25 PUB: Assessing the Need for the Integration of Hydrological Techniques

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INTRODUCTION

The Perth PUB Workshop aimed to bring together a number of international researchers and practitioners for an in-depth discussion of the current state of hydrological predictions in Australia, Japan, and the Asia-Pacific region, and of potential new problems that are likely to arise in the future in the context of declining hydrological gauging networks, natural variability and human-induced long-term climate and land-use changes.

An important component of the Workshop was the series of breakout group discussion sessions. The delegates were split into small groups of between four and seven, each focused on particular areas of hydrological prediction. Their task was to identify the state of the art in hydrological prediction and to be the catalyst for the formation of a number of international PUB working groups formed around research opportunities (theories, data, models) that show the greatest promise to advance our predictive capability for management of water quantity, water quality and natural hazards. The formation of PUB working groups will, in addition to assisting the PUB initiative, enable hydrologists to work together across state, national and disciplinary boundaries on common problems, thus bringing a considerable amount of coherence to hydrological research. The breakout groups had intense discussions about the specific scientific questions that should underpin the working groups, and aimed to help formulate the strategies to answer these questions through collaborative research. The individual groups were then required to address a series of questions relating to current practice and future potential integration.

The groups were divided between the following hydrological predictive areas:

- Flood hydrology
- Drought hydrology
- Rainfall variability
- Evapotranspiration and land surface–atmosphere fluxes
- Sediments and erosion
- Assessing the impact of land use/cover change
- Water quality and ecosystem health
- Integrated comprehensive environmental assessment

Each group then addressed the following questions/issues:

- What are the societal needs, as you see it, for your predictive objective? What is

the societal understanding of the importance of your predictive objective and how can this understanding be improved?
- What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?
- Which of these methods performs best, under what circumstances and why?
- What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?
- Can any of the methods listed be integrated to improve prediction?
- Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?

FLOOD HYDROLOGY

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?

Respondents identified a range of key variables that are required for prediction. The issue of flood risk on a range of time scales was identified by all groups as the key variable to be addressed. There is clearly a need for short-term operational flood forecasting in ungauged basins to provide robust warning of imminent extreme flood events. On longer time scales, the problems of short-term flood forecasting could largely be mitigated if robust long-term flood risk could be achieved in ungauged catchments. The long-term flood risk is a key variable in developing secure urban growth, free from routine and often devastating floods.

Related to flood risk, secondary variables were identified by the breakout groups. These included the area of inundation for specific flood events of various magnitudes but also the time of inundation. The latter may be particularly important given the range of flooding environments, from large alluvial lowlands to flash-flooding highland environments, and in areas where damage is related to both magnitude and length of inundation.

Regarding societal understanding, there was some consensus that society is generally highly aware of the personal impacts of flood events but that different societies may not necessarily understand how they contribute to flood risk through uncontrolled urban development. After flood events, it was argued that some communities have "small memories" and may consequently return to vulnerable areas through economic necessity. It was also suggested that in developing countries, rural communities have a greater appreciation of flood risk than their urban counterparts, and, that with increasing urban development, some communities may actually be losing understanding of how a specific hydrological regime may operate.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?

For estimating flood risk, a whole range of empirical methods and techniques as well as conceptual hydrological models were identified by the different groups. In particular, the use of the rational method, curve number, regional frequency curves are key empirically-based methods, largely relying on data on a regional basis if not in the catchment of interest. Many hydrological models were identified ranging from the conceptual VIC and Sacramento-type models through to distributed models such as SHE.

In terms of inundation area, it was generally acknowledged that hydraulic techniques are available that can provide reasonable estimation of inundation given a predicted flood volume. A valuable source of information on inundation and length of flooding can often be the experience from previous flood events, although this can be difficult to include in modelling endeavours.

For short-term specific flood warnings in ungauged basins, methods typically applied are more *ad hoc*. Whilst generalized regional forecasts are made on the basis of meteorological forecasts, informal extrapolation is often then utilized for ungauged basins.

Which of these methods performs best, under what circumstances and why?

It was generally agreed that for estimating long-term flood risk, regional flood frequency analysis provides the best estimate of risk. However, this does rely on nearby catchments with similar hydrological regimes to be gauged in sufficient quantity over a sufficient length of time. The decline in gauging networks is an obvious barrier to the application of this technique. However, an advantage of this approach is that reasonably robust quantification of uncertainty can be provided.

Rainfall–runoff methods can work well in certain circumstances. Lumped models are simple to apply and can be tuned to even local knowledge if not to available gauged data, and they can provide some reasonable simulations of the systems if the study catchments are small enough. When the scale of the catchment is much larger than the flood delivering rainfalls, these models may struggle to capture the spatial variability of runoff production. Distributed models are then required. Uncertainty is hard to quantify given the uncertainty of choosing a specific model for the application, but also given the uncertainty associated with the appropriate parameter values for these models. The issue of parameter uncertainty grows as the complexity of the model employed increases. This is particularly the case as one moves from the use of relatively parsimonious lumped models to spatially-distributed models requiring parameterization at each sub-unit scale.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?

