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PC-RIVER - PROBABILISTIC RELIABILITY ANALYSIS FOR RIVER DIKES

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ABSTRACT: Traditional dyke safety analysis in Germany is based on mean values for hydraulic parameters. Since measured input data suffers statistical uncertainties, the output data variation range is unknown for calculated flood events different to the original calibration datasets. Additionally, dyke resistance against hydraulic impact suffers statistical uncertainties as well. A probabilistic design concept which accounts for the parameter statistics is applied in the PCRiver project, which is part of the German research activity “Risk Management of Extreme Flood Events” (RIMAX). Hence, the hydraulic loading of dykes must be specified by the statistical mean and the respective higher moments of all physical parameters involved. For this project, the PCRing software, designed for the Dutch delta areas, is adapted to lowland rivers. The Upper Elbe River is presented as an example. The hydraulic uncertainty analysis is based on a Monte Carlo Simulation with the 2D hydrodynamic numerical model “Flumen 2.0” The presented probabilistic and numerical analysis provides a useful tool for water authorities as well as consulting companies in order to make risk-based decisions in structural river flood protection. For further project information see the accompanying paper “RELIABILITY ANALYSIS FOR RIVER EMBANKMENTS USING ANALYTICAL METHODS AND FINITE-ELEMENTS” [Möllmann, Vermeer, Westrich] which is also part of the “Symposium on Flood Defense 2008” proceedings.

Key Words: Reliability Analysis, River Dike Stability, 2D-HN-Model, Monte Carlo Simulation, Probabilistic Dike Design

1. INTRODUCTION

1.1 The RIMAX PCRiver Project at the Elbe River in Saxony

Almost 70% of all Eastern German dikes were older than 70 years when the 2002 flood event hit eastern Germany and Czechia. A significant percentage of these dikes were build during the emperor’s days in the 19^{th} century by armies and bondsmen. Densification methods were manual, materials were chosen by shortest transport ways and steepest slopes reduced the dikes soil volume. Even trees within crests and slope could be found in some sections. During the days of the German Democratic Republic no significant improvements were made. During the 90’s and after the big flood in 2002, which reached a recurrence period beyond 1000 years in some areas, reconstructions and new measures improved most dikes. But up to day, there are still some of these oldest dikes waiting for maintainment.

In spring 2006 another outstanding event hit the project area. This time the flood wave was almost as high and even longer than in 2002, but with a less damage to the reconstructed dikes in Saxony and

Saxony-Anhalt. Therefore no dike break related retention effects reduced the discharge, and the Lower Elbe was hit even stronger than in 2002. (IKSE, 2004)

In the aftermath the search for a more reliable and more economic dike design was the consequence. International and interdisciplinary projects provided a very good data fundament, which is only available at few rivers, for new research and design projects.

1.2 The Probabilistic Idea

1.2.1 Weaknesses of common dike design rules

Common Dike Design approaches in Germany and most other countries are based on fixed design values for dike geometries, materials, hydraulic and hydrological parameters. A lumped parameter, like Manning's or Strickler's roughness coefficients, cannot reflect the uncertainties of hydrological, hydraulic and topographical data as well as numerical models own uncertainties.

Alternating wind directions and linked wave effects, changing roughness due to seasonal vegetation and morphological processes might affect local water levels. Additionally, increase of flow resistance due to sediment transport processes can have a significant impact. Therefore, each category of input data has a statistical variance that impacts water levels and flow velocities. In common design methods all these uncertainties are compensated by adding a more or less fixed freeboard to the necessary dike height.

1.2.2 Consideration of Variability for dike design

The probability distribution of these input parameters is normal distributed in most cases. (fig 1). If we look on the discharge, for example, hydrologists give us statements like this:

$HQ_{100} = 3500\,m^3/s$ +/- $500\,m^3/s$ (95% confidence interval)

Converted to water levels, we have to expect variability in our dike load *L*, also named as stress *S*, of up to 40 cm in the narrows of the Upper Elbe to some centimeters in the vast floodplains of the Middle Elbe region. The above stated parameters, retention effects due to breaches or polder flooding and many other effects superpose and result in sometimes lower, sometimes higher water levels for the same discharge. In a view cases it might be much higher, or much lower. But mostly it is somewhere in between the extremes. Failure is the consequence if the stress, in form of water levels or shear stress, exceeds the maximum resistance of a defense measure.

1.2.3 Limit State Equation

To combine these probability distributions, the "Limit State Equation" $Z = R - S$ serves as governing formula. It can be calculated easily with the "first order second moment" method (FOSM). Failure occurs if $Z < 0$. Both input parameters R and S have a mean value (μ_S, μ_R) and standard deviations (σ_S, σ_R). Mean value and standard deviation of the target function are defined as

$$\sigma_z = \sigma_R^2 + \sigma_S^2 \qquad \mu_Z = \mu_R - \mu_S \qquad \beta = \frac{\mu_z}{\sigma_z}$$

The safety index β, helps to obtain the failure probability by using the standardized normal distributions probability function. The total failure probability equals the integration of –infinite to β. (Plate 1998) This method is fast in usage but not that easy to grip. The more understandable Monte Carlo method, on the other hand, is more laborious to perform as we will see during the next chapters.

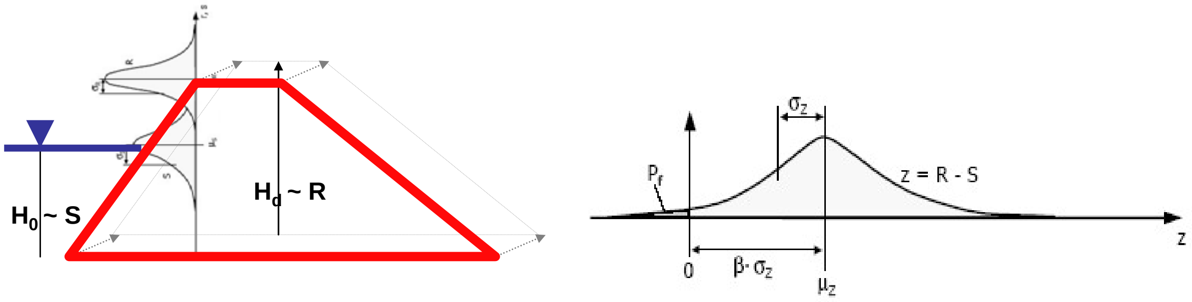

FIGURE 1 - Left: FOSM - Varying water levels meet varying dike heights, failure occurs when R < S .
Right: PD-function of Z; the probability of failure equals the area in the negative quadrant.

1.3 State of the Art in probabilistic dike design

The limit state equation and the probabilistic approach are known in many familiar engineering disciplines for some decades. Especially mechanical engineers or structural engineers work with these methods. For dike safety this concept is up to day only available as proprietary system for Dutch delta dikes (PCRing) and the German ProDEICH sea dike system.

1.3.1 The Dutch Software PC-Ring

As most parts of the Netherlands (>70%) are below 5m above medium sea level, dike strength has an outstanding priority and needs economic considerations. Therefore in the early 1990's Dutch Authorities established a probability based flood design method which is mainly based on the software PC-Ring. This software combines more than 50 variables of geotechnical, hydraulic, geometric and spatial character to estimate a failure probability for every single dike section in a specific dike ring. Probabilities of all sections are combined to a total failure probability. A risk based approach then enables planners to find those sections, where the available financial input results in best benefits.

This software, