

Model system and scenario development for the provisional management of extreme floods in large river basins*

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Abstract

A research project is introduced in which a modelling system is being developed to quantify risks of extreme flooding in large river basins. In the system, computer models and modules are coupled together to simulate the functional chain: hydrology – hydraulics – polder diversion – dyke failure – flooding – damage estimate – risk assessment. In order to reduce uncertainty in flood frequency analyses, data sets will be complimented with information from historical chronicles and artwork. Probable maximum precipitation and floods will be calculated to indicate upper bounds of meteorological and hydrological extremes.

1. Introduction

Worldwide there is a continuous increase in damages caused by extreme natural events. In part this is due to the fact that human society is becoming increasingly more vulnerable to the effects of these occurrences. In addition, it is presumed that the climatic changes that are momentarily being observed will intensify and increase the magnitude and frequency of the climate-dependent catastrophic events. Apart from naturally occurring extremes, anthropogenic developments are also increasing the potential for damages.

Due to the flood damages in August 2002 in the Elbe river basin in Germany and the Czech Republic public awareness for the improvement of the provision and management of such emergencies has risen. This gave impetus to establish a junior research team at GeoForschungsZentrum in Potsdam in cooperation with the University of Karlsruhe (within the network CEDIM – Center for Disaster Management and Risk Reduction Technology) dedicated to research of extreme flood events in large

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river basins. The group is staffed with five scientists (a team leader, a post-doctoral researcher, a research associate and two doctoral students) for a duration of three years (August 2004 – July 2007).

The visionary goal to be reached at the completion of the research is:

*Development of a modelling system allowing the implementation and interchangeability of hydrological and hydraulic processes of varying degrees of complexity...
... for the provisional management of extreme flood events in large river basins...
... using a computer-automated methodology that is easily and flexibly transferable to basins of different (macro)scales.*

A modelling system is required which couples all the models and modules together into one integrated system, which ensures that the most important components of the hydrological cycle for extreme floods are simulated. The main components include runoff generation and routing. The latter can be greatly affected by polder diversions and dike breaches hence, their impact must be incorporated as modules into the simulations.

An important question in developing such a modelling system is how complex should the description of the hydrological and hydraulic processes be in order to retain both good accuracy and high predictive power in the system's state variables. More complexity may lead to higher accuracy since more processes are represented to reflect reality. Cox (1999) shows using models for risk assessment that greater complexity leads to more certainty in risk estimates but also states that the additional complexity included in the model must allow additional relevant observations to be incorporated. The downside is that such complex systems become over-parameterised (or overly sensitive as stated by Snowling and Kramer (2001)) making validations and predictions of flood events with different initial and boundary conditions difficult. Hence, an aim of the project is to answer the question:

*How complex must the modelling system be to ensure good accuracy
and predictability of the simulation results?*

Lindenschmidt and Hesse (2004) found that the relationship of accuracy and predictive ability with model complexity may also change at different scales. Models of smaller scale require a more detailed description of the processes to accurately simulate the state of the modelled area for a given time frame. Sivapalan (2003) mentions that increased complexity is required to capture the hydrological response at the hillslope scale compared to the catchment scale. For example, Butts *et al.* (2004) and Perrin *et al.* (2001) found that hydrological variables modelled for large river basins were more accurately simulated using simpler process descriptions. van der Linden and Woo (2003), who applied models with increasing complexity to simulate hydrological conditions in subarctic catchments, also

found that with decreasing temporal and spatial scale, process representation needs to be more complex. Hence, an additional question that will be pursued in this research project is:

How does the complexity – uncertainty relationship of the modelling exercise change when the modelling system is applied to different macro-scales (e.g. Elbe basin and Mulde subbasin)?

An important prerequisite for developing provisional management concepts for the mitigation of extreme flood events is to identify areas of potentially high risk to such events. Risk maps are extremely useful, however its methodology for very large river basins is still in its infancy. Kron and Willems (2002) identify eight independent regional loss accumulation zones in Germany in which probable maximum losses are calculated for five different flood scenarios corresponding to return periods ranging from 10 to 200 years. Zoning is carried out, not of rivers alone, but of entire large catchment areas. Similar efforts for Germany have been carried out by Kleeberg (2001), who concentrated the zoning to the flood regions along rivers and who implemented the method in the software package ZÜRS (Zoning System for Floods, Backwater and Heavy Rains). Rodda and Berger (2002) established differentiated risk zones in the flooded areas near the river itself, and Hall et al. (2003) and Sayers et al. (2002) have extended this approach to include the probabilities of dike failures. The implementation of these dike fragility curve has also found application in the USA (USACE 1996, 1999). These methods provide a rough orientation of where “hot spots” occur in terms of flood risk on very large (nationwide) scales. These have their justification for high-level strategic planning for entire countries and provide information on a scale that is valuable for re-insurance companies, which base their policies on probable maximum loss estimates. The downside of these methods is that the spatial resolution is generally too coarse and the results not differentiated enough to be applicable for the development of mitigation concepts. Hence, an additional aim of this project is to investigate:

How much explanatory power is forgone in making reasonable risk assessments for the development of provisional management concepts when applying the modelling system methodology to larger scales? How can explanatory power be improved for the largest basins?

2. Methodological concept

The concept of the research project is illustrated in Figure 1. An aim of the project is to develop a modelling system whose core consists of the coupling of four models. The runoff generation components describe the precipitation runoff on the land surfaces. As flooding events become more extreme hydrograph routing of the generated runoff becomes increasingly important, especially in the lowland river reaches. A dike breach module calculates the probability of a dike failure depending on

the condition and type of dike and on the hydraulic variables in the river, such as water level and water velocity in the main channel. In the event of a dike breach a dispersion model is executed to simulate the movement of water from the breach area into the hinterland. This model may also be used to simulate the movement of water through a polder system. Since the dispersed water also affects the hydraulics in the river, there is an interactive linkage between the dispersion and routing components.