Essential data identified for applying the techniques include basic catchment characteristics: area, slope, land cover, channel characteristics and local climatology. For the application of regional flood frequency analyses, basic catchment properties are required but more substantially, long-term gauge records from surrounding catchments is essential.

In an ideal world, much more detailed information would be available including intensity–frequency–duration (IFD) information, robust estimates of evapotranspiration losses necessitating vegetation and soil type information, topographic details, geomorphology, surface–subsurface interactions and detailed *in situ* rating curves at highest flood increments may all be utilized in developing flood risk estimates at a range of time scales.

Can any of the methods listed be integrated to improve prediction?
The breakout groups all agreed that much more robust understanding of flood hydrology in ungauged basins would result from an intercomparison and integration of the identified techniques, though it was acknowledged that this was rarely, if ever, achieved. As an example, the use of statistical regional flood frequency curves can provide a direct estimate of long-term flood risk in an ungauged catchment. Stochastic simulation of flood risk through continuous simulation offers the prospect of integrating much more detailed catchment characteristics into an appropriately chosen hydrological model to provide estimates of flood volume at a range of different time scales. These could then be compared with the regional analysis to provide some estimate of the uncertainty associated with adopting either one or other of the techniques. This was seen as a first step toward understanding which was most likely to be inaccurate if the results were divergent to a substantial degree. With either or both techniques, hydraulic models can then be used with the resultant flood volumes to provide area of inundation. These estimates could then be verified if remotely-sensed area of inundation imagery were available for previous flood events of known magnitudes in the catchment of interest. This would provide an holistic approach to the multiple facets of practical flood hydrology.

Other examples of potential integration were also proposed. In particular, the formal incorporation of informal, local expert knowledge represents one area where integration with models may be highly valuable. Another is in the use of state-of-the-art palaeo-flood reconstruction techniques to provide independent time series of long-term flood risk; these can then be used to adjust regional or model-based techniques by providing a much longer flood series than is commonly available even at gauged sites. A key difficulty is that not every hydrological environment retains records of flood history, by virtue of the geomorphic processes operating in the specific catchment. Nonetheless, all groups identified key areas where integration of multiple techniques may yield more robust risk quantification as well as representing a process by which better understanding of the diverse techniques can be acquired.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?
A PUB working group devoted to the evaluation of techniques would need to provide more focus on the relative value of the current suite of techniques available to the practitioner. At present, the available techniques vary considerably in the information that they utilize as well as the underlying philosophy of their application. For instance, a purely statistical approach is vulnerable to the regional data available as well as the inherent unique properties of the specific catchment. In contrast, the application of distributed hydrological models at least attempts to incorporate site specific information but might never utilize knowledge from surrounding gauged basins available from regional approaches. There is obviously a balance to be struck in incorporating all information, both statistical and physical. A working group addressing the issue of flood risk estimation at a range of time scales could evaluate each method individually and then assess the worth of integration in reducing uncertainty associated with the risk estimates. Success factors could be defined as prediction of flood peaks, flood

frequency and flood inundated area and persistence of inundation. Successful integration of techniques could be assessed by a general reduction in the uncertainty associated with the predictions as well as an improvement in their accuracy.

Other scientific communities that might contribute to this effort include: geomorphologists, to better understand the long-term processes in the catchment; remote sensing experts to provide historic imagery of inundations; model identification and uncertainty estimation researchers, to provide appropriately-chosen models and robust estimates of predictive uncertainty.

DROUGHT HYDROLOGY

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?

Key variables of societal importance that require prediction include the severity, spatial extent and the length of individual droughts. Other predictive objectives include long-term drought risk for agriculture, ecosystem health and water supply infrastructure. Societal understanding of the impacts of individual droughts is high. However, perception of long-term drought risk is highly dependent on individuals (particularly their experience over time, and so is age dependent) and location (where local effects may not be representative of the regional impact of drought). The public are aware that drought is bad and that it needs to be managed. However, they are not so aware of the formal definitions of drought, which can lead to gross misunderstandings. For example, one storm does not break a drought, reservoirs are still not filled, soil profiles need to be replenished before significant surface water returns. It was also suggested that the public at large does not necessarily understand the meaning of probabilistic forecasts.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?

