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The COST 731 Action: A Review on Uncertainty Propagation in Advanced Hydro-meteorological Forecast Systems

Andrea Rossa[1], Katharina Liechti[2], Massimiliano Zappa[2] , Michael Bruen[3], Urs Germann[4], Günther Haase[5], Christian Keil[6,7], Peter Krahe[8]

(1) ARPAV, Centro Meteorologico Teolo, Italy

(2) Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

(3) Centre for Water Resources Research, University College Dublin, Ireland.

(4) Swiss Federal Office of Meteorology and Climatology MeteoSwiss, Switzerland

(5) Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden

(6) Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

(7) Meteorologisches Institut, Ludwig-Maximilians-Universität München, München, Germany

(8) Bundesanstalt für Gewässerkunde, Koblenz, Germany

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Corresponding Author:

Dr. Andrea Rossa

ARPAV, Centro Meteorologico Teolo

Via Marconi 55

I-35037 TEOLO (PD)

arossa@arpa.veneto.it

Abstract

Quantifying uncertainty in flood forecasting is a difficult task, given the multiple and strongly non-linear model components involved in such a system. Much effort has been and is being invested in the quest of dealing with uncertain precipitation observations and forecasts and the propagation of such uncertainties through hydrological and hydraulic models predicting river discharges and risk for inundation. The COST 731 Action is one of these and constitutes a European initiative which deals with the quantification of forecast uncertainty in hydro-meteorological forecast systems. COST 731 addresses three major lines of development: (1) combining meteorological and hydrological models to form a forecast chain, (2) propagating uncertainty information through this chain and make it available to end users in a suitable form, (3) advancing high-resolution numerical weather prediction precipitation forecasts by using non-conventional observations from, for instance, radar to determine details in the initial conditions on scales smaller than what can be resolved by conventional observing systems. Recognizing the interdisciplinarity of the challenge COST 731 has organized its work forming Working Groups at the interfaces between the different scientific disciplines involved, i.e. between observation and atmospheric (and hydrological) modeling (WG-1), between atmospheric and hydrologic modelling (WG-2) and between hydrologic modelling and end-users (WG-3).

This paper summarizes the COST 731 activities and its context, provides a review of the recent progress made in dealing with uncertainties in flood forecasting, and sets the scene for the papers of this Thematic Issue. In particular, a bibliometric analysis highlights the strong recent increase in addressing the uncertainty analysis in flood forecasting from an integrated perspective. Such a perspective necessarily involves the area of meteorology, hydrology, and decision making in order to take operational advantage of the scientific progress, an aspect in which COST 731 is successfully contributing to furthering the flood damage mitigation capabilities in Europe.

Keywords: Uncertainty, flood forecasting, radar, NWP, EPS, COST, MAP D-PHASE

1 Introduction

Floods are among the most commonly occurring types of natural disasters in Europe and their frequency and people's vulnerability is increasing across Europe (Barredo, 2007). This is because of increased development pressures on floodplains with more and more people and valuable infrastructure moving into flood-prone areas. Thus an increase in flood-damages in Europe is foreseeable, even without taking climate change into account, (Mitchell, 2003). The Munich Re interactive system NATHAN (natural hazard assessment network, see www.munichre.com) contains an interactive map and thematic information on more than 140 major flood events in Europe from 1900 to the present, including data on casualties and economic losses. The European Commission recognized the paramount importance of the natural hazards issue for the protection of the environment and the citizens and made significant investments in associated research and development ever since the 4th Framework Programme launched in 1994. One particular focus is the real-time forecasting of extreme events with significant flooding potential, which is the basis for triggering a range of mitigating actions. This is a difficult task for many reasons, a main one being related to successfully integrating the contribution of the different 'spheres' (atmosphere, hydrosphere) each of which with its different modelling approaches, inherent uncertainties, limitations and, not least, paradigms of application.

Uncertainty recognizes a certain amount of fuzziness in the forecasts which contrasts with the definitive, categorical, decisions that flood relief managers have to take in order to launch mitigating actions. Significant effort is needed towards reconciling this apparent clash of paradigms by working on the conceptual and communication issues between scientists and decision makers related to uncertainty information (e.g. Demeritt et al., 2007). Such clarification is necessary even on a purely scientific level, in that uncertainty information seems to be perceived fundamentally differently by weather forecasters and flood forecasters.

The COST 731 Action can be seen as the expression of the will of a large number of European meteorological and hydrological services to further both understanding and, even more so, application of systematic uncertainty information. It hence focuses on hydro-meteorological forecasting and how to deal with the uncertainties inherent in the entire forecast chain. The COST 731 Action was proposed and launched mid 2005 for a five-year period as an offspring of a series of COST Actions related to radar meteorology (Rossa et al., 2005a). While the COST Actions 72, 73, and 75 dealt with pure scientific issues related to single weather radars, radar networking, and advanced radar capabilities (Meischner et al., 1997), Action 717 focused on the application of radars in hydrological and NWP models (Rossa et al., 2005b). Here, the unparalleled ability of the radar to observe precipitation in 3+1 dimensions was explored for validating NWP precipitation forecasts and to improve the model's initial conditions. In addition, COST 717 sought to promote the use of radar quantitative precipitation estimates (QPE) for hydrological modelling. On a non-technical level, two issues stood out: the need for a clearer communication between the participating scientific groups, and the necessity to quantify, or at least describe, the variable quality of the radar-derived QPE. The lack of understanding of this uncertainty often led to the exclusion of these data. COST 731 was, therefore, designed to address the quantification and communication of the uncertainty in meteorological observation and forecasting along with their effect on hydrological forecasting, and the subsequent impact on the decision making process.

Full-fledged flood forecasting systems which make use of meteorological forecasts to extend warning lead times are relatively recent but many operational centers around the world are now increasingly moving towards such systems (e.g. Cloke and Pappenberger 2009). In these, testbeds are often developed and play an important role in exploring the potential of integrated probabilistic flood forecasting systems (Schaake et al., 2007b; Rotach et al., 2009). Also, they are indispensable opportunities for gathering hands-on experience and provide training for operational staff, without which it will be very hard to resolve the communication and paradigm difficulties. Figure 1 shows a COST 731 testbed example which consists in a real-time implementation of the semi-distributed rainfall-runoff model PREVAH (Viviroli et al., 2009) for flash flood modelling in a steep Alpine catchment with a probabilistic radar rainfall input. It is one of the first experiments of its kind worldwide producing operational ensemble runoff nowcasting.

In this paper some recent advances in dealing with uncertainties in flood forecasting systems are reviewed to provide the scientific context for COST Action 731 'Propagation of Uncertainty in Advanced Meteo-Hydrological Forecast Systems'. In section 2 the organization and strategy of COST 731 is described and a bibliometric analysis of the scientific and operational relevance of the topic is presented, while section 3 contains the main scientific review. Then the major emerging results of the Action are given in section 4, before closing with a short summary and outlook in the final section.

2 Scientific context and operational relevance of COST Action 731

The main goal of the COST 731 Action can be summarized as quantifying, reducing, and propagating uncertainty in advanced hydro-meteorological forecast systems. In this section the context for COST 731 is given in terms of how this subject has recently gained momentum in the international scientific community, important research and demonstration initiatives as MAP D-PHASE, HEPEX and a number of European Framework Programme projects, and basic considerations on conceptual and operational implications of having to deal with uncertainty. Also goals and structure of the COST 731 Action are described.

2.1 Bibliometric analysis

It is important for a COST Action to deal with topics which are currently highly relevant within the scientific and/or the operational community. An increasing number of analyses based on bibliometric information, obtained from publication databases such as the "ISI Web of Knowledge" (http://www.isiknowledge.com/) or "Google-Scholar" (http://scholar.google.com/), are used to determine if certain research topics are "hot", i.e. are active research areas. Such analyses depend, to a certain extent, on the subjective choice of the terms for querying the databases and the criteria used for refining the "hits" in order to eliminate irrelevant publications. One approach could be to compare the hits given by a series of slight variations on a specific query and this might provide a more objective measure of the evolving of research within a specific field.

On April 15th 2009 a series of queries related to COST 731 topics were submitted to the "ISI Web of Knowledge" database (Table 1). The search was limited to papers within the following subject areas:

- WATER RESOURCES OR,
- ENVIRONMENTAL SCIENCES OR,
- GEOSCIENCES, MULTIDISCIPLINAR OR,
- METEOROLOGY & ATMOSPHERIC SCIENCES

The results of the query are divided into hits up to 2005, roughly the time of writing of the COST 731 proposal, and hits after 2005. It is immediately apparent that the field of hydrological and meteorological modelling and especially the combination of the two has experienced increasing scientific attention in the last few years. Queries for "AND HYDRO* AND MODEL" and for "AND METEO* AND MODEL" show about the same amount of papers for the whole period up to 2005 as from 2005 on. In contrast the hits for "AND HYDRO* AND METEO* AND MODEL" almost double after 2005, this demonstrates a substantial interest in combining meteorological and hydrological models to form model chains. This development probably reflects advances in computing sciences. Powerful computers are able to produce timely forecasts which meet the deadline constraints and extend lead-times for flood warnings, and this despite the increasing complexity of model chains.

