Andreas H. Schumann
Editor

Flood Risk Assessment and Management

How to Specify Hydrological Loads, Their Consequences and Uncertainties

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Cover illustration: bridge destroyed during the flood 2002 at the Mulde River in Germany. Photographer: Prof. A. Schumann.

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Preface

This book was planned with two intentions. The first one was to close the gap between the holistic view on flood risk, which was established in the last decade by risk oriented planning, focused on socio-economic consequences of floods, and a flood hydrology, which was still based on a safety oriented approach inherited from structural flood protection in the past. In safety oriented planning it was sufficient to specify a single flood event which was assessed as the limit of flood safety. If this event was exceeded the system was at risk. This remaining risk was not considered any further. Nowadays it is widely accepted that the consideration of remaining risks is an essential component of Integrated Flood Management. Integrated Flood Management, as proposed e.g. by the WMO and the Global Water Partnership, demands risk management. Risk management calls for identification and assessment of risk. Risk has to be assessed and eliminated or at least minimised if it is unacceptable. In this process we are faced with many uncertainties, which are mainly hydrological uncertainties. These uncertainties have to be specified and considered with regard to multiple failure modes and the complex relationships between hydrologic loads and social vulnerabilities.

The second intention was the propagation of new instruments of flood risk management, which were developed within the framework of the National Research Program "Risk Management of Extreme Flood Events" (RIMAX), funded by the German Federal Ministry of Education and Research. With regard to this program it was not feasible to present all projects here as the number of these projects was large. Thirty eight projects were supported between the year 2005 and the year 2010. Instead of entire projects a selection of tools and ideas will be presented here which were developed and applied in some of these projects. These components are on the one hand essential for flood risk estimation and management and on the other hand at the cutting-edge in this field of research. This selection from RIMAX-projects has to be not comprehensive as another publication about RIMAX-result is under preparation by the RIMAX-project steering group. Several innovative solutions, which were provided by RIMAX-projects, were not integrated in this book. On the other hand some aspects of flood risk estimation, which the RIMAX-programme did not entail, but should be discussed in their relevance for flood risk estimations (e.g. regionalization of flood probabilities) were integrated here.

The resulting book is not a report about research projects or a collection of papers which were presented at a scientific conference. It is also definitely not a textbook; yet some general aspects are included in the introduction of the different chapters. The readership of this book is expected to consist of hydrologists and water managers which are interested in recent developments of hydrological tools and methodologies for flood risk estimation, assessment and management.

The editor wishes to thank not only the authors, with whom he co-operated for 2 years, but also the Chief-engineer of the Institute of Hydrology and Water Management, Dr. Markus Pahlow, and the secretaries Mrs. Smolka and Mrs. Mueller who supported him with the compilation of chapters.

Bochum, Germany Andreas Schumann

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Chapter 1
Introduction – Hydrological Aspects of Risk Management

Andreas H. Schumann

Abstract Flood risk is widely under discussion. It is understood as a result of interactions between mankind and nature. In this chapter the definitions of risk, risk estimation and risk assessment are discussed. The main emphasis is given to hydrological aspects of risk and challenges for flood hydrology. It is shown that the problem of hazard specification cannot be solved without consideration of the needs of risk management. It is shown that the flood probability alone is not sufficient if multiple failure modes have to be considered in planning. At the other side operational flood risk management depends strongly on hydrological forecasts. Based on this discussion the different chapters are summarized to give an impression about the overall content of this book and its relevance for flood risk estimation and management.

Contents

1.1 Determinants of Flood Risk

Flood risk management became an item on the political agenda of the European Union (EU) due to severe floods in Europe around the turn of the century. In the year 2007 the EU issued the European Flood Directive (European Commission, 2007).

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It demands the assessment and management of flood risk with the aim to reduce adverse consequences of flooding. In the Directive flood risk is defined as “the combination of the probabilities of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event”. This combination of probabilities and consequences interprets risk as an expected value of consequences. However, there is a need to apply a more holistic view on flood risks. First of all, consequences are not unambiguously related with flood probabilities. Harm, losses, damages, perturbations or stress result from hazards only if vulnerability to theses impacts exists. Hence consequences are uncertain but not probabilistic. The vulnerability of a society depends strongly on socio-economic conditions. Socio-economic categories which are determining the extent of adverse consequences of flooding are considered in the concept of “vulnerability”. There are many different definitions of the term “vulnerability”. A very short one was given by the U.N.: “Degree of loss (from 0 to 100%) resulting from a potentially damaging phenomenon” (U.N. 1992). A more common definition was formulated by Kasperson et al. (2010) “the degree to which a system or unit (such as a human group or a place) is likely to experience harm due to exposure to perturbations or stresses”. These authors discuss three dimensions of vulnerability: 1. the exposure to stresses or perturbations, 2. the sensitivity to the stress or perturbation including to anticipate and cope with the stress and 3. the resilience, the ability to recover from the stress, to buffer themselves against and to adapt to future stresses and perturbations. For a social system, e.g. a community, vulnerability can be defined by “A set of conditions and processes resulting from physical, social, economical and environmental factors, which increase the susceptibility of a community to the impact of hazards” (U.N. ISDR 2002). With regard to floods Merz et al. (2010) characterised the vulnerability V by a combination of exposure E, susceptibility S and response capacity RC. The exposure E is specified by social, economic, ecologic and cultural consequences that may be affected by floods. The susceptibility S is the degree to which the system is damaged by floods. The response capacity RC describes the ability to respond to and to recover from a flood.

