It is aimed at formulating and implementing appropriate science programmes to engage and energize the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make reliable predictions in ungauged basins.

Why drainage basins?

Drainage basins are a fundamental landscape unit for the cycling of water, sediment and dissolved geochemical and biogeochemical constituents. As such, they integrate all aspects of the hydrological cycle within a defined area that can be studied, quantified and acted upon. The drainage basin, thus, is a metaphor for integration of hydrological processes related to surface water, groundwater, evapotranspiration, etc., and the explicit coupling of hydrology, geochemistry and ecology.

Definition of an "ungauged basin"

An ungauged basin is one with inadequate records (in terms of both data quantity and quality) of hydrological observations to enable computation of hydrological variables of interest (both water quantity or quality) at the appropriate spatial and temporal scales, and to the accuracy acceptable for practical applications.

For example, if the variable of interest has not been measured at the required resolution, or for the length of period required for predictions or for model calibration, the basin would be classified as ungauged with respect to this variable. Variables of interest can be, for example, precipitation, runoff, erosion rates, sediment concentrations in streamflow, etc., so every basin is "ungauged" in some respect.

Definition of "predictions in ungauged basins"

PUB is defined as the prediction or forecasting of the hydrological response (e.g. of streamflow, groundwater, sediments, nutrients, etc.) of ungauged or poorly gauged basins, and its associated uncertainty, using climatic inputs (observed, forecast or otherwise specified), soils, vegetation, geology and topography, including any predicted or expected future climatic or land-use changes, but without the benefit of past observational time series of the particular hydrological response that is being predicted, i.e. with no possibility or allowance for direct *calibration*.

Nature of predictions

Prediction is concerned with estimating the frequency of occurrence, in the future, of events of any given magnitude, without reference to the times at which they would occur. Forecasting is concerned with what will be happening at a stated point of time in the future, such as discharge tomorrow, or runoff in the coming month. PUB is concerned with **both** *prediction* and *forecasting* in ungauged basins.

Which hydrological response it is necessary to predict depends on the nature and scale of the problem. PUB recognizes that water quantity and water quality problems have different implications for management and the emphasis in hydrological predictions may be different. Examples of water quantity predictions include floods of given exceedence probability, mean annual water yield, reliability of water supply, crop yields, and soil moisture patterns needed for irrigation scheduling. Examples of water quality predictions include conservative and non-conservative constituents in rivers and other water bodies, such as salinity, sediments, nutrients and heavy metals. Water quality predictions require prior knowledge of water sources and pathways within basins and cannot be performed adequately without first addressing issues related to water quantity and the distribution of flow pathways and residence times. Consequently within PUB, predictions of hydrological response in ungauged basins may, initially, be focused more heavily on water quantity, recognizing that advances in the knowledge and predictions of the flow partitioning (pathways) are critical for subsequent water quality predictions.

Current approaches to predictions in ungauged basins

A number of approaches are currently available for prediction of basin responses. Methods appropriate for ungauged basins include extrapolation of response information from gauged to ungauged basins, measurements by remote sensing (e.g. passive and active radar, satellites, etc.), application of process-based hydrological models where the climate inputs are specified or are measured, and application of combined meteorological–hydrological models without the need to specify precipitation inputs.

Whichever of the above approaches is used, the underlying model or estimation method that is employed for predictions in ungauged basins must be: (a) inferred from observed data in gauged basins; (b) obtained from process understanding and descriptions obtained through laboratory studies, e.g. Darcy's law of porous media flow, or field experiments (plot scale, hillslope scale, small-catchment scale, meso-scale); and (c) obtained through application of fundamental theories, which must still be conditioned by observations. This is also the case with the remote sensing approach—the model that connects the remotely sensed product to the hydrological quantity of interest also must be inferred or developed in gauged/ground-truthed sites, before being extrapolated to ungauged sites. Therefore, one way or the other, and to varying degrees, predictions in ungauged basins must involve extrapolation of some kind from what is observed or inferred at one basin to a time in the future at the same location, or to another basin at a different location in an ungauged basin.

Each of the approaches presented above has a number of limitations when it comes to predictions in ungauged basins. These pertain to the inadequacies of the models or estimation methods themselves, due to the inadequate representations of critical processes governing the basin response of interest, and the incomplete specification of information relating to the properties of the basin of interest and the climatic inputs. A key difficulty is that the predictions by the model cannot be conditioned or validated by observations in the ungauged basin of interest, and that information, knowledge and understanding must be extrapolated from gauged to ungauged basins. Consequently, predictions in ungauged basins cannot be evaluated or verified with confidence, and are inherently uncertain.

If the level of understanding of hydrological systems at-a-place was much better than it is, then the *status quo* might be acceptable. However, the understanding of the basic processes of where water goes during rainfall and snowmelt, its flow paths to surface water bodies and the residence times of this water, is still so limited that one is often forced into unrealistic black-box approaches. In other words, even in the case of highly gauged basins, one cannot often, based on the current level of process understanding, say much about the functioning of even a neighbouring site! Thus, PUB is as much about improved process understanding as it is about prediction, where the increased focus on process is seen as the pathway to better model estimates for the future.

Natural and human-induced heterogeneity and variability

A major concern in recent times is the realization that the statistics of many hydrological variables of interest are not stationary and may contain long-term trends caused by global-scale phenomena, and by land-use changes at the local or regional scale.

At the seasonal to inter-annual timescale, the influence of climate variability on hydrological statistics (and the occurrence of extreme hydrological events such as floods and droughts) is now well recognized. These influences (and others yet to be identified) can generate seasonal distortions in the statistics of hydrological variables, thus threatening the validity of the operational rules applied to water management systems. There is also an increasing realization that the strength of important fluctuations in the global climate (such as those associated with El Niño and La Niña) may themselves vary at the decadal timescale. Moreover, model studies suggest, and observational evidence confirms, that an intensified hydrological cycle is likely to be an important consequence of global climate change caused by "greenhouse warming", in addition to any changes caused by the natural variability of solar insolation.

An additional concern is that, due to the increasing population pressures, a steadily increasing fraction of the land surface is being converted from natural vegetation to agriculture, industry and human settlements. This may have a severe impact on the local, regional and global-scale water cycle, reflected in changes to streamflows, and flood and drought frequencies, and increased soil erosion and sediment transport, with associated water quality problems in rivers and other receiving waters.

It should be noted that the regions that suffer the greatest human impacts are usually those where measurement networks are least developed, and undergoing further cutbacks. This is true of many developing country regions where lack of hydrometric data, coupled with the effects of climatic and land-use changes, have led to depletion of water resources and ecosystem degradation.