In addition there has been an increase of about 75 % to 100 % in citations of these papers after 2005 compared to the whole period up to 2005 for all queries except the one for "AND METEO* AND MODEL". This reflects the fact that operational experience with determining uncertainty in the meteorological community dates back at least to the early nineties (Palmer and Buizza, 2007).

Surprisingly, despite the huge number of publications which emerged after 2005, only about a quarter of the recent cites refers to recent papers. It seems that the new applications are emerging on the basis of previous work of the groups presenting their own implementation of probabilistic hydrometeorological forecast models. This might also indicate that there is no innovative approach generating a large impact in terms of citations so far.
In addition, in the last few years a significant number of journal special issues dedicated to operational hydrometeorology and flood forecasting have been produced. They reflect the development towards the present state in probabilistic flood forecasting (Table 2).

2.2 The Structure and Objectives of COST 731 Action

COST is an intergovernmental framework for European Cooperation in Science and Technology, allowing the coordination of nationally-funded research on a European level. COST contributes to reducing the fragmentation in European research investments and opens the European Research Area to worldwide cooperation, thus ensuring that Europe holds a strong position in the field of scientific and technical research for peaceful purposes, by increasing European cooperation and interaction in nine key domains, one of which is the Earth System Science and Environmental Management (ESSEM, see www.cost.esf.org). The COST 731 Action was proposed within the ESSEM Domain and launched mid 2005 for a five-year. By the end of the Action in 2010 23 countries joined the action: Australia, Belgium, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Rumania, Spain, Sweden, Switzerland, United Kingdom.

COST 731 was designed to address the quantification of the uncertainty in meteorological observation and forecasting along with their effect on hydrological forecasting, and the subsequent impact on the decision making process. Dealing with uncertainties in a flood forecasting and warning production chain (Figure 2) in a consistent way requires the following general stages:

1. atmospheric observation (e.g. precipitation by radar) and quality characterization;
2. assimilation of atmospheric observations into a NWP system;
3. probabilistic atmospheric forecasting in a NWP system (ensembles, neural networks, others);
4. hydrological modelling with atmospheric observations and forecasts, including their associated uncertainties;

5. flood response decision making (especially protection vs. evacuation), management decisions during the event and public warnings.

Radar scientists are mainly concerned with stage 1, NWP modellers with stages 2 and 3. Hydrologists deal with stage 4 but, at present, without making extensive use of radar precipitation estimates and NWP precipitation forecasts. Learning from the COST 717 experience and recognizing the need for an effective interdisciplinary collaboration in order to deal with the propagation of uncertainty from one part of the forecasting/warning system to the next in a coherent way, Working Groups (WGs) are defined on the interfaces between the participating scientific communities in the following way in order to maximise the interactions:

- WG-1 Propagation of uncertainty from observing systems (radars) into NWP (Rossa et al., 2010a);
- WG-2 Propagation of uncertainty from observing systems and NWP into hydrological models (Zappa et al., 2010);
- WG-3 Use of uncertainty in warnings and decision making (Bruen et al., 2010).

A number of interdisciplinary links were implemented to guarantee the transfer of knowledge among the different scientific communities on an appropriate level and to allow for an effective modelling/decision making chain.

The main objective of the Action was to address issues intimately associated with the quality and uncertainty of meteorological observations from remote sensing and other potentially valuable instrumentation, along with their impacts on hydro-meteorological outputs from advanced forecast systems. This was achieved through specific objectives which can be summarized as follows:

- **Radar data assimilation in NWP**: provide radar data errors in a form suitable for assimilation schemes, and compare different assimilation techniques for the cloud resolving scale, including nudging, 3- and 4-dimensional variational assimilation and the ensemble Kalman filter techniques and establish their sensitivity to the specification of radar uncertainty.
- **Radar data quality description**: in collaboration with OPERA (Holleman et al., 2006), update the NWP user requirement for radar data to assist operational data providers.
- **Radar ensembles**: Investigate methods for generation of ensembles based on uncertainty in radar observations.

- **Understand Uncertainty**: clarify and understand the meaning of uncertainty and to establish and agree upon ways to measure and express them.
- **Use of uncertainty in hydrological models**: establish a standard methodology which has the potential to be a reference in the future, and to provide feed back for improvement of meteorological input data (Section 2.4).
- **Methodology transfer:** explore the potential of techniques used to quantify uncertainty commonly used in meteorology applied to hydrology, and promote them to end users.
- **Test beds as proof of concept:** set up (a) European test bed(s) in which to run a demonstration project as a proof of concept for probabilistic flood forecasting systems. Test beds integrate observation and forecast uncertainty into a hydrological forecast to provide warning uncertainty. A "simulation package" including a hydrological model and all aspects of decision making can be used for presentation, education and training as well as to perform sensitivity studies.

2.3 MAP D-PHASE and HEPEX

Numerous regular contributors of COST 731 have been and are also involved in MAP D-PHASE and HEPEX, two large initiatives on demonstrating the potential of hydrological ensemble prediction systems. The following section gives a short overview on these two projects.

"MAP D-PHASE" is an acronym for Mesoscale Alpine Program Demonstration of Probabilistic Hydrological and Atmospheric Simulation of flood Events in the Alps (Rotach et al., 2009).

The MAP D-PHASE initiative was an important element of the COST 731 Action, right from its initial planning. This WWRP (World Weather Research Programme)-approved Forecast Demonstration Project (FDP) D-PHASE was a follow-on project of the Mesoscale Alpine Programme (MAP, Volkert and Gutermann, 2007) to demonstrate the societal impact of MAP by showcasing the progress achieved in high-resolution and probabilistic numerical weather prediction in complex terrain, along with the consequent benefits for hydrological forecasting.

The heart of D-PHASE was a distributed end-to-end forecasting system geared to Alpine flood events which was set up to demonstrate the state-of-the-art in forecasting precipitation-related high-impact weather. The forecast products from 7 ensemble prediction systems (EPS), 23 deterministic NWP models, and 7 hydrological models during the six-month real-time demonstration phase, were prepared in a harmonized way and accessible through a single, central Visualization Platform. The probabilistic forecasts based on EPS had a lead time of a few days. Shorter-range forecasts were based on high-resolution atmospheric and hydrologic models for selected regions or catchments. These were complemented with real-time nowcasting and high-resolution observed information.

Throughout the forecasting chain, warnings were issued and re-evaluated as the potential flooding event approached, allowing forecasters and end users to issue alerts and make decisions at appropriate times. A first insight into MAP D-PHASE with a focus on operational ensemble hydrological simulations is presented in Zappa et al. (2008).

The Hydrological Ensemble Prediction Experiment (HEPEX) was launched as a bottom-up process by scientists and users at an ECMWF workshop in 2004. This international research activity is designed to address questions related to end-to-end forecast systems in order to build useful systems and to promote their rapid development and deployment. Schaake et al. (2007b) present some of the key scientific questions associated with the major components of a probabilistic hydrological forecast system, including calibration and downscaling of ensemble weather and climate forecasts, hydrological data assimilation, and user issues. Additional science questions were defined at the third HEPEX workshop held in Stresa in June 2007 (Thielen et al., 2008). Approximately ten site specific test beds, as well as four multidisciplinary test beds have been activated, focusing on one or more clearly defined HEPEX science questions. These have the potential to develop data resources needed for community experiments to address all of the scientific questions, and are expected to include active user participation.

COST 731 joined with both the MAP D-PHASE (Bologna, 2008) and HEPEX (Toulouse, 2009) communities for common workshops with the goal of sharing expertise and establishing scientific collaboration.

2.4 Link to EU FP projects

A number of recent and ongoing EU projects deal with flood risk management and flood forecasting issues, many of which are related to the objectives of the COST 731 Action. Since the end of 1980’s, the European Commission has been continuously supporting research on floods and other natural hazards (see Table 3 for a list of projects and references to their websites). At the beginning, the EC-sponsored projects were focused on understanding phenomena, identifying concepts and problems, and defining suitable models. As a result of the 3rd Framework Programme (FP) and the 1st phase of the 4th FP, the European Scientific Community had a solid scientific and integrated research infrastructure in this field. Then there was a switch in focus from basic research towards applied research and its problem-solving approach. Stimulated by the knowledge gathered by the RIBAMOD Concerted Action (Balabanis et al., 1999), the EC launched a series of new research projects up to the currently running 7th FP with the declared objective of making substantial progress in the field of flood management. Within the EUROflood research project Parker and Fordham (1996) evaluate flood forecasting, warning and response systems (FFWRS) in the European Union. This research project is a part of the EC funded EPOCH programme

(European Programme on Climatology and Natural Hazards). They conclude that despite advances in flood forecasting, FFWRS often under-perform because of unsatisfactory dissemination of warnings and unsatisfactory responses.