1.2 Importance of Detailed Flood Characterisations in Risk Estimations

Exposure, susceptibility and response capacity are categories which depend on different flood characteristics in a nonlinear way. The loss susceptibility S will be extremely high if it is related to a probable maximum flood, but low for a “normal” flood, e.g. with a return period of 10 years. Also, the response capacity depends on the severity of the flood event that is being considered. There are attempts of more differentiated views on flood risk. Merz et al. (2009) argue that “Low probability/high damage” events are more important from the societal point of view than it is considered by the expected annual damage. They suggest a penalizing of events with disastrous consequences by integrating risk aversion into decision making. In this argumentation high damages are connected with floods which have a low probability. This one-to-one assignment is doubtful. Normally, extreme large floods will result in large damages. However, the severity of socio-economic consequences depends on multiple flood characteristics, which can not be specified by a single probability. To give an example for this thesis: damages in agriculturally used floodplains will differ with seasons. Another significant factor which influences consequences is the spatial extent of a flood event, which determines not only the degree of a disaster, but has also impacts on the response capacity. A flash flood is confined to the direct neighbourhood of a river and often to small watersheds only. Floods in alluvial plains of large river basins with widely extended inundated areas could paralyse national economies.

Usually flood events are specified only by the probabilities of their flood peaks. These probabilities are derived from statistical analyses of yearly discharge maxima or discharges above a threshold. Other flood characteristics are considered as conditioned on the peak. The statistical relationships between multiple flood characteristics can not be handled by the probability of the peak. If these probabilistic interdependencies between flood characteristics, e.g. between the shape of the hydrograph, its volume and its peak, are disregarded, the risk estimation for a flood event of a certain dimension will not be reliable. The estimation of these interrelationships is difficult as the database is often insufficient for statistical analyses of multivariate characteristics. Here we are confronted with a number of epistemic uncertainties. Uncertainties can be differentiated into three different types: (1) the epistemic uncertainty, which is the uncertainty attributable to incomplete knowledge about a phenomenon that affects our ability to characterise it, (2) the aleatoric uncertainty, inherent in a nondeterministic (stochastic, random) phenomenon and (3) the surprisal uncertainty which results from totally unexpected factors, e.g. from human behaviour (Table 1.1). The probabilistic methodologies which are widely applied in flood hydrology are an attempt to describe the second type, but the outcome will be affected strongly by the first type. As the epistemic uncertainty may be reduced with time if more data are collected and more research is completed, scientific activities should be focussed on it. Aleatoric uncertainty can not be reduced by further studies, as it expresses the inherent variability of a phenomenon. With regard to risk communication the problem exists that the aleatoric uncertainty has to be specified with a large impact of epistemic uncertainty. Even if the epistemic component could be reduced, uncertainties in general and epistemic uncertainties in particular will be an integral part of flood risk management. This becomes evident also in flood control. Uncertainties are one reason why river training, construction of dykes or flood storages and other technical measures with the aim to reduce the probability of flooding never ensure complete safety to floods (the other main reason is the aleatoric uncertainty and the need to limit flood control on a reasonable goal).

If epistemic uncertainties are neglected then the illusion of flood safety or of perfect flood control arises. The remaining risk endangers flood affected regions and their inhabitants if epistemic and aleatoric uncertainties are disregarded. Technical flood protection structures may increase this risk. This “levee effect” of flood protection structures was described by Tobin as follows: “the structure may generate a false sense of security to the extent that floodplain inhabitants perceive that all

Table 1.1 Types of uncertainties

Type of uncertainty	Epistemic uncertainty	Aleatoric uncertainty	Surprisal uncertainty
	Incomplete knowledge about a phenomenon that affects our ability to describe it, can result from ignorance, from scarce data and from unknown biases	Nondeterministic (stochastic, random) phenomenon, usually modelled by probability distributions	Covers matters which are unexpected Mostly arising from human factors
Ways to handle	Can be reduced with the acquisition of more information and by research	Can not be reduced by further studies, but can be quantified with standard probability theory	Minimize the chance of error and the unexpected occurrence Ensure that the system does not fail when the unexpected occurs
Type of knowledge	Ignored unknowns Known unknowns	Known unknowns	Unknown unknowns

flooding has been eliminated" (Tobin, 1995). Possible effects of this false sense of security are reduced preparedness and a significant economic development of flood protected areas. As a result the risk will be increased. Even if these effects are difficult to specify in terms of monetary values, they become evident in public discussions after floods which mirror the unfulfilled expectations of flood control by technical measures.

The adverse consequences of floods depend on the resistance of affected structures or systems. In safety engineering these interactions between load and resistance are considered. Here the probability of a failure is defined by superimposing the probability density functions (pdfs) of the load and of the bearing capacity of a structure. With regard to the different failure modes of flood protection systems it becomes necessary to specify the hazard in greater detail by its strength, intensity or extension. A detailed characterisation of typical failure modes is essential for a relevance ranking of multiple flood characteristics. To give some examples for this thesis: A dyke e.g. is endangered by overtopping but also by seepage. With regard to these two different failure modes the water level of the flood peak is not sufficient to specify the total risk of a failure. Other examples are: The function of flood storages depends on the volume but also on the shape of the hydrograph, or the stableness of a building during a flood depends on the hydrodynamic load and the buoyancy. More holistic hydrological analyses are obviously essential to characterize the hazard with regard to these different failure modes. An integration of such information in flood risk assessments provides options to identify the weakest points in flood protection systems and the impacts of possible failures. To give a practical example of this approach: The author was asked to analyse the flood risk in a river basin which was affected by land subsidence caused by mining activities. Some areas are drained by pumping stations. The estimation of flood risk was based on a detailed modelling of the flood processes and an analysis of possible damages within the inundated areas. The question was raised how the pumping stations should be considered within the risk estimation process. If the pumping stations would be turned off during a flood, the resulting inundations would be higher. The operating company precluded a failure of the artificial draining system, e.g. caused by an areal power blackout, completely. They argued that in such cases an emergency power supply would be established locally. Nevertheless, the flood simulations were done twice: with operating pumping stations and without pumping. The inundated areas of both scenarios were compared. Based on this comparison it was possible to identify the neuralgic points of the pumping system. The operating company improved the planning of the emergency power supply system based on the most critical locations within the basin. In this risk assessment, the duration of the floods and their volume were specified with probabilities which were derived from statistical analyses of rainfall events with different durations.