The consequence of these human impacts is that past hydrological records may no longer be reliable guides to what will happen in the future. Many standard procedures in hydrology are no longer valid under changing hydrological regimes, and new analytical procedures need to be developed (or existing ones modified). These include the following: estimation of annual maximum floods and low flows with specified exceedence probabilities, and annual runoff volumes; generation of synthetic runoff sequences by time series models to estimate frequencies of occurrence of extremes; intensity–duration–frequency curves for rainfall; regionalization, of any kind; rainfall–runoff models and water balance estimation methods that are calibrated using past records.

PUB SCIENCE PLAN

PUB scientific objectives

The science programmes to be implemented within PUB have the following five broad community objectives:

1. Develop an observational field programme for conducting research in highly instrumented and extensively gauged basins in different hydro-climatic regions of the world. To make concrete progress in the next decade, a few basins will need to be identified that will serve as illustrative examples for addressing diverse PUB needs and goals.
2. Increase the awareness of the value of data, especially the gauging of hydrological variables, for the management of water resources and water quality worldwide, and demonstrate the need for targeted gauging of currently inadequate or nonexistent data sources by quantifying the links between data and predictive uncertainty.
3. Advance the technological capability around the world to make predictions in ungauged basins, firmly based on local knowledge of the climatic and landscape controls on hydrological processes, along with access to the latest data sources, and through these means to constrain the uncertainty in hydrological predictions.
4. Advance the scientific foundations of hydrology, including the understanding of the climatic and landscape controls on the natural variability of hydrological processes, and on the resulting uncertainty of predictions, and the impacts of human-induced alterations to climate and landscapes.
5. Actively promote "capacity building" activities in the development of appropriate scientific knowledge and technology to areas and communities where it is needed.

PUB SCIENCE FOCUS: REDUCTION OF PREDICTIVE UNCERTAINTY

PUB has chosen to focus on the estimation and subsequent reduction of predictive uncertainty as its central theme. In order to make predictions of any specified response of a river basin, a general hydrological prediction system must contain three components:

– a model: a model or prediction method that either implicitly or explicitly incorporates the combination of processes that lead to the quantity of interest, at the required space and time scales;

– climatic inputs: appropriate meteorological inputs (if needed by the model) that drive the basin response; and
– parameters: a set of parameters that represent those landscape properties that govern the basin response of interest.

Each of the components of the prediction system, namely the model, climatic inputs and parameters, is either not known at all, or at best known imperfectly due to the inherent space–time heterogeneity, especially in ungauged basins.

Set against these enormous heterogeneities, available measurements relating to each of these are extremely sparse and patchy, this problem being most acute in the case of hydrological processes, since they are the least monitored quantities in basins, except in some highly focused field experiments. Therefore the scientific focus of PUB will be on evaluating the consequences of inadequate knowledge, understanding, or data, and their connection to the uncertainty of predictions.

In the context of the general prediction system and the tremendous heterogeneity of nature, there are therefore three kinds of uncertainties (Fig. 1): (a) uncertainty in process descriptions in the adopted model due to the "uncertain mapping of landscape space to model space" (model structure uncertainty), (b) uncertainty in the climatic inputs (input uncertainty), and (c) uncertainty in the model parameters (parameter uncertainty).

PUB will include scientific programmes to make inferences about climatic inputs, parameters and model structures from available but inadequate data and process knowledge, at the basin of interest and from other similar basins, with robust measures of the uncertainties involved and their impacts on the uncertainty of predictions, combined with efforts to reduce that predictive uncertainty. Measures of predictive uncertainty will be adopted as the criteria of the success of PUB, which is a key point of departure when compared to previous IAHS-sponsored and other national and international hydrological initiatives. Importantly, the quantification of uncertainty will be a pre-requisite for the evaluation of the informative power of different data in reducing the predictive uncertainty. Through the evaluation of the worth of data, new insights into appropriate predictive strategies as a function of data availability will be developed.

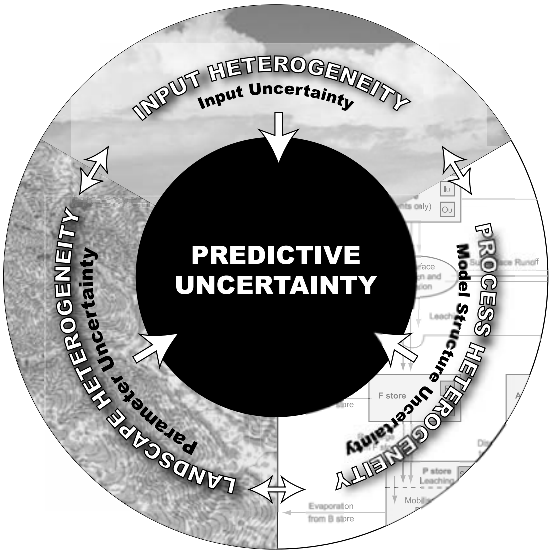

Fig. 1 Predictive uncertainty and links with climatic and landscape heterogeneity.

Through its sharp focus on predictive uncertainty, PUB will therefore adopt and foster a self-critical approach to hydrological predictions, by addressing what is not known or not understood, and emphasizing the need for empirical exploration and explicit attempts to generate, falsify and validate new ideas and new forms of knowledge. The focus on predictive uncertainty will enable hydrologists to go beyond quick fixes, to search for new and innovative solution approaches, and to seek knowledge and understanding of natural processes beyond the immediate problem-solving needs of infrastructure development, and environmental management or regulation. Additionally, the focus on quantifying predictive uncertainty provides a quantitative measure for assessing any consequent reductions of predictive uncertainty, through additional or novel data, new regionalization theories and/or improved conceptual understanding of hydrological processes.

PUB SCIENCE QUESTIONS

Keeping in mind the sharp focus on predictive uncertainty and its connection to the heterogeneity of climatic and landscape factors, the proposed PUB Science Plan will include a suite of "enabling" research programmes, integrating across various hydrological sub-disciplines, which are articulated through the following key science questions:

What are the key gaps in our knowledge that limit our capacity to generate reliable predictions in ungauged catchments?

Enabling research Investigate the connection between heterogeneity and predictive uncertainty, through addressing:

(a) The lack of concurrent datasets at multiple space–time scales that limits the development of tools and approaches that are capable of dealing with extreme multi-scale variability, including the dearth of integrative technologies to utilize new data acquisition and archiving methods.
(b) The lack of understanding of:
   - hydrological functioning at a multiplicity of scales within basins, and
   - nonlinear coupling and feedback that exist between vegetation, landforms, water and energy at these scales.
(c) The limitations of existing theoretical and modelling approaches to satisfactorily deal with the above.

What are the minimum information requirements to reduce predictive uncertainty in the future?

