CHy STATEMENT ON THE SCIENTIFIC BASIS FOR, AND LIMITATIONS OF, RIVER DISCHARGE AND STAGE FORECASTING

This statement was prepared by participants of the thirteenth session of the WMO Commission for Hydrology to provide a perspective on the current state of hydrological forecasting. The intent is to provide an overview and summarize factors affecting forecast accuracy and lead-time that reflect the priorities of the Commission in strengthening hydrological forecasting.

Introduction

With increasing demand for water resources worldwide, the issue of uncertainty in estimating water availability, predicting flood stages and areas of inundation, and predicting low flows and hydrological drought is a growing imperative. Hydrological forecasts are used to protect lives, infrastructure, and property at all levels of national development, manage water resources, and enhance environmental benefits.

In 2002, the WMO issued a statement entitled the *Scientific Basis for, and Limitations of, Weather and Climate Forecasting*. While the uncertainties in weather and climate forecasts have a direct impact on the uncertainties in hydrological forecasts, the limitations inherent in hydrological forecast modelling also need to be acknowledged. Skill in hydrological modelling and forecasting has increased significantly since the middle of the 20th century. Yet each component of hydrological modelling and forecasting has unique uncertainties. Accordingly, continued research into the uncertainties associated with hydrological measurements (observations), modelling, and forecasting is essential to ensure a secure water supply and to protect against water-related hazards. In addition, the hydrologist must be attentive to the effectiveness of the forecast, whether in saving lives and property in conjunction with a flood forecast, or in its effectual use in river system planning and operations. The achievement of desired societal benefits is, therefore, predicated on the *effective* communication of the forecast to the user.

A hydrological forecast is a statement of expected hydrological conditions for a specific time and place, and involves estimating hydrological characteristics temporally and spatially. The present discussion focuses on river discharge and stage (water level), but very similar issues exist with other state variables that, depending upon local needs, may be included in a hydrological forecast such as snow water equivalent, soil moisture content, and evapotranspiration.

In this document, inaccuracies due to uncertainty in data, mathematical models, and forecasting procedures are stated, and their impact on the accuracy of forecasts described qualitatively. A hydrological forecast involves a sequence of activities: selecting a model or analysis method, determining model parameters, estimating initial states, and presentation of information in the appropriate manner to the target audience. The information presented in the following sections is, therefore, intended to be useful to persons preparing forecasts, particularly on those occasions when forecasters brief decision makers about uncertainties involved in the forecast.

Sources of Uncertainty

Measurement uncertainty, the natural variability of hydrological as well as meteorological inputs to water resources systems, and a lack of perfect knowledge of all the physical processes occurring in catchments are causes of uncertainty in hydrological forecasts.

i) *Measurement uncertainties*

Hydrological analysis is based on well-established principles. The central problem in hydrological analysis is the application of these principles to a natural environment that is non-homogeneous (heterogeneous), sparsely sampled, and only partially characterized. Analyses are performed to obtain spatial and temporal information about certain variables, regional generalizations, and establish relationships among the variables.

Heterogeneity refers to the amount of variation over a spatial area and it presents a challenge to parameter identification. Parameters in conceptual models are derived from observed values and refined through calibration procedures while in process models they are usually measured from observable properties. The model parameter is usually taken as a generality, such as the area-weighted average over a model domain. In a conceptual model this could be a catchment average, while a process model may require the average over a small grid cell. However, what is actually needed is the effective parameter value(s) over the model domain. The inability to accurately estimate parameters in a heterogeneous environment can lead to forecast errors.

ii) *Model Initial Conditions*
Most models used in hydrological forecasting must be initialized, so the state of the system needs to be estimated at the time the model begins its computations. A key initial condition for most hydrological models is the initial soil moisture content. Moisture content is highly heterogeneous in most catchments. The actual moisture content must be synthesized as the initial condition for the model. The heterogeneous nature of the moisture content thus becomes an uncertainty in the modelling process. Similar challenges exist with many of the other initial conditions in hydrological models.

The frequent inability to measure accurately the initial condition means that it is not known with certainty. The user is often required to estimate a value as skillfully as possible given the uncertain nature of the catchment soil moisture content. For example, field techniques can be used to measure soil moisture at a certain point; such measurements are not generally part of instrumentation networks. Satellite techniques have also been developed to estimate soil moisture content using remote sensing techniques, but are limited in very large spatial scales and are also limited to sampling the soil surface and for real-time forecasting due to the fly-over period.