1.3 Hydrological Information for Flood Risk Management

Hydrological information plays the major role in flood risk management (Plate, 2009). Flood risk management can be subdivided into two different parts. In a narrow sense flood risk management describes the process of managing an existing flood risk situation (Plate, 2002). In a wider sense it includes the planning of activities which will reduce flood risk. This planning can be directed to an optimisation or improvement of existing systems with the aim of being prepared for a flood and to minimise its adverse impacts or to set up a new or revised system. A system has not necessarily to be a constructional system. The installation of an early warning system based on meteorological and hydrological forecasts, a system of flood insurances or a legal system specifying building codes could also reduce flood risk at different levels. In all cases the performance of such measures has to be assessed within the process of risk analysis. Risk analysis provides the base for decisions on maintaining, improvement or abandonment of existing flood control systems. It should include the estimation and evaluation of residual risks for the case that existing flood protection systems fail. In all cases where the residual risk has to be reduced or an increase of risk caused by changes seems to be unbearable, the planning of further measures has to be started again. In this planning process the causes and consequences of potential disasters including the remaining risks have to be estimated. These analyses have to be repeated for each of the planning alternatives to mitigate not only adverse consequences of flooding, but also the risk that planned systems have a lower performance than expected.

The relationship between hazard, consequences and planning decisions was specified by Plate (2002) with the following definition of risk *RI*:

$$RI(\boldsymbol{D}) = \int_{0}^{\infty} K\,(x|\boldsymbol{D}) f_x\,(x|\boldsymbol{D})\,dx \tag{1.1}$$

where $K(x|\boldsymbol{D})$ describes the consequence function, depending on x, the magnitude of the event causing the load (e.g. water level) and $\boldsymbol{D}$ is the vector of decisions that influence the consequences K of event x. The function $f_x(x|\boldsymbol{D})$ is the pdf of the occurrence of x. Flood control measures can modify this pdf. Other decisions have impact on the consequences, indirectly by reducing hydrological loads or directly by reducing their adverse consequences. Thus the function K is conditional of x and $\boldsymbol{D}$. In his definition Plate considers two types of decisions, decisions which influence the consequences of flooding and decisions which modify the pdf of floods. With regard to the argumentation given under point Section 1.2, the magnitude of the event x is also a vector, as different flood characteristics have to be considered. A single pdf of x is insufficient to describe the multivariate probabilistic structure of flood events, which in turn determines the consequences of flooding.

We have to differentiate between "risk analysis", which is an examination of the complex item "risk", its elements (hazard and vulnerability) and their relationsships and "risk assessment", which determines the importance, size, or value of risk. Risk assessments have to be based on risk analyses. Plate (2002) differentiates between three parts in flood risk assessments for the planning stage (Fig. 1.1):

- Flood risk analysis, which consists of hazard determination, vulnerability analysis and risk determination,
- Disaster mitigation, which can be achieved by technical and non-technical measures and
- Preparedness, which involves planning for disaster relief and early warning and evacuation.

As discussed above, hydrological input is essential for risk analyses. Hydrology has to characterize floods as part of the hazard determination and it is a precondition

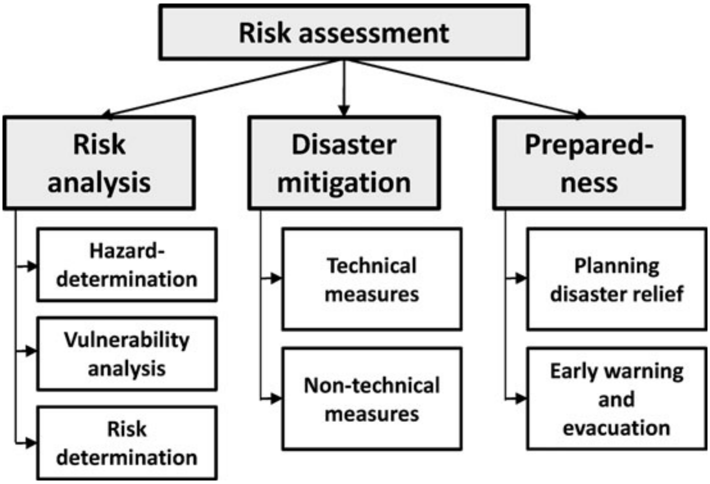

Fig. 1.1 Project planning as part of risk management from Plate (2002)

for assessments of vulnerabilities. Hydrological information is needed to specify measures of disaster mitigation by their efficiencies and remaining risks. Preparedness can be ensured only if the degree of a potential disaster is known, which depends on the hazard, and if the options for early warnings, which depend on hydrological and meteorological forecasts, can be assessed in a realistic way.

Hydrological information will be never complete. Flood risk changes in time (Merz et al., 2010). Many of these changes are highly uncertain and can not be assumed in advance. Any improvement of a flood protection system requires monitoring of hydrological and socio-economic changes and a reassessment of risks depending on the newest information. But also the options to provide the necessary information increase. New technologies and methods are under way. Some approaches which were developed in the last years or which are still in the stage of development are presented here.

1.4 The Content of This Book

In this book multiple facets of applications of flood hydrology in risk management are discussed. Special emphasis is given to uncertainties in operational flood management and in the planning of technical flood protection measures. The two stages of flood risk management, the operational stage and the planning stage, subdivides this book in two parts.