Enabling research Advance theories, data and models relating to the heterogeneity of climatic inputs, landscape properties and processes.

(a) Develop appropriate testable multi-scale theories for characterizing climatic inputs, landscape properties and the resulting hydrological processes.
(b) Assemble suitable datasets for testing of the theories developed in (a) above, including through re-analyses of observed streamflow data after accounting for human interventions such as water withdrawal, storage and land-cover changes.

(c) Develop approaches to evaluate predictability limits and compare the prediction performances of models in ungauged and poorly gauged basins to these limits.

What experimentation is needed to underpin the new knowledge required?

Enabling research Process studies and field experiments worldwide for theory development and model improvement.

(a) Concurrent measurements over a wide range of time–space scales in nested river channel networks and within associated hillslope and landscape elements.
(b) Well-defined space–time resolution of new data acquisition systems for the testing of theories of hydrological processes, and improving process descriptions in models.

How can we employ new observational technologies in improved predictive methods?

Enabling research Advance the use and development of remote sensing and other novel observational and tracer technologies.

(a) Development of new instruments and models for data acquisition as needed.
(b) The fusion of data collected with the help of multiple sensors, both space-borne and on-ground, along with natural and applied tracers of water flow path, flow source and water age.

How can we improve the hydrological process descriptions that address key knowledge elements that can reduce uncertainty?

Enabling research Advance better and more robust process descriptions through field experiments and comparative evaluation of models.

(a) Advance process descriptions through field experiments and comparative evaluation of existing models, conditioned upon data in selected basins in a variety of environments.
(b) Couple hydrological processes and conservation equations with the patterns and statistics of hydrological variables obtained at multiple scales.

How can we maximize the scientific value of available data in generating improved predictions?

Enabling research Interpret existing hard and soft data, and patterns in such data, through assimilation with dynamic models.

(a) Advance the theoretical framework for interpreting patterns in data through tests of hypotheses involving the use of simple models of basin responses, and the discovery of laws governing those responses.
(b) Develop new uncertainty criteria to detect, evaluate and interpret patterns caused by nonlinear interacting, and/or threshold, processes, including new uncertainty bounds to deal with the resulting pattern dynamics.
(c) Develop new data interpretation, archiving and usage techniques that help to combine space-borne and on-ground datasets in an integrated manner.
(d) Evaluate the role and worth of data in constraining and reducing predictive uncertainty.

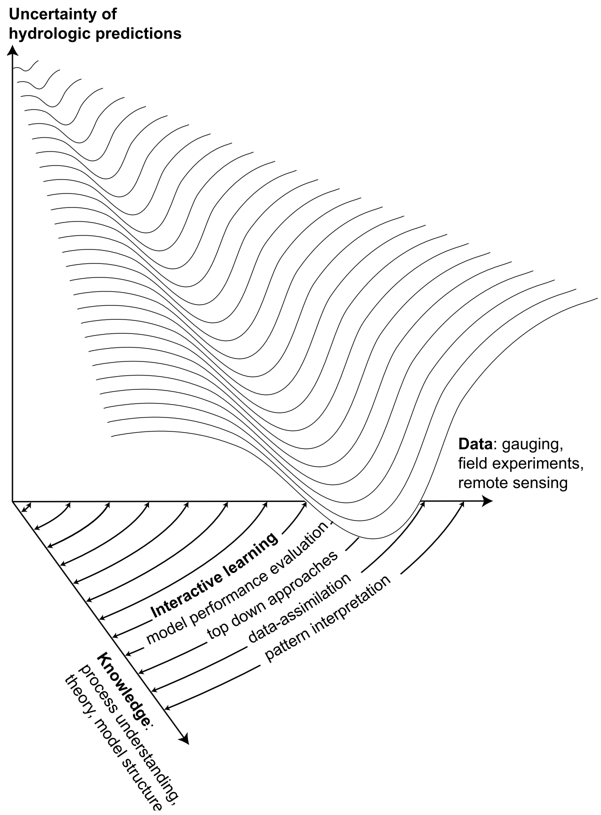

Fig. 2 Uncertainty reduction through interactive learning: data, knowledge and theories.

The enabling research programme described above utilizes advances in knowledge through analysis of existing and new data sources, process studies, model inter-comparisons and diagnostic studies, to effect major reductions in prediction uncertainty. Indeed, PUB takes the view that learning through a combination of these different forms of knowledge can yield a much faster reduction of predictive uncertainty than when they are used singly (Fig. 2).

PUB SCIENCE TARGETS

Prediction in Ungauged Basins (PUB) aspires to foster and stimulate the development of new predictive approaches that are based on a deeper and more complete "understanding" of hydrological functioning at multiple space–time scales than is available at present. It is expected that PUB will herald a major change of paradigm in surface hydrology from one that is dominated by "calibration" to a new exciting one based on "understanding", as indicated in Fig. 3.

This paradigm shift will act as a catalyst to force even process hydrologists to change their orientation, from being strictly hydrologically oriented, and to adopt approaches that enable learning from hydro-ecological couplings, hydro-biogeochemical feedbacks, hydro-geomorphological controls, etc. Looking beyond disciplinary boxes and learning from different forms of data (past, present and future) will be a major point of departure of PUB from other similar programmes.

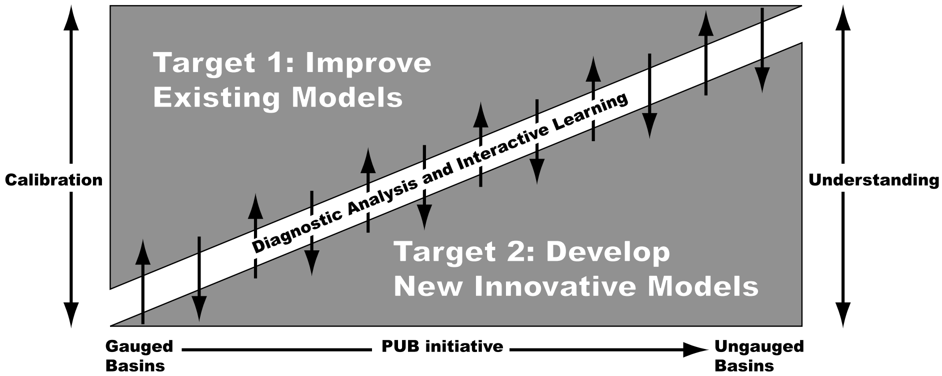

Fig. 3 Targeted research—towards paradigm change—from models based on calibration to models based on increased understanding.