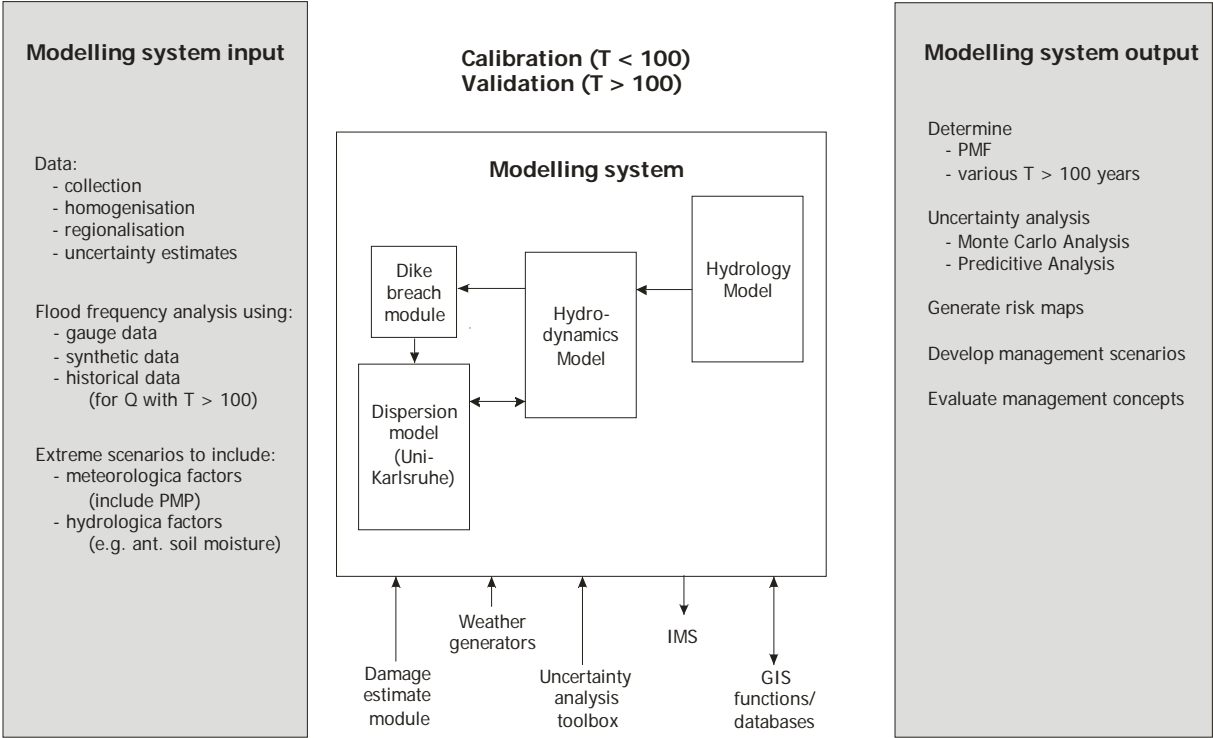


Figure 1: Concept for the research project

Other components may be implemented into the system such as a damage estimator module, a weather generator and an uncertainty analysis toolbox. Databases and a library of GIS (Geographical Information System) functions are to be accessible by the system and results are to be displayed using an IMS (Internet Map Server).

Data is required as input to run the modelling system, which needs to be collected, homogenised and regionalised from point samples to area descriptions. Estimates of the statistical uncertainty in the data and parameter values are required for an uncertainty analysis. The modelling system can then be calibrated globally with reasonable “certainty” for events with return periods less than 100 years. Data sets longer than one century are rare and uncertainty increases when extrapolating the discharges for return periods of 250 or 500 years from these data sets (see for example Figure 2). To gain more certainty and reduce confidence intervals the interpolated values are to be complimented with historical data. Chronicles may provide insight on discharge and precipitation. Artworks may additionally provide estimates of water levels at certain locations for corresponding discharges from

documented meteorological conditions. Weather generators may (time permitting) also be used to produce synthetic data to fill data gaps in time series and to mock extreme weather conditions by superimposing extreme meteorological variables which may not necessarily overlap. These data will also provide a data set that can be used for the validation of the modelling system for extreme flooding events ($T > 100$ years).

Gewässername: Schwarzwasser
 Pegelname: Aue 1
 Beobachtungszeitraum: 1927 - 2003 Anzahl der Fehljahre: 0
 Berechnungszeitraum: 1927 - 2003 Anzahl der berücksichtigten Jahres-HQ: 77

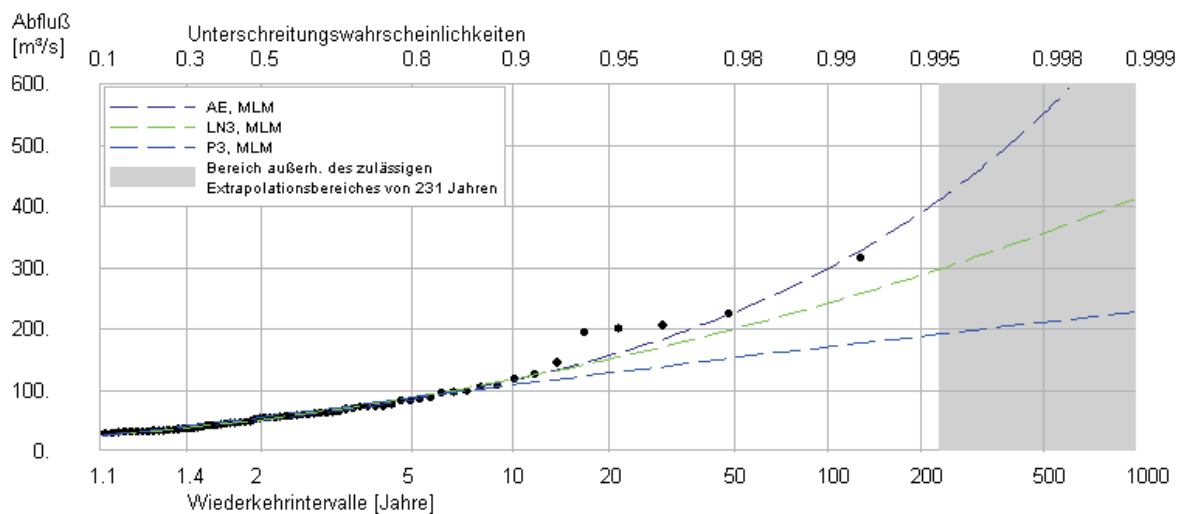


Figure 2: Flood frequency distribution at gauge Aue on the river Mulde

Superimposing the extreme values of meteorological variables also serves as a basis for the calculation of the probable maximum precipitation (PMP) of a subbasin. Together with extreme hydrological factors such as very high antecedent soil moistures the probable maximum flood (PMF) can be simulated. This will set the upper limit of flooding possible in the basin.

Once the modelling system has been set up a Monte Carlo Analysis (MOCA) can then be carried out to determine probability distributions of hydrological output variables, such as discharges and water levels, for certain return periods. These output distributions are obtained when parameters and input data of the modelling system are varied according to specific probability distributions within their uncertainty limits. Only those parameters and data will be used for the MOCA which are most reactive to the output variables. This is determined by running a sensitivity analysis (SENA) of the system.

The probability of occurrence calculated from the MOCA together with the intensity of the event (return period) establishes the hazard induced by the flood event. Using land-use information and damage costs as functions of water depth and perhaps other factors (i.e. flow velocities) the vulnerability of certain land-use types that are exposed to the flood and their susceptibility to damage

by the flooding can be assessed. Both hazard and vulnerability are combined to calculate risk (see Figure 3) and can be used to establish risk maps (see Figure 4). Once areas of exceptionally high risk (“hot spots”) have been identified scenarios can be run to test various management concepts for flood mitigation.

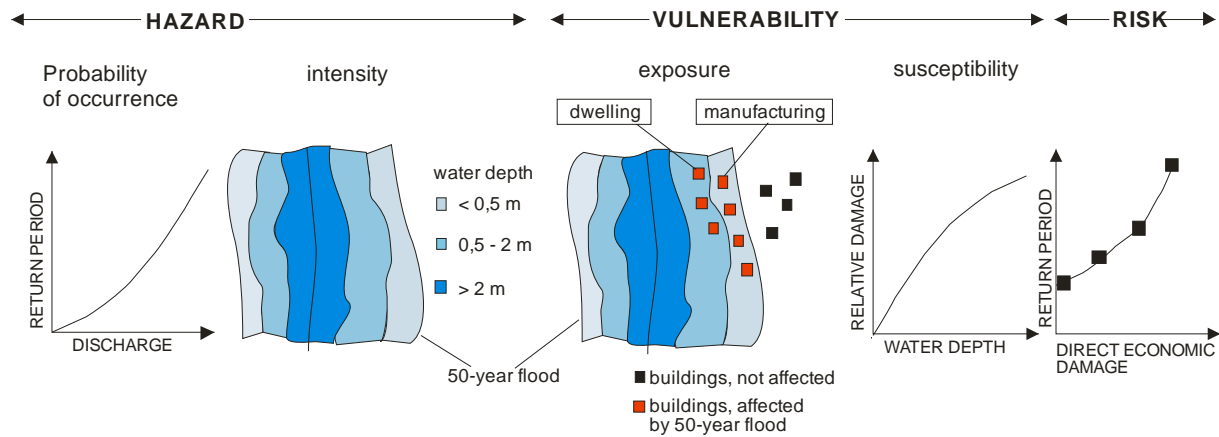


Figure 3: Flood risk as interaction of hazard and vulnerability (adapted from Merz and Thielen, 2004)

3. Model complexity and uncertainty

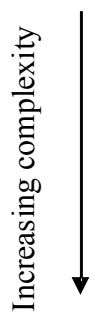
One aspect of the project is to model the numerous hydrological and hydraulic processes with varying degrees of complexity. The aim is to determine how complex a model setup must be in order to obtain the required accuracy of the results. Table 1 shows various processes corresponding to different complexity levels of selected components of the hydrological cycle. Several complexity mixes can also be tested for accuracy by combining processes of different complexity from each hydrological component. The discretization of the catchment area can also be carried out with varying degrees of resolution (see Table 2). This may range from a very coarse (low complexity) to a very fine (high complexity) discretization:

Table 1: Processes of different complexity levels

Complexity	← Hydrological component				
	Dispersion	Routing	Losses	Evapotrans.	Snowmelt
I	Water balance	Muskingam-Cunge	Uniform loss	Wendling	Degree-Day
II	Storage Cells	Kinematic	Horton	Priestly-Taylor	Energy balance (simplified)
III	Branched 1-D	Diffusion	Green-Ampt/Phillips	Penman-Monteith	Energy balance

- lumped parameters of each subbasin, an approach found for example in the HEC-1 model (HEC, 1998),
- landscape units in which discretized units are derived from lateral flow characteristics in the surface areas (Güntner and Bronstert, 2004),
- hydrological response units in which units are discretized according to related geomorphologic characteristics (Flügel, 1995) and
- grid cells, as used in, for example the WaSiM-ETH model (Schulla, 1997).