Within the 5th FP the European Flood Forecasting System (EFFS, de Roo et al., 2003) aimed to develop a prototype of an European flood forecasting system for lead times of 4-10 days in advance by using the ECMWF NWP ensemble forecast product. The FLOODMAN project developed, demonstrated and validated a prototype information system for cost effective near-real time flood forecasting, warning and management using earth observation data, in particular space borne Synthetic Aperture Radar data, hydrological and hydraulic models and in-situ data. The EU-FP 5 project FLOOD RELIEF developed and demonstrated on two highly flood prone regional basins (Odra catchment in Poland, Welland and Glen catchments in the UK), a new generation of flood forecasting methods. These basins were selected because they include a wide range of flood producing storms and hydrological regimes over a broad spectrum of spatial and temporal scales. Improved flood forecasting technologies made the results more readily accessible both to flood managers and those threatened by floods. This was achieved by exploiting and integrating different sources of forecast information, including improved hydrological and meteorological model systems and databases, radar, advanced data assimilation procedures and uncertainty estimation, into real-time flood management decision support tools designed to meet the needs of regional flood forecasting authorities.

Within the subsequent EU-FP6 Programme, the FLOODsite Integrated Project (Samuels et al., 2006; Klijn et al., 2008) aimed at an improved understanding of specific flood processes and mechanisms and methodologies for flood risk analysis and management ranging from the high level management of risk at a river-basin, estuary and coastal process cell scale down to the detailed assessment in specific areas. It included specific actions on the hazard of coastal extremes, coastal morphodynamics and flash flood forecasting, as well as understanding of social vulnerability and flood impacts, which are critical to improving the mitigation of flood risk from all causes and thus contributing to FLOODsite's main vision of what a comprehensive approach to flood risk assessment and management ought to encompass. The objectives of the HYDRATE project (Borga et al., 2008; Marchi et al. , 2010) included to improve the scientific basis of flash flood forecasting by extending the understanding of past flash flood events, advancing and harmonising a European-wide innovative flash flood observation strategy, and developing a coherent set of technologies and tools for effective early warning systems. The observation strategy proposed in HYDRATE aimed to collect flash flood data by combining hydrometeorological monitoring and the acquisition of complementary information from post-event surveys. The EU-funded FP6 Integrated Project

PREVIEW (PREVention, Information and Early Warning, Mueller et al., 2009) aimed at developing operational geo-information services in support of European civil protection units and local / regional authorities for the management of risks at the European scale. The risk areas covered are flood, fire, windstorm, earthquake, volcanoes, landslide and man-made products and services. Flood forecasting products and services using the ensemble technique are developed, tested, and tailored for flash flood, short-range and medium range fluvial flood forecasting as well as forecasting of so called Northern Floods, triggered by snowmelt.
The European capacity to respond to emergency situations like fire, floods, earthquakes, volcanic eruptions, landslides and humanitarian crisis will be fortified through the SAFER project, a follow on effort of PREVIEW funded by EC FP7. Amongst other SAFER intends to integrate the lessons learnt within PREVIEW to consolidate the European Flood Alert System. This will be done by developing a best practice flooding approach based on an enhanced partnership between the public at risk from flooding and the authorities responsible for spatial planning, flood protection and flood emergency response management. IMPRINTS (IMproving Preparedness and RIsk maNagemenT for flash floods and debriS flow events) is part of the ongoing EC FP7 and started in 2009. IMPRINTS aims to contribute to a better preparedness and a better operational risk management for flash floods and debris flow events. These improvements shall help reducing fatalities and economic damage, caused by these kinds of natural hazards. To achieve this, methods and tools are developed which will help risk managers and decision makers in emergency agencies and utility companies to take the necessary measures in good time.

2.5 Considerations on quantifying uncertainty

The Flood Risk and Uncertainty Glossary of the Flood Risk Management Consortium (FRMRC) defines uncertainty as ‘a general concept that reflects our lack of sureness about someone or something, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome’ (Pappenberger et al., 2006). Probably one of the most common ways for a scientist to view uncertainty is in terms of a mean value which can vary often by plus or minus one, less often by two, and rarely by three units of the variance, typically assuming a Gaussian or Normal probability density function. In complex systems the uncertainties, or errors, can deviate substantially from the Normal distribution to the extent that mean and variance do not have such an intuitive meaning. The Monte Carlo approach is a frequently used approach to exploring the form of the probability density of such complex systems. It simulates a large number of realizations of the system within a given set of constraints to estimate a large number of possible outcomes. If the system, such as a complete hydro-meteorological forecast chain for instance, consists of a number of individual components with a complexity of their own, the Monte Carlo approach can require very significant computing resources, as the total number of realizations can be as large as the product of the realizations necessary for each of the individual components (e.g. Pappenberger et al., 2005).

The sources of uncertainty in a hydro-meteorological forecast system include incomplete observations, approximate forecast models due to unavoidable simplifications or errors in the mathematical representations of the processes, and the chaotic dynamics of the atmosphere, all of which concur to make meteorological, and therefore also hydrological, predictions essentially probabilistic (Palmer, 2001). Wilks (2006) stresses that the randomness of a system does not imply that it is unpredictable or void of information, but rather not precisely predictable. Probability, provides the tools to represent the precision of the forecast and this in turn can be valuable information.

Ideally, the prediction of any future state of a hydro-meteorological system should be expressed in terms of a probability density function, which allows making a statement about the system's expected value and the associated spread or uncertainty. In this sense, a good forecast reduces the uncertainty regarding the future state, i.e. the predictive uncertainty which is the 'total uncertainty about, for instance, a hydrological predictand. This is expressed in terms of a probability distribution conditional on all available information and knowledge, where the knowledge typically is embodied in a model (Krzysztofowicz, 1999). In order to know the predictive uncertainty it is necessary to characterize a forecast system with respect to the actual observations which, at the time of the forecast, are unknown.

Todini and Mantovan (2007) strongly suggest distinguishing predictive uncertainty from model uncertainty, implying that only by rigorous Bayesian learning using historical observations can predictive uncertainty effectively be assessed. They point out that too often model uncertainty is evaluated instead, such as in the generalized unbiased linear estimator (GLUE) method for estimating uncertainty (Beven and Binley, 1992). For complex systems, however, this kind of conditioning may not be practicable because there are too many unknowns and the assumption that every residual is informative may not automatically hold (Beven et al., 2008). On the other hand, Beven et al. (2008) retain that if a (good) model is able to span past observations, then it should be expected to also span future observation, in which case the model uncertainties would be an assessment of the predictive uncertainty. Decision makers need to learn to incorporate this uncertainty into the decision making process, while scientists need to decide how to deal with the known and unknown errors of their prediction systems.

To achieve a common understanding of uncertainty it is of utmost importance to develop standardized ways and measures to quantify the uncertainties. Only by agreeing on the various possibilities for quantifying uncertainty and how to interpret them (e.g. skill scores) will it be possible for the different disciplines to work together efficiently and to combine the advantages of the many models and systems in use.

3 Review of recent interest in dealing with uncertainties

To appreciate the challenge of providing a reliable flood forecast it is sufficient to realize that precipitation is the most difficult of the atmospheric parameters to forecast and observe (Sevruk, 1996; Walser et al., 2004). Quantitative precipitation estimation (QPE, Germann et al., 2006) and quantitative precipitation forecasting (QPF, Richard et al., 2007) are key tools for quantifying the potential for flooding, especially on short time scales and for relatively small river and urban catchments. Collier (2007) reviews the factors that limit the predictability in flash flood forecasting and discusses the uncertainties involved in QPE and QPF. Over the last decade, operational meteorological models have achieved spatial scales compatible with operational hydrological models for large, medium, and medium-to-small scale catchments (Volkert and Gutermann, 2007). Meteorological input uncertainty is usually assumed to be the largest source of uncertainty in the prediction of floods, at least for lead times of 2-3 days. Moreover, statistical treatment of any kind in connection with rare events is extremely difficult and again provides little predictive skill (Frei and Schär, 2001). In the 1990s, atmospheric modellers started to use ensemble prediction systems to assess the uncertainty involved in forecasting precipitation in time and space and to gain additional information on the characteristics of possible events (e.g. Palmer and Buizza, 2007).

However, the actual threat to society that potentially occurs only becomes effective through the involvement of the hydrosphere. In other words, after the prediction of a precipitation event with a certain uncertainty, the uncertainty in the prediction of a related potential flooding event must take catchment behavior and anthropogenic behavior into account (e.g. Jaun et al., 2008). Finally, the possible action taken by the appropriate authorities (or groups with a certain economic interest) again is based on or can benefit from knowledge of the uncertainty of the modelling chain that provided the forecasts of potential damage. Looking at the process from the reverse angle, uncertainty translates into sensitivity: it is as important for the modeler to know how uncertain the input data is to assess the uncertainty of the model result, as it is for the data provider to know how sensitive the model results are to variations and uncertainties in a certain input variable. For example, the relevance of uncertainty in the precipitation field used as input into a hydrological model depends strongly on the size of the catchment. The larger the catchment the stronger it acts to effectively low-pass filter the variations and uncertainties in the precipitation input. For smaller catchments, however, the details in the precipitation field and the corresponding uncertainties may be determining as a peak may or may just not fall into the catchment. Also, not all parameters of a hydrological model will have the same influence on the representation of the flood peak.

3.1 Using imperfect precipitation observations

Meteorological observations have an uncertainty which should be assessed and expressed in a suitable way. Quantitative precipitation estimation (QPE), both from rain gauge networks and meteorological radars, are traditionally expressed in a deterministic way, i.e. without specifying any ‘error bars’. Germann et al. (2006) established an error description of radar QPE by comparison with a dense rain gauge network in complex terrain. Recently, several approaches to estimating the uncertainties in radar QPE have been proposed. They are all based on the recognition that the number of error sources limit the accuracy with which radars can measure both reflectivity and Doppler velocities. Such errors are discussed by Joe (1996), Saltikoff et al. (2004), and Michelson et al. (2005) among others. Some significant problems associated with estimating precipitation form radar information include clutter, anomalous beam propagation, attenuation, shielding, and variations of the vertical profile of reflectivity. Doppler wind measurements might be affected by aliasing where velocities higher than the unambiguous velocity are folded back into the fundamental velocity interval. On the other hand, well calibrated radars can, over flat terrain and at ranges shorter than about 100km, deliver generally good QPE, i.e. within typical uncertainty limits ranging from 1 to 3 dB in terms of QPE (e.g. Germann et al. 2006, Rossa et al. 2010a).

In recent years advanced quality control and characterization schemes for radar data have been developed (e.g. Friedrich et al., 2006; Parent du Châtelet et al. 2006). These schemes are now ready to be applied in NWP and hydrological models. On the other hand, the synergy between radar and NWP model data can lead to improved QPE and improved radar data quality characterization. The increasing attention which is being payed to radar data quality led, for instance, to the WMO project on Radar Quality and Quantitative Precipitation Estimation Intercomparison (RQQI) with the aim of identifying best practices in QPE.

The EUMETNET OPERA programme (“Operational Programme for the Exchange of weather RAdar information”, http://www.knmi.nl/opera) provides a European platform for the exchange of expertise on operationally-oriented weather radar issues and where management procedures are optimized in support of applications where radar-based information is required (Michelson et al., 2005). The successful collaboration between OPERA and COST 717 (“Use of radar observations in hydrological and NWP models”; Rossa et al., 2005b) is continued with the COST 731 Action. In OPERA phase 2 (2004-2006) a generalized framework has been developed to facilitate the propagation of uncertainty information at the interface between weather radar and meteorological and hydrological applications (Holleman et al., 2006, 2008). Due to the amount of interest in quality information, this work is continued in OPERA phase 3 (2007-2011).

Several groups within COST 731 have proposed methods of making use of the quality description or error characteristics of the radar QPE to formulate a probabilistic, or ensemble, QPE (e.g. Krajewski and Georgakakos, 1985). The originally retrieved precipitation field is perturbed with a stochastic component, which has the appropriate space–time covariance structure. To determine this error structure Germann et al. (2009) utilize the error climatology of radar QPE assessed by comparison with a rain gauge network, while Schröter et al. (2010, this volume) attempt a real time comparison against a best possible, or benchmark, QPE field. Einfalt et al. (2010) circumvent the challenge of defining the actual precipitation error by using a radar data quality index which is then translated into an error. Pegram et al. (2010, this volume) take yet another, pragmatic approach in that they identify and separate the noise from the signal in a radar QPE field and set the noise equal to the random error, which then is used for ensemble generation. This procedure, however, relies on QPE fields for systematic errors have been accounted for separately, in particular the biases. Ahrens and Jaun (2007), on the other hand, introduce statistical interpolation of the measurements of a dense rain gauge network to produce gauge based precipitation ensembles. Clark and Slater (2006), Bellerby and Sun (2005), and Bellerby (2007) provide examples of ensemble techniques for rain-gauge and satellite data.

3.2 Using imperfect models

In numerical weather prediction (NWP) modelling there seems not to be a simple way to make assumptions about the error structures of NWP QPF based on observations from rain gauges or radar QPE. This makes it difficult to adapt the statistical process used for radar ensemble QPE (Section 3.1) to determine the corresponding NWP QPF uncertainty. As a matter of fact, the meteorological community tackled this problem from a different angle, i.e. by recognizing that neither the models nor the initial conditions from which they are integrated are perfect. Hereby, the resulting model sensitivities to both specific parameters and the initial conditions is taken as an approximation of the predictive uncertainty (e.g. Palmer et al., 2005). These well known approaches of the meteorological community to produce probabilistic ensembles (Molteni et al., 1996) were taken up by the hydrological community in the last few years (see Cloke and Pappenberger, 2009 for a review).

Insufficient spatial and/or temporal resolution, both in the observations and the modelling, along with a general decrease of predictability when going from larger to smaller scales, can be viewed as another source of uncertainty. NWP models describe larger scale features, such as the advection of a cyclone or an active front for example, quite well even on time scales of a few days, although their smaller-scale details in terms of QPF may be erroneous. When going to the convective scale, models are too approximate, while observations are generally too coarse to represent the convective environment well enough. This source of uncertainty is especially relevant when the resulting QPF is used at smaller scales, e.g. probabilistic global-scale QPF, typically delivered on a grid with a mesh size of tens of kilometers, for a small to medium-scale river catchment with a size of the order of 100-1000 km^2. To deal with this dilemma, a number of statistical downscaling techniques were developed with the aim of generating precipitation ensembles which are consistent with the NWP QPF value but have prescribed statistical properties, which give, most importantly, indications on how intense precipitation can expected to be on any area smaller than the NWP model mesh. These statistical approaches are based on multifractal cascades (Deidda, 2000; Seed, 2003), autoregressive models (Ferraris et al., 2003), and analogue methods (Wetterhall et al., 2005; Gutiérrez et al., 2004). Because there is a significant scale gap between EPS derived from NWPs and typical hydrological models the EPS QPFs must be downscaled or disaggregated for scale correction. Furthermore, the derived ensembles may have to be adjusted for bias or for spread, i.e. representing the appropriate range of uncertainty (Cloke and Pappenberger, 2009).

Convective-scale NWP EPS is a very recent approach to assessing QPF uncertainty at small scales, both in space and time (Gebhardt et al., 2010 this volume). Unlike their medium-range (2-5 days) counterparts for which a sound theory based on the synoptic-scale error growth, there does not seem to be a promising analogous procedure based on convective-scale error growth (Hohenegger and Schär 2007). Convective-scale ensembles can be produced by combining forecasts started at different times to form lagged-time ensembles (e.g. Mittermaier 2007), or by perturbing boundary conditions and/or initial conditions coming from a coarser scale ensemble. Recognition of the fact that several processes related to convection are only approximate in the models is used to perturb related model parameters. Keil and Craig (2010) examined forecast uncertainty of a convection-permitting EPS and identified a flow dependence. During weak synoptic-scale forcing perturbations of the model physics are more useful, whereas the lateral boundary conditions are more important when precipitation is forced by the synoptic-scale flow. Another promising approach comes from ensemble Kalman Filter type assimilation schemes, which are being developed in the COSMO consortium to include radar data at the convective scale. These do not only deliver the most probable state of the atmosphere given the available observations, but also quantify uncertainty and thus provide probabilistic information for the initialization of the ensemble forecasts (Hunt et al. 2007).

Input uncertainties are only one of the factors that influence the uncertainties in the output of hydrological models. There are other important sources of uncertainty for instance initialization uncertainty associated with the assumptions made about the initial state of the catchment, the uncertainty of model parameterization and model structure and uncertainties in measurements (Vrugt et al., 2005; Jaun et al., 2008). Ferraris et al. (2002) distinguish between two major sources of uncertainty in the coupled meteo-hydrological forecasting chain. They define an "external" uncertainty associated with numerical approximations, boundary and initial conditions at the meteorological scale and the "internal" uncertainty associated with the hydrological processes involved. In hydrological modeling, the uncertainty is usually conceptually divided into contributions from model structure, model parameters, initial conditions, and meteorological inputs (e.g. Beck, 1987). Model parameters can be divided into physical parameters which can be directly measured, empirical parameters which can be experimentally determined, and conceptual parameters used in approximating process equations which need to be optimized, i.e. indirectly determined. There are a number of methodologies developed for this purpose (see e.g. Mantovan and Todini, 2006), GLUE being one of these. In the past, simulation models have optimized their parameters as if they were steady over time. But in fact representing the time varying nature of hydrological responses related to seasonality and the changing antecedent conditions in the system is an interesting aspect of the problem of finding acceptable models (Choi and Beven, 2007). Two studies addressing this problem (Wagener et al., 2003; Freer et al., 2003) confirm that hydrological processes switch their dynamic behaviour between different seasons or periods and this is not expressed properly in most models. Choi and Beven (2007) formulate and evaluate a GLUE-based approach for multi-period and multi-criteria model conditioning of a physically-based distributed model (TOPMODEL) with time-varying hydrological data. In this approach the model calibration is based on identifying periods of different hydrological characteristics. They classified different hydrological periods using the so-called Fuzzy C-means clustering technique. Different parameter sets were determined for each individual cluster. Such multi-period conditioning reduces the forecast uncertainty.