PUB is a decadal, time-bound research initiative. Therefore, to achieve its objectives within this time frame, the enabling research programme based on the set of key science questions presented above, must be channelled towards a more targeted research programme. With this in mind, a pragmatic approach to making and demonstrating progress on PUB has been developed that is focused on two clear targets:

TARGET 1: Examine and improve existing models in terms of their ability to predict in ungauged basins through appropriate measures of predictive uncertainty

- Develop new approaches for hydrological interpretation from existing data archives and potential new datasets: data rescue and re-analysis, basin inter-comparisons and global hydrology.
- Advance existing theories regarding process heterogeneities, and improve their descriptions through detailed process studies.
- Advance learning from the application of existing models, through uncertainty analyses and model diagnostics, and evaluate the role and worth of different data in constraining and reducing predictive uncertainty.

TARGET 2: Develop new, innovative models to capture space–time variability of hydrological processes for making predictions in ungauged basins, with a concomitant reduction of predictive uncertainty

- Use of new data collection approaches, both space-borne as well as on-ground, for large-scale process understanding, model development and improved predictions.
- Develop new hydrological theories based on scaling, multi-scaling and complex systems approaches, nonlinear pattern dynamics and eco-hydrological relationships.
- Develop new, multi-scale spatially distributed modelling approaches with a focus on falsification of model predictions, over a wide range of basin scales, so that different physical hypotheses and assumptions may be tested.

There is the clear intention that while every effort will be made to improve and advance current methods of prediction, there will be an equal emphasis on, and encouragement for, the development of new innovative approaches, and an even greater emphasis on interactions between these two strategies so that the resulting cross-fertilization of data, understanding and modelling skill will help improve models of *all* kinds, and lead to a sharper reduction of predictive uncertainty.

PUB SCIENCE STRATEGY: SCIENCE THEMES

Based on an assessment of the key science questions underpinning PUB, especially the connection between heterogeneity and predictive uncertainty, and the two research targets, PUB has identified six Science Themes to serve as a framework for the organization of its research activities.

The six themes stress comparative, diagnostic analysis and interactive learning (data *vs* theory, existing models *vs* new models, and detailed observation and analysis of hydrological processes *vs* lateral perspectives into ancillary sciences). In addition, the themes attempt to balance *existing vs new* technology and science, i.e. learning from existing data, models and theories and process understanding (as in Target 1) as opposed to the use of new data, novel theories and process understanding, and the development of a new generation of models (as in Target 2).

The brief descriptions given below are indicative of the kind of research activities that may be carried out under each theme, but are not exhaustive or exclusive. They will be re-evaluated and refined along the way as PUB advances.

THEME 1: Develop new approaches for hydrological interpretation from existing data archives: data rescue and re-analysis, basin inter-comparisons and global hydrology

Brief description Promote the improved understanding of regional characteristic hydrological cycle response and prediction using inter-comparisons and re-analysis of observations from single basin studies, long-term experimental basins set up during the International Hydrological Decade, and national research basin networks. Collect and analyse *existing data* on hydrological responses in different "biomes" or "hydro-climatic regions" (e.g. humid tropical, mid-latitude temperate, high latitude, sub-alpine/alpine, arid, etc.), and interpret the observed differences (within and between different biomes), in terms of underlying climate, soil, vegetation, topography, and land-use interactions, to help form a rational, quantitative classification of drainage basins.

THEME 2: Advance existing theories regarding process heterogeneities, and improve their descriptions through detailed process studies

Brief description Improve the understanding of how climate and landscape heterogeneities determine space–time variability of the dominant hydrological processes in different hydro-climatic regions of the world. Use various methods and technologies to identify and characterize the *interactions* between vegetation, soils and substrate, snow/ice, channels, and atmosphere at various space–time scales. Investigate the heterogeneity of hydrological processes at multiple scales through detailed process studies, and measurements of soil moisture patterns, groundwater levels, saturation areas, surface geophysics, terrain attributes, snow/ice, etc., for the parameterization of the effects of sub-grid heterogeneity in highly instrumented and extensively gauged basins in different hydro-climatic regions. Adopt innovative techniques: (a) to explore subsurface properties, (b) to measure fluxes (rainfall and runoff), (c) to monitor state variables (e.g. snow pack and soil moisture), and ecological indices that may reveal soil moisture regimes based on indicator plants, soil types and topography. Measure isotopic and geochemical composition of hydrological fluxes for constraining model predictions, testing of hypotheses, and for scaling up to basins scales. Develop improved understanding of the interactions between runoff processes and the chemical and biological processes, at all time and space scales, crucial for water quality predictions (salinity, sediments, nutrients, heavy metals, etc.) at the basin scale.

THEME 3: Advance the learning from the application of existing models, towards uncertainty analyses and model diagnostics

Brief description Promote a movement from standard model structures towards model structure improvement, of evaluation through multi-criteria model identification and development of new top-down modelling approaches. These may include methodologies for improved parameter estimation, the use of soft data, pedo-transfer functions, tracers, and measurement of internal state variables. Also included will be comparisons of model performances, with a focus on diagnostic studies and on relating model performance to understanding of climate–soil–vegetation interactions, and with a particular focus on learning from key signatures of basin response rather than mere curve fitting. Model inter-comparisons will lead to a harmonization of models into a few generic types for basins globally stratified by hydro-climatology (e.g. humid tropical, mid-latitude temperate, high latitude, sub-alpine/alpine, arid, etc.).

THEME 4: Use of new data collection approaches for large-scale process understanding, model development and improved predictions

Brief description Extend the range and scale of observations by employing new techniques ranging from standard gauged measures to remotely sensed hydrological surrogates for large-scale process understanding and improved model predictions. Expand observational availability beyond that normally considered in national and international operational hydrology monitoring networks by including hydrological flux and state data (precipitation, soils, vegetation cover, snow cover, ice extent, soil moisture, saturation area dynamics, flood plain inundation, runoff, evaporation, etc.) obtained through advanced satellite remote sensing. Improve mathematical techniques to characterize such data in an efficient manner, and to downscale them to the basin or process scale to satisfy the requirements of hydrological models. Improve model predictions by combining remotely sensed hydrological or surrogate data through the use of four-dimensional data assimilation methods. Develop methodologies, including physically based models, to enable downscaling of large-scale meteorological predictions, such as those by Global Climate Models, to the basin-scale information needed for local and regional water resources management, with special attention given to promote collection of water use and human intervention data on the ground.

THEME 5: Develop new hydrological theories based on scaling, multi-scaling and complex, systems approaches, nonlinear pattern dynamics and eco-hydrological relationships

Brief description Move from standard gauged basin approaches to new basin-scale theories for addressing how multi-scale heterogeneities, nonlinear dynamics and feedback mechanisms affect the predictability of hydrological dynamics at multiple scales in different biomes. Work towards a thorough understanding of how the dominant hydrological processes and patterns at multiple scales are determined by nonlinear climate–soil–vegetation interactions and self-organization in different hydro-climatic regions and ecosystems. These theories might employ concepts and methods from various disciplines such as the theories of multi-scaling, complex systems, self-organization and synergetics, pattern dynamics as well as ecology and eco-hydrology, for developing parsimonious process descriptions within a novel framework for predictive hydrological modelling that can accommodate these novel concepts.

