Intl. J. River Basin Management Vol. 6, No. 1 (2008), pp. 41–50

Flood warning – on the value of local information

GÜNTER BLÖSCHL, *Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology, Karlsplatz 13/222, A-1040 Vienna, Austria. Tel.: +43 1 58801 22315; fax: +43 1 58801 22399; e-mail: bloeschl@hydro.tuwien.ac.at*

ABSTRACT
Based on the experience with the flood forecasting system of the Kamp catchment in Austria the role of local information in warning is discussed. Local hydrological process information from field surveys can be used to build more reliable models than is possible with regional data bases. River basin management processes are difficult to quantify in a general way, so familiarity with the local situation and interaction with local stakeholders will help to more accurately quantify the effects of river basin management on the flood situation. Local real time data, such as runoff data and water levels of reservoirs, can be used to improve forecasts by updating the routing and rainfall runoff models. Communication and the credibility of warnings may be strongly enhanced by local human forecasters that are familiar both with the model and the flood situation in the area of interest. Global information can assist at the local scale to extend lead times by precipitation forecasts and to assess forecast uncertainty by ensemble forecasts but much additional information at the local scale is needed to maximise the credibility of the forecasts.

Keywords: Hydrological processes; distributed model; reservoir simulation; stakeholders; Kalman filtering; communication; credibility of warnings.

1 Recent trends in flood forecasting and warning – a matter of perspective

The major flood events in the past years have re-focussed the attention of river basin management on floods in many countries of the world. Management authorities are now shifting from past policies of flood control to an integrated flood management approach that entails integration with broader water resource management objectives (Hall *et al.*, 2003). Strategies have shifted from a focus on structural responses to introducing more non-structural responses. One of the important non-structural measures are flood warnings. Typically, warnings are used in a dual mode (Du Plessis, 2002). Over short time scales quantitative forecasts of flooding levels are made to assist in operational flood management activities of civil protection agencies and other players. Over longer time scales, early warning may enhance the preparedness immediately before a flood.

Powerful computer technology, availability of satellite data, fast data transmission networks and global weather forecasts have expanded the array of forecasting technologies. At the same time, there is increased pressure from politicians and the public on local flood forecasters to produce reliable and timely forecasts, partly because of expensive assets on flood prone land.

The recent developments in flood forecasting and warning can be viewed from at least three perspectives. The first is the global modelling perspective where the goal is an ambitious one – to represent the coupled physical, chemical and biological processes of the atmosphere-land-ocean system in a unified computer system. Models known as Operational Earth System Models (e.g. Hill *et al.*, 2004) attempt to represent the relevant processes as completely as possible and are hence extremely complex. Assimilating satellite remote sensing information is an important part of the modelling strategy. There is a trend of convergence of hydrological and atmospheric models in this community where hydrological models are increasingly used as land-atmosphere schemes in atmospheric models and conversely, land-atmosphere schemes are increasingly used as stand-alone hydrological models. While operational Earth System Models, potentially, allow a global assessment of flooding it is important to note that this line of research is set in a positivistic world view which assumes that, if enough data are analysed in the right way, one can understand and resolve even the most complex problems.

The hydrologic modelling perspective of the 1970s and 1980s has been similar in the effort of fully representing the hydrological cycle by numerical models. Although there is still some controversy about the issue, there is increasing consensus that there are limits to the degree by which one can represent the hydrological cycle. The discussion has been anticipated by Freeze and Harlan (1969), triggered by Beven (1989) and echoed by numerous others in the field. It has now become clear that any increase in the complexity of hydrological models will not necessarily translate into improved modelling accuracy because of a lack of information on subsurface characteristics among other reasons (Grayson and Blöschl, 2000). Catchments do not change much in time but a lot in space, so calibrating models to runoff data almost always helps remove bias. Typically, uncertainties are large relative to

Received on July 20, 2007. Accepted on September 20, 2007.

what is still useful to clients, so model calibration is an essential step in the development of any flood forecasting system. From this perspective, what matters is how well can flood processes be represented *in the catchment of interest*.

The local forecaster perspective tends to differ from the previous ones. The overriding concern of local flood forecasters, usually, is credibility – credibility to the public and credibility to the representatives of other agencies involved in flood management (DESA, 2004). Credibility entails timeliness and accuracy of the forecasts as well as consistency between forecasts issued at different times. Typically, model type is much less important to forecasters than the fact that the model has been well calibrated to the particular catchments as well as familiarity with the model. The international scientific literature is not the typical forum of discussing forecaster perspectives but national conferences and meetings are (e.g. Gutknecht, 2006). Forecasters are faced with three challenges and opportunities today: (i) Forecasts are often needed for smaller catchments where runoff routing times are shorter than the forecast lead times; (ii) Longer forecast lead times are needed, including preparation of early warning on potential flooding; (iii) Use of new technology including distributed hydrological models, weather radar and satellite data. Points (i and ii) involve large uncertainty and this uncertainty needs to be assessed and communicated to the public.

Against the backdrop of these developments it is the aim of this paper to discuss operational flood forecasting and warning in the context of global technologies, local scale requirements and local scale opportunities. Specifically, it will be emphasised that local information has a very important role to play in the forecasting process. The discussion will be illustrated by the example of the flood forecasting system of the Kamp catchment in Austria that has been in operational use since early 2006. The paper is organised into four sections: Local hydrological processes, local river basin management, local real time data, and local communication and credibility of warnings.