The magnitude of the impact of the uncertainty in the initial condition depends on a number of factors. For example, depending on the climatic conditions, the effect of uncertainty in the initial condition might be minimal after the initial period of the simulation; while under different climatic conditions, the initial condition may have an effect on simulation results for a much longer period of the simulation. The duration of the effect of the initial condition is also heavily influenced by the selection of the modelling technology: black box, conceptual, or process. Depending on the type of model, there may be techniques that can minimize the effect of uncertainty in the initial conditions, such as through data assimilation, though such techniques are much more critical for short-term flood modelling than for longer-term water resources issues.

iii) *Meteorological input*
The primary meteorological input to hydrological models is the quantitative precipitation estimate (QPE; past observations) and the quantitative precipitation forecast (QPF; future prediction). Temperature and other meteorological variables may also be required as part of the meteorological input. Forecasts of meteorological variables are produced over a wide range of spatial and temporal scales. Uncertainty in these forecasts generally increases with lead-time and decreases with larger spatial averaging. The accuracy in meteorological modelling has been discussed extensively elsewhere (WMO Statement on the Scientific Basis for, and Limitations of, Weather and Climate Forecasting). In producing accurate hydrological forecasts, a lack of accuracy in the external meteorological conditions leads to an unpredictable decrease in the accuracy of the hydrological forecast over time and space.

iv) *Hydrological model choice and use*
Modelling of hydrological systems involves the application of mathematical and logical expressions that define quantitative relationships between flow characteristics and flow-forming factors. This general definition describes a wide range of tools that can be useful for simulating the response of hydrological systems. Statistical models make a discharge prediction on the

basis of correlation to observed properties without regard to the physical processes connecting the two properties. These may also be called black-box models and are typified by regression or neural network models. Physically based models use mathematical equations such as the conservation of mass and momentum, or energy balance, to represent a process from the first principles of physics. These models often have parameters that can be directly measured. A conceptual model uses a simplified view of the physics and consequently may be considered intermediate between statistical and physically based models, and sharing properties of both types of model.

Many considerations exist when selecting a model for a forecasting application, and are unique for each catchment. A significant concern is the amount of data available to configure and calibrate the model. Statistical models have proven useful under certain circumstances, but there is potentially a serious error when using them to extrapolate beyond the range of data used to develop the model. Conceptual and physically based models are generally considered superior in ungauged situations because their parameters can usually be estimated from regional relationships or measured directly through field observations. All models are improved through the use of calibration data and testing. Insufficient calibration data will increase the uncertainty in model results, even when using physically based models. Another concern is the spatial scale; different models are best applied at different scales. In general, physically based models are best used for small catchments, while conceptual models are best used for large catchments. Other factors could also be considered when selecting a model, including user familiarity, regional standards, and previous local studies.

Some applications require the conversion of forecast flows to stage (water level). This conversion is frequently performed using a stage-discharge relationship. Thus, the accuracy of the stage-discharge relationship can significantly impact the accuracy of the computations as well as creating additional errors when converting back to a stage forecast. Such relationships, resulting from observations of stage and discharge from field measurements, add sources of uncertainty before the final product (the stage forecast) reaches the user.

Systematic bias in the model is another potential cause of decreased hydrological forecast accuracy. For example, a small error in daily flow estimates may accrue each day of the forecast time period. As a systematic bias, the error will be additive each day. The result will be a decrease in accuracy as the time length of the forecast increases. However, depending on the nature of the error, there might be data assimilation techniques that could be used to minimize these errors. While some techniques exist for controlling errors due to systematic bias, it is still a very active area of research within hydrology and few standardized procedures have emerged for operational use.

Other causes of decreased hydrological accuracy may apply in any individual catchment, depending on the complexity of that catchment.

Stochastic Considerations/Probabilistic Forecasting

The length of the forecast period also introduces challenges in predicting the external conditions and controlling systematic bias. One way to address these sources of error is to use stochastic analysis procedures. In this framework, once a model is selected, each of the inputs to the modelling system is represented with a statistical distribution. Instead of selecting a single parameter value, each parameter is represented with a probability distribution function. Initial state conditions can be addressed in the same manner. Similarly, the external conditions in the future meteorology or downstream boundary conditions must also be estimated with inclusion of statistical uncertainty.

The use of a stochastic analysis technique introduces a new challenge. The hydrological forecast becomes probabilistic so that no single answer is given for the future flows. Consequently, the forecast must be stated in terms of probabilities. That is, a particular discharge value has a certain probability of being exceeded. As an example, the stochastic analysis may produce a forecast assessing whether a particular discharge has only a 10% chance of being exceeded. Consequently the use of stochastic analysis to aid in the communication of uncertainties throughout the modelling process changes the way uncertainty is addressed and expressed.

The challenge is for hydrologists to work with the user community to develop effective ways to communicate the uncertainty in the modelling process such that it is understandable to the users and contributes to the decision process.

Concluding Comments

The value of a hydrological forecast depends, to a large extent, upon its accuracy, its timeliness, and the purpose for which it is used. Accuracy requirements should be appropriate for the intended use. A description of the uncertainty in the forecast process should also be communicated when providing a hydrological forecast.

The importance of properly *communicating* hydrological products, including forecasts, to water resources and emergency management professionals, as well as to the broad spectrum of governmental, business and recreational users, should not be underestimated. In this respect, activities related to education and outreach should be part of the planning when forecasting activities are performed. The education should be customized according to the specific user.