THEME 6: Develop new, multi-scale, spatially distributed modelling approaches with a focus on model falsification over a wide range of basin scales

Brief description Improve available approaches to represent multi-scale variability of hydrological processes, and their dependence on the heterogeneity of climatic and catchment properties, within an advanced framework of mathematical modelling. These new approaches should address the inherent multi-scale heterogeneity, nonlinearity, complex patterns and scaling phenomena that are characteristic of basin hydrology, as well as incorporating relevant new process/pathway descriptions and data sources, aggregated to appropriate basin scales, for hydrological prediction. Derive a new set of balance equations at the basin scale, combined with appropriate closure schemes to parameterize the effects of sub-grid variability, with the possibility of remote monitoring of state variables using novel approaches (i.e. field experiments, remote sensing, tracer and surrogate measurements) to observe previously unobserved space–time variabilities of hydrological processes, thus unifying and integrating the observations of hydrological processes at various scales within a coherent theoretical framework.

OBSERVATIONAL STRATEGY FOR PUB SCIENCE: PUB BASINS

To support the core scientific agenda of PUB (science questions, enabling research and themes), and to achieve the two core targets described above, requires a coherent research programme centred in extensively gauged drainage basins, as well as the development of new observing strategies for hydrological phenomena on multiple space and time scales. New theories and models cannot be developed if suitable data sets are not available to test them. Predictive uncertainty cannot be reduced without an assessment of the uncertainty structure in observed or estimated key hydrological quantities such as precipitation, soil moisture, evapotranspiration and runoff, as well as in groundwater storage. Therefore this requires intensive, sustained and coordinated measurements at a rate and density sufficient to reveal dynamic water, energy and transport components across multiple scales.

Therefore, an effective strategy for building PUB science will rely on conducting research in highly instrumented and extensively gauged catchments in different hydro-climatic regions, where fluxes and state variables are simultaneously observed in representative ways. As part of PUB, hydrologists worldwide will be encouraged to form highly instrumented and extensively gauged, nested PUB basins in different hydro-climatic regions of the world to underpin the PUB enabling research programme.

PUB IMPLEMENTATION PLAN

The science plan presented so far, consisting of science questions and key research themes, provides the scientific framework for PUB activities. Yet, these form only part of the activities that PUB will generate and support. The implementation plan presented below is designed to ensure that the focus on the estimation and progressive reduction of predictive uncertainty is not compromised, and to prevent PUB becoming "all things to all people", or "business as usual."

What sets apart PUB is that the multiplicity of research programmes outlined above will all focus on reduction of predictive uncertainty as the ultimate goal. Through insistence of a key set of two constraining elements, namely: (a) comparability of performance of a variety of predictive approaches, and (b) the merging or assimilation of different forms of knowledge (e.g. data, understanding, theory), PUB will retain a high level of coherence, with excellent chances for major breakthroughs.

Organizing principle: "Design the process, not the product"

The PUB implementation plan is underpinned by a few guiding principles that arise from the fundamental nature of IAHS as an organization, and the nature and present status of the science itself. Firstly, IAHS is an international association of hydrologists, but is not a funding body or even a research organization. It can play coordinating and catalytic roles in mobilizing the hydrological community towards achieving PUB targets, but cannot by itself produce research outcomes. Because of the diversity of interests of hydrologists, and geographical and regional differences, etc., it is strongly believed that outlining a process and a set of principles to be followed, is preferable to specifying a set of rigid outcomes.

Secondly, hydrology as a combination of natural science, earth science, empirical science and applied science, has placed on itself demands from each of these affiliations, and PUB must accommodate the activities of hydrologists in each of these fields of specialization. Therefore, PUB has been designed to be a grassroots level activity or mass movement, accommodative of the diverse interests of hydrologists worldwide (Fig. 4).

Thirdly, PUB recognizes the variety of contexts within which predictions are required for management of drainage basins (e.g. scales, applications, hydro-climatic zones). Similarly, PUB recognizes the variety of models or predictive methods that may be applied. Regardless of the context and the methods used, PUB has also identified a variety of enabling research programmes to make improvements to the

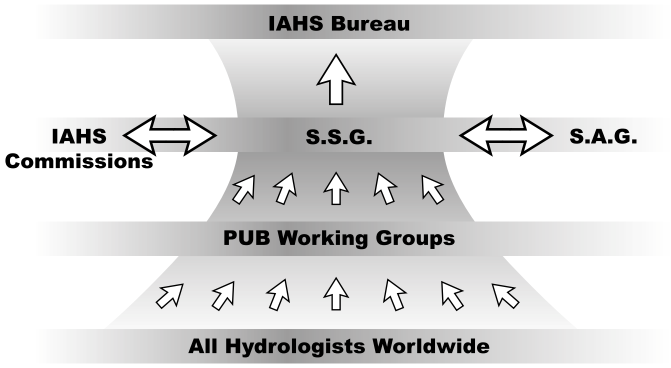

Fig. 4 PUB as a grassroots mass movement; hydrologists worldwide coming together, through the formation of working groups in a self-organized manner.

overall predictive capability. In each of these cases, PUB has chosen to adopt and support a plurality of approaches, hoping to build synergistically on ongoing activities.

Fourthly, PUB recognizes that the hydrological responses of basins are highly heterogeneous across the major hydro-climatic zones of the globe. Models and prediction methods that may be applicable, for any specific estimation problem, in humid regions of the world may not be applicable in semiarid regions, for example. PUB therefore adopts the view that a plurality of approaches must be pursued to account for the major differences in hydrological behaviour between these hydro-climatic regions, and that a comparison of existing models and prediction methods in basins selected in different hydro-climatic regions of the world can lead to the improvement of process descriptions in *all* models for *all* basins, and the harmonization of modelling approaches used worldwide.

Fifthly, PUB is designed to benefit from, and encourages, lateral perspectives into ancillary sciences, such as geomorphology, ecology, meteorology, space science, etc. Since questions about basin responses are increasingly likely to be defined in broad multi-disciplinary terms, the resulting cross-fertilization of ideas and knowledge will lead to the discovery of new phenomena and insights.

Nevertheless, in contrast to such encouragement of a plurality of applications, prediction methods, models, hydro-climatic regions, and enabling research programmes, PUB will have:

– a single minded focus on "predictive uncertainty",
– a single, common objective of "reduction of predictive uncertainty", and
– a singular belief in the adoption of a plurality of prediction approaches and model improvement strategies.