Short-term monitoring policy is often based on reactive methods, i.e. not predictions as such but simple monitoring tools are used to guide management options for current droughts. Examples include the monitoring of storage levels in reservoirs, simple rainfall deciles, the Palmer Drought Severity Index (PDSI), and other crude models and indices. Long-term operating strategies for predicting drought are now being adopted, primarily in the agricultural sector. One example is Rainman, developed by the Queensland Department of Primary Industries (QDPI, Australia). A relatively crude SOI index-based method of forecasting future months/seasons, Rainman, provides future rainfall estimates based on the El Nino–Southern Oscillation (ENSO) phenomena and antecedent conditions. Most importantly, Rainman is utilized by individual farmers who are best placed to assess their own unique consequences of future rainfall estimates.

In terms of long-term planning processes for drought, often historic data are available in a given dammed catchment. Where drought risk estimates are required for ungauged basins or where the historical record is too short, rainfall–runoff models are developed for the specific catchments and forced with stochastic models of rainfall to develop long-term simulations. Emerging methods include the use of General Circulation Models (GCMs) although these are at present too crude to be robustly relied upon for realistic drought risk estimates.

Which of these methods performs best, under what circumstances and why?
Problems with the current approaches include the definition of rainfall districts based on raingauge location, and not based on catchment areas. It is also acknowledged that rainfall is a poor estimate of hydrological or water supply drought due to the nonlinear response of the land surface. A key issue, particularly in Australia, is the issue of stationarity of rainfall and drought producing climate processes.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?
Essential data for drought hydrology are rainfall measured for as long as possible. Any streamflow data would be a bonus even if the gauge was discontinued. In an ideal world these data would be available for at least the last century to encapsulate some of the extreme droughts. Ideally these gauged records would extend back much further. These data are used to calibrate rainfall–runoff and stochastic rainfall models. Clearly the models themselves could be improved through the incorporation of more appropriate process representations, such as catchment characteristics and the constraint of the key dominant flow generating mechanisms.

Other data that may play a valuable role in better understanding drought at a range of time scales include *in situ* soil moisture and to a lesser extent, remotely sensed soil moisture. *In situ* is preferable due to the inherent problems of translating remote sensing imagery into a meaningful hydrological quantity. It is acknowledged that active microwave remote sensing at best can only provide insight into the uppermost 3–5 cm of the soil profile. Palaeo-climate records would also represent a valuable resource in providing much longer term measures of historic droughts that may not appear in the relatively short instrumental records. However, not all catchments will offer the opportunity for assessing palaeo-drought risk.

Remote sensing also offers some promise for monitoring the response of the land surface to drought. In particular, vegetation status/health information may be gathered by multi-spectral imagery providing a better understanding of the response of vegetation to moisture stress. Remote sensing also offers the prospect of quantifying the spatial variability of drought responses on a much finer resolution than can be estimated from point raingauges. Rainfall radar may also play a role in better assessing where the rain is falling allowing more detailed information on spatial impacts.

Can any of the methods listed be integrated to improve prediction?
For operational forecasts, an opportunity exists for greater use of soil moisture estimates by integrating these within weather/seasonal climate forecasts to provide more robust "hydrological" forecasts. Remote sensing does offer many opportunities but integration is costly and the value of the information is largely dependent on the translation of the sensed signal into hydrologically-meaningful quantities.

To assess long-term drought risk, as with flood hydrology, an improved understanding of land surface processes would lead to improved representation of the rainfall–runoff transformation required for stochastic generation of flow, and hence for robust estimation of drought frequencies. Similar arguments also apply to the development of stochastic rainfall models that are primarily based on the observed statistics of historic rainfall events rather than on a process-based understanding of how and why they occur. An obvious opportunity to incorporate greater mechanisms into rainfall generators lies in the observation that ENSO provides a controlling mechanism on interannual variability. If one could understand ENSO dynamics from physical principles, then this could form the basis of more robust stochastically generated rainfall scenarios offering more robust characterization of both flood and drought risk.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?
A PUB working group on drought monitoring and risk estimation could focus on the integration of *in situ* and remotely sensed measures of drought variables such as soil moisture and streamflow. If soil moisture estimates and streamflow measures could be assimilated into numerical weather prediction (NWP) models, then more robust estimates of the hydrological impacts of drought could be achieved. Success would be evident if it could be shown that the integrated hydrological predictions were more informative and accurate than the current operational use of the PDSI and rainfall deciles.

In terms of improving long-term planning, palaeo-reconstructions could be integrated into the stochastic streamflow generation techniques to provide longer samples of natural climate variability. There are also many improvements to be made in the identification of the most appropriate hydrological model through better process understanding or else through improved regionalization techniques. An intercomparison of existing against integrated techniques would be deemed successful if it could be shown that the integrated techniques provide less uncertainty or even different estimates of drought risk.