Table 2: Complexity levels of different discretization schemes.

	Complexity	Discretization
Increasing complexity 	I	Sub-basins (lumped)
	II	Landscape Units (LU) (different # of layers)
	III	Hydrological Reponse Units (HRU) (different # of layers)
	IV	Grid Cell (differnt resolution)

Snowling and Kramer (2001) proposed a hypothesis in which model sensitivity and error, which constitutes model uncertainty, is related to the model's complexity level (see Figure 5). "Model sensitivity increases with model complexity due to the larger number of degrees of freedom and the structure of the interactions between parameters and state variables. Modelling error decreases with increasing model complexity as the more complex models are able to better simulate reality with more processes included and fewer simplifying assumptions" (Snowling and Kramer, 2001, p. 21).

Snowling and Kramer (2001) confirmed their hypothesis on a sorption model for radioactive zinc onto sediments in solution (LeBeuf, 1992 cited in Snowling and Kramer, 2001). In a second model in which the transport of a groundwater tracer plume was simulated, sensitivity does increase with increasing complexity but no relation was evident between error and complexity. The hypothesis has also been tested and confirmed using a water quality model developed for the Saale river (Lindenschmidt, 2004) and a lock-and-weir system on the same river (Lindenschmidt and Hesse, 2004).

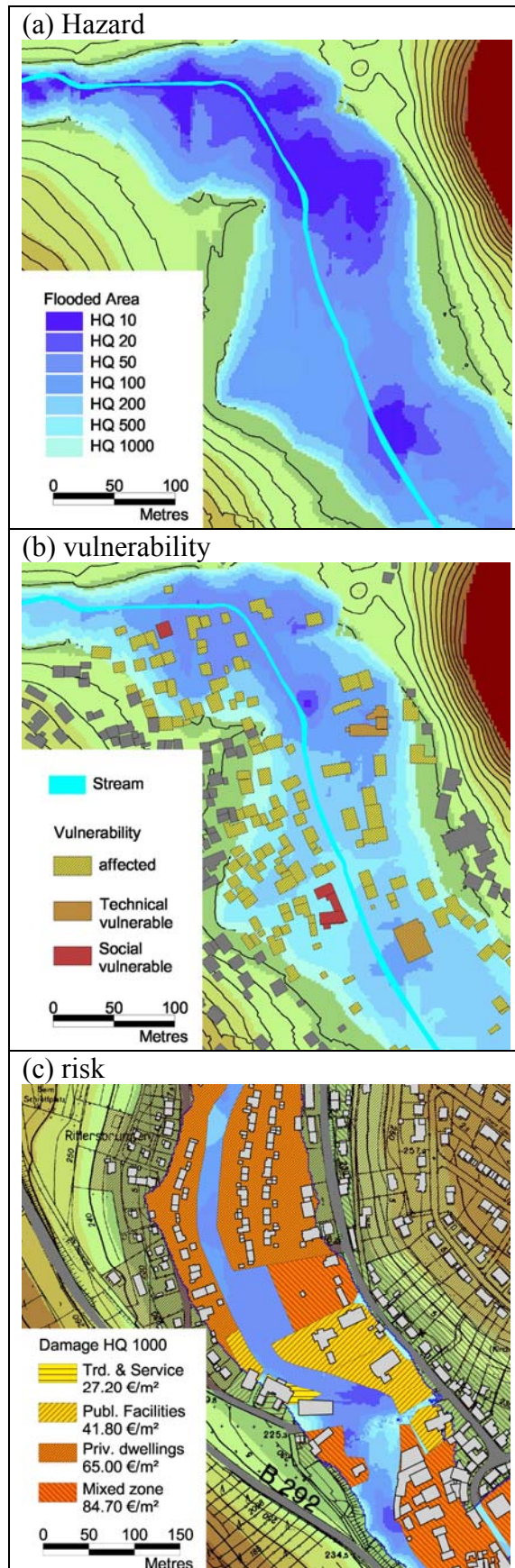


Figure 4: Example of flood hazard, vulnerability and risk maps. Distribution of the damage in €/m² to be expected for the 1000-year flood (source: Merz et al. (2004)).

Ideally, the best model is one in which both sensitivity and error are minimised. Here, a utility function may be implemented to evaluate which complexity is best suited for the characteristics of the study site.

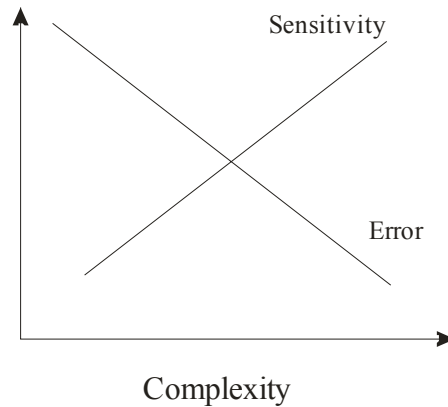


Figure 5: Complexity versus the uncertainty components, sensitivity and error (adapted from Snowling and Kramer (2001))

4. Development of scenarios

The rare frequency of flood events makes the accurate estimation of discharges very challenging. Calculations for design floods and large dams are mostly based on sound extreme value statistics of available digital discharge and water level data. However, as these data often cover short time periods of less than 50 years, the extrapolation can incorporate large uncertainties depending on the distribution function utilized (Stedinger, 2000).