In the first part hydrological aspects of operational flood management are presented. Often early warnings and damage prevention (e.g. evacuation) depends on hydrological forecasts. These forecasts are associated with different levels of uncertainty. These uncertainties depend strongly on the forecasting lead time and the time of reaction of the hydrological system (watershed, river basin or river reach) of interest. For fast reacting systems a forcing of forecast models by observed data from different sources could be insufficient. In such cases the forecast horizon is limited by the time it takes the flood producing precipitation to reach the river profile of interest. With regard to operational flood protection measures this time span could be too short. The lead time can be extended by quantitative precipitation forecasts based on numerical weather prediction (NWP) models. High-resolution NWP can be coupled directly with flood forecasting systems. However, the quality of forecasted precipitation is often not sufficient for flood forecasts in fast-reacting basins where the precipitation fields can vary significantly with time and space. Precipitation forecasts in hilly regions are characterised by a wide range of uncertainties. For flood risk management the current uncertainties in NWP, as well as the handling of these uncertainties have to be taken into account. In Chapter 2 a brief introduction to the generation of weather forecasts with particular focus on the accuracy of rainfall prediction is given. Special emphasis is placed on meteorological ensemble forecasts which can be used to mirror uncertainties. Precipitation forecasts are provided for areas, but if flood forecasts are based on rainfall measurements a spatial estimation of rainfall is needed to provide the input into a hydrological model. In Chapter 3 conventional and geostatistical methods are presented for the spatial interpolation of the point measurements to raster cells and areas. It is focussed on the application of stationary and non-stationary geostatistical methods. The latter type of methods becomes increasingly important as additional information e.g. from weather radar can be considered for the estimation of mean areal rainfall. In this chapter also methods for conditional spatial simulation of precipitation are discussed. Those simulation approaches preserve the high spatial variability of rainfall and can be used for uncertainty assessments.

The benefits resulting from flood forecasts depend on their uncertainties. In Chapter 4 tools are presented which can be used to characterise these uncertainties and to reduce them in nowcasting by assimilation of observed data. It is focused on ensemble methods. Ensembles can be combined with data assimilation to produce "best guess" forecasts based on the Bayes' theorem. It starts with the well-known Ensemble Kalman Filter which is widely applied to update state variables of hydrological models. Other ensemble forecasts which are discussed here are based on meteorological ensembles forecasts and parameter ensembles. This forecasting part ends with an overview of currently available neural network designs with the purpose of a timely warning for operational flood risk management, which is given in Chapter 5. As neural network models are very effective with regard to their computational requirements they provide new options for operational scenario analysis and ensemble forecasts.

The second part of this book is dedicated to hydrological methods which are essential for the planning stage of flood risk management. There are two ways to specify the hydrological hazard: a deterministic one which is based on a transfer of precipitation into runoff by deterministic models and the probabilistic characterisation of flood risk with methods of mathematical statistics. The most common characterisation of a design flood is the flood peak and its probability. Despite many methodological developments since the pioneering work of the mathematician Gumbel, the general problem of flood statistics consists in their high epistemic uncertainty. Derived from a rather limited database, the resulting assessments about flood probabilities are highly variable in time. This is caused mainly by the stochastic character of flood inducing processes. This temporal variability of statistical results is very problematic for long-term planning. The occurrence of a single extreme event may modify the results of flood statistical analysis significantly. Another problem consists in the limited spatial information value. Flood regionalisation methods can be applied to reduce the uncertainties of flood estimations from local data in gauged catchments by pooling flood data within a region. These methods can be used also to provide flood statistical information for ungauged catchments, where no local streamflow data are available. Chapter 6 summarizes the most important methods and recent findings from the literature with a focus on the ungauged catchment case. Regionalisation methods, which are based on a transfer of flood information from hydrological similar catchments to catchments, where flood statistics have to be estimated, are discussed together with multiple regressions between flood statistics and catchment attributes and geostatistical methods, which use spatial proximity as a measure of hydrological similarity.

Precipitation series are essential for deterministic simulations of design floods. These series are often to short. The database for flood estimations can be improved by a coupling of stochastic rainfall generators with deterministic models. Chapter 7 is dedicated to stochastic rainfall synthesis focusing on methods for generation of short time step precipitation as required for flood studies. Here different characteristics of rainfall as stochastic process are discussed. Alternating renewal models, time series models, point process models are described as well as disaggregation and resampling approaches. The applicability of daily and hourly space-time precipitation models is demonstrated with two case studies.

Compared with observed data, generated flood series cover a wider range of possible flood situations. As described under point Section 1.2 such a broad characterisation of possible flood situations is essential to estimate the risk of failures. Also in the planning process of technical retention facilities it is necessary to use simultaneously multiple flood characteristics (peak, volume and shape). Nevertheless, a probabilistic specification of such events is needed. This can be done by multivariate statistical methods which are described in Chapter 8. The proposed Copula method can be applied to derive multivariate distributions from multivariate frequency analyses of correlated random variables. It has the main advantage that the marginal distributions of these random variables can be different.

After the characterisation of the hydrological hazard the consequences which would result from them has to be specified. For this purpose the next three chapters are dedicated to risk estimations and consideration of risks in flood management planning. In Chapter 9 the options of hydraulic modelling are presented. Two important aspects are discussed: the high spatial resolution of these models, which is essential to provide flood risk information at the local scale and the need for efficient algorithms which ensure short computational time requirements and an operational use of these models in nowcasting. Both aspects are contradictory. It is shown how the focus of modelling approaches can be shifted between flood risk planning and operational management to assess flood height, inundated areas and flood velocities in a problem-oriented way.

A special flood risk for urban areas results from sewer system and rising groundwater levels. Chapter 10 describes these problems of interactions between groundwater aquifers and sewer systems. A coupled modelling approach which considers these interdependencies is presented. It combines individual modules considering different model geometries, time synchronization and data exchange. The coupled model was applied for the City of Dresden (Germany). It describes the impact of floods on groundwater and can be used for a mapping of subsurface flood hazard in flood endangered urban regions. As described before, risk combines hazard and consequences.