3.3 Methodology transfer from the atmosphere to the hydrosphere

The meteorological community has been using probabilistic forecasting for more than one and a half decades. The most common methodology is Monte Carlo-based ensemble prediction systems (EPS, Palmer and Buizza, 2007). Even if blueprints for ensemble streamflow forecasting are older than one decade (e.g. Schaake et al., 1998; Droegemeier et al., 2000), probabilistic forecasting is still relatively novel in hydrology. However the transfer of the established methodologies used in meteorology may lead to an accelerated development of similar approaches for hydrological purposes. Cloke and Pappenberger (2009) give a comprehensive review of ensemble techniques. They describe the scientific drivers behind the use of EPS in flood forecasting, they critique some limitations of the case studies in the literature, and highlight some remaining key challenges in using EPS for flood forecasting. The latter include the conceptual complexity of the total uncertainty in the resulting forecast, the limits to improvement posed by the present-day computing resources, and the difficulty of communicating forecast uncertainties adequately.

In this context Xuan et al. (2009) contribute to a better understanding of the implications of the spatial/temporal variability of rainfall forecasts applied in the flood forecasting environment. They used a short-range (24h) ensemble QPF system to produce rainfall forecasts (2 km weather model grid) to drive a distributed rainfall-runoff model (500 m grid size). On the one hand, they establish the potential value of ensemble forecasts for flood forecasting by concluding that ensemble hydrological forecasts driven by ensemble rainfall forecasts can produce results comparable to forecasts driven by rain-gauge data. On the other hand they also reveal that the bias, especially the common underestimation of rainfall at fine scale, can lead to unrealistic low river flow forecasts. Verification of such probabilistic forecasts is a particular challenge (Demargne et al., 2009; Cloke and Pappenberger, 2009; Demargne et al., 2010; Brown et al., 2010), in that ‘right and wrong’ no longer have well-defined meanings when it comes to a single forecast observation pair, or a single case study. Verification needs to take the frequency of occurrence of events into account and requires longer time series.An example is presented by Jaun and Ahrens (2009). Their analysis of two years of hydrological ensemble hindcasts for the upper Rhine catchment shows that the ensemble is able to represent the uncertainty for a variety of different weather situations with an appropriate spread-skill. Roulin (2007) evaluates a hydrological ensemble prediction system using verification methods borrowed form meteorology. To advance adequate procedures to evaluate flood forecasts Cloke and Pappenberger (2008) present a six-step approach for screening new forecast performance measures tailored for use with extreme events in hydrological applications. Some open questions remain on the need for specific components for hydrological applications and how far the “meteorological way of doing” is adequate / applicable for hydrological questions. Schaake et al (2007a) describe a technique, used at the US National Weather Service, for generating an ensemble from a single-valued forecast of precipitation and temperature. They divide the spatial domain into subbasins and the time period into model time-steps. They then construct a joint distribution of observations and forecasts and use it to generate ensemble members using the “Shaake shuffle”, Clark et al (2004). The method demonstrates skill in forecasting both temperature and precipitation for at least five days lead time, but requires a long record of past data for model calibration. The associated estimates of uncertainty are scale dependent (Weygandt et al 2004).

3.4 Radar data assimilation: one avenue to improving SRNWP QPF

Assimilation of radar data is a major challenge for high-resolution numerical weather prediction models, especially the newest generation of models that explicitly simulate deep convection. Nevertheless, it is a promising avenue for hydrological applications in small river catchments, as it has the potential to bridge the temporal gap between radar-derived QPE and nowcasts and short-range NWP QPF (Collier, 2007). Radar reflectivity measurements are the standard data source for characterising the spatial distribution of precipitation, and one would expect significant benefits from using this information in the initial conditions of an NWP forecast. However, the nonlinear relationship between reflectivity and the NWP model variables that describe precipitation, the lack of observations that provide a consistent description of the cloud-scale dynamics, and the general low predictability of the atmosphere on small scales, combine to make it difficult to assimilate reflectivity in such a way that the model will retain the information and produce an improved forecast over a longer period of time.

Research on data assimilation methods for models with kilometer-scale resolution (so-called cloud-resolving, or cloud-permitting models) is still in its infancy (Sun, 2005), and many methods are being explored (Sun and Crook, 1998; Caya et al., 2005; Kawabata et al., 2007). The most common method in operational use at the time of writing is latent heat nudging (LHN: Jones and Macpherson, 1997; Leuenberger, 2005; Leuenberger and Rossa, 2007; Montmerle et al., 2007; Stephan et al., 2008; Dixon et al., 2009), although a variety of more advanced techniques have been studied in research contexts. Operational experience suggests that the impact of the assimilated radar data is often short-lived, e.g. a couple of hours, although individual cases can show a much longer lasting positive impact. For example, Stephan et al. (2008) report that within their two month trial period assimilation of radar data on occasions continued to have a strong positive impact after 6 hours of free forecast. Dixon et al. (2009), on the other hand, report on five convective cases in which the data assimilation has a dramatic impact on skill during both the assimilation and subsequent forecast periods on nowcasting time scales. Rossa et al. (2010b) confirm this finding for an exceptional case of convection which caused flash flooding and documented the benefit of radar rainfall assimilation in hydrological forecasting The fact that the impact of the radar data normally decreased rapidly in the first 4 hours of the free forecast is likely to be linked to the short life time and predictability of cumulus convection, as well as to deficiencies in current data assimilation methods, particularly those of LHN. Craig et al. (2010) found that the length of time that a high resolution model retains information from assimilation of radar rainfall data is proportional to a convective adjustment time scale. When convection is controlled by the large-scale flow, the convective time scale amounts to few hours and the impact time is short, whereas during weak large-scale forcing situations, when convection is triggered by local-scale phenomena like orography or boundary layer processes, the impact is considerably longer.

3.5 Uncertainty cascading

The determination of uncertainty in a complex forecast system is a formidable task, which involves systematic cascading, or propagation, of the uncertainty of each of the individual system components through the entire system. Given the often heavily non-linear nature of the modelling system components it is difficult to use traditional linear statistical methods for assessing the overall system uncertainty. Pappenberger et al. (2005) investigated such cascading of model uncertainty from medium range weather forecasts (10-day ahead rainfall forecasts) through the LisFlood rainfall-runoff model down to flood inundation predictions within the European Flood Forecasting System (EFFS). Although there have been a number of studies about uncertainties in real-time flood forecasting which addressed uncertainty cascading through two of these three system components, Pappenberger et al. (2005) were the first to consider the complete modelling chain. Their aim was to assess the uncertainty in the forecast over all combinations of rainfall inputs, runoff forecasts and flood routing models. To reduce the computational demand which arises from applying some form of Monte Carlo technique, they reduced the number of runs required by applying the concept of functional similarity to the parameter sets of the rainfall-runoff model (Pappenberger and Beven, 2004). They found that including medium range rainfall forecasts in the modelling system for real time flood inundation prediction can give useful longer lead times for decision making.

McMillan and Brasington (2008) also studied the end-to-end estimation of uncertainty in a coupled model cascade and produced maps of inundation area estimations at various return periods showing also the uncertainty related with the predictions. Their approach to the problem of computational limitations was different to that of Pappenberger et al. (2005). From the simulated hydrographs they extracted time series of yearly maxima to calculate design flows for various return periods. Design hydrographs for each return period at the 5%, 50% and 95% percentiles of the cumulative distribution were than produced by applying an empirical flow-volume relationship. The design hydrographs were input to the inundation model and transfered the estimated uncertainties on to the inundation estimation map.

In hydrological modelling the diversity of input error sources is an aspect requiring study and needs methodologies to estimate the impact of the different error sources (see Zappa et al., this issue). The influence of radar rainfall input and model parametric uncertainty on the character of the flow simulation uncertainty in hydrological models has been investigated by Collier (2009) based on a stochastic hydrological model. He compared results derived from the model in the stochastic mode to results from the model in deterministic mode. As rainfall input he used raingauge data, weather radar data (with only ground clutter removed) and a combination of both. He looked at the model performance as a function of the input error in the rainfall and found that the stochastic model produced smaller timing errors than the deterministic model for every type of input error. But the errors in the estimated peak flows were only smaller when the errors associated with the rainfall and runoff input were below the mean input errors used to formulate the stochastic model. Otherwise no advantage was gained form the stochastic model.

Werner and Cranston (2009) compared hydrological forecasts made using predicted rainfall from nowcasts with reference forecasts made with observed rainfall data and with observed radar rainfall in the forecast period. The forecast skills using the predicted rainfall from the radar nowcast were lowest and had highest false alarm rates. But, for fast responding catchments, using the nowcasts was significantly better than not using any rainfall forecast at all. So even if they contain considerable uncertainties the nowcasts contribute positively to the skill of the forecast.