2 Local hydrological processes

Spatially distributed hydrological models are frequently used today for producing forecasts as they are able to represent the spatial variability of both rainfall and runoff generation processes. However, these types of models need a large number of model parameters for each grid element and if the parameters are not suitably specified and default values are used instead, e.g. from soil, terrain and land use maps, the simulations can be much poorer than those that can be obtained by traditional lumped models. The model comparison of Reed *et al.* (2004) concluded that in most of the cases examined, lumped models showed better overall performance than distributed models. The crux is that, in most climates, runoff response is controlled by the subsurface characteristics such as the saturated conductivity and soil water release characteristics. In regional studies they are typically inferred from relationships to soil texture based on pedotransfer functions. While soil texture data are now widely available, it is not uncommon for soil properties to vary as much between soil types as within a soil type (e.g. Warrick *et al.*, 1990). This makes Wösten *et al.* (2001) conclude that pedotransfer functions are sufficiently accurate for interpolation purposes between soil hydraulic measurements in the catchment of interest whereas they are not recommended to be used in catchments where no measurements are available. This conclusion invalidates the use of distributed models driven by regional data bases for flood forecasting. To obtain reliable models (a) calibration against local runoff data is needed and (b) experience and understanding of the local hydrological situation needs to be incorporated in the model. Reed *et al.* (2004) noted in their model comparison that calibration consistently improved the performance of both lumped and distributed models. Understanding of the local hydrological situation can be accommodated in various ways and this will be illustrated by the Kamp example.

The Kamp catchment is located in northern Austria. The layout and available data are shown in Fig. 1. The catchment area is

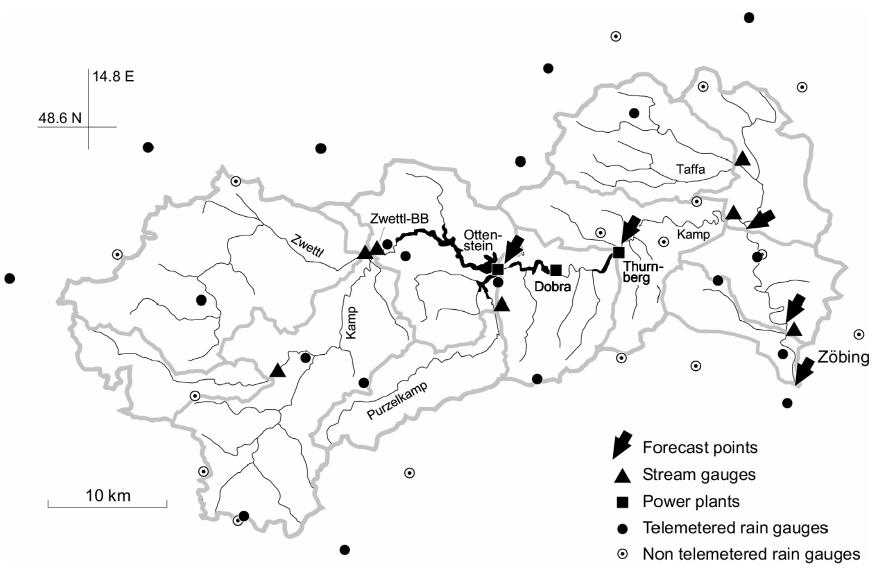

Figure 1 Kamp catchment (1550 km^2) with data network, hydropower scheme (squares) and forecast points shown. Thick grey lines and thin black lines represent the catchment boundaries and the river network, respectively.

1550 km^2, elevations range from 300 to 1000 m a.s.l. and the geology of the catchment is mainly granite and gneiss. Weathering has produced sandy soils with a large storage capacity throughout the catchment. The catchment response times at the catchment outlet are on the order of 6 hours. In calibrating the distributed model used at the Kamp (Blöschl *et al.*, 2007) a wide spectrum of data has been used, including quantitative and soft data. Quantitative data included runoff at the outlet and a number of internal points. The runoff data were stratified by time scale and hydrological situations. Based on a seasonal analysis, the magnitude of the evaporation parameters, the percolation parameter and the parameters of the slow groundwater components were inferred. In the context of the flood forecasts, the seasonal dynamics are important to estimate well the initial conditions of the forecasts, in particular the catchment soil moisture state as well as the snow distribution. Based on an analysis of the event hydrograph shapes, the characteristics of fast catchment response as well as the associated model parameters were inferred. The event analysis was stratified by event magnitude and event types. Synoptic (large scale) and convective (small scale) events, snow melt events, and rain-on-snow events have characteristic runoff dynamics. These types were examined separately to enhance the model's ability to represent a spectrum of hydrological situations which will improve the forecasts of future situations that differ from those in the calibration data set. As the catchment includes both porous and hardrock aquifers, the time scales of the subsurface dynamics within the catchment vary by orders of magnitude. These were analysed by groundwater data and used in the model. Other quantitative data were inundation levels to examine the routing model, as well as snow data to examine the snow component of the model. Of equal importance as the quantitative data were qualitative or soft data. These included an assessment of different parts of the catchment through field surveys based on overland flow marks, connectivity to the stream and soil characteristics, and a more general assessment of the hydrological functioning of various landscape units. Examples of the type of information that was considered relevant are given in Fig. 2. The left photo in Fig. 2 shows permeable soils that can cause initial losses of about 60 mm. The right photo in Fig. 2 shows saturation areas that lead to immediate response of runoff to rainfall in this part of the Kamp catchment. This type of information was used to classify the catchment into hydrological types. Discussions with locals on overland flow and flow pathways during the past floods as well as on water logged areas were another important source of information. The various pieces of information were then combined in an iterative way to construct a coherent picture of the functioning of the catchment system.

The plausibility of the model was tested, among other things, by assessing the simulated spatial pattern of overland flow against the verbal information obtained from locals. Figure 3 shows maps of simulated overland flow at the beginning of a large event (the 2002 flood) and during the same event. At the beginning of the event it were mainly the sealed areas and the near stream areas that contributed to the flooding in the north west of the catchment while there was almost no overland flow in the remainder of the catchment. During the flood event the spatial pattern changed. 18 hours later, the precipitation intensity was somewhat lower and hence overland flow on the sealed areas was lower. Additional areas contributed to overland flow, particularly the gullies and the rolling hills of the west of the catchment. The shift in the runoff patterns during the event is consistent with the understanding of runoff processes obtained during the recognisance trips. This type of model development on the basis of combining various pieces of evidence, including local information, is time consuming. The effort does not consist of performing a large number of simulations and minimising an objective function but it consists of detailed hydrological interpretations of the catchment system involving hydrological reasoning. This effort was considered essential in order to identify the model structure and the model parameters in a plausible way to arrive at a model that can be deemed to represent different hydrological situations well, including those that have not been observed in the past.

