7. STATE-OF-THE-ART FOR FLOOD FORECASTING MODELLING

Gábor Bálint
Water Resources Research Centre, Hungary (VITUKI)

7.1 Definition of the flood forecasting domain

There are several different types of flooding. The analysis below focuses on precipitation (both rainfall and snowmelt) induced floods regardless whether those occur in localised or distributed forms or develop as fast response or slow gradual process. Ice jam induced floods, mudflows, ravines and floods caused by the failure of hydraulic structures are not directly addressed. Inundation generated by marine conditions is left out from the scope of this domain.

Flood forecasting (FF) modelling is aimed at producing future estimates of a flood related hydrological variable based on the present state and past behaviour of the modelled catchment or river reach. As in case of any forecasting procedure, “real-time” and “future” remain the key words and purely statistical predictions of flood frequency fall out of scope of the given analysis. However it does not mean the exclusion of probabilistic forecast, ‘ensemble’ forecast, which represents transient approaches based both on assumptions and/or set of forecast of input variables on one side and on the current state of the modelled system.

Distinction is made between flood detection, indicating the likelihood of flood formation from hydro-meteorological analysis; flood forecasting, meaning quantitative estimates of hydrological variables during forthcoming flood events; and flood warning issued to the appropriate authorities, specialised users and to the public on the extent, severity and timing of the flood or giving only qualitative estimates indicating the possibility of exceedance of certain thresholds. No strict limits exist between the above activities but attention is given only to the first two stages. Any modelling tool being able to work in flood conditions can be considered. Consequently no strict distinction is made between general purpose hydrological forecasting and flood forecasting.

The whole ranges of possible catchment size and possible lead time are covered by flood forecasting: from very small (urban catchments few km² large or hilly, mountainous catchments covered by flash flood watch and warning – lead time of forecast from 5 minutes up to 3-6 hours) through small and medium size river basins up to large basins covering large regions in continental scale (over 10,000 km² – lead time of forecasting days or even months).

Flood forecasting is an operational, result-oriented activity and as such pays less attention to the modelled system than to the output of the forecasting procedure. Outputs usually can be peak river flow, peak stage or flood crest, flood flow and stage or water level hydrographs, flood volume, and inundation depths over the floodplain.

An attempt to get a prior estimate of the listed variables may require only a single data collection or modelling step, but often requires a whole chain of coupled or integrated modules. Flood forecasting modelling may need observed meteorological data, hydrometeorological analyses, meteorological forecast, rainfall-runoff modelling, channel routing, hydraulic or hydrodynamic modelling, and updating or error correction steps. Beside the above listed process-oriented elements representing analysis and forecasting models the flood forecasting system includes or is closely linked to observation and data transmission network, pre-processing module handling, data ingestion, assimilation and post-processing module(s) occupied with forecast product
preparation, dissemination and to decision support systems. Consequently, the flood forecasting system is rather the managing and integrating shell of the listed modules, which also performs the role of the interface to the linked systems. Flood forecasting modelling is rather the implementation of different modelling tools for a given application than a completely autonomous domain.

Owing to its large practical importance FF modelling is crucial in any water related decision-making. In the context of the HarmoniQuA project, it has close links with other domains. First of all, precipitation-runoff modelling, since this is the most essential tool that many forecast systems apply. Flood forecasting is also directly related to the hydrodynamic domain, and flood forecasting is one of the fields where this type of modelling is implemented. Floods play an important role in the wash out, leaching, transport of sediment and pollutants. Therefore flood forecasting is the basis for real-time modelling of pollutant transport, and also of early warning for pollution incidents during flood events. Links therefore also exist to the surface water quality domain.

7.2 Needs of QA guidelines

Generally, hydrological forecasting has a well-defined application value, and within that field even more interest is focused on flood forecasting. Simple gauge relation based flood forecasting dates back to ancient civilisations. The application of this simple approach in graphical form first appeared in the flood forecasting system of the Seine basin soon after the mid-XIX century, but in some places it is used until nowadays. The development of complex FF models is historically a more recent development. One of the first computerised rainfall runoff models that found practical application in flood forecasting dates back to the 1960s (Sittner et al., 1969). Wide spread FF modelling and application really started even later with the advent of the age of personal computers in the late ‘70s and early ‘80s.