3.6 Testbeds and demonstration/training platforms

One of the major quests of the hydro-meteorological community is to have a model chain that integrates all the uncertainties inherent in observations and meteorological forecasts and that is able to propagate these into hydrological forecasts and produce measures of meaningful warning uncertainty. For that purpose test beds are set up for demonstration projects (Schaake et al., 2007b; Zappa et al., 2008) which serve as proof of concept for end users who have never had the opportunity to work with the concept of uncertainty propagation. COST731 WG3 identified and described 7 operational systems with a variety of different objectives (Bruen et al., 2010)

Germann et al. (2009) propose a radar ensemble generator (ensemble of precipitation fields) for use in Alpine catchments using LU decomposition (REAL) which preserves the spatial dependence of the mean and covariance of radar errors. It has been implemented in real-time within the framework of MAP D-PHASE and is linked with the semi-distributed rainfall-runoff model PREVAH (Viviroli et al., 2009) for flash flood modelling in a steep Alpine catchment. It is one of the first experiments of its kind worldwide and can show, operationally, visualizations of ensemble runoff nowcasting with REAL and PREVAH (Fig. 1). Runoff simulation verification on a one year data set for a 44 km^2 subcatchment reveals a reduced bias when using radar QPE or radar ensemble QPE input compared to rain gauge input. Forecast uncertainty measured as scatter between modelled and observed runoff is comparable for radar and rain gauge input, the advantage of the radar ensemble being that it directly provides an estimate of uncertainty for an individual forecast run.

Like MAP D-PHASE, the TIGGE project (**T**HORPEX **I**nteractive **G**rand **G**lobal **E**nsemble) is a World Weather Research Programme project. It aims to accelerate the improvements in the accuracy of 1-day to 2-week high-impact weather forecasts. Park et al. (2008) describe the preliminary results on comparing and combining ensembles. He et al. (2009) were amongst the first to use TIGGE for flood warning. They used TIGGE ensemble forecasts to drive a coupled atmospheric-hydrological-hydraulic model system for a meso-scale catchment (4062 km^2) located in the Midlands region of England. They show that the TIGGE database is a promising tool for runoff and inundation forecasting, yielding results comparable to observed discharge and inundation simulations driven by observed discharge.

In 2003, the development of a European Flood Forecasting System (EFAS) was launched as a reaction to the severe Danube and Elbe inundations in 2002. Its goal is to increase the preparedness for floods in trans-national European river basins by supplying medium-range and probabilistic flood forecasting information to local water authorities 3-10 days in advance. The prototype of this system covers all of Europe on a 5 km grid (Thielen et al., 2009).

3.7 Decision making with uncertain information

For some time, hydrologists have recognized the need to integrate uncertain climatic, meteorological and hydrological information into decision making procedures in water resources management (e.g., Georgakakos et al., 2005). In a simplified scheme, four groups of people participate in the overall flood risk management system. Three of them are involved in managing an actual flooding situation: meteorological and hydrological forecasting services, operational water resource managers and civil response managers (Catelli et al., 1998; Mross et al., 2005; Mross et al., 2008). The technical part, i.e. the technological components of the flood forecasting systems used by these flood risk management communities is developed by the meteorological, hydrological, and engineering scientific communities. The application and interpretation of the resulting output involves the fourth group of people, who constitute the social part of the flood risk management system, and must be interpreted on the basis of general information theory as well as social and economic science. These four groups have different needs, perceptions and approaches to handling and using uncertainties. In fact, dealing with uncertainty in hazard warning is necessarily tied to the measure and meaning of the uncertainty information, as well as to how it is communicated and applied. Communication of uncertainty at the interface of science and risk management is not straightforward and needs specific investigation. There are substantial differences between predictive and model uncertainty, the former being relevant for decision makers, while the latter describes the scientifically relevant model-related uncertainty of flood risk assessments (Hall, 2002; Todini, 2004; Beven et al., 2008).

Scientists see scientific uncertainty as a demanding part of the professional domain. On the other hand, managers have to make decisions that often have considerable implications for cost, safety and health of the people and liability of the professionals. So it is not surprising that scientific uncertainty is a rather unwelcome part of decision uncertainty for the professional managers (Faulkner et al., 2007). The communication of risk in flood risk management between scientists and emergency management professionals could be improved by hydrometeorological and engineering models specifically designed to serve as communication tools between the two. In any case, operational flood emergency managers may have difficulties understanding probabilistic or ensemble forecasts if there is no additional explanation or some sort of translation provided (McCarthy et al., 2007).

One important issue to emerge is concern over the use of expected value methods. Experience suggests that its behavioural assumptions are often violated (Machina, 1987) particularly in relation to high-impact, low-probability hazards, such as extreme floods. This has been studied by economists in relation to financial crises (Bussiere and Fratzscher, 2008) and Climate Change mitigation policy (Lange, 2003). The latter describes a combination of the expected utility criterion with a max-i-min approach giving more importance to more extreme events. Birnbaum (2008) discusses a range of alternatives to expected utility, including prospect theory. Others have studied how best to represent risk-aversion (LiCalzi and Sorato, 2006) while Geiger (2000) also studied low probability, high-impact risks. The value of public participation, particularly in comparison with technical experts, in decision making is illustrated by Gamper and Turcanu (2009).

Uncertainty estimates of decision variables, i.e. quantities whose values are set by a risk manager or policy maker, may be viewed as important only to the extent that they contribute to good-decision making, Cox (1999). In addition to the different kinds of uncertainty, Buizza et al (2007) propose to consider the so called functional quality of forecasting products. In contrast to the technical quality, another term for model oriented uncertainty, the functional quality of the forecasting products and services has to be taken into account by judging their benefits for decision making. The framework developed for assessing the functional quality encompass the four attributes ‘availability and means of distribution’, ‘content and format’, support, maintenance and training’ and ‘communication of product’s technical quality’.

Demeritt et al. (2007) tested how hydrological forecasters involved in real-time flood forecasting handle the uncertainties and possible benefits inherent in EPS. A groups of forecasters were asked to complete a couple of simulated forecasting exercises based on real events. The study showed that the forecasters used the EPS more as a confirmation of their own deterministic models than as a precautionary tool. In situations where the deterministic and the EPS model deviated, they tended to be very cautious in issuing early flood warnings and rather waited and saw how things proceeded. This reaction was explained by the forecasters’ consciousness of the possible costs of a false alarm and the associated loss of credibility. So there is a public sensitivity to false alarms in flood forecasting that contrasts with a relative tolerance in weather forecasting. This fundamentally different attitude between meteorologist and flood forecasters in dealing with EPS information is supported by Doswell (2004) who reported that in meteorological weather forecasting not forecasting an event that happens (false negative/miss) is considered worse than forecasting an event that does not happen (false positive/false alarm).

Another experiment by Joslyn and Nichols (2009) investigated how the public handles and understands uncertainty in weather forecasts. The objective question was if uncertainty expressed as frequency is better understood by public than uncertainty expressed as probability. People understood the forecasts better when they were expressed in a probability format, moreover some additional information like a reference class did not improve their understanding.

Georgakakos et al. (2005), in describing the practical use of meteorological-hydrological forecasts in multi-objective reservoir operation, stress the importance of providing demonstration platforms. They list the essential ingredients for a system to be widely accepted as (i) a reliable and adaptive numerical forecast capability (ii) mutually agreed performance criteria, (iii) a baseline system representing current practice is also available for comparison with the new forecast system, (iv) rigourous, quantitative, intercomparison of methods using historic or real-time data and (v) active and continuing participation of decision-making end-users in workshops. Georgakakos (2004) describes one such system implemented in the Nile catchment,

There is a growing range of powerful quantitative uncertainty, sensitivity, risk and decision analysis techniques, on which flood risk management has begun to draw, but unfortunately, a number of factors conspire to limit the rate and the extent of their uptake. Harvey et al. (2008) discuss these factors and have developed a prototype of a software system named REFRAME to support flood risk analysis. This implements an idealised but realistic flood risk analysis. Another example of a framework of flood risk assessment addressing and taking into account the different sources of uncertainty are given by Apel et al. (2004). Although these tools focus on long term flood risk planning issues they contain most of the ingredients (e.g. tools for assessing the managers perspective of losses by well defined damage functions, inventory and costs of the reaction potential of a certain area) needed for flood forecasting products and formulating guidance material (e.g. Ntelekos et al., 2006)

A consistent result from workshops with end-users in both COST Actions (717, 731) and EU research projects (e.g. CARPE DIEM) is a desire for uncertainty information but a strong call for training in the use of such information. End-users can see its relevance, but are uncertain about how it can best be used. The spaghetti plots often used to represent ensemble results are acknowledged to have some value, but while the producers of these plots worry about undue (in their view) emphasis being placed on the worst member of the ensemble, decision makers do want to know what the worst case scenario entails as well as a history of predictions and outcomes.

4 Outcomes of COST 731

COST 731 can be seen as a timely European initiative to make concerted progress in the field of probabilistic flood forecasting with a particular emphasis on operational applications. The most significant emerging results and trends can be summarized as follows:

- One of the most innovative developments emerging from the COST 731 Action is related to probabilistic quantitative precipitation estimation (QPE) from radar (see review in section 3). Three groups implemented slightly differing methodologies based on a quality description of the precipitation estimates (Germann et al., 2009; Rossa et al., 2010a, Zappa et al. 2010), while Pegram et al. (2010, this volume) implemented a signal-theory based approach. It is to be seen as a sign of good progress that all of these probabilistic QPE methods are being used in combination with hydrological models for simulation of small river catchments in Switzerland, Spain, and Poland, respectively.
- An increasing number of hydrological models are now using EPS QPF for operational medium- to long-range forecasts for river flow forecasting and water management purposes (Cloke and Pappenberger, 2009; Zappa et al., 2010; Bruen et al., 2010).
- A large number of testbeds have been implemented in quasi operational mode, especially during the MAP D-PHASE Operations Phase (Rotach et al. 2009, see section 2.2), some of them have been online for the duration of MAP D-PHASE in 2007 only, some systems are still providing results in real time.
- A recommendation to OPERA has been made to include a systematic radar data description for European radar data exchange (Rossa et al., 2010a).
- Progress has been made on the convective-scale NWP by radar data assimilation. This is particularly relevant for flash flood prediction in small river catchments where extending the warning lead time is crucial (Rossa et al., 2010a, Rossa et al., 2010b).
- A set of demonstration platforms and tools for communicating uncertainty have been identified and presented to various sets of end users (Bruen et al., 2010). Hereby, visualization of and access to typically very large volumes of data emerged as crucial for the efficient use.

Following on from work started in COST 717 (Rossa et al., 2005b) an earlier, systematic radar data quality description has been taken to the next level. Here, several aspects are worth mentioning in the context of a more extensive and quantitative use of radars, both in NWP and hydrological modelling. The European radar panorama is extremely heterogeneous in terms of type and age of the radar hardware, as well as the observation strategy. Therefore, and given the numerous factors impacting on the measurement, radar data quality is expected to vary significantly from country to country. The EUMETNET Programme OPERA (Holleman et al., 2006) took the COST 731 recommendation to include data quality description in the definitions of the international radar data transmission protocols. As described above, an adequate data description is the basis for the generation of probabilistic radar QPE, while statistical data assimilation systems in NWP, like 3/4DVAR, need the observation error to be quantified in a proper form. Finally, hydrological models can take account of radar QPE uncertainty for example in form of QPE ensembles.

A very successful aspect of the MAP D-PHASE is the large number of participating modelling groups, totaling 7 meteorological ensemble prediction systems, 23 deterministic meteorological model, 7 coupled hydrological models covering 43 catchments in the Alpine area (Rotach et al., 2009). The single most important factor of success for this complex initiative was probably the interoperability of all the models: common formats, common warning levels, and common routines to actually determine the warnings from the model outputs rendered the results comparable and therefore highly valuable (Rotach et al., 2009).

From the operational institutions represented in COST 731 there are more than five operational or quasi-operational implementations of integrated flood forecasting systems (Bruen et al., 2010). A particularly interesting example of a testbed implementation is related to the construction of the Zurich railway station underground extension that involved closing 2 of 5 gates through which the river Sihl flows under the railway station (Romang et al., 2010). A hydrometeorological forecasting service started in mid 2008 to run for three years and deliver medium-range probabilistic forecasts of the flow of river Sihl to support the planning of construction work in the river. In critical conditions, the closed gates must be opened, which necessitates stopping construction in the river bed and evacuating the site, and the construction time table is delayed. The loss for not opening the gates, if a flood comes, is very high as a part of the Zurich downtown area would be flooded. This makes an excellent self-contained evaluation exercise and is a unique opportunity available to COST 731.

The Demonstration activities allocated within COST 731 produced a list of existing or potential demonstration platforms or published case studies (including simulation exercises) that could be useful in training or research in the use of uncertainty information. These were discussed at a COST 731 end user workshop in Dublin and include inputs from a wide range of European countries:

- The MAP-D-Phase visualization platform, covering the greater European Alpine area (Rotach et al., 2009);
- The hydrological ensemble prediction System for Zurich Railway station in Switzerland (Romang et al., 2010);
- The river simulator used by the Swedish HydroPower industry;
- SMHI's WebHyPro system in Sweden (Arheimer et al., this volume);
- Flood risk management and flood forecasting in the River Rhine basin operated in Germany and Switzerland;
- Flood risk management and flood forecasting in the River Danube Basin;
- The Results of the EU-FP-6 Project PREVIEW;
- The Finnish Flood forecasting and warning system (Vehviläinen et al., 2005).

5 Outlook and future efforts

The potential value of improved flood forecasting capabilities is beyond controversy. This review testifies to the great effort which is being invested in this field in Europe and elsewhere, both by the research as well as by the operational community. The fact that forecasts of this kind are inherently uncertain, a characteristic that will not change even in the future, seems to be increasingly appreciated, as is the need to adequately quantify and formulate this uncertainty and to make proper use of this information in a decision making context. The COST 731 Action 'Propagation of Uncertainty in Advanced Meteo-Hydrological Forecast Systems' is an expression of and contributes to this trend. A particularly positive aspect hereby is that the meteorological and hydrological community, traditionally quite separate, have increased their cooperation in a very significant way. Avenues of improvement of flood forecasting include the respective improvement of the individual system components, as well as establishing improved combined systems and promote the interpretation of the system output, notably:

- improving radar QPE for small- to medium-scale river catchments;
- improving short-range NWP QPF by making better use of radar and other non-conventional meteorological information, especially at the convection scale;
- improving observations and use of snow cover and soil moisture, both in meteorological and hydrological models;
- Extending limited area EPS to forecast ranges of 7-8 days for water management;
- Increasing spatial resolution of NWP EPSs, e.g. at convection scale with radar precipitation and wind assimilation;

- Implementing and extending to wider areas existing test bed implementations, e.g. to cover the entire Alpine range;
- Enhancing end user and decision maker involvement and training in using probabilistic forecast systems;
- Establishing Economic-Value Issues (Cost/Loss Analyses; Roulin, 2007) as a tool for tailored decision making.

The COST 731 has ended mid 2010 but the work will continue on, especially in the scientific networks that have formed as a result of the Action.

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Table 1. Bibliometric analysis by queries through the “ISI Web of Knowledge” on April 15th 2009.

(UNCERTAINTY OR PROBABILISTIC OR ENSEMBLE) AND …	First Hit	UP TO 2005		AFTER 2005		
		Papers	Cites	Recent Papers	Recent cites	Cites to recent papers (%)
HYDRO* AND MODEL*	1973	1263	10828	1324	20644	25.3
METEO* AND MODEL*	1990	438	5110	495	6354	24.7
HYDRO* AND METEO* AND MODEL*	1991	74	809	133	1451	28.5
FORECAST	1972	684	7085	757	12643	23.4

Table 2. Selection of recent Special Issues of ISI Journals on topics related to COST 731.

Title	*Journal*	*Vol*	*#*	*Topics*	*Selected Articles*
HYREX: the HYdrological Radar Experiment	HESS 2000	4(521-679)	12	- radar precipitation measurements for hydrological purposes - stochastic space-time rainfall forecasting for real time flow forecasting - short period forecasting of catchment-scale precipitation - sensitivity runoff ⇔ rainfall data at different spatial scales	Mellor et al. (2000a,b) Bell and Moore (2000)
Hydrological and meteorological aspects of floods in the Alps	HESS 2003	7(783-948)	11	- Model parameterization - Flood forecasting - Model comparison	Bacchi and Ranzi (2003) Bach et al. (2003) Benoit et al. (2003)
Scientific results from the MAP SOP field experiment.	QJRM 2003	129(341-899)	25	- orographic precipitation events, Alpine storms - airflow within/across Alpine river valleys/Alpine ridge - Validation tools for atmospheric models	Ranzi et al. (2003) Jasper and Kaufmann (2003) Reitebuch et al. (2003)
Quantitative Precipitation Forecasting II	JOH 2004	288(1-126)	15	- Rainfall assimilation - Convection-resolving precipitation forecasts - Development of precipitation forecasting and its predictability	Walser and Schär (2004) Orlandi et al. (2004)
VOLTAIRE – An EU framework programme	MetZet 2006	15(5)483-573	10	- Variation of weather radar sensitivity - Radar data quality control - Downscaling model for radar-based precipitation fields - Improvements in weather radar rain rate estimates	Golz et al. (2006) Franco et al. (2006)
Advances in radar, multi-sensor and hydrological modelling methods for flash flood forecasting	NHESS 2006	6,7		- Weather radar beam propagation - Analysis of sever convective events/ dual polarisation doppler radar - Spatio-temporal precipitation error propagation in runoff modelling - Combined clutter and beam blockage correction technique	Berne and Uijlenhoet (2006) Fornaserio et al. (2006)
Uncertainties in hydrological observations	HESS 2006	10(755-601)	9	- soil moisture from point observations; soil physical data - remote sensing observation for model calibration - uncertainties digital elevation models and land use data - geological and hydrogeological data - stochastic simulation experiment → radar rainfall uncertainty	Pappenberger et al. (2007) Van der Keur and Iversen (2006) Uijlenhoet and Berne (2008)
MAP Findings	QJRM 2007	133(809-1071)	16	- MAP results and findings, benefits, lessons - Quantitative precipitation forecasting in the Alps - Hydrological aspects of MAP	Richard et al. (2007) Ranzi et al. (2007)