PUB recognizes that a plurality of models and modelling approaches may be valid for the same basin and application (e.g. empirical models, stochastic models, distributed models, lumped models). While each method has its own limitations, each of them incorporates different information and different forms of knowledge, and each may have some advantage over the other. PUB adopts the view that a comparative evaluation of the predictive performances of a variety of models, when simultaneously applied to selected "gauged" basins, can lead to cross-fertilization of ideas and insights into basin responses, and general improvements in process descriptions, and will contribute to a harmonization of the models and modelling approaches.

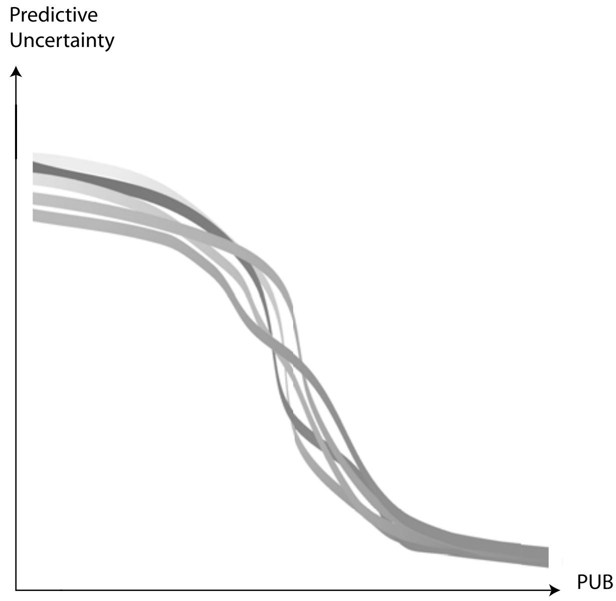

Fig. 5 Convergence of a plurality of approaches towards the single objective of "reducing predictive uncertainty", with a single-minded focus.

It is expected that the diversity engendered by the encouragement of different forms of knowledge and different prediction approaches, together with the pooling or convergence of different forms of information and knowledge from different basins, when combined with strong enforcement of a comparability of performance, will lead to a greater harmony of prediction approaches and sharp reductions of predictive uncertainty (Fig. 5).

PUB ORGANIZATIONAL STRUCTURE

PUB aims to mobilize the entire worldwide hydrological community to achieve its stated objectives through research, educational, and outreach activities. In the light of the guiding principles stated above, the proposed structure for PUB research activities has been aimed at fostering a flexible, self-organizing framework which:

- is inclusive of the diverse range of research interests within the hydrological scientific community, and a similarly wide range of applications;
- is amenable to the adoption of uncertainty estimation on a routine basis;
- enables comparability of the performance of a plurality of approaches with regard to specific objectives;
- encourages the integration of different areas of expertise towards specific common objectives;
- emphasizes the merging or assimilation of theoretical advances, process understanding, new data acquisition and archiving technologies, and evaluation of model performances in different contexts (scales, applications, hydro-climatic zones, etc.) towards the reduction of predictive uncertainty; and
- through insistence of these fundamental organizing principles in the conduct of the various science programmes within PUB, helps to unify and harmonize the hydrological community for rapid advances of the science and its societal relevance.

PUB Working Groups

PUB research will be carried out through a global network of working groups (WGs) comprising interested researchers in any area of prediction in ungauged basins, cutting across traditional thematic areas (such as remote sensing, field-based approaches, theoretical developments, calibration, model evaluation, etc.) (Fig. 6). Indeed, WGs will be the main engines of PUB research activities. WGs will align themselves with one or more of the science themes to maximize their linkage to the PUB movement and to allow for some semblance of central coordination. WGs shall define their own objectives but will be required to have an emphasis on enabling comparability of different approaches towards well-defined common goals, including, especially, reduction of predictive uncertainty. The emphasis on comparability of approaches within and between WGs is aimed at value-adding to individual research efforts, and helping to harmonize and reach consensus in approaches to making hydrological predictions. There will be a particular emphasis on, and promotion of, the setting up a small number of highly instrumented PUB basins in different hydro-climatic regions of the world—this will be achieved through coordination with key WGs.

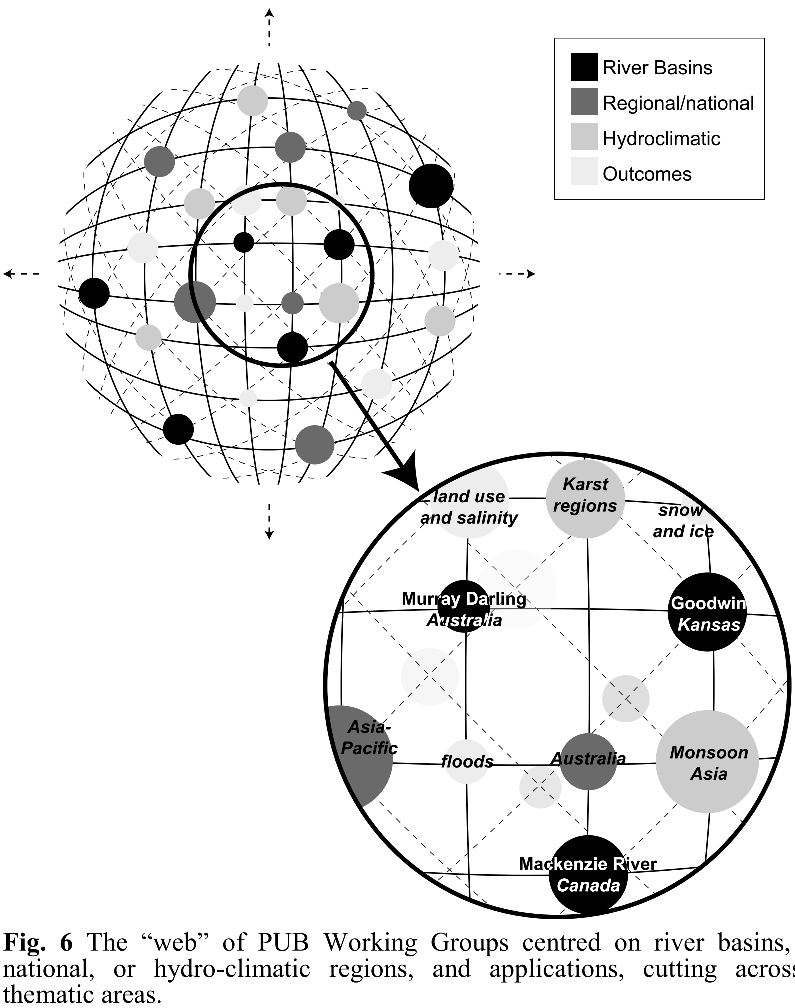

Fig. 6 The "web" of PUB Working Groups centred on river basins, geographic, national, or hydro-climatic regions, and applications, cutting across traditional thematic areas.