Risks depend on hazard and susceptibility to hazards. Vulnerability has to be considered in risk management as an integral part of the analysis of consequences. Chapter 11 gives an overview about the assessment of direct economic losses as consequences of flooding. The basic concepts of damage assessments are introduced and the factors that influence flood damage are discussed. A damage model which can be used to estimate flood losses of private households is presented. It is based on extensive surveys of flood damages in Germany.

The book closes with Chapter 12 which presents a planning approach for technical flood retention facilities where the uncertainty of the hydrological hazard is considered. Copulas were applied for a multivariate statistical description of flood scenarios. With regard to the known unknowns the multivariate statistical characteristics of flood scenarios were handled by imprecise probabilities. These imprecise probabilities are specified by Fuzzy Numbers and integrated in a Multi Criteria Decision Making framework, which was developed for flood retention planning in a river basin.

In total this book is an attempt to integrate multiple facets of flood risk, where priority is given to hydrological methodologies, which were developed recently or which are still under development. It has the intention to show new options in such a way that it could be useful for practitioners and scientists.

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Chapter 2
Uncertainties in Weather Forecast – Reasons and Handling

Dirk Schüttemeyer and Clemens Simmer

Abstract The generation of precipitation forecasts by means of numerical weather prediction (NWP) models is increasingly becoming an important input for hydrological models. Over the past decades the quality and spatial resolution of meteorological numerical models has been drastically improved, which makes it now possible to incorporate high-resolution NWP output directly into flood forecasting systems. The quality of forecasted precipitation, however, is still close to insufficient because rainfall constitutes merely the very end of a complex of interlinked process chains acting at a broad range of spatial and temporal scales. Consequently the precipitation fields can vary significantly with time and space and inherit wide ranges of uncertainties. For the purpose of flood risk management it is of particular interest to investigate both the potential and implications of the related variations and uncertainties. For this endeavour the general background and current uncertainties in NWP as well as the handling of the uncertainties has to be taken into account. This chapter gives a brief introduction into the generation of weather forecasts with a particular focus on the accuracy of rainfall prediction. It includes in this context the relatively new field of ensemble forecasting and discusses ways to link numerical NWP with radar-based precipitation nowcasting.

Contents

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2.1 Introduction

Flood risk management at various lead times is taking advantage from the improvement in quality and spatial resolution of meteorological numerical models used for quantitative precipitation forecasts (QPF) and numerical weather prediction (NWP) in general. The forecast quality necessary for a successful prediction of flood events to support civil protection actions, however, still poses a considerable challenge for operational weather forecast systems. The challenge results from the fact, that weather development and precipitation in particular results from the intrinsically nonlinear characteristics of fluid dynamics on a sphere coupled with complex thermodynamic processes e.g. phase changes of water, surface heat and water exchange at the surface, interaction with radiation from the sun and the atmosphere itself and so forth (compare e.g. Dirmeyer et al., 2009). The resulting precipitation fields – the by far most important and decisive input for hydrological models – constitute merely the very end of this complex of interlinked process chains acting at a broad range of spatial and temporal scales. Consequently the precipitation fields can vary significantly with time and space and inherit wide ranges of uncertainties.

The prediction of precipitation is closely connected to weather prediction in general. The quality of weather prediction especially in the medium range scale (several days) has been improving since the beginning of applying numerical methods roughly by 1 day per decade. This means, that the quality of the current 2-day forecast will roughly improve up to the quality of the current 1-day forecast within a decade. This statement also holds for the medium range forecast of precipitation (Bougeault, 2005). Considerable progress has also been achieved over the last decade in numerical weather prediction (NWP) on shorter and smaller scales e.g. by improved cloud microphysics modelling and the exploitation of the increasing available computing power for higher spatial model resolutions. The latter is also important for data assimilation strategies to further enhance the prediction capabilities of current NWP models. Especially for high resolution hydrological forecasts in fast responding catchments different combinations of Nowcasting and very short range NWP could be more suitable and are under development. The major aim is to produce reliable forecasts with high resolution in space and time. Most important for these applications are Precipitation Radar (PR) data, which are nowadays available from many national Radar networks[1] almost immediately after the measurement process with horizontal resolutions of kilometres and temporal resolution of minutes. The German Weather Service (DWD) for example operates one of the most advanced Radar networks in the world. The network is currently upgraded to polarisation diversity, which will allow – besides improving quantitative precipitation estimation (QPE) – to distinguish between different hydrometeors. Together with the anticipated improvements in the treatment of cloud and precipitation processes in weather forecast models, this will enlarge the

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[1] The OPERA initiative of the national European weather services strives to unify the different formats and procedures in order to allow for European radar data composites.

potential of Radar information for data assimilation into forecast models and for improving precipitation nowcasting (usually up to a few hours) based on PR data alone.

The nonlinearity of the climate and weather system dictates, however, that prediction skill drops with increasing time starting from the initial condition. Thus, there remains an upper temporal bound to deterministic predictability of the atmosphere (Lorenz, 1963) currently believed to be between 10 and 15 days. Furthermore, the chaotic nature of weather and the non-Gaussianity of prediction errors on the short and very short scales – when convective events tend to dominate the system state – further limit deterministic predictability and require new concepts. It must be accepted that a complete description of the weather prediction problem should be formulated in terms of the time evolution of an appropriate probability density function (PDF) in the phase space of the atmosphere (see e.g. Molteni et al., 1996). In such a probabilistic framework the potential user of a weather forecast obtains information on the likelihood of a range of weather states and developments. Ensemble prediction methods are one (if not the only) method to obtain such information because it is computationally unfeasible to forecast the complete evolution of the probability density function in the future (Ehrendorfer, 1994a, b).

For ensemble forecasting a limited number of forecasts are generated by integrating a numerical model of the weather system forward in time starting with a limited set of distinct and plausible initial conditions (Leith, 1974). Figure 2.1 depicts such a probabilistic forecast system from the start until its final verification, where the different atmospheric states at the beginning (denoted by grey dots) are illustrated for an ensemble forecast with disturbed initial conditions. By means of uncertainty analysis during the forecast time the best members of the ensemble are

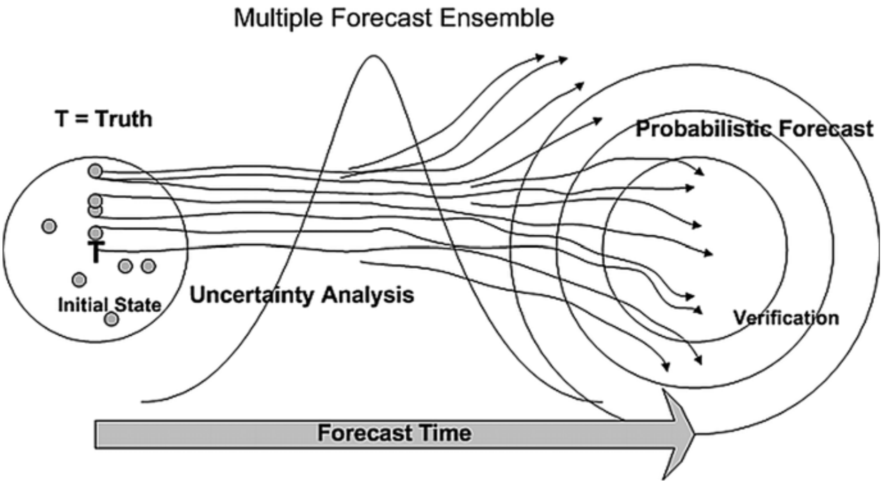

Fig. 2.1 Basic principle of a probabilistic forecast (source: http://chrs.web.uci.edu) adapted from Wilks (1995)

selected and thus enhance model system performance. The individual integrations can be done by the same model (*single model ensemble*), by different versions of the model in order to accommodate effects of model uncertainties, or by a set of different models (*multi model ensemble*). An example of this process is given by Stensrud et al. (2000), who tested different sets of ensemble conditions separately, with both perturbed initial conditions and different model physical parameterisations. These methods are already used by the leading weather prediction centres like the European Centre for Medium-range Weather Forecast (ECMWF), the National Centers for Environmental Prediction (NCEP), the Meteorological Service of Canada (MSC), and also by the German Weather Service (DWD) in the near future.

One of the most crucial problems in ensemble prediction is the construction of an ensemble, which takes due account of the numerous sources of uncertainty in the forecast. In addition, the allocation of the demanding computational resources is an important consideration for the implementation of operational ensemble forecasting systems.

2.2 Background and Current Uncertainties in Weather Forecast

During the last decades numerical weather prediction models have been developed, which explicitly model many of the important precipitation related processes, leading to an improved simulation of the nonlinear atmospheric evolution. In these numerical prediction systems, the atmospheric state at any time step is given by the predicted values of the model variables within a three-dimensional domain given the a priori information on the initial state of the weather system denoted as *analysis*. The latter is typically generated by an optimal merging of observations with a prior forecast (=background) through a statistical process. For every NWP model a number of coupled partial differential equations for the temporal development of the 3D-fields of the state variables (usually pressure, temperature, humidity, cloud water, precipitation water, and wind as a minimum) have to be integrated. These integrations have to be performed

- by taking into account the *boundary conditions* at the ground and the upper part of the atmosphere
- by *parameterizing the non-resolved processes* like turbulence, radiation, convection, cloud microphysics, exchange processes at the surface,. . .
- by *nesting* models of different resolution (thus creating additional boundary-value problems) – or – *variable grid-resolutions* (creating the need for scale-adaptable parameterisations).

Different examples for so-called meso-Gamma scale models are the 5th generation Penn State University/NCAR mesoscale model MM5 (Grell et al., 1994), its

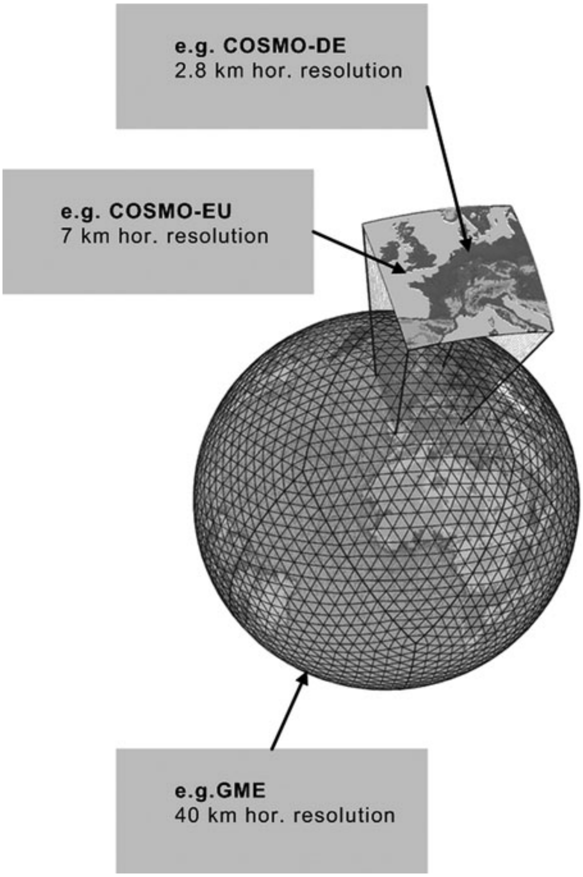

Fig. 2.2 Typical model setup for NWP using the COnsortium for Small-scale MOdeling (COSMO) model system as an example (source: DWD)

successor Weather Research & Forecasting (WRF), and the COnsortium for Small-scale MOdeling (COSMO) model. These models are non-hydrostatic limited area atmospheric weather prediction models, meaning that vertical velocity – and thus convection – is predicted at least partially directly, and that lateral boundary values for all predicted state variables need to be imported from a larger scale – usually global – model. Figure 2.2 gives an overview of a typical setup for such a numerical model system, utilizing the operational setup for the COSMO-model, centred over Europe and Germany. The operational version of COSMO currently runs with a horizontal resolution of 2.8×2.8 km^2 ranging over 421 grid cells in longitude and 461 grid cells in latitude at its finest resolution. The atmosphere is vertically resolved into 50 terrain following layers. In general, the finest grid might reach from 1×1 km^2 to 5×5 km^2 grid size for the horizontal domain and 20–60 vertical layers

For the nesting procedure or interpolation of boundary conditions from a driving host model (with lateral as well as top boundary conditions) the EU domain is taken from the same model with 7 km resolution which is again nested in a global model (currently the so-called GME).