Flood forecasting for most countries is a task carried out by state or regional environmental or water related agencies. Meteorological services always play a certain role and flood forecasting typically is their direct responsibility in cases of joined hydro-meteorological services or institutions. Local authorities, municipalities may also be involved by their role prescribed by legislation or voluntarily recognising local interests filling up the gaps or inadequacies of nation wide or regional systems.

Since the first flood forecast centres were established at the very beginning, hydrological forecasts have been issued for a flood crest at a given point on a river or stream. Each flood forecast was based on a pre-determined flood stage where damage would occur in the reach surrounding the forecast point. These forecast products were issued as single point values for an expected time when the crest might occur. The watershed areas affecting these forecast points were generally large, on the order of thousands of square kilometres. In later years, the number of hydrological forecast points increased and the hydrological (rainfall-runoff) forecast areas have become increasingly smaller, 500 to 1,000 km² in the USA and most European countries (Braatz et.al., 1997; Packman, Chapter 17). These tendencies may change general attitudes towards flood forecasting systems, instead of looking at each of those as unique entities, forecasting schemes can be treated rather as the realisation of fairly similar elements requiring uniform Quality Assurance procedures to guarantee their proper functioning.

As technologies have been advancing and the demands for more accurate and timely flood forecasting has been increasing, the public, private and other state agency sectors are insisting upon the expanded use of hydrological/meteorological analyses and products for the flood management of water courses. To meet this need, services responsible for hydrological forecasting are capitalising upon modernisation in remote sensing, data automation and advanced hydrological hydrometeorological modelling. Extreme flood events from 1993 until recently give impetus to apply more and more FF modelling tools in real life conditions (Casale et al., 1996). Similar tendencies are
reported from the USA, where the National Weather Service Advanced Hydrologic Prediction System (AHPS) intends to meet these objectives (Green et al., 1994, Braatz et al., 1997).

The diversity and complexity of flood forecasting technologies have on the other hand made it difficult to find overall satisfactory solutions to the implementation of different FF models in operational practice. The gap between the community of model developers and the user community in many European countries in the field of rainfall runoff modelling reported by Perrin et al. (Chapter 5) is also valid for all flood forecasting applications.

The above factors explain the almost non-existence of Quality Assurance guidelines in the field of FF models. However given the wide range of existing hydrological techniques, and operational tools to link and apply them, makes it feasible to select different FF models. In this respect, coupling them into integrated, complex systems is also an issue to be addressed together with the creation of interfaces to decision support systems. All these steps are to be supported by QA guidelines to maintain good practice to meet users needs towards flood forecasting or at least urging forecasters to clearly state accuracy and other quality criteria their systems are able to pass.

Guidelines are needed to elaborate and implement procedures to validate model outputs to prevent false warnings. However natural inherent uncertainty of any flood forecast has to be recognised and evaluation of the flood warning system is part of the planning of a decision support system (Haimes et al. 1996).

7.3 Discussion in scientific literature

Flood forecasting schemes may have the most diverse structure depending on catchment size, response or concentration time and the availability of real-time input data. The core of the forecasting system is often shifted from modelling tools to the observation and data collection systems. In such cases the remotely sensed, telemetred or otherwise observed and transmitted precipitation or upstream river flow value with or without very simple transformation may generate an alarm or early warning.

Under similar conditions meteorological forecast, namely quantitative precipitation forecast (QPF), occupies the same role and serves as basis for flood warning. More complex nowcasting or very short time weather forecasting schemes may have similar applications (e.g. Stallings, and Wenzel, 1995; HYDROMET 2001).