RAINFALL VARIABILITY

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?
The characterization of rainfall in both space and time is arguably the most fundamental predictive variable as ultimately rainfall drives all things hydrological. It is the main forcing of all hydrological models and provides the most basic information for hydrological studies and applications. In particular, extremes of rainfall are important to get right. There is also a critical need to identify design rainfall for infrastructure planning and utilization. Whilst rainfall variability and its characterization is fundamental within our community, society does not generally understand the research issues involved but is definitely aware of the problems associated with excess or deficient rainfalls.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?
There are many available technologies for measuring rainfall at a variety of spatial and temporal scales including raingauge networks, radar-based spatial measures of storm intensity, satellite monitoring of rain-bearing cloud formations and estimates of rainfall rates. For developing spatial rainfall fields, for instance as input to hydrological models, there are a multitude of relatively basic interpolation schemes based on Thiessen polygons, linear interpolation, kriging, isohyets, etc. However, these are

largely simple mathematical methods that do not incorporate the known effects of topography and/or orography on rainfall. The thin plate splines method represents one interpolation technique for incorporating physical spatial controls that appears to offer advantages over the purely statistical interpolation techniques.

In stochastic modelling of the impacts of rainfall variability, typically statistically-based rainfall generators are used. These can suffer from the length of data available to calibrate them, as well as the location of the gauges relative to the application site.

In terms of methods to characterize rainfall variability, the use of intensity–duration–frequency (IDF) methods is widespread although this technique is also highly dependent on the length of available data to characterize the extremes as well as the location of suitable records relative to the ungauged location. More recently, coupled ocean–atmosphere models have been utilized along with rainfall downscaling methodologies to provide rainfall variability estimates for assessing the effect of potential future climate change. These techniques offer future advantages for characterizing rainfall by linking rainfall to causal mechanisms via atmospheric circulation. These have the possibility of being used at ungauged locations after robust calibration to available data.

Which of these methods performs best, under what circumstances and why?
In terms of providing rainfall characterization at ungauged locations the simpler statistical techniques work best. However, they do require sufficient data at gauged locations to be used in a regionalization process for the ungauged catchment. There is always a need for some observations somewhere to train the algorithms. The dynamical approach utilizing atmospheric circulation is inherently more complex but, being process-based can, in principle, be applied anywhere. Again, observations are required for training and evaluating these algorithms.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?
Essential data for characterizing rainfall variability are ground-based observations of rainfall. Fundamentally we are still limited to the best measure of rainfall being, in essence, to catch some of it. In an ideal world, to better understand the processes behind rainfall variability in time and space, much more data would be available and reliable. In particular, radar and satellite estimates of space–time fields of rainfall can be very useful. Radar techniques themselves require calibration against ground-based observations, although the resultant spatial fields are essentially the best interpolator of ground-based estimates. Measures of atmospheric circulation based on pressure or geopotential-height data can be useful in linking rainfall to the causal circulation patterns. For developing understanding of longer term variability, sea surface temperature data can be used to establish teleconnections, such as ENSO.

Can any of the methods listed be integrated to improve prediction?
There is a clear need for further integration of the techniques currently employed. In particular, more work is required on linking radar- and satellite-based rainfall estimates to established ground-based networks to develop a better understanding of the radar and satellite signals. Coupled modelling efforts are still in their relative infancy and so offer strong promise if integrated into current methodologies on a routine basis.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?

A PUB working group could be formed to address the issues of radar algorithm development, to address the development and performance of stochastic rainfall generators, and to address the use of downscaling techniques. We need to develop improved methods for merging radar and ground-based approaches to develop a more fundamental understanding of the radar signals. Stochastic rainfall generators need to move beyond being based on the statistics of rainfall and should try to develop to be more process oriented. Downscaling techniques offer many opportunities but have been approached from a wide variety of different methodologies. A PUB working group could be formed to assess and compare these schemes where the uncertainty associated with their use is quantified in a comparable and consistent manner.

EVAPOTRANSPIRATION AND LAND SURFACE-ATMOSPHERE FLUXES

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?

There are numerous societal needs for robust estimation of evapotranspiration, in: agriculture, drought development and impacts, irrigation, water resources estimation, and numerical weather prediction. Different communities who utilize evapotranspiration estimates have different appreciations of its role, e.g. agricultural communities are very aware of its importance, in particular for irrigation scheduling. Other applications are largely unknown to the public, such as its role in numerical weather prediction.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?

Over the years, many diverse methods have been developed for estimating evapotranspiration ranging from empirical through to highly bio-physically based soil–vegetation–atmosphere transfer (SVAT) models. Simple climate based estimation equations have been developed primarily for estimating potential evaporation. Other simple seasonal linear interpolation techniques have been utilized for regionalizing pan evaporation data between sites. SVAT models are in principle bio-physically based and therefore offer the possibility of calibration against known land surface properties; however, these are typically complex requiring many parameters to be specified as well as high quality meteorological forcing data. In recent years, satellite based remote sensing data has been used to estimate evapotranspiration in otherwise ungauged basins.

Which of these methods performs best, under what circumstances and why?