An increasing forecast domain size demands higher computational resources given the same resolved spatial scale. Finer model resolution usually leads to a better physical description of the details in the future state of the atmosphere; at least it gives the potential to do so.

Enhanced computer resources led in the past to a particular focus on the improved representation in the models of convectively driven precipitating systems. A large body of literature on numerical simulations of convective storms suggest – as a rule of thumb – that mesh sizes of the order of 1 km will suffice to simulate deep moist convection (e.g. review by Wilhelmson and Wicker, 2001). A study of Bryan et al. (2003) advocates, however, that in order to realistically represent deep convection, mesh sizes of the order of 100 m are necessary; they concede, however, that simulations on a 1 km grid are already able to reproduce the basic convective circulation itself, even if several aspects of it (e.g. precipitation amount, system phase speed) are modelled incorrectly. Most numerical studies on severe convection have been performed for the USA, so the applicability of the results in other regions, particularly mountainous areas, still remains to be shown. A first attempt to gain a deeper understanding of convective systems was made in the context of the COPS (Convective and Orographically-induced Precipitation Study, Wulfmeyer et al., 2008) experiment that took place in southwestern Germany and eastern France in the summer of 2007. During COPS the pre-convective conditions and deep convective systems were observed during most of their stages of development with ground-based and airborne instruments. Based on surface, in-situ, and remote sensing data, 4D data sets of key meteorological variables were acquired in order to understand convection initiation processes and hence improve mesoscale model forecasts of convective precipitation by e.g. advanced mesoscale data assimilation projects (Zus et al., 2008). Figure 2.3 shows the basic ideas of COPS, which might also explain the general background for improving model performance for NWP.

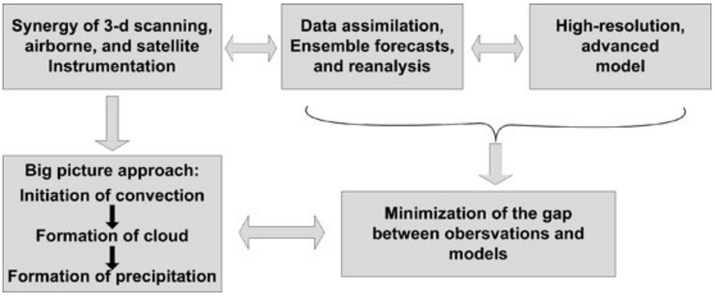

Fig. 2.3 Basic ideas of the Convective and Orographically-induced Precipitation Study (COPS) study that took place in summer 2007 for 3 months over the Black forest in Southern Germany (source: Wulfmeyer et al. (2008))

2.3 Data Assimilation Strategies

Besides model quality the generation of initial conditions for the higher resolved prediction systems becomes more demanding. As more weather satellite platforms and denser weather radar coverage become available, advanced cloud and precipitation assimilation algorithms are often advocated as the solution to the problem of mispredicted rainfall (Macpherson, 2001; Marécal and Mahfouf, 2002; Fillion and Mahfouf, 2003; Hou et al., 2001). The general idea of data assimilation is described in Fig. 2.4 where an optimal merging of observations with a prior forecast (=background) through a statistical process (described below) forms the basis to adjust the different model runs. For any data assimilation scheme the precipitation location and its structure as well as the correct movement are key topics to be addressed.

There are two general approaches to data assimilation: variational and non-variational. Variational assimilation methods effectively deal with the solution of linear estimation problems thereby incorporating the model dynamics (see e.g., Courtier, 1997) and aim to minimize a cost function that depends on the error covariance matrix of both the background state and the observations (Bouttier and Courtier, 1999). In this framework the so-called analysis state is the most likely one, given the observations and their statistical errors (Kalnay, 2003). This framework is, however, under-determined and an a priori estimate (background) of the model is needed.

Typical examples for variational implementations are Optimal Interpolation (OI), where local measurements are directly taking into account or three-dimensional variational (3DVAR) data assimilation, where a first guess, background error statistics, and observations are combined. With these three sources of information, cost-function minimization is performed in order to produce an "optimal" analysis.

In recent years four-dimensional variational assimilation (4DVAR) techniques became increasingly popular, also due to the fact that computational resources