As mentioned above flood forecasting modelling includes process models including updating or error correction modules and a number of steps representing the workflow of the preparation of hydrological forecasting. The quality and timeliness of flood forecasting is often decided by the efficiency of observation and data transmission network and the possibilities of data assimilation. Also the presentation of forecast results, the quality of forecast product and its timely transmission, dissemination decide the overall value of the flood forecasting system together with effective use of the skills of professional employees occupied with the job. The weight of flood forecasting modelling should be judged in this context.

The proper selection of modelling tools for flood forecasting purposes is, beside the type of flood, decided by the degree and development of the observation network and telecommunication and data processing facilities; the length and quality of data records; and not least the availability of qualified personnel to run and maintain the models on a routine bases (WMO 1994; Boyle et al., 2001).

Data, and the quality of the data, are critical to any hydrological forecasting procedure. Operational use of models is preceded and accompanied by developing, implementing, and maintaining hydrological models and systems. The forecast models
used are developed and calibrated for specific rivers and watercourses based on historical events. They are conditioned and constrained operationally using current observations and, in the case of operational ensemble forecasts, with historical data as well. Inaccurate, inconsistent, incomplete or insufficient data can cause significant problems in the forecast process.

There are several high standard approaches for data analysis of both operational and historical data, as well as for archiving and retrieving historical data. The data analysis approaches are targeted at helping users to reduce uncertainties associated with the use of data, and they include: automated double-mass analysis for inconsistency checks, wavelet transform for nonstationary time-series analysis, cluster analysis for the study of regionalisation, and robust outlier detection for spatial inconsistency checks (Haimes, 1979). These approaches are being integrated into our operational development and forecast processes.

Traditional sources of historical data have to be used. A recent tendency is to capture and archive operational data that have been lost in the past. Tools that provide new ways to view and access historical data and inventories of historical data may support the forecasting procedure. World Wide Web (WWW) facilities (Pan et al., 1998; Vähviläinen, 2002) have been developed as simplified interfaces to traditional data access utilities and a new interactive "browser" has been developed that allows users to query and browse inventories of the historical data as well as view and retrieve the data itself. The ability to query and view the data inventories greatly improves the user's effectiveness in selecting data and the efficient use of forecasting models.

**Quality control (QC) of input data**

The purpose of quality control is to prevent "bad" data from being used in various hydrological processes (calibration, modelling, forecasting, etc.). For quality control of hydrometeorological data one performs a variety of checks, such as range checking, spatial inconsistency checking, temporal inconsistency checking, internal consistency checking, and multi-sensor inconsistency checking (Krajewski, 1986,1987). Real-time quality control systems are to be designed to support forecasting operations. The features of these systems include real-time access to operational data as it is captured from the observation network, efficient and robust outlier detection, reanalysis, integration of a variety of information for decision making, and multiple temporal scale data handling (Bissell and Zimmerman, 1992). Real-time access and processing are important because they support the forecaster's need to make decisions in short time frames (one minute or less) as the data are arriving.

The proper strategy and methods to be used for spatial inconsistency checks is the key issue. To satisfy the operational requirements, simple and robust algorithms are needed to perform efficient and effective detection of suspect data, and then these suspect data have to be reanalysed. Finally, in a proper system users can perform multi-sensor data comparison, and if possible, validate these outliers. Regionalisation, elevation zones etc. are needed for the implementation of spatial inconsistency checks that support efficient real-time quality control (Fovell et al., 1993). Cluster analysis tools can be applied for regionalisation using different temporal scale data as input. The steps of robust outlier detection are: Determine the median and mean absolute deviation (MAD) of N stations in each climate region (step 1); Determine indices of different percentile for each station (step 2). Madsen (1992) has implemented a similar approach for daily precipitation quality control. Similar approaches including reanalysis and estimation methods are also suggested (Miller et al., 1992).