Generally, data driven approaches are better if adequate data are obtainable. Otherwise, simple models with limited data perform reasonably well. SVAT models are the most physically-based approaches and hence in principle should provide the most realistic representation of land surface fluxes, but the data requirements are prohibitive for many applications. When embedded with numerical weather prediction (NWP) models, the land surface schemes can have reasonable accuracy although the scale of the representation means that small-scale variations are in practice important.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?
Given the diversity of methods available for estimating evapotranspiration, often that chosen is a function of the data available. Bare minimum data for estimating land surface evapotranspiration include rainfall, temperature and radiation (or else some estimate of available energy). In an ideal case, but also for more complex modelling tools such as SVAT models, more detailed data is required. For instance, incoming irradiance, wet- and dry-bulb temperatures, wind speed data (preferably at two heights), soil moisture throughout the soil profile, NDVI (Normalised Difference Vegetation Index) and aerodynamic/radiometric surface temperatures, can all be utilized by SVAT models. Scintillometry, weather stations and remote sensing are all key data sources for improving current estimation techniques

Can any of the methods listed be integrated to improve prediction?
There are many opportunities for integrating current methodologies utilized in the estimation of evapotranspiration and land surface fluxes. In particular, there are many possibilities for data fusion or assimilation; e.g. annual water budgets could be used to validate or improve SVAT models that may then be applied to ungauged basins. The integration of remote sensing with all estimation methodologies offers much promise for improved estimation of fluxes across ungauged basins. However, interpretive models are required to utilize radiometric signals from thermal scanners.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?
PUB working groups could be organized to evaluate the traditional temperature/radiation based estimation methodologies. Objectives could include the evaluation of these diverse techniques in different environments to gauge their applicability in different areas where different processes as well as different data apply. One successful outcome would be the identification of guidelines, given the environment and available data, for optimal estimation of land surface evapotranspiration.

Another PUB working group could evaluate the integration of remote sensing techniques in SVAT modelling efforts and assess the ability to regionalize these models to data-poor or ungauged locations. Success could be defined by a reduction in predictive uncertainty associated with SVAT model applications. Efforts to represent both water and carbon cycles within these models would also represent a significant step forward for integrating hydrological fluxes and process understanding with bio-physical modelling.

SEDIMENTS AND EROSION

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?
Erosion has major societal impacts; consequently there are substantial societal needs for improved prediction of sediments and erosion. On-site agricultural impacts of erosion can lead to loss of production. Landsliding and mass movement of hillslopes is

a major problem in many parts of the world. Impacts of erosion and sediment movement can have major impacts on downstream water quality. There is a clear need to reduce the impact of land management on sedimentation and water quality. There is a broad awareness of the problems of erosion and sedimentation but understanding is generally poor. Problems are often oversimplified and dramaticized. Farmers tend to have a good appreciation of the problems on the paddock scale but are not necessarily good at understanding downstream problems.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?
Approaches to quantifying and predicting erosion rates are many and varied. The most basic approach is simple visual observation of developing problems on relatively small scales. Many techniques are available for tracing sediments and erosion, including the use of radionuclides. In terms of models available for erosion estimation, a wide range exists from simple empirically-based formulae such as the Universal Soil Loss Equation (USLE) through to higher physically-based models for identifying spatial variability of erosion and landslide risk. Complex landscape evolution models also exist to estimate how hillslopes may evolve over time scales from hundreds to thousands of years.

Which of these methods performs best, under what circumstances and why?
Observations of contemporary erosion are very useful if transferring information to similar but ungauged basins. Empirical methods are widely applied; however, the basis for extrapolation is largely unknown and scale issues are important. Models such as USLE were primarily developed for North American environments. Similar models have been developed in southern Africa which may be more relevant for similar semi-arid environments. Physically-based methods suffer from the complexity of the models and the requirement to specify many model parameters which may not be easily measured in the field. Geochemical and other tracer techniques are very useful for estimating sediment sources. However, these are either instantaneous or else integrate sedimentation processes over very long periods.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?
For the empirical class of erosion rate estimation methods, the basic information required are topography, soil types, land-cover classifications, rainfall data and land-use practice. Geochemical tracer techniques require the quantification of the geochemical signatures of different sources and sinks for sediments within a study area. Mechanistic/physically-based approaches requires much more detailed information such as high resolution terrain models, soil erodibility parameters, much better defined hydrological processes and more plot-scale studies.

In an ideal world, data for empirical models would be available from a much broader range of environments, e.g. tropics, arid, humid etc. Geochemical tracer studies always benefit from a wide a range of physical or chemical tracers that can reveal unique signatures between sources and sinks. As more tracers are available, more opportunities exist for robustly distinguishing between different sources and sinks. In the case of the physically-based class of models, more data is always required. Ideal data would be those that can provide a better understanding of the relevant processes operating in the study catchment.