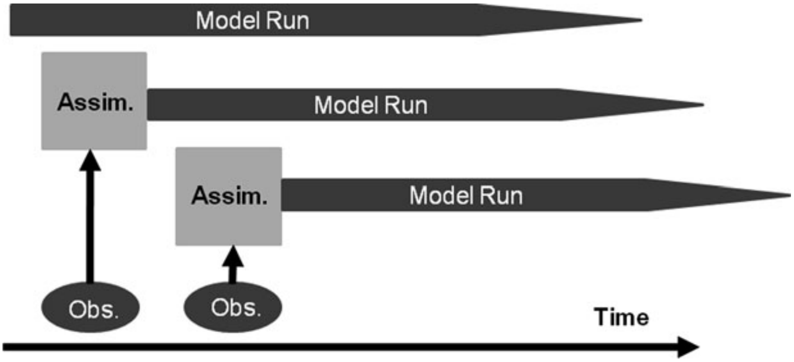

Fig. 2.4 Basic principle of data assimilation, where observations together with a prior forecast are utilized to adjust the model run (adapted from F. Ament, private communication)

became larger. 4DVAR is based on the same information as 3DVAR; but 4DVAR uses this information over a certain time period – the assimilation window – (e.g. 3, 6 or 12 h) in a model-consistent way. 4DVAR produces the initial condition, which leads to a free model run closest to the observation during the whole assimilation period. It has demonstrated its potential for mesoscale and storm-scale forecasting using Doppler radar winds and reflectivity data (Sun and Crook, 1997). In addition Zupanski et al. (2002) demonstrated for a Great Plains tornado outbreak that the NCEP 4DVAR system is well able to analyse precursor features for tornado activity, including wind shear, humidity, high and low level jet streaks, and convective available potential energy, although they also admit that model errors are a critical limitation. However, often even sophisticated and development-intensive data assimilation algorithms like 4DVAR fail to demonstrate the desired performance despite its outstanding suitability for remote sensing observations (for an example see Marécal and Mahfouf, 2002). Park and Droegemeier (1999, 2000) found the phase error to contribute more to the total error in the forecasts of developing convective systems than the amplitude error for domain integrated accumulated rainfall.

Another method for data assimilation is physical initialization (PI) which was introduced by Krishnamurti et al. (1991). The authors showed that PI entails the assimilation of observed rain rates in a numerical prediction model. Haase et al. (2000) and later Milan et al. (2008) extended the original PI to a scheme called PIB (Physical Initialization Bonn). To give an example for a typical application of such an assimilation scheme the PIB is explained in more detail and applied to one case to better perceive the impact of such a scheme.

The basic idea of PI and PIB is that the improvement of precipitation forecasts depends strongly on the coupling of humidity and wind fields in the atmosphere and it assumes that updrafts connected with horizontal humidity flux convergence in the lower part of the cloudy column lead to rain formation (compare also Wilson and Schreiber, 1986; Cotton and Anthes, 1989). The PIB connects the observation space directly with the model space in such a way that both the model and the observed precipitation at every grid point for every time step is taken into account. In case the difference between model precipitation and analyzed precipitation exceeds 20%, the profiles of vertical wind, specific water vapour, cloud water content and the cloud ice content are modified. The threshold is a rough guess of the uncertainty of the precipitation estimate. The modification consists of the following steps:

- For every grid point with analysed precipitation above 0.1 mm/h a single column cloud/precipitation model is utilised to modify the simulated cloud base and top heights, the vertical wind profile, and the humidity profile.
- At grid points with analysed precipitation below 0.1 mm/h PIB reduces the water vapour content, the cloud water content and the cloud ice content based on the information from the satellite data.
- In areas where precipitation data are not available, the model fields are not modified.

An advantage of PIB compared to other assimilation methods is the short assimilation window: Only a few time steps are necessary to achieve acceptable results.

The scheme is applied for one forecast by means of the COSMO-model (described above) during the COPS experiment, where the radar-based RADOLAN (radar online adjustment, Bartels et al. (2004)) data are used to estimate surface precipitation. The results are compared to another assimilation technique, the Latent Heat Nudging (LHN). This scheme is based on the work of Manobianco et al. (1994) and on the successive application from Jones and Macpherson (1997). The principal idea is to correct the model's latent heating at each time step by an amount calculated from the difference between observed and modelled precipitation. Practically this scheme nudges (Anthes, 1974; Hoke and Anthes, 1976) the model temperature profile to the estimated temperature profile (using a saturation adjustment technique).

For the chosen example the weather is characterised by an upper low pressure system near the western part of Brittany in the early hours of the day. Its cold front moves slowly eastwards while the convective activity weakens until noon. In the radar data (Fig. 2.5) an area with convective activity moves across southern and central Germany. During this event the DWD rain gauge network in Germany shows strong precipitation, e.g. the 6 h rain gauge accumulation was 48 mm at Cologne-Bonn Airport (in the middle of the model region). This case is interesting to see if and how PIB improves a poor model forecast. The operational COSMO prediction in the time range between 0 and 6 UTC indicates no or only little precipitation. At the end of the assimilation window, the PIB run reproduces the cold front, although with some overestimation of precipitation in the middle of western Germany.

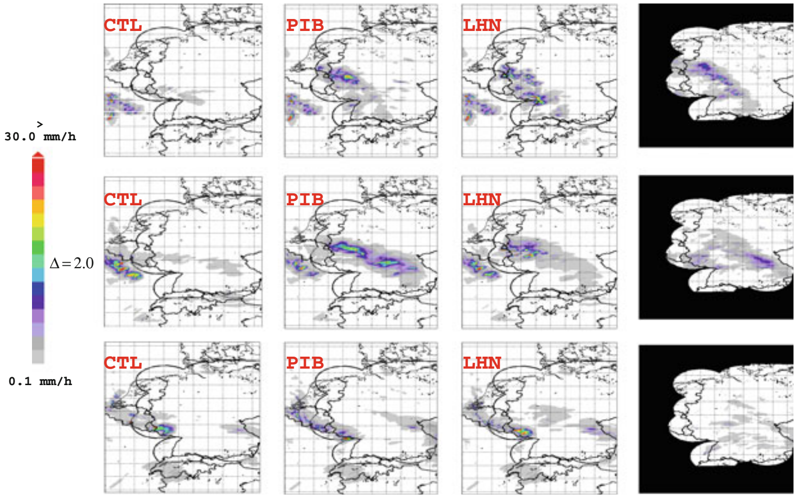

Fig. 2.5 Hourly accumulated precipitation. Results at the end of the assimilation window, *upper* row, after 3 h, *middle* row, and after 6 h of free forecast, *lowest* row