**Calibration of FF models**

The general statements (Refsgaard and Henriksen, Chapter 3) regarding the assessment, selection, calibration and running models are valid also for FF use. Fread et
al. (1995) suggest to combine procedures needed to process historical hydrometeorological data and to estimate model parameters for a specific basin. The models simulate snow accumulation and ablation, calculate runoff and the temporal distribution of its delay from the basin to the basin outlet, and route streamflow through reservoirs and channel systems. There are many modular systems used for hydrological forecasting purposes that allow the hydrologist to select from a variety of models and to configure them in a manner that is descriptive of the basin. As part of the calibration procedure, for a particular basin, the simulated streamflow is statistically and visually compared to the observed streamflow to determine the necessary model parameter adjustments. The ideal model parameters are those with which the model simulated streamflow most closely matches the observed streamflow.

**Criteria**

Flood forecasting is a well defined area of model application of (e.g. rainfall runoff), but the choice of criteria is still largely user dependent. Different criteria listed by Perrin et al., (Chapter 5) for rainfall runoff modelling, and those recommended by WMO (1992) together with other tools for the simulated real-time intercomparison of forecasting models may serve:

- different forms of model error (cumulative, quadratic, absolute);
- different target variables (streamflow or transformed values with root square or logarithmic transformation);
- absolute or relative forms, for example the classical root mean square error or the Nash and Sutcliffe (1970) criterion $R^2$;
- multiple step ahead forecast statistics, such as the root mean square error of the step ahead forecasts, applied for flood event wise or according to different lead times of forecast;
- peak statistics: maximum forecasted peak, time of occurrence of the maximum forecasted peak, differences in times and occurrence of the maximum forecasted and actual peaks, forecast of the time when the flow will cross the threshold, differences in forecasted and actual times of crossing the threshold;
- additional to the Nash – Sutcliffe criterion this one is compared with the criterion calculated for the ‘naive’ forecast model given by “one step ahead forecast = value now”. This description is valid for any existing lead time of the forecast. The given criterion is sometimes referred as efficiency or persistence criterion (Corradini 1986; Kitanidis and Bras, 1980);
- the statistics are calculated for model residual errors, i.e. errors without updating to enable the separate evaluation of the performance of the process model and that of the statistical updating.

Many prescribed procedures suggest to use linear or logarithmic graphs of calculated and observed flood variables plotted against time (Glaudemans et al., 2002).

**Real-time updating**

Once the models have been calibrated for a basin, they can be used operationally with real-time hydrometeorological data to forecast river flows and stages. Real-time hydrological forecasting models consist in one or more “process models” or “simulation models” which can be supplemented by a procedure of forecast updating. The process model utilizes measured or estimated input data. The process model consists of a set of equations that contain state variables and parameters. The process model output is observable and is generally discharge or stage. Updating procedures consider the prediction errors (differences between computed and measured discharges/stages) in order to modify the model’s forecast and improve the model’s performance during operational use. The difference between simulated and measured discharges up to the time of forecast can be accounted for by errors induced by the model input data, imperfect model structure, limitations in model calibration in terms of short data series,
the time dependent change of catchment characteristics, and errors in the discharge hydrographs at the gauging station.

The real-time updating procedures differ from the techniques of periodical, historical recalibration of models. The periodical recalibration of the model parameters may be necessary as the characteristics of the catchment slowly change in time due to non stationary influences.

Forecast updating procedures consist of approaches, which update one or more of the following: input variables, parameters or output variables. They generally consist of either completely automated methods or manually interactive ones (e.g. trial and error). One of the most widely studied updating technique, that generated considerable attention in the last decades is that of the Kalman filter (Refsgaard et al. 1983, Szöllősi-Nagy 1987, Refsgaard 1997). Despite the initial high expectations raised among hydrologists concerning Kalman filter as an updating tool for flood forecasting reservations concerning its superiority have emerged. Xiong and O’Connor (2002) advocate the use of simpler approaches such as autoregressive (AR) schemes, and they insist on the reasonable and proportional use of statistical updating. The function of these procedures is to improve the performance of process models rather than hiding their inadequacies.

One of the WMO (1992) intercomparison studies concludes that, it is valuable for models to adopt automatic updating algorithms. This reduces the need for human intervention and subsequently increases the operational nature of the forecast model. This also increases the transferability of the procedures.