Can any of the methods listed be integrated to improve prediction?

The wide range of different modelling/estimation philosophies demonstrate the clear need for the integration of the available techniques. Empirical methods are largely based on relationships identified in other, and potentially very different, catchments and environments. These models could be validated through intercomparison against more physically-based methodologies in a data-rich environment. The use of geochemical tracers for sediment fingerprinting can yield actual estimates of how much sediment is being delivered to a specific sink. The techniques offer the opportunity to validate all erosion models, from empirical through to the physically-based. In particular, landscape evolution models could particularly benefit from validation via tracer experiments.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?

The key needs for improving erosion and sedimentation prediction lie in greater understanding of the processes in specific catchments and of the scaling and transferability of these processes. PUB working groups could be formed to evaluate and compare the wide range of available methods. A focus on the integration of diverse techniques would indicate which methodologies can benefit from validation in specific environments and catchments. Success could be measured by achieving consistency between the different methods, or else in identifying which methods work best and why. If future models could be developed that require less input data but perform to a satisfactory level of uncertainty, then significant progress could be said to have been made. Greater interaction with ecologists, tracer specialists and remote sensing experts may be of great benefit in moving the science forward.

ASSESSING THE IMPACT OF LAND USE/COVER CHANGE

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?

The impacts of land use and cover change on hydrology require prediction because of the general importance of water to society. Changes in land use and cover can lead to marked impacts on flood and drought risk, low flows, biodiversity, water quality, water for irrigation. Impacts can be downstream or even offshore. There is some perception of these impacts but typically only a poor understanding of the processes involved. However, it is widely accepted that changes to land surface management and use will cause alterations to hydrological regimes. Land-use changes are often seen as a rural issue although it is also an urbanization issue. Societal understanding also differs from country to country. For instance, algal blooms and salinity impacts are widely acknowledged in Australia, whereas in the UK there appears to be little perception of the links between land management and water outcomes. Misunderstandings are still widely prevalent, especially with respect to forests and floods.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?
Key approaches to assessing the role of land use or cover change on hydrology include the use of paired catchment studies. Other approaches utilize hydrological models to estimate changes to the land surface hydrology. Relatively parsimonious models, such as IHACRES, have been utilized for this purpose. Empirical rules are developed to adjust model parameters to account for proposed changes. More sophisticated approaches are available, typically through the use of detailed, distributed hydrological models. One example is LACSAM which can readily incorporate distributed land cover information.

Which of these methods performs best, under what circumstances and why?
In terms of assessing alternative approaches it is currently unclear which approaches/ models work best and why because it is a rare luxury to perform model intercomparisons. Ultimately subjectivity is endemic in current model applications and predictions are often untestable. There is a clear need for determining the “fitness for purpose” of models, and for quality assurance of models and predictions.

As a general rule, simple data-based models such as IHACRES should work reasonably well when catchments are similar and when applied on relatively small scales in wetter environments. More sophisticated approaches, such as LACSAM can be calibrated to catchments where data exists. However, when transferred to an ungauged catchment it is assumed that the model is applicable. It is currently too early to make judgements about the general effectiveness of the various approaches.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?
Essential data are rainfall, runoff and land-use data in nearby gauged catchments. These data must be long-term, covering at least a decade, and should include some assessment of the reliability of the records. Ultimately, the essential data depends on the model being used in the exercise. In an ideal case, the full suite of meteorological data would be available. Remote sensing data, terrain models, groundwater levels, hydraulic conductivity would all be available for improving the understanding of the processes that affect the hydrological regime.

Can any of the methods listed be integrated to improve prediction?
Yes—as noted above there is a clear need of the intercomparison and assessment of individual models performance in a controlled experiment. In any case, multiple models could be used in a land-use change assessment exercise to provide an ensemble of model predictions. This could include a hierarchy of models from simple to complex. New data techniques need to be integrated with existing models to improve the understanding and representation of hydrological processes and ultimately provide more physical meaning to model parameters.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the “success factors” for such a group? What other scientific communities do you feel you need to further engage with?

A PUB working group could provide some valuable insight into the performance of the plethora of models typically used for this purpose. In the first instance, there is a need to benchmark the current state of the art. This should be performed in gauged catchments prior to change in an attempt to improve the predictions of land-use change in a controlled environment. This could then be extended to evaluate the models over a range of different environments. One useful task could also be to collate available information on the known impacts of land management changes. A successful outcome would be a solid understanding of what model to apply where.

WATER QUALITY AND ECOSYSTEM HEALTH

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?

Water quality and ecosystem health parameters are of key societal importance for many reasons, including the provision of clean drinking water, unpolluted waterways, prevention of algal blooms and the maintenance of biodiversity. Understanding of these issues is generally good compared to other hydrological predictive aims. Many of the issues are of direct relevance to daily life. Media reporting of acute events is typically high although long-term chronic events may also receive such high levels of reporting. Water quality issues are “easy to sell” to the lay public.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?