				- Data assimilation - Inter-domain cooperation	
Hydrological Prediction Uncertainty	HESS 2007	11, 12, 13	6	- Skill and value of hydrological ensemble predictions - Bias-correction methods, verification tools, uncertainty analysis	Roulin (2007) Xuan et al. (2009)
The German Priority Program Spp1167 "Quantitative Precipitation Forecast"	MetZet 2008	17(6)703-948	17	- Assimilation of radar and satellite data in mesoscale models - Scale dependent analyses of precipitation forecasts and cloud properties - Hybrid convection scheme - Systematic errors in QPF	Milan et al. (2008)
HEPEX Workshop: Stresa, Italy, June 2007	ASL 2008	9(27-102)	11	- HEPEX → Aims, challenges, progress - Probabilistic prediction: value, error correction and evaluation of ensembles - MAP D-PHASE: real time demonstration - Probabilistic quantitative Precipitation Forecast for flash flood forecasting - Hydrological aspects of meteorological verification	Buizza (2008) Pappenberger et al. (2008) Zappa et al. (2008) Bogner and Kalas (2008)
Propagation of uncertainty in advanced meteo-hydrologial forecast systems	NHESS 2008	8	7	- Uncertainty in radar-based data - Verification of operational Quantitative Discharge Forecast - End-user requirement for surface water runoff design - Model intercomparison	Szturc et al. (2008) Jaun et al. (2008)
Flood Forecasting and Warning	MA 2009	16(1)	11	- Long lead times - Flood forecasting in England - Radar rainfall nowcasting for flood forecasting and warning	Collier (2009) Werner et al. (2009) Werner and Craston (2009)

Table 3. Selection on past and ongoing EU framework programmes projects are related to COST 731.

Acronym	*Project title*	*Duration*	*FP#*
TELFLOOD	Forecasting floods in urban areas downstream of steep catchments	1997-1999	FP4
RAPHAEL	Runoff and atmospheric processes for flood hazard forecasting and control http://www.map.meteoswiss.ch/map-doc/NL7/RaphaelProject.htm	1998-2000	FP4
EFFS	European Flood Forecasting System http://effs.wldelft.nl/	2000-2003	FP5
MUSIC	Multi-sensor precipitation measurements integration, calibration and flood forecasting http://www.geomin.unibo.it/hydro/music/	2001-2004	FP5
MANTISSA	Microwave attenuation as a new total improving stormwater supervision administration http://prswww.essex.ac.uk/mantissa/	2001-2004	FP5
CARPE DIEM	Critical Assessment of Available Radar Precipitation Estimation Techniques and Development of Innovative Approaches for Environmental Management http://carpediem.ub.es/	2002-2004	FP5
VOLTAIRE	Validation of multisensors precipitation fields and numerical modelling in mediterranean test sites http://www.voltaireproject.net/	2002-2006	FP5
FLOODMAN	Near real time flood forecasting, warning and management system based on satellite radar images, hydrological and hydraulic models and in-situ data http://projects.itek.norut.no/floodman/Index.htm	2003-2006	FP5
FLOOD RELIEF	A real-time decision support system integrating hydrological, meteorological and radar technologies http://projects.dhi.dk/floodrelief/index2.asp	2003-2006	FP5
PREVIEW	Prevention, information and early warning pre-operational services to support the management of risks http://www.preview-risk.com	2005-2008	FP6
HYDRATE	Hydrometeorological data resources and technologies for effective flash flood forecasting http://www.hydrate.tesaf.unipd.it/	2007-2009	FP6
FLOODSITE	Integrated Flood Risk Analysis and Management Methodologies http://www.floodsite.net/default.htm	2006-2009	FP6
IMPRINTS	IMproving Preparedness and RIsk maNagemenT for flash floods and debriS flow events http://www.imprints-fp7.eu/	2009-2012	FP7

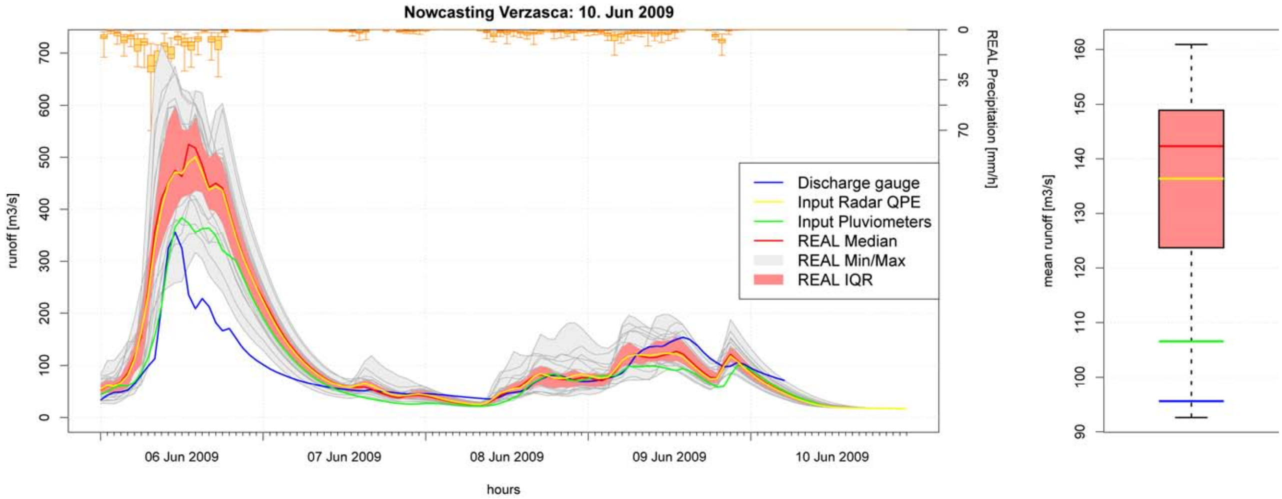

Figure 1. Hydrological ensemble nowcasting with REAL and PREVAH, starting on 6 June 2009 for the Verzasca basin in southern Switzerland. The 25 members from REAL (light grey) are shown with corresponding interquartile range (REAL IQR, red area) and the median (red line). Additionally, two deterministic runs are shown: deterministic radar QPE (yellow line) and forcing with interpolated pluviometer data (green line). The observed runoff is shown in blue. The left panel show the hydrograph from the initialization point up to June 10 2009. Spatially interpolated observed precipitation as ensemble precipitation from the REAL members (orange whisker-plots). The right panel shows the average runoff between June 6th and June 9th 2009.

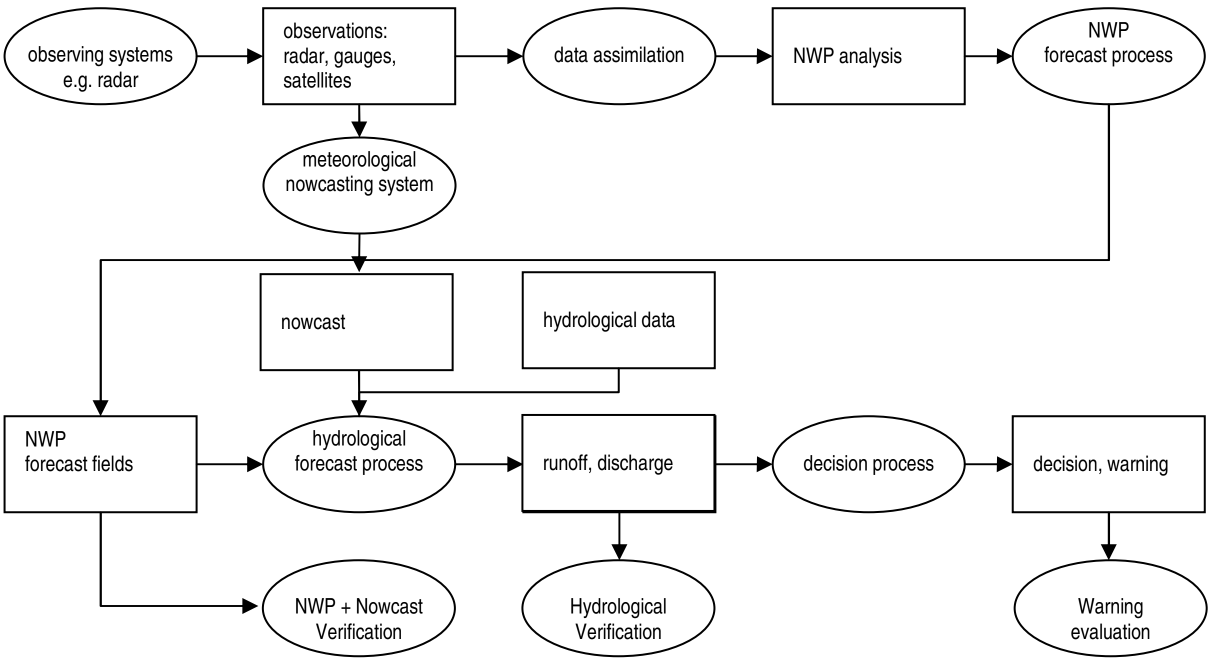

Figure 2. Schematic to depict the production chain of a flood forecasting, decision making and warning system. Boxes denote products while ellipses denote processes. Note that "NWP" may include any numerical forecast output, deterministic or probabilistic, e.g. ensemble prediction system (EPS) products.