In our study we will develop scenarios for extreme flood events for the entire German part of the Elbe river and for two additional subbasins which exhibit potentially high risk to extreme flooding. One of these subbasins will most probably be the Mulde catchment (6171 km²), which was particularly affected by the August 2002 Elbe flood event. These scenarios will be based on:

- flood frequency analyses of available digital gauge data,
- historic data,
- analyses of time series of precipitation and temperature, and
- development of large scale probable maximum precipitation (PMP) maps.

The Mulde catchment is a particularly interesting study area as it is very heterogeneous in its topography and discharge system (Menzel and Bürger, 2002). Alone digitized daily discharge data from 74 gauges in the Mulde catchment will be analysed, of which 17 gauges have time series of more

than 75 years. Although there is a large number of equally long water level time series, they are currently not yet digitally available.

The comparatively long flood history of the study area provides a good data base of several hundred years for both flood frequency analysis of observed gauge data and the analysis of historic flood events before the beginning of continuous measurements. If discharges and water levels of historic events are known, return periods can be estimated (DVWK, 1999). With the help of these reconstructed historic events an extended flood frequency analysis will be possible.

The first existing document of flooding in the Mulde catchment is from the year 1017. The documents become more comprehensive from 1433 onward. Besides the extreme flood event in August 2002, five other historic summer flood events will be analyzed (1573, 1771, 1897, 1927, 1954). Although summer floods are less frequent, they can cause tremendous damage as experienced in 2002 (DKKV, 2003). Moreover, research will be performed on extreme historic spring floods as they frequently result from a combination of rapid snowmelt and extensive rainfall in this area. Based on the analysis of the historic events maps of inundation and damage will be established. These maps will be used to test the plausibility (validity) of the modelling system for extreme flood events.

In the Mulde catchment a sharp distinction in topography exists, which might influence precipitation types and the distribution of meteorological extremes. Large scale PMP maps will be produced after having analysed a variety of meteorological data such as precipitation and temperature fields. It might be necessary to subdivide the Mulde catchment into smaller catchments or topographic units in order to properly capture the topographical characteristics which influence the PMP distribution. Numerous methods exist to derive PMP maps for both mountainous and lowland areas of different scales and precipitation durations (Hershfield, 1965; Haiden, 1991; DVWK, 1997). The resulting PMP maps will serve as input maps for the modelling system and will be combined with different hydrologic (e.g. soil moisture, dike breach) and land-use conditions for the simulation of extreme scenarios.

By integrating the different approaches of extreme flood risk estimation the uncertainty associated with the distribution function used in the flood frequency analysis will be reduced and thus the estimation of discharge and water levels for rare extreme flood events will be improved.

5. Regionalisation

Discretization

To identify relevant processes, a different spatial regionalisation in different scales will be applied. The hydrological response of the catchment should be adequately represented, hence a requirement of

the hydrological modelling is to account for the spatial variability of landscape characteristics and for the relevant processes (Güntner et al., 2004). Moreover, our objectives are to assess the required complexity level of discretization elements on different catchment sizes. The increased complexity will be achieved by a nesting approach of lumped modelling of sub-catchments, by a discretization of land units (LU) following Güntner et al., 2004), and by the advanced Hydrological Response Unit- (HRU-) concept developed by (Staudenrausch, 2000) (see Table 3). These three different levels will be applied to different scales: the German part of the Elbe basin ($\approx 81.000 \text{ km}^2$) and to the Mulde subbasin ($\approx 6000 \text{ km}^2$).

Conceptualisation

The lumped concept takes no account of spatial variability of processes, input data, boundary conditions, and system geometry. A parameter set of five or less parameters is fitted to an observed rainfall-runoff response, which determines the shape of the stream flow recession curve of the sub-catchment area.

The LU concept is mainly based on the sub-division of the catchment into sub-catchments, which are linked via the river network. The delineation of the topologic based HRU (Staudenrausch, 2000) is based on the process-oriented HRU concept by (Flügel, 1996).

Derivation of discretization elements

A digital elevation model with 75 m resolution and the national land-use map for Germany will be used to derive necessary input data. A subbasin map will be created delineating a number of subbasins within the Elbe catchment with corresponding gauging stations. In addition, the soil map BÜK-1000 and the geological map obtained from the German Federal Institute for Geosciences and Natural Resources (Bundesamt für Geowissenschaften und Rohstoffe, BGR) will be used to derive LUs and HRUs.

Daily precipitation and discharge measurements will be used for the distributed modelling of the Elbe basin, the subbasins within the Elbe basin and for the lumped approach of the rainfall-runoff reaction of the nested subbasins.

After the subdivision of the catchment into sub-catchments which are linked via the river network for the derivation of the LU, the topography characterised by slope gradient, vegetation by land-use, soil and lithology characteristics lead to the final discretization of the LU (Güntner et al., 2004). The HRU delineation will be based on the same physio-geographical properties needed for the discretisation of LU completed with rainfall distribution and aspect. The polygon coverages are transformed into a raster format for use in the overlay analyses. The HRUs are delineated by screening through the

Table 3: Some hydrology models with particular characteristics.