Many methods exist for tackling the wide ranging issues of water quality and ecosystem health. There are regionalized acid deposition models for assessing water acidity, AUSRIVAS and other rapid assessment techniques for estimating water quality impacts on freshwater ecosystem health, export coefficient techniques for river mass load (hydrochemical budgets), sediment models for nutrient export estimation, end-member analysis and hydrological models containing water quality components.

Which of these methods performs best, under what circumstances and why?

Many models and techniques are available for assessing and predicting water quality and ecosystem health although they are rarely compared and evaluated in different environments. Many models are potentially useful for policy analysis but the underlying assumption is possibly unrealistic. Some models are applicable for only limited types of environments. Many are based on highly simplified assumptions and are often entirely unverifiable. Ultimately all methods perform badly if controls on water fluxes are largely not understood in the application of interest.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?

Essential data are largely dependent on the modelling objective and the approach adopted in a given application. Data that can be of importance include geological maps, atmospheric inputs (i.e. sources of pollutant inputs and water fluxes), residence times in hillslopes, channels etc., water quantity and any information that provides insight into flow paths and dynamics. Ideal data would include all data that would lead to improved understanding of the physical and chemical processes affecting the issue at hand.

Can any of the methods listed be integrated to improve prediction?
It is currently difficult to see how the plethora of diverse techniques could be easily integrated for the purpose of assessing and predicting water quality and ecosystem health. Fundamentally the developed methods and models tend to be issue specific with the underlying philosophies being very different (from statistical-empirical through to physically-based). Clearly no single model can address all water quality and ecosystem issues. The prime problem in water quality and ecosystem prediction is the current lack of understanding of the hydrological, ecological bio-geological processes at work. This poor understanding is compounded in ungauged catchments. A greater emphasis must be placed on the linkages between the different components of a given hydrological system in determining ecological and water quality status.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?
In the first instance, a PUB working group could be formed to provide better methodologies for quantifying catchment flow pathways and residence times, improving water quality–quantity relationships and for assessing water quality evolution. If robust methodologies could be developed for estimating these in ungauged basins, then significant progress will have been made. This naturally requires a strong interdisciplinary approach which would involve isotope geochemists, geophysicists, biogeochemists, ecologists and hydrologists.

INTEGRATED COMPREHENSIVE ENVIRONMENTAL ASSESSMENT

What are the societal needs, as you see it, for your predictive objective? What is the societal understanding of the importance of your predictive objective and how can this understanding be improved?
Some of the most important devastating events to society concern water. Droughts and floods have different characteristics but they have enormous societal and economic consequences. Sustainability for society deals with the presence of adequate quantities and acceptable quality of water. The quality of water is an important issue for drinking water and there are numerous accepted guidelines for safe standards.

To improve predictive ability in the context of water resources and their environmental impact, one of the most important issues is to improve dialogue between the various parties concerned. In most cases there is an adequate amount of water but the quality of water and its distribution over the year (non-availability in summer and adequate presence in other seasons) are problematic. There is always a set of competing objectives, e.g. maximum head storage in lakes behind a dam for power production whereas, minimum head storage would help flood containment but be harmful towards fish and wild life and not help recreation (underscoring individual *vs* public needs).

There is always a need for conflict resolution between numerous parties and therefore a sense of societal trust in the Integrated Water Management (IWM) scientific approach based on cost benefit analysis should be achieved. This means that the various stakeholders must be involved in the IWM process which should be as transparent as possible. Of particular concern is the proper handling (politically) of inter-regional transfers of water, i.e. pumping/transportation of water between watersheds.

What methods, models and techniques have previously been used to achieve your predictive objective in ungauged basins?
Most of the models used historically rely on the top-down rather than bottom-up approach. There is not, in general, good socio-economic model integration with our mathematical models for prediction of environmental impact assessments (EIA). In addition, there has been none or minimal consideration of political and/or psychological issues associated with environmental impact assessments. We need to move simple uncertainty based approaches to probability distributions of various decisions so that the IWM process produces a range of solutions with associated probability distributions that would help more in decision making. Employment of observation networks and/or satellite observations would help in un-observed areas (specific to the PUB problem). Use of case history information from other cases that have strong resemblance either in a physical problem context and/or socio-economic context would help in shortening the learning curve and preventing repetition of past mistakes.

Which of these methods performs best, under what circumstances and why?
The methods that work best are listed in their order of importance:

- Probabilistic methods that incorporate notions of uncertainty.
- Methods that use information from past case histories, studies from physically similar basins and/or similar socio-economic context.
- The top-down approach is best suited to the IWM, EIA problem.
- Integration of biophysical/ecological principles as well as socio-economic information is a major plus in this effort.