3 Local river basin management

River routing effects, typically, can be represented in a more straightforward manner than hydrological models if stream

Figure 2 Permeable soils and saturation areas in the Kamp catchment.

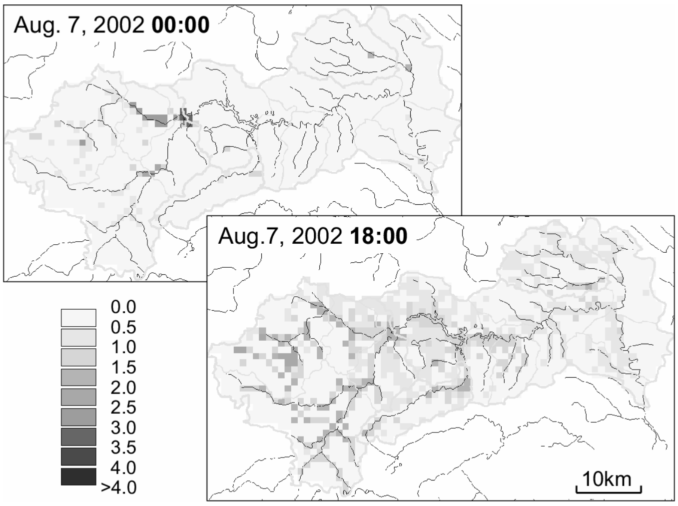

Figure 3 Simulated patterns of overland flow (mm/15 min) at the beginning (left) and halfway into a major flood event (right) used in a plausibility check against verbal information from locals.

Figure 4 Channel of the Kamp downstream of the Dobra reservoir. Left: Dry channel during below average inflow into the reservoir. Right: Flow during a flood when the spillway of the dam was in operation.

profile data are available, although the roughness of routing models needs to be calibrated against river stage data. River works are harder to integrate in a forecasting model because their hydraulic characteristics are not necessarily well defined during floods. For example, levee failure is essentially impossible to predict so, typically, warning systems assume there is no failure and the forecaster manually overrides the automatic forecast in case of failure. Other examples are the effect of bridges on the flood flow that may clog with large wooden debris. Yet another example is reservoir operation that can have a major effect on floods, particularly in small to medium sized catchments when the flood volume is on the order of the storage volume. The magnitude and shape of the flood flow is then controlled by the release operations of the reservoir. The physical characteristics of a reservoir are well defined so one would expect to be able to represent the effect of the reservoir operation on the hydrograph well. In practice, however, operators tend to have significant flexibility within the operation rules to optimise for a particular purpose or a number of purposes that may not be well defined. It is therefore inherently difficult to portray reservoir operation well. Reservoir optimisation models exist (e.g. Georgakakos, 1993; Bowles *et al.*, 2004) but optimum operation, often, is not well defined as reservoir operators usually take into account a range of objectives including hydro-economics, safety, tourism and fisheries. A positivistic modelling perspective is hence hardly realistic and identifiability issues similar to those with hydrological catchment models may arise. Understanding of the local river basin management situation can be accommodated in various ways in a warning model and this will, again, be illustrated by the Kamp example.

The western part of the Kamp catchment drains into the Kamp hydropower scheme that consists of the Ottenstein, Dobra und Thurnberg reservoirs. The active storage capacity of the scheme is 72 million m^3 vis a vis an average annual inflow into the reservoir of about 170 million m^3. The event outflow hydrographs from the scheme can hence significantly differ from the inflow hydrographs. Figure 4 shows the channel of the Kamp downstream of the Dobra reservoir during below average inflow into the reservoir when no water was released into the channel, and during a flood when the spillway of the dam was in operation. Accurate flood warning downstream of the scheme hence hinges on an accurate assessment of the future hydropower operation including operation of the spillway gates. Future operation is decided by the operator on a case by case basis. The main factors that control future release are the technical characteristics of the reservoir system, legal constraints such as pre-releases, maximum operating levels and maximum release discharges under certain inflow conditions, anticipated inflow into the reservoirs, and other pieces of information that cannot be easily quantified, such as 15 min fluctuations of the market price of electricity, tourist activities and, in case of flooding, political considerations. The operation of the scheme is hence much more complex than what could be represented by an optimisation scheme that minimises, say, a cost function. Because of this, the philosophy of developing the reservoir simulation routine was to mimic the decisions of the operator of the scheme in terms of released discharges for different situations rather than to minimise a cost function. The simulation routine is based on hierarchical rules that have been formulated as a function of the state variables of the three reservoirs as well as the predicted inflow. These rules encode the knowledge of the operators in past flood situations and his/her understanding of future situations. For some of the rules, the operation is optimised to represent a trade-off between pre-releases to provide additional flood control space and the potential loss of stored water for hydro power generation if the vacated space is not refilled.

The rules were developed in an iterative procedure through the efforts of a multi-agency team in which the hydropower operators were involved (Fig. 5). In a first step, preliminary rules were selected based on the past operation of the reservoirs during floods. For these rules, test simulations were performed using forecasted inflows into the reservoirs and their uncertainties. In a second step, the results of these test simulations were discussed with the hydropower operator to examine whether the staff

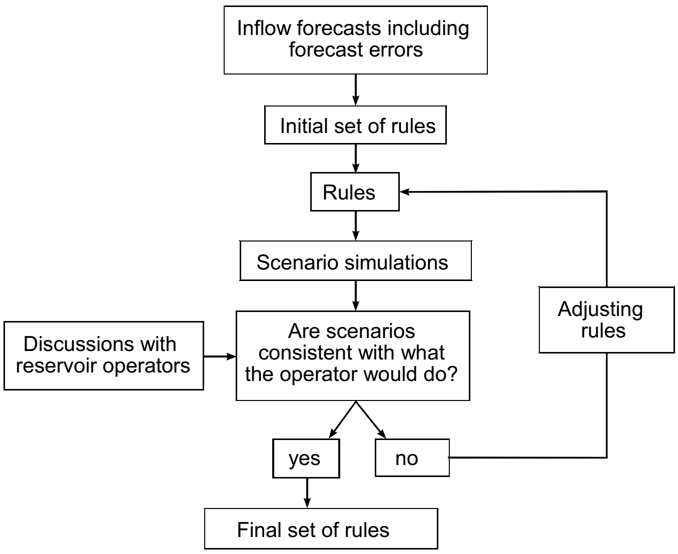

Figure 5 Iterative procedure of developing the reservoir simulation model based on the judgement of the reservoir operators.

would have operated the reservoirs in the same way provided the given inflow forecasts were available. The hydropower operator brought in their experience with the local situation including tourism, local political issues during floods as well as economic issues. In a third step, the rules were adapted to the assessment of the operators. These steps were repeated until the simulations matched the assessment of the operators. In other words, the simulation model was calibrated to the past operation of the reservoirs and the assessment of the operators of hypothetical scenarios. An additional advantage of this procedure is to allow for training of the operator staff for a range of meteorological and hydrological scenarios including extreme floods. Also, the iterative procedure has contributed to building confidence of the operator staff in the simulation routine. As an example, Fig. 6 shows the simulations of an observed flood event at the Ottenstein reservoir. The start of the pre-release is simulated earlier than the actual decision of the operator during the past flood. However, given

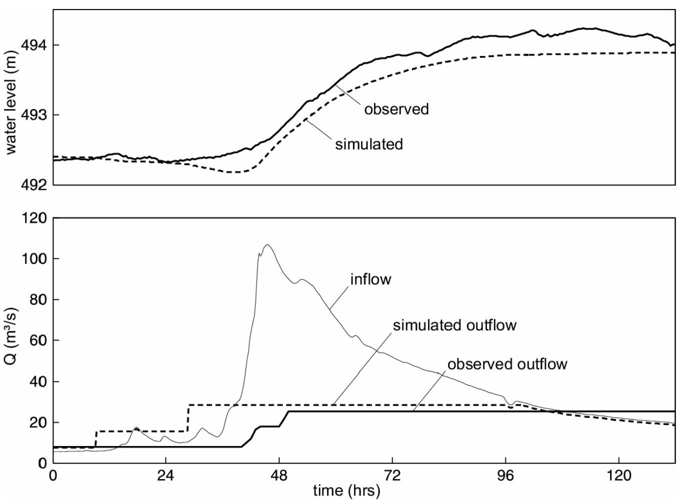

Figure 6 Example of pre-releases of the Ottenstein reservoir simulated by the rule-based model that reflects the judgement of a group of operators.

the information on inflow forecasts (including their uncertainty) the group of operators decided that, in the future, this would be the way they operated the gates of the Ottenstein reservoir. It is important that the technical characteristics of the scheme are all honoured by the routine, it is the action of the operator in response to a multitude of factors that is represented by the rules.

4 Local real time data

There is a fundamental difference between the simulation mode of a model and the real time mode. The real time mode has advantages and disadvantages. On the downside, data issues may become important. While simulations are usually performed with quality checked data, the real time mode of a model has to cope with data errors and data transmission failure. Although redundancy in data collection and transmission systems will reduce problems with data and are usually an important consideration in setting up operational warning systems, data issues are still much more important than in the simulation mode. For example, blockage of the stream gauge by ice or large wooden debris can be an issue. These problems can be detected by local staff. On the upside, simulations usually attempt to represent the processes in the most consistent way while real time routines may sacrifice some of the consistency for increased accuracy by exploiting information as it becomes available. In the case of a flood forecasting system it is the current system state, such as water levels, snow cover and soil moisture that contains rich information on the immediate future. As they become available, the real time data can be used as an input, e.g. in runoff routing models and in reservoir simulation routines. In addition, some of the real time information can be exploited by updating procedures. Updating procedures are widely used in real time forecasting as they can significantly increase the accuracy of the system. The most obvious data to be used in the updating are runoff data but other possibilities exist. Rainfall runoff models use soil moisture as a state variable, so one possibility would be to update the soil moisture state of the model by assimilating satellite data. Parajka *et al.* (2005) examined the potential of assimilating soil moisture retrieved from ERS-scatterometer satellite data into hydrological models to improve runoff simulations. They compared the soil moisture dynamics simulated by a rainfall runoff model in 320 Austrian catchments with the soil moisture dynamics inferred from the satellite data. Assimilating the satellite data into the rainfall runoff model during the calibration phase improved the relationship between the two soil moisture estimates. For the case of ungauged catchments, where the rainfall runoff model was not calibrated against runoff data, one would hope to obtain an increase in runoff simulation performance by assimilating the satellite data but their comparison indicated that this was not the case. This means that, in well instrumented regions of the world such as Europe, no advantage can be gained from using soil moisture retrieved from satellite data, as the runoff data, even in neighbouring catchments, contain more relevant information. Runoff is hence the main data source to be used in real time updating of flood forecasting models in such regions.

Table 1 Typical lead times for the 1550 km^2 Kamp catchment and the accuracy of the model components.

	Lead time	Accuracy
Runoff routing	2 h	High
Rainfall runoff model	6 h	Moderate
Precipitation forecasts	48 h	Low

In the Kamp forecasting system, a combined approach was hence adopted that exploits information as it becomes available (Table 1). The most accurate forecasts can be obtained by flood routing using real time runoff data as an input. The lead time so obtained is on the order of the travel time in the stream. The Kamp catchment is a rather small catchment, so the travel times are a few hours while the required forecast lead time is 48 hours. In order to extend the lead time, a rainfall runoff model is used based on observed precipitation and air temperatures as inputs. The main motivation of using air temperature data to parametersise evapotranspiration and snow melt instead of, say, radiation data, is that air temperatures can be measured in a more robust way. This is very important in the operational case. The lead times are further extended by using quantitative precipitation and temperature forecasts but their uncertainties are much larger. These forecasts are based on weather model runs of the European Centre for Medium-Range Weather Forecasts and the Austrian Central Institute for Meteorology. This is a component of the flood forecast system that uses results from Global Circulation Modelling.