Model	Scale	Stream flow	Snow-	Routing	ETp
Application		components	melting		
J2000 (Krause, 2000), 5 Elbe sub-basins (Krause, 2000; Richter, 2004; Krause, in prep.)	HRUs or raster	direct runoff, interflow, two baseflow components	degree-day, simplified energy balance	kinematic wave	Haude, Wendling, Penman-Monteith
WaSIM-ETH (Schulla, 1997), Thur, Ticinio (Jasper et al., 2004)	Raster	direct runoff, baseflow	simplified energy balance	kinematic wave	Hamon, Wendling, Penman-Monteith
LARSIM (Bremicker, 1998), Neckar (Bremicker et al., 2004)	Raster	direct runoff, baseflow	simplified energy balance	routing from each raster	Penman-Monteith
ARC-EGMO (Becker et al., 2002), 18 Elbe sub-basins (Klöcking et al., 2001)	elementary units, hydrotop classes, subcatchments, and catchment	direct runoff, baseflow	-----	-----	Haude, Turc, Penman-Monteith
SWIM (Krysanova et al., 1998), 25 Elbe sub-basins (Haberlandt et al., 2001)	Hydrotopes, subcatchments, and catchment	direct runoff, interflow, baseflow	degree-day	Muskingum-Cunge	Priestley-Taylor, Hart-graves, Penman-Monteith
HBV (Bergström, 1995), Mulde (Menzel et al., 2002), Elbe basin, 44 Elbe sub-basins (Krysanova et al., 1999)	sub-basins	direct runoff, interflow, baseflow	degree-day	Muskingum-Cunge	-----

various raster files and sorting of those grid cells which fulfill common physiographic criteria defined by the analyst. The topological flow routing between HRU sub-areas will be integrated into the process based distribution concept (Staudenrausch, 2000).

6. Runoff generation

Among the distributed models that have been applied at larger scales (see Table 3) the model J2000 has proven to be a robust tool for the assessment of the runoff dynamics of the Elbe subbasins Mulde, Unstrut, Orla and the Wilde Gera (Krause, 2000; Richter, 2004; Krause, in prep.). The system J2000 is implemented inside the NetBeans (2004) environment in Java, which makes the system independent and flexible. It is a toolbox that can be adapted for specific needs. The system core and the more generic components are strictly separated from the modules representing the hydrological processes. These modules simulate evapotranspiration, interception, snow, soil water, groundwater and flood routing from the knowledge part of the system components are implemented as separated modules (Krause, in prep.).

Following Flügel (1996) the inherent HRU concept is a reliable method for the hydrological basin modelling and allows spatial scaling. The spatial variability of landscape characteristics will therefore be adequately represented for the investigation of an appropriate complexity level. Prange et al. (2000) showed that snow storage and melting are the most important factors for flooding in the Elbe basin. Hydrograph separations by Uhlenbrook et al. (2002) demonstrated that 50% of the runoff during peak flow was event water with a residence time of several hours to a few days. In J2000 the event water can be represented by the two flow components, direct runoff and interflow.

The advantages of the model are the:

- possibility to scale in different complexity levels,
- account of snow melting in two different approaches,
- separation of the simulated flow in four components and coverage of the most important runoff-generating processes, and
- flexibility to implement further modules.

7. Routing and dike failure

Table 1 shows the different complexities of routing that will be implemented in the modelling system. A short description of each method will now be given:

Muskingum-Cunge

The Muskingum-Cunge routing technique can be used to route either lateral inflow from either kinematic wave overland flow plane or lateral inflow from collector channels and/or an upstream hydrograph through a main channel. The channel routing technique is a non-linear coefficient method that accounts for hydrograph diffusion based on physical channel properties and the inflowing hydrograph. A mathematical description and methodology can be taken from HEC (1998) from which this excerpt has been taken.

The advantages of this method over other hydrologic techniques are the:

- parameters of the model are physically based
- method has been shown to compare well against the full unsteady flow equations over a wide range of flow situations and
- solution is independent of the user specified computation interval.

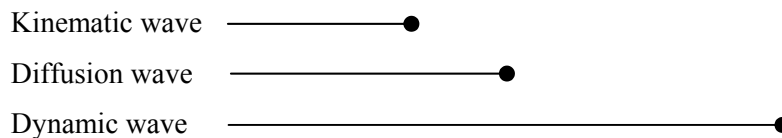
The major limitations of the Muskingum-Cunge application are that

- it can not account for backwater effects
- the method begins to diverge from the full unsteady flow solution when very rapidly rising hydrographs are routed through very flat slopes (i.e. channel slopes less than 0.2 m/km).

Kinematic and Diffusion Waves

The kinematic wave and the diffusion wave are both derived from the St. Venant equations in its simplified forms. The St. Venant equation for momentum is given by (Chapra, 1997):

$$0 = \underset{(1)}{g \cdot S_f} - \underset{(2)}{g \cdot S_o} + \underset{(3)}{g \frac{\partial y}{\partial x}} + \underset{(4)}{\frac{1}{A} \frac{\partial}{\partial x} \left(\frac{Q^2}{A} \right)} + \underset{(5)}{\frac{1}{A} \frac{\partial Q}{\partial t}}$$



where: A = cross-sectional area, g = gravitational acceleration, Q = discharge, S_o = channel slope, S_f = frictional slope, t = time, x = longitudinal distance, y = lateral distance. The terms are: (1) friction force, (2) gravity force, (3) pressure force, (4) convective acceleration and (5) local acceleration.

The kinematic wave is the most simplified case in which the pressure and acceleration force terms are dropped so that

$$S_f = S_o$$

which can be solved together with the continuity equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

Theoretically, a flood wave routed by the kinematic wave technique through the channel is translated, but does not attenuate. Consequently, the kinematic wave routing technique is most appropriate in channels where flood wave attenuation is not significant, as is typically the case in urban areas (HEC). Another disadvantage of this approach is that back-water effects cannot be considered. The diffusion wave, however, includes the pressure force allowing back-water effects to be simulated in the routing. This approach has been implemented for the German portion of the river Elbe (Helms et al., 2002) and will be extended for the Mulde river in this project.

Dike failure

A module to derive probabilities of dike breaches along the course of a river has been developed at GeoForschungsZentrum Potsdam and tested for the lower Rhine river (Apel et al., 2004). Failure probabilities are estimates of dike failure at certain points, representing the measurement error of the dike geometry. Consideration of the spatial variability of the dike geometry and the length effect of different long river stretches on the failure probability is still in development. For the calculation of the (point-)failure probability of a dike, a breach condition is defined as the exceedance of a load factor over a resistance factor. This concept was applied to dike failures caused by overtopping of the dike crest which is the most common failure mechanism of modern zonated dikes. The breach criterion was defined as the difference q_D between the actual overflow q_A (the load factor) and the critical overflow q_C (the resistance factor):

$$\text{if } q_A > q_C \rightarrow \text{breach}$$

or

$$\text{if } q_D > 0 \rightarrow \text{breach}$$

8. Flood water dispersion

To determine the hazard of floods and quantify their risks for cities and communities near rivers, the relevant hydraulic processes of stream flow need to be analysed. Here, two approaches can be used which are broadly classified as (Arora et al., 2001):

- *hydrodynamic-numerical (HN) models* - based on the St-Venant formulations (described earlier) consisting of a continuity equation which describes the balance between input, storage and output in a river section and a momentum equation which relates the change in momentum to the applied forces (Oberle et al., 2000);

- *hydrological routing* – also based on the continuity equation but replaces the momentum equation with empirical relationships (e.g. Muskingum-Cunge as described above).

The former has a more complex description of the flow processes and provides more accurate results but has a higher demand for data and require far more computational resources.

For the simulation of dynamic flooding processes in inundated areas (e.g. the propagation of flood waves caused by dike breaches or the diversion of flood water through a polder system), fully-dynamic two-dimensional (2D) HN models are normally used. With these models it is possible to obtain information about flood depth and flow velocity with a high temporal and spatial resolution. The limiting factors of the application are the computing power and time expenditure for the simulations. As one-dimensional (1D) models need minutes to some hours for calculations the computing time for two-dimensional models is from hours to several days. Hence, it is the aim of this work package to implement less complex variants of the 2D HN models and determine if these simplifications retain their descriptive power and accuracy for the characterisation of the flooded regions. The variants of the fully-dynamic 2D HN models in order of decreasing complexity include:

- *2D HN model with lower resolution* – the computing time of a fully 2D model can be shortened by reducing the number of the computational cells which retains the extension of the area but with a lower spatial resolution.
- *Simplified 2D model* – the required computational power is mainly determined by the complexity of the hydraulic equations. In a simplified 2D model terms of the hydraulic equation are assumed negligible and omitted which reduces computational time. The spatial resolution remains the same as in a fully 2D model.
- *Simplified 2D HN model with lower resolution* – combination of the first two simplifications in which spatial resolution and process description are both reduced.
- *Branched 1D model* – comparable to branched river systems in which the inundated area is discretized as a network of flow paths and retention cells and requires only a 1D description of the flow equations.

All the variants are to be compared with the fully 2D model in order to test their utility in terms of accuracy of the results, computing time and required computational power.

9. Modelling system

The challenge of integrating various models in one modelling system resides in the selection and implementation of a coupling approach capable of running a continuous simulation and ensuring information transfer between system components. One can distinguish between loose model coupling based on automated data transfer in a predefined format at runtime and integrating modelling components within a modelling framework by implementing standardised interfaces. The latter

approach leans towards the development of modular modelling systems and is currently being explored in several research groups. Examples are the Object Modelling System (OMS) (David et al., 2002) and the Open Modelling Interface (OpenMI) (Blind and Gregersen, 2004). However, these modelling frameworks are still in development but seem to offer a rather promising future.

The successful selection of a coupling approach depends on the fulfilment of the following criteria:

- it should be capable of integrating legacy model codes (hydrological, hydrodynamic, dyke breach and water dispersion) implemented in heterogeneous programming languages (Java, FORTRAN);
- it should be easily implemented and require minimum changes in a source code of existing models;
- it must allow distributed simulations on a number of computing platforms (Windows, Linux);
- the software should be free of charge with the open standardized interfaces in order to ensure non-restricted technology transfer to other users or to the developer community.

The High Level Architecture (HLA) (<https://www.dmsomil/public/transition/hla/>) and the Typed Data Transfer (TDT) (<http://portal.pik-potsdam.de/research/topiks/topik7/simenv/modenv/tdt>) are loose coupling approaches and are considered for creation of a modelling system.

The HLA was developed by the US Ministry of Defence and is a free software up to version 1.3, consisting of a Runtime Infrastructure (RTI) and a set of open interfaces for coupling models (called federates) into a modelling system (federation) (see Figure 6). It was originally developed for integrating complex military simulators, however, is extensively used for production simulations and in some environmental modelling applications (Lindenschmidt et al., 2004). Although it allows extensive control over simulations, particularly with regards to simulation time management, the system seems to be rather complex for simple data transfer and requires significant changes in the source code. Furthermore, the available interfaces are applicable only for C, C++ and Java simulators, whereas for models coded in FORTRAN an additional wrapper needs to be developed. Finally, the HLA is being transferred from a free to a commercial product and is no longer supported by the developer on a free basis.