PUB and PUB-sponsored activities

The global range of PUB and PUB-sponsored activities will be coordinated with existing national, regional and international groupings, international programmes as well as IAHS commissions, to capitalize on potential synergies for the advancement of PUB.

PUB will pro-actively work towards enhanced coordination amongst the many WGs formed around the world, and centred on different basins, applications, hydro-climatic zones, etc., but organized around the six core Science Themes outlined above. This is in order to provide greater coherence to its research programme and to ensure realization of the two research targets.

As PUB research takes hold, the main PUB-sponsored activities will be in three areas:

– organization of meetings, workshops and congresses,
– regular publication in journals, reports and books, special issues, and progress reports of PUB activities, and
– technology transfer through various means, but with a specific focus on web-based communication.

Role of, and links with, IAHS and its International Commissions

PUB is an initiative of IAHS and will be carried out under the guidance and umbrella of the IAHS Bureau. A Science Steering Group (SSG) has been appointed to plan, lead and implement the PUB initiative, and to maintain coherence of the research agenda through coordination of the activities of all PUB WGs. The SSG will report directly to the IAHS Bureau as a fully-fledged IAHS Working Group (Fig. 7). A Strategic Advisory Group (SAG) has also been appointed to offer advice and assistance, and is especially responsible for lobbying, fundraising, fostering closer cooperation with other national and international programmes, and developing and promoting capacity building activities through global partnerships and outreach. The memberships of the SSG and SAG will be renewed every two years.

It is expected that all the international commissions of IAHS, in partnership with the SSG, will also take up key roles in the implementation of PUB scientific programmes, and in the delivery of the outcomes of PUB research towards improved water resources and water quality management. PUB will benefit from the diversity of disciplinary strengths, experience and organization contained within each of the IAHS

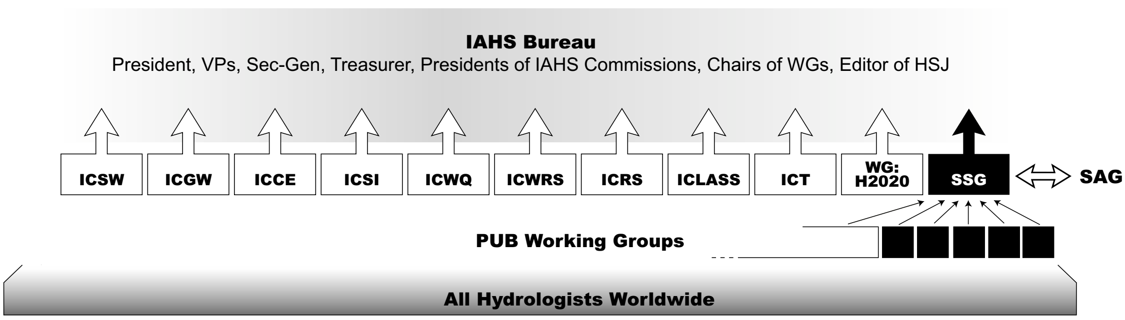

Fig. 7 Place of PUB within IAHS. The PUB Science Steering Group (SSG) becomes a fully-fledged IAHS Working Group, reporting to the IAHS Bureau.

commissions. These relate to different sub-disciplines of hydrology dealing with land–atmosphere interactions, water quantity, water quality, surface water, groundwater, snow and ice, continental erosion, and observational (remote sensing, tracers) hydrology. It is also envisaged that some of the IAHS commissions, either individually or in partnership with other commissions, will form affiliated PUB working groups to carry out integrative research, targeted towards reducing predictive uncertainty in specific applications, river basins, or geographic or hydro-climatic regions.

Links to other international programmes

PUB will link up, and closely coordinate its activities, with other basin-scale and planetary-scale programmes such as HELP, FRIEND, IHP, WWAP, WHYCOS, GEWEX, CEOP, WRAP, GWSP and other "space-borne" measurement programmes, to share data, resources and expertise, and to participate in joint activities, such as the meso- and larger-scale field experiments being organized by HELP and GEWEX (Fig. 8). It is envisaged that at least some of the HELP/FRIEND, GEWEX/CEOP basins will be adopted as PUB basins by PUB working groups. In addition, due to the focus of HELP on applications of scientific advances for improved water management and policy, links with these programmes will advance the societal relevance of PUB outcomes.

Links with the extensive international network of basins and scientists assembled, especially under the UNESCO and WMO international programmes, will also assist towards the capacity building objective of PUB, for the benefits of PUB to be shared and propagated towards the user community. PUB invites all relevant or related professional organizations, such as IAHR, IWRA, IWA, WWC, the various ICSU programmes and UN agencies, to work together so that the scientific achievements of PUB can be made available for practical management applications.

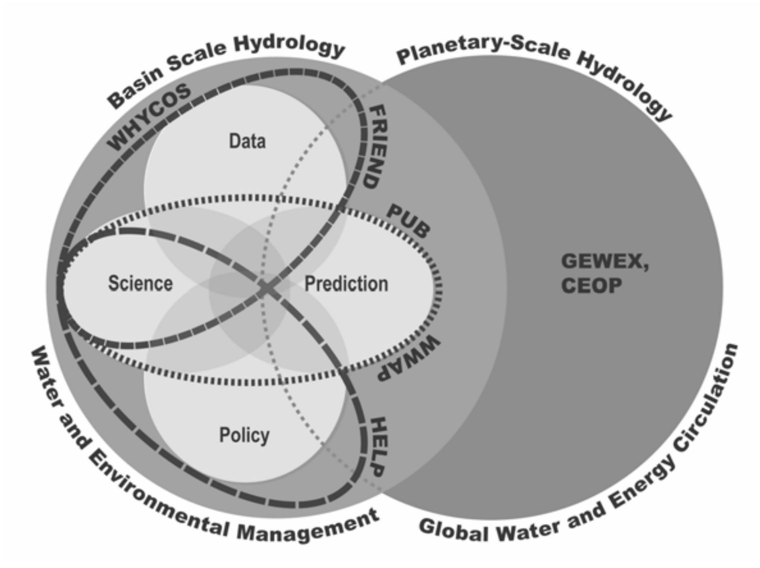

Fig. 8 Place of PUB amongst related international programmes focused on water. Significant overlaps exist between all programmes, which PUB will capitalize on.