Real time runoff data from seven telemetered stream gauges are used to update the rainfall runoff model by the Ensemble Kalman Filter method (Evensen, 1994). The uncertainties in the runoff measurements are interpreted as the observation errors and the uncertainties in the rainfall inputs and evaporation (and their effect on soil moisture) are interpreted as the model errors. In the Kamp catchment, runoff generation very strongly depends on antecedent soil moisture, so updating soil moisture should help reduce bias. While, in most instances the runoff model mimics observed runoff very well, there are occasions when this is not the case. One example is shown in Fig. 7 to illustrate the way the Ensemble Kalman Filter operates in the Kamp model. From early January, the simulated hydrograph starts to fall below the data which is due to uncertainties in simulating snow accumulation and snow melt. These biases result in underestimating soil moisture at the beginning of the flood event in April 2006 which is then significantly underestimated. The simulation with updating performs much better during the low flow period. The antecedent soil moisture at the beginning of the flood event in April is larger than for the simulation case without updating and the flood event is represented much more accurately. This updating is only possible if real time runoff data are available. In addition to the Ensemble Kalman Filter updating, an additive error model (model output statistics, MOS) was applied to increase the accuracy of the forecasts over lead times on the order of an hour. The system runs on a time step of 15 minutes.

The value of the updating schemes is illustrated in Fig. 8. Shown is the mean absolute normalised error for five large flood events for the Zwettl/Kamp gauge. Four variants were analysed. In the first variant (dashed line) future precipitation was assumed to be known and the initial conditions of soil moisture were not updated. The average errors are about 15% and do not depend on the lead time as this is a simulation problem. In the second variant (thin solid line) initial soil moisture was updated by the Ensemble Kalman Filter, again based on the assumption that future precipitation were know. The updating reduces the errors, particularly for the short lead times. The dashed dotted line shows the variant were, additionally, the forecasts were updated by the additive error model (MOS) which decreases the forecast errors further for the short lead times. In the fourth variant, the two updating procedures were used in the same way but future precipitation was not assumed to be known but precipitation forecasts were

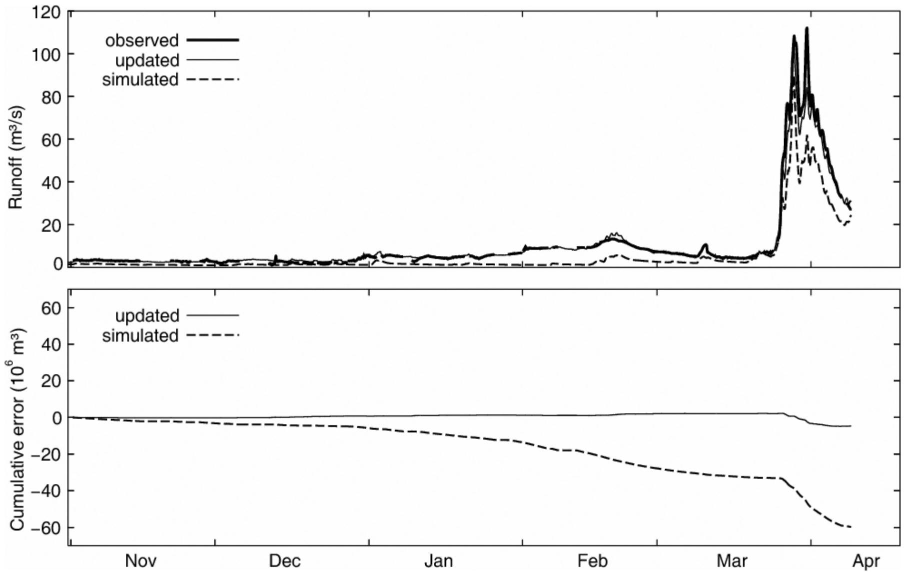

Figure 7 Simulations without updating (dashed lines) and updating (thin solid lines) of runoff (top) and cumulative errors (bottom) at an internal forecasting point (Zwettl/Kamp, 622 km^2) from November 2005 to April 2006. Example of poor model performance where the benefits of updating are significant.

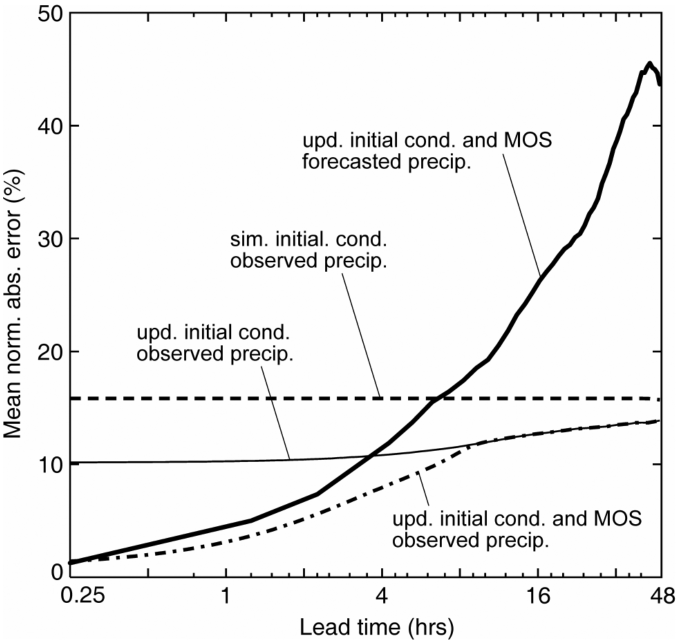

Figure 8 Accuracy of flood forecasts at the Zwettl/Kamp stream gauge ($622\ km^2$) for four updating variants. Five large flood events during 2002–2005.