What data are essential (i.e. bare minimum) for implementing the methods listed? In an ideal world, what additional data would improve the implementation of these methods?
Essential data include:

Value of water and ecosystem It is important to realize the "value" attached to the water and the ecosystem. Is it worth it if we exploit the water resources without any concern for environmental impacts?

Availability and demand for water Integrated water resources assessment using data from precipitation information, inflow into the basin (if available) or using models for this purpose. The demand for water depends on the various stakeholders and their requirements.

Stakeholder profiles Who are the competitors for the same resources? What are their time period requirements? How do the various stakeholders interact with each other (friendly *versus* acrimonious)?

Economic revenue and damage associated with various decisions i.e. with each outcome of the IWM/EIA model, we can attach a monetary value to help make decisions.

Culture and history Most societies have culture and tradition associated with the use of water as well as the value attached to ecosystem and environmental impacts.

Ideal data would include all the data listed above plus detailed forecast information from weather and climate models for future seasonal and decadal precipitation and hence availability of water resources. Future population growth as well as possible changes in economic and industrial focus are also relevant.

Can any of the methods listed be integrated to improve prediction?
The combination of the top-down approach with the probabilistic/uncertainty models would greatly help in the construction of a methodology that would help improve prediction and quantify the key areas of uncertainty.

Based on the assessment of this group, list the key objectives of a PUB working group that would evaluate, integrate and improve predictive capability? What are the "success factors" for such a group? What other scientific communities do you feel you need to further engage with?
The key aims of a PUB working group would be to develop predictive tools for fluxes of water and its constituents as needed in particular for land-use change, climate variability and society. Factors that contribute most are: membership—we should attract a wide diversity of members, not just hydrologists, but agriculturalists, economists, social scientists; ability to problem solve from different perspectives; collaboration and cooperation between various stakeholders as well as different modelling (deterministic *vs* probabilistic) groups; devising a common test bed to examine the viability of various approaches; look for guidance from politicians, policy-makers and stakeholders to understand and help refine the process. Collaboration with human geographers would greatly help in the quantification of the socio-economic impact as well as psychological understanding.

SUMMARY—PATHWAYS FORWARD

The results of the breakout group discussions have demonstrated that data are the very cornerstone of the application of hydrological science. Key to many existing methods for prediction in ungauged basins is the availability of data in nearby or similar catchments for regionalization type approaches. Importantly, all groups identified the fundamental issue of identifying and adequately representing hydrological processes if predictions are to be improved. If predictions are to be improved, then ultimately we need to move from a reliance on data elsewhere and develop a more process-based approach for prediction.

The results also indicate that there are many areas of hydrological prediction where benefits would result from greater integration of current techniques. In the first instance, the simple intercomparison of the available techniques would provide valuable guidance as to the performance of different approaches in different environments with different availability of data. It may also be that numerous diverse technologies when viewed in isolation toward a particular hydrological objective can only achieve so much. Through the intercomparison and integration of these diverse techniques it may be that biases induced by a particular technique can be checked through alternative and independent techniques. The comparison and integration of techniques may therefore serve as a tool for progressing techniques for hydrological estimation in ungauged basins.

Another key theme underlying all the groups deliberations was the issue of the quantification of uncertainty. The robust estimation of the reliability of predictions is a necessary prerequisite for the intercomparison, evaluation and improvement of current methods and models. Ultimately, the quantification of uncertainty provides a framework for assessing the worth of hydrological techniques in application. The breakout groups have all identified key issues that could be addressed with the IAHS Prediction in Ungauged Basins (PUB) framework. It is hoped that the issues raised through this process may be addressed by collaborative working groups so that demonstrable progress in the practical application of hydrological science can be shown.

In summary, the following recommendations are made:

- Individual hydrological studies tend to be somewhat *ad hoc*, especially in the selection of specific models toward a given problem. Intercomparison projects of alternative approaches are recommended to gain deeper understanding of what models and methods work best, where and why.
- In the case of the hydrological aspects of modelling water quality and ecosystem health, greater effort must be placed in developing models that are capable of more universal applicability. This must surely be achieved through greater efforts into developing more fundamental understanding of the complex interactions between water quantity, quality and ecosystem dynamics.
- New measurement technologies are increasingly available. However, these should not be seen as replacing traditional gauging of catchments. Greater emphasis needs to be placed on evaluating how these technologies can be integrated into existing methodologies and modelling strategies to increase the power of hydrological techniques in predicting in ungauged basins.
- The intercomparison of alternative approaches as well as the evaluation of the worth of integrating new technologies requires a formal framework for fair comparison. This needs to be done within a robust and formal uncertainty estimation framework. Consequently, greater emphasis needs to be placed on the development of robust frameworks for the routine quantification of uncertainty in hydrology.