**Ensemble forecast**

Since the 1980s the idea to enable a hydrologist to make extended probabilistic forecasts of streamflow and other hydrological variables (Day 1985) has been developed. The assumption usually made is that historical meteorological data are representative of possible future conditions and these data are used as input data to hydrological models along with the current model states obtained from the forecast component. A separate streamflow time series is simulated for each year of historical data using the current conditions as the starting point for each simulation. The streamflow time series can be analysed for peak flows, minimum flows, flow volumes, etc., for any period in the future. A statistical analysis is performed using the values obtained from each year's simulation to produce a probabilistic forecast for the streamflow variable. This analysis can be repeated for different forecast periods and additional streamflow variables of interest. Short-term quantitative forecasts of precipitation and temperature can be blended with historical data to produce a more realistic transition in meteorological conditions.

A number of attempts exist to make use of medium range weather forecasting (ECMWF, DWD etc) for hydrological, especially flood forecasting purposes. 41 different perturbed realisations of future weather conditions (Todini 2000; EFFS) are routed through forecasting models.

**Interactive forecasting procedures**

Similarly to ensemble forecast testing different scenarios, changing initial and boundary conditions may serve in sake of holistic search of better forecast result. The forecaster can interactively make changes to the parameters, data, or current conditions used for hydrological simulation and quickly see the results of such changes. These changes can be categorized into those affecting time series and those affecting a specific hydrological model. A graphical user interface may support to perform the required changes.
Product generation

The value of flood forecasting can be enhanced by proper presentation of forecast results. As an example US National Weather Service River Forecasting System prepares the following products: River Statement (RVS), Flood Statement (FLS), and Flood Warning (FLW) (Office of Hydrology, 1996). When initiated, it compares observed and forecast river stage data with threshold stages, and tracks the history of recently issued products, and then determines a recommended product and the forecast points the product should include. The forecaster can accept these recommendations and generate the product using predefined templates that control the product format and content. Alternatively, the forecaster can customize the product extensively - e.g., a different product can be created with different forecast points included. Also, the forecaster can select from the predefined templates for each section of the product, and thereby control the precise wording and appearance of the product. A default set of predefined phrase templates is provided, and each office is able to modify or add to these templates to meet their local needs. In addition to providing the functions necessary to customize, generate, and edit a product, RiverPro provides textual displays of information to support the forecaster in the decision-making process for product issuance. The forecaster can view tabular summaries of the stage data and reference data for stations, and can review information about previously issued products, including the product itself. After the product has been tailored as necessary, and reviewed, the product can be issued to the appropriate data dissemination circuits.

Uncertainties and risk communication

Hydrological forecasting systems should provide information regarding the relative uncertainty of hydrological variables (i.e., river stage and discharge). The increased lead-time of forecast may greatly improve the capability of water facility and emergency managers to take timely and effective actions that significantly mitigate the impact of major floods, however the increased lead-time is usually associated with increased uncertainty.

Interface to Decision support systems (DSS)

FF remains one of the most important field of hydrological model application and potential difficulties identified by Cunge and Samuels (1996) should be considered in case of forecasting usage, namely:

- lack of appreciation of the range of uncertainty in the forecast results;
- the temptation to believe every number that a computer produces;
- illusory visualisation of model results;
- possibility of using models outside their range of definition;
- unsatisfactory calibration of the model.