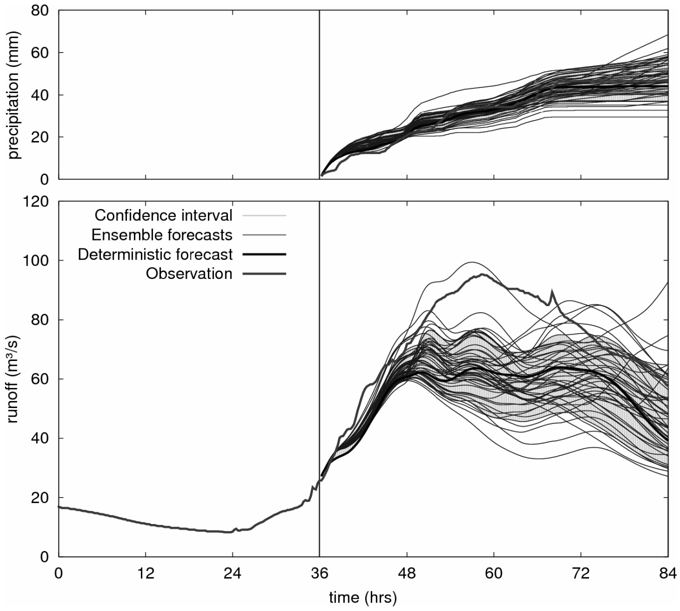

Figure 9 Ensemble forecasts (top: cumulative catchment precipitation, bottom: runoff) on July 10, 2005 at 12 h (time 36 in the figure). Kamp at Zwettl, $622\ km^2$. Grey shaded area represents confidence intervals. From Komma *et al.* (2007).

used (thick solid line). For the first hours, the errors are identical with the previous variant as the forecasts are controlled by fallen precipitation. For larger forecast lead times, the errors increase significantly which is related to the uncertainty of the forecasted precipitation. For short lead times, the errors are small as runoff routing is the most accurate model and the updating procedures increase accuracy additionally.

It is important to note that the main updating takes place between the events as the model error is attributed to the small errors of rainfall input and evaporation that occur between the events. If the model is updated, soil moisture between events is capture more accurately than without updating which provides more accurate initial conditions for the events and hence more accurate flood forecasts.

5 Local communication and credibility of warnings

For the issues of communication and credibility an assessment of the forecast uncertainties is of key importance. Global ensemble forecasts are now produced by the large meteorological forecast centres (Buizza *et al.*, 2005) that provide uncertainty ranges of quantitative precipitation forecasts. This is very useful as the uncertainties tend to be large. The main idea of the use of ensembles in flood forecasting is that the uncertainties will differ depending on the meteorological situation even though the deterministic forecasts may look similar. In the case of the Kamp, ensemble forecasts of the European Centre for Medium-Range Weather Forecasts (ECMWF) have been downscaled by the Austrian Central Institute for Meteorology. The ensemble consists of 50 precipitation forecasts that are used as an input to the rainfall runoff model to produce 50 flood forecasts. Quantiles and confidence intervals of runoff have been estimated based on the assumption that each of the simulations is equally likely. Figure 9 shows an example of the ensemble forecasts. For the short lead times, the confidence intervals are narrow and increase in width with increasing lead time. This is consistent with the increase in the forecast errors with lead time as shown in Fig. 8. It is interesting that, in this example, the ensemble variability of precipitation approximately doubles when transformed to runoff, illustrating that uncertain future precipitation can be a real problem in flood forecasting. This means that it may be wise for a flood forecasting centre to issue different types of warnings. This is depicted schematically in Fig. 10. Early warnings may be issued on the basis of precipitation forecasts, preferably with a measure of uncertainty based on ensembles. Pre-warnings may be issued for shorter lead times and with more certainty. Once rainfall has been observed on the ground, actual warnings can be

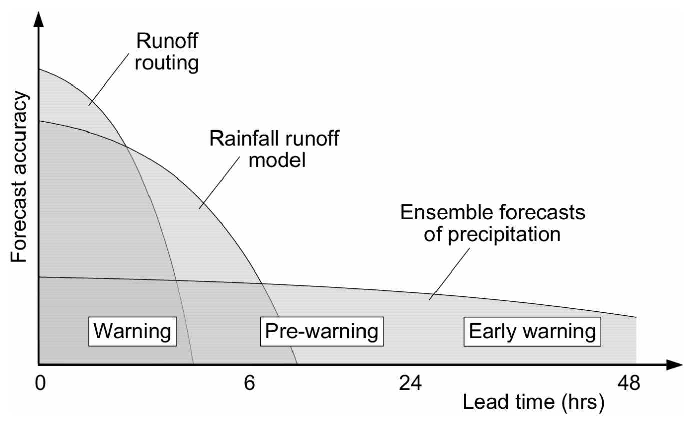

Figure 10 Warning stages and forecast accuracy. The warning is based on the runoff routing and rainfall runoff models that use local real time data as inputs and for updating. The pre-warning and early warning are based on quantitative precipitation forecasts. Time scales are shown for the $1550\ km^2$ Kamp catchment.

issued that have the highest confidence and are based on runoff routing and rainfall runoff models that use local real time data as inputs and for updating the models.

When it comes to the procedures of issuing warnings there are probably the largest differences between local practice and global modelling perspectives although forecast uncertainty is central to both. From a global modelling perspective, exceedance of a warning threshold is usually the main criterion, either based on deterministic or ensemble forecasts. From a local forecaster perspective, as mentioned above, the overriding concern is credibility and there are many more factors to consider than the forecast alone. The forecast uncertainty as predicted by ensemble methods is certainly a valuable piece of information for forecasters but other uncertainties and factors may be more important. These may be difficult to quantify such as the effects of river basin management and the consequences of false alarms. It requires the experience and judgement of a skilled forecaster to assess the situation properly, as DESA (2004) noted: "In determining the operational readiness or hydrological forecast capability of a forecast centre, the education, knowledge and skills of the forecasters are as important as the tools they use."