CONCLUSIONS

The PUB activities described in this science and implementation plan, it is hoped, will lead to new predictive approaches based on a combination of current and new theories, and of existing and potentially new data sets, including both space-borne and on-ground, that are unimaginable at the present time. In particular, over the next 10 years PUB is expected to lead to:

– development of a sound framework for, and implementation of, routine estimation of predictive uncertainty in all future hydrological predictions,
– a new suite of models and methodologies that can be used with confidence for predictions in ungauged basins in different hydro-climatic zones,
– a network of scientists and groups around the world, especially in developing countries, with the necessary scientific expertise and experience to solve emerging hydrological problems,
– an array of measurement networks in selected basins around the world, and associated databases of hydrological measurements, to serve as a reference pool for new emerging questions.

In addition, PUB stands to benefit the science of hydrology through providing greater coherence to the hydrological science agenda, greater coordination and harmony of scientific activities (Fig. 9), and increased prospects for scientific breakthroughs, and therefore excitement for the science. Its focus on predictive uncertainty not only provides a unifying theme, but also provides a distinct goal to attain, and a measure of the progress made in achieving the set targets. By linking predictive uncertainty to data, and including new forms of data, PUB will help to quantify the worth of data for improved understanding and predictions, and will go a long way towards justifying the restoration, and even expansion of hydrological gauging and monitoring, including the collection of traditional and new forms of data.

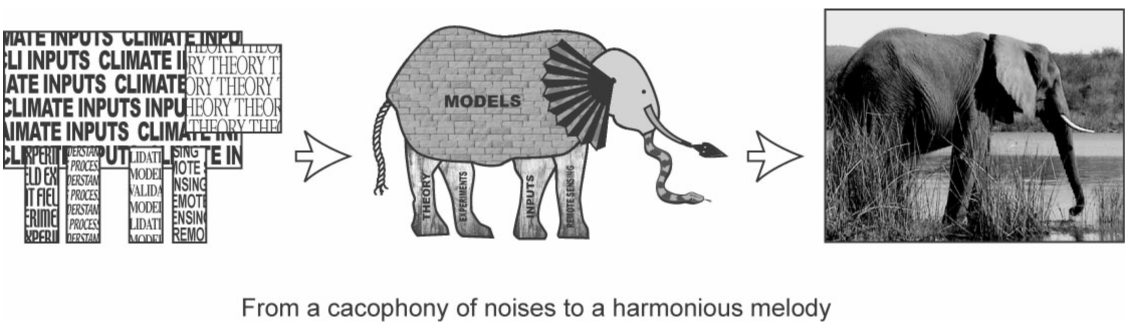

Fig. 9 PUB will undoubtedly lead to a greater harmony of scientific activities, and increased prospects for real scientific breakthroughs. (Illustration of the elephant as described by blind people reproduced by permission of Jason Hunt©1999.)

While PUB is a science driven programme, it does not stop at science, nor will it operate in isolation. It will build on and link up with a number of existing international programmes focused on water. With its focus on hydrological predictions and the reduction of predictive uncertainty, PUB will be able to contribute an advanced scientific and predictive capability to other international programmes that are focused on water resources assessments, natural hazards, and water quality.

In devising the science and implementation plan, PUB has tried to achieve a balance between what is fundamental and enduring, and what is immediately useful and necessary in hydrology. It also attempts to involve and mobilize hydrologists and other scientists worldwide from the grassroots level, and to provide an inclusive framework for the utilization of different perspectives, forms of knowledge and expertise, including those not traditionally utilized by hydrologists. Individual scientists worldwide, of whatever persuasion, are invited to consider joining the PUB movement if the ideas presented in this paper resonate with them and their research. Unlike many other programmes, PUB will make participation open to everyone, and with a minimum of bureaucracy.

Acknowledgements The PUB Science and Implementation Plan was arrived at through free discussion by IAHS members on the World-Wide Web, and during a series of IAHS sponsored meetings at Maastricht, Kofu, Brasilia and Sapporo, and through feedback received at other international meetings including AGU, EGU and MODSIM. A detailed record of the discussions that led to this science plan, including a longer, complete version of the plan, the current membership of the SSG and the SAG, the present status of PUB activities, and calls for expressions of interest, can be obtained from the IAHS website: www.iahs.info

The authorship of the present paper is a small group, a mere subset of the large number of scientists who participated in the many meetings and discussions that led to the science and implementation plan. The enthusiasm, active participation and support of the worldwide hydrological community towards the development of this plan, through ideas, comments and constructive criticism, have been extremely valuable. An especial debt of gratitude is owed to Jim Shuttleworth, Lars Gottschalk, Eric Wood, Toshio Koike, Levent Kavvas and Dennis Lettenmaier, for their efforts in helping to shape the ideas that are now summarized in this paper. The enthusiastic support and encouragement of Pierre Hubert, Jim Wallace, John Schaake, Hiroshi Ishidaira and Daniel Koide, who helped to move the PUB initiative to its present advanced state, is gratefully acknowledged. The authors are especially grateful for the critical and constructive comments on an earlier version of the manuscript submitted to *HSJ* that were received from Keith Beven, Jan Szolgay, Demetris Koutsoyiannis, Ross Woods and two other anonymous reviewers, which helped in making substantial improvements to the content and presentation of the paper.

Guide to Abbreviations

CEOP	GEWEX Coordinated Enhanced Observing Period
FRIEND	Flow Regimes from Experimental and Network Data
GEWEX	Global Energy and Water Cycle Experiment
GWSP	Global Water System Project
HELP	Hydrology for the Environment, Life and Policy
IAHR	International Association of Hydraulic Research
IAHS	International Association of Hydrological Sciences
ICCE	International Commission on Continental Erosion
ICCLAS	International Commission on Coupled Land–Atmosphere Systems

ICGW	International Commission on Groundwater
ICRS	International Commission on Remote Sensing
ICSI	International Commission on Snow and Ice
ICSU	International Council for Science
ICSW	International Commission on Surface Water
ICT	International Commission on Tracers
ICWQ	International Commission on Water Quality
ICWRS	International Commission on Water Resources Systems
IHP	International Hydrological Programme
IWA	International Water Association
IWRA	International Water Resources Association
PUB	IAHS "Decade on Predictions in Ungauged Basins" Initiative
SAG	PUB Strategic Advisory Group
SSG	PUB Science Steering Group
UNESCO	United Nations Educational, Scientific and Cultural Organization
WG: H2020	IAHS Hydrology 2020 Working Group
WHYCOS	World Hydrological Cycle Observing System
WMO	World Meteorological Organization
WRAP	GEWEX Water Resources Application Project
WWAP	World Water Assessment Project
WWC	World Water Council

Received 26 September 2003; revised 17 October 2003; accepted 17 October 2003.