Trans-boundary rivers

Distribution of forecasting tasks may need special organisational and managerial efforts even within national borders regulating inter agency collaboration, but trans-boundary rivers certainly need special approaches. Several major rivers cross or form national or provincial borders. Thus flood forecasting in these river basins has the additional complexity of requiring international co-ordination and co-operation. The issues in forecasting trans-boundary rivers are not restricted to the major rivers as far as administrative borders do not coincide with limits of drainage basins. The RIBAMOD project identified some trans-national issues on flood management, among those many are directly related to FF issues (Samuels, 1999):

- hydro-meteorological networks for flood forecasting;
- trans-boundary compilation of radar images for flood forecasting;
- exchange of flood forecast information between states.
Combination of elements with evident heterogeneity is the main issue flood forecasting faces on trans-boundary rivers (Balint et al, 1990). Quality assurance should tackle problems arising from the use of input data having different data formats, accuracy, observation time and frequency. Inclusion of foreign forecast results is often needed although they bring additional uncertainty into the system. European standardisation of data exchange and forecasting approaches could deliver real benefit in improving flood forecasting.

### 7.4 Existing guidelines

As underlined previously, flood forecasting for most of the countries is a task carried out by state or regional environmental or water related agencies or meteorological/hydrometeorological services. There is today a lack of guidelines in the flood forecasting domain partly linked to this institutional set up.

In the UK case study (Packman, Chapter 17) it is reported that flood–forecasting modelling in the UK is wholly an EA/SEPA function, separate modelling strategies have developed in each region and even for different catchments within each region. Basic rainfall-runoff models, real-time updating, data gathering procedures, and operating systems all vary considerably. Models range from simple graphical relationships between flow gauges, through transfer function models, to complex deterministic models that include hydrodynamic river routing. Following recent flood events, the EA is developing a more standardised, modular approach, recognising a role for models of differing complexity, but including them as generic modules within a standard operating shell. The approach is being implemented through large contracts to upgrade flood forecasting hardware and software – initially in three EA regions. The Tender documents comprise four stages:

**Stage 1** *Data abstraction* - appropriate checking of hydrometric, catchment, and channel data  
*Schematisation* – appropriate division into sub-catchments, reaches, and structures.  
*Outputs* – preliminary model, programme of work, required accuracy/reliability

**Stage 2** *Review* – test significance of model components, sufficiency of data, consultation

**Stage 3** *Calibration* – continuous data & events, automatic & manual method, physical limits  
*Verification* – to required accuracy. Recalibration & re-verification  
*Outputs* – verified model, detailed verification report and data sets.

**Stage 4** *Test real-time operation and updating.*

Overall, the use of standardised section headings emphasises the modularity of the approach, but does not give a clear structure for presenting modelling issues and guidelines.

In the USA the National Weather Service's (NWS) river forecasting centres (RFC) work under uniform requirements. The NWS Office of Hydrology is currently developing a subset of these applications, referred to as the WFO Hydrological Forecast System (WHFS), that provides the WFO forecaster with the capability to issue warnings of flood and flash flood events in real-time.

More guideline types of documents are available for flood warning purposes, however in this domain flood forecasting occupies a minor place only. (US ACE 1988, FCD Maricopa County 1997). The “Flood Control District of Maricopa County:
Guidelines for developing a comprehensive flood warning program” mostly deals with the dissemination of warnings and emergency response measures. Forecast procedures are hidden within the task of “flood threat recognition”. The main concern is the setting of the system of observations: observers, automated gauges, radar and satellite data, meteorological support. Hydrological models are dealt within the category of decision aids.

Co-ordination of national and provincial hydrological forecasting agencies exist in the Rhine and Danube basins (IKSR-CIPR 1995, ICPDR).

7.5 Conclusions and recommendations with respect to the further HarmoniQuA work

At this stage of the work, it was not possible to identify general good practice guidelines about flood forecasting modelling. The previous analysis shows however that scientific studies and several works related to water issues made by hydrologists could serve as a basis to build practical guidelines in the context of the HarmoniQuA project.

In such guidelines, one could distinguish several quality assurance procedures concerning model selection, model evaluation (with a selection of adequate criteria), model parameter determination and operational implementation.

It can also be mentioned that the review of previous and ongoing comparative assessments of models WMO (1992), AFORISM (Todini, 1996), and EFFS could be of help to define standard procedures for model evaluation.

Concerning criteria, links should be made with the BMW project that aims at proposing criteria for model evaluation.

7.6 Acknowledgement

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