In the past years, however, the actual benefit of human forecasters in issuing warnings has been debated, as the staff costs incurred are usually much higher than the hardware and software costs. From a pure modelling perspective, ensemble forecasts such as those shown in Fig. 9 do represent the uncertainty, so the additional benefit of the forecaster is not obvious. In the context of meteorological forecasts, Doswell (1986) noted: "Since machines do not have access to qualitative information, they cannot provide as complete a diagnosis as humans. Further, in humans, the diagnostic and prognostic steps are blurred, allowing qualitative knowledge to influence the forecast as well." 17 years later, when numerical models had largely replaced synoptic charts, Doswell (2003) stated "In particular, it is important that he [the forecaster] be able to identify the 'abnormal' situations when the idealized models (be they dynamical or statistical) are likely to be inadequate." Floods are almost always abnormal and this is particularly the case for extreme floods as pronounced by Pielke (1999) in an analysis of the reasons for flood forecast failures: "Most responsibility for the error lies with the simple fact that the river had never before been observed at these levels. Therefore, the hydrological models … were 'flying blind' in the sense that there was no historical basis on which to produce a reliable forecast." Also, since floods and their effects are much more dependent on the local situation than are meteorological forecasts it is clear that the human forecaster has to play a much more important role in hydrology than it may play in meteorological forecasts. A forecaster is usually expected to modify forecasts so there is added value through forecasters' judgement based on his/her past experience with flood situations in the area and the model. An example is the flood of August 12, 2002 in Salzburg which was at the level of a 100 year flood. The warning centre was alerted at 3 a.m. and at 5 a.m. the first forecasts suggested the potential of a major flood. A warning was issued to the disaster management centre, the local fire brigade and the locals according to the flood management plan. At 10:30 the maximum flows (2300 m^3/s) were reached in Salzburg. Although the forecasts of the model were not perfect, the flood predictions issued by the forecast centre were within a few centimetres of the actual values as the forecast staff adjusted them based on their personal experience with flood situations in the area and the model. Of key importance was the close interaction with politicians during the emergency situation. Figure 11 shows the forecaster explaining the hydrological predictions to the state minister, illustrating the role of forecasters in communication.

A delicate issue are false alarms as "… there is nothing worse for the credibility of a flood forecast than 'crying wolf'" (Ibbitt and Woods, 2003). It is clear that the level of public response to warning is diminished in a given area by previous false alarms. Again, the forecaster and other local staff may have a role to play here in confidence building as well as in raising flood awareness. These are processes that are best done locally. While in meteorological forecasts, computer based generation of uncertainty products is often considered essential in communicating uncertainty to the public (NRC, 2006), for flooding it is the assessment of the local situation that matters most. Parker and Handmer (1998) noted: "Most research on flood warning systems is preoccupied with official or formal systems designed by government organizations to warn other agencies and the public-at-risk. Yet those at risk may obtain much of their flood-related information from unofficial sources, such as personal networks and direct observation. Despite this, informal or unofficial systems are often afforded little official credence, even though empirical evidence indicates that formal flood warnings often fail. Exploration of the value of 'folk' or local, as opposed to specialist-technical, knowledge suggests that such knowledge satisfies a range of important needs which are likely to be unfulfilled by official warnings. The scope for personal networks to relay warnings and to contribute local knowledge towards system design appears to be large." The Swiss flood hazard information and warning system, known as IFKIS-Hydro (Romang *et al.*, 2007), puts significant emphasis on local information, such as the water levels during events, and integrates it with more regional information on a web-based platform. The system involves a total of about 200 local observers.

Figure 11 Forecaster (right) explaining the hydrological forecast to the state minister (left) during the 2002 flood. (Photo Courtesy Hydrographic Service of Salzburg).

Their task is to provide an assessment of the local situation which feeds back into the system. Romang *et al.* (2007) emphasise the value of local observers over telemetered sensors. Their reporting tends to be much more robust than that of automatic sensors during floods which is crucially important in an operational context. Also, local observers have the ability to report a wide variety of information (such as soil slips in the area) much of which cannot be captured by telemetered sensors.

6 Conclusions

It is argued in this paper that local information has a very important role to play in flood forecasting and warning. Local hydrological information includes qualitative or soft data obtained in field surveys, such as overland flow marks, connectivity to the stream, soil characteristics and an assessment of flood runoff processes through discussions with locals. This process information can be used to build more reliable models than is possible with regional data bases. River basin management processes are difficult to quantify in a general way, as decision making may be based on a wide variety of factors. In the case of hydropower schemes these may include electricity prices, public safety, tourist activities, fisheries and political considerations. Familiarity with the local situation and interaction with local stakeholders will help to more accurately quantify the effects of river basin management on the flood situation, for example, by using rule based methods that mimic the decisions of hydropower operators. Local real time data, such as runoff data and water levels of reservoirs, can be used to update the routing and rainfall runoff models by Ensemble Kalman Filtering and error models. These improve the forecasts, in particular for short lead times. Communication and the credibility of warnings may be strongly enhanced by local human forecasters. Their role is to judge unusual situations and modify forecasts based on their familiarity with the model and the flood situation in the area of interest, as well as confidence building which is best done locally. It is hence clear that flood forecasts that are to be trusted require the extra step of a human forecaster. Global information can assist at the local scale to extend lead times by precipitation forecasts and to assess forecast uncertainty by ensemble forecasts. However, much additional information at the local scale is needed to maximise the credibility of the forecasts.

Acknowledgement

Development of the forecasting model was funded by the State Government of Lower Austria and the EVN Hydropower company, Austria. Financial support of the EC (project nr 037024, HYDRATE) is acknowledged. The author would like to thank Dieter Gutknecht for numerous suggestions on this research and Hans Wiesenegger for providing one of the photos. Christian Reszler and Jürgen Komma were instrumental in developing the forecasting model. The comments from two anonymous reviewers are gratefully acknowledged.