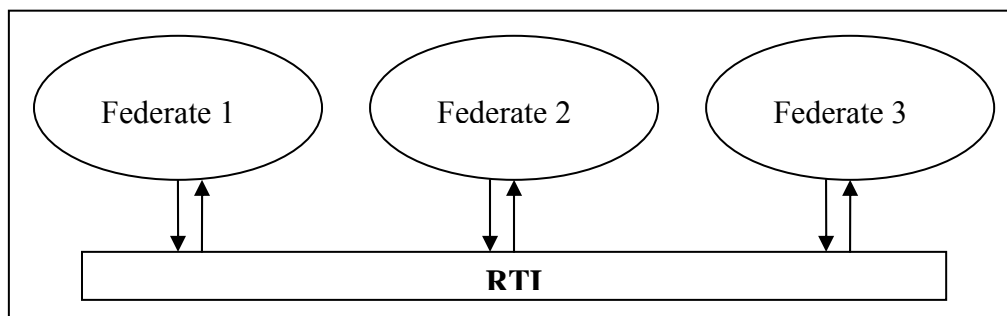


Figure 6: Schematical representation of the HLA architecture.

Contrary to the HLA, the TDT library developed by the Modelling Environment (ModEnv) Group at the Potsdam Institute for Climate Impact Research (PIK) is freely available under the GNU General Public License (GPL) and represents a simple interface of data transfer between the computer programs across the computing platforms. Schematically, loose model coupling using the TDT library is shown in Figure 7. The data of primitive data types are passed to the local host (socket) by calling the TDT library functions in a modelling code, where a subscribed listener can read the data. The data is transferred according to the specified XML description. TDT is developed in C and currently supports C, C++, FORTRAN and Python interfaces. The recently developed Java interface has been successfully tested. The TDT is easily implemented in a modelling system requiring a minimum change in the models' source code. The ease of implementation and availability of support favours an application of the TDT library for coupling the models. However, the model programmer is responsible for the correct synchronisation of the data transfer in order to avoid the 'dead lock' situation, where the simulators are waiting for the data and cannot proceed with the simulation any further. A disadvantage of TDT compared to HLA resides in a slower computation progress because a server model in TDT can wait for an available client, whereas in HLA the data are passed to the RTI in the absence of client and further computation step can be initiated. This performance difference might be relevant for Monte Carlo analysis, where several thousand model runs are performed.

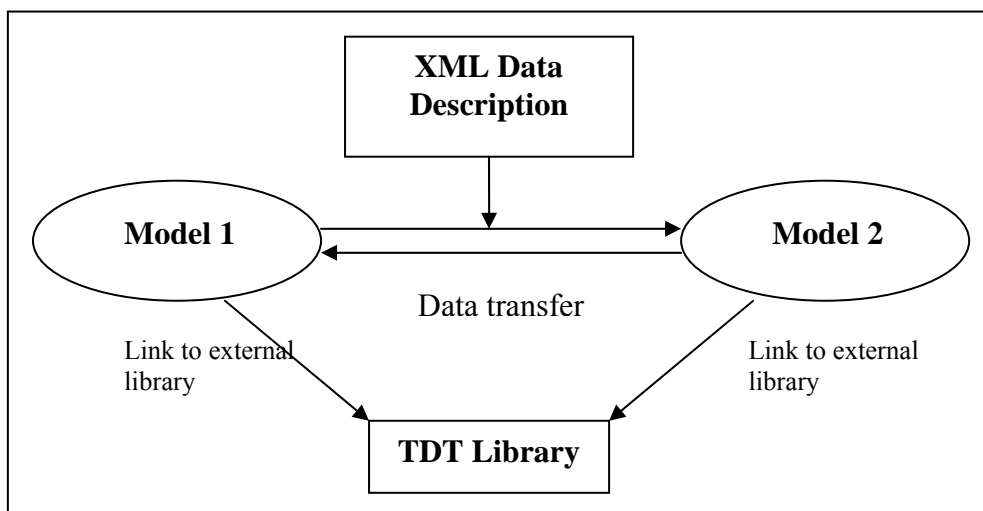


Figure 7: Schematic representation of the TDT architecture

Taking into account the large data flow in a simulation process the necessity of implementing the database component in a modelling system might arise. The free PostgreSQL/PostGIS – spatially enabled database supported by the GRASS geographical information system can be set up. This architecture further supports the implementation of the free available UMN Internet MapServer (<http://mapserver.gis.umn.edu>) for communicating, for instance, the flood risk maps to the public. This spatial data architecture can be quickly set up with moderate experience requirements and is, for

example, implemented in the FLUMAGIS project (May et al., 2004). However, the challenge is faced in integrating the database with the modelling components to ensure efficient data accommodation and retrieval.

The modelling system comprising the process description of various complexities would allow the uncertainty of the system's structure to be analysed and compared with other sources of uncertainty. A convenient user interface should be provided in order to chain process modules of different complexity in a modelling system. Georgakakos et al. (2004) mentions a number of studies investigating the input data and parameter uncertainties, whereas very few studies are dedicated to the model structure uncertainty. Butts et al. (2004) reason the lack of such studies by the small number of available modelling systems allowing the process mixes of different complexity. Although the experiment with the NAM (Nielsen and Hansen, 1973) / MIKE11 (<http://www.dhisoftware.com/mike11/index.htm>) / MIKE SHE (Abott et al., 1986a, 1986b; Refsgaard and Storm, 1995) modelling systems indicates that the model structure can significantly contribute to the total model output uncertainty for stream flow simulation. Furthermore, application of an ensemble of the models characterized by varying complexity can provide a better performance than a single model (Georgakakos et al., 2004, Butts et al., 2004).

The quantitative description of the modelling system structure uncertainty is aspired in this work, so that it can be related to the resulting error and sensitivity. Finally, the optimal structure complexity can be derived for a particular problem and input data availability constraints minimising the error and sensitivity.

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