References

1. Beven, K. (1989). “Changing Ideas in Hydrology – The Case of Physically Based Models,” *Journal of Hydrology*, 105, 157–172.
2. Blöschl, G., Reszler, Ch. and Komma, J. (2007). “A Spatially Distributed Flash Flood Forecasting Model,” *Environmental Modelling & Software*, 23, 464–478.
3. Bowles, D.S., Mathias, J.D., Chauhan, S.S. and Countryman, J.D. (2004). “Reservoir release forecast model for flood operation of the Folsom project including pre-releases.” *24th USSD Annual Meeting and Conference Proceedings*, United States Society on Dams, Denver, Colorado.
4. Buizza, R., Houtekamer, P.L., Toth, Z., Pellerin, G., Wei, M. and Zhu, Y. (2005). “A Comparison of the ECMWF, MSC, and NCEP Global Ensemble Prediction Systems,” *Monthly Weather Review*, 133(5), 1076–1097.
5. DESA (2004). “Guidelines for Reducing Flood Losses,” United Nations Department of Economic and Social Affairs (DESA). available on-line at www.unisdr.org.
6. Doswell III, C.A. (1986). “The Human Element in Weather Forecasting,” *National Weather Digest*, 11(2), 6–17.
7. Doswell, C. (2003). Is There a Role for Humans in the NWS of the Future? (Is there an NWS in our future at all?) Posted 11 May 2003 on http://www.flame.org/∼cdoswell/forecasting/ human_role/future_forecasters.html.
8. Du Plessis, L.A. (2002). “A Review of Effective Flood Forecasting, Warning and Response System for Application in South Africa,” *Water SA*, 28(2), 129–137.
9. Evensen, G. (1994). “Sequential Data Assimilation with a Nonlinear Quasi-Geostrophic Model using Monte Carlo Methods to Forecast Error Statistics,” *Journal of Geophysical Research*, 99(C5), 10143–10162.
10. Freeze, R.A. and Harlan, R.L. (1969). “Blueprint for a Physically-Based, Digitally Simulated Hydrologic Response Model,” *Journal of Hydrology*, 9, 237–258.
11. Georgakakos, A.P. (1993). “Operational Trade-Offs in Reservoir Control,” *Water Resources Research* 29(11), 3801–3820.
12. Grayson, R. and Blöschl, G. (2000). “Spatial Modelling of Catchment Dynamics,” in: Grayson, R. and Blöschl, G. (Eds.), Chapter 3, Spatial Patterns in Catchment Hydrology: Observations and Modelling. Cambridge University Press, Cambridge, UK, pp. 51–81.
13. Gutknecht, D. (2006). (Editor) Hochwasservorhersage – Erfahrungen, Entwicklungen & Realität. (Flood forecasting – experiences, development and reality). *Proceedings Symposium Vienna*, 19–20 October 2006, Wiener Mitteilungen Band 199, Vienna University of Technology.
14. Hall, J.W., Meadowcroft, I.C., Sayers, P.B. and Bramley, M.E. (2003). “Integrated Flood Risk Management in England and Wales,” *Natural Hazards Review*, 4(3) 126–135.

15. Hill, C., DeLuca, C., Balaji, V., Suarez, M. and da Silva, A. (2004). "Architecture of the Earth System Modeling Framework," *Computing in Science and Engineering*, 6(1), 18–28.
16. Ibbitt, R. and Woods, R. (2003). Enhancing flood forecasts. TEPHRA Vol. 20 Wet and Wild, Ministry of Civil Defence & Emergency Management, PO Box 5010, Wellington New Zealand, www.mcdem.govt.nz, pp. 35–39.
17. Komma, J., Reszler, C., Blöschl, G. and Haiden, T. (2007). "Ensemble Prediction of Floods – Catchment Non-Linearity and Forecast Probabilities," *Nat. Hazards Earth Syst. Sci.*, 7, 431–444.
18. NRC (2006) Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions using Weather and Climate Forecasts. The National Academies Press, Washington, D.C., pp. 112.
19. Parajka, J., Naeimi, V., Blöschl, G., Wagner, W., Merz, R. and Scipal, K. (2005). "Assimilating Scatterometer Soil Moisture Data into Conceptual Hydrologic Models at the Regional Scale," *Hydrology and Earth System Sciences*, 10, 353–368.
20. Parker D.J. and Handmer, J.W. (1998). "The Role of Unofficial Flood Warning Systems," *Journal of Contingencies and Crisis Management*, 6(1), 45–60.
21. Pielke Jr. R.A. (1999). "Who Decides? Forecasts and Responsibilities in the 1997 Red River flood," *Applied Behavioral Science Review*, 7(2), 83–101.
22. Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., Seo, D.-J. and DMIP participants (2004). "Overall Distributed Model Inter-Comparison Project Results," *Journal of Hydrology*, 298, 27–60.
23. Romang, H., Hegg, C., Gerber, M., Hilker, N., Dufour, F. and Rhyner, J. (2007). "IFKIS-Hydro – Informations- und Warnsystem für hydrologische Naturgefahren (IFKIS-Hydro – Information and warning system for hydrological hazards)." *Wasser-Energie-Luft*, 99(2), 129–132.
24. Warrick, A.W., Zhang, R., Moody, M. M. and Myers, D. E. (1990). "Kriging Versus Alternative Interpolators: Errors and Sensitivity to Model Inputs," in: Roth K. *et al.* (Eds.), Field-scale water and solute flux in soils. Birkhäuser Verlag, Basel, pp. 157–164.
25. Wösten, J.H.M., Pachepsky, Ya.A. and Rawls, W.J. (2001). "Pedotransfer Functions: Bridging the Gap Between Available Basic Soil Data and Missing Soil Hydraulic Characteristics," *Journal of Hydrology*, 251(3–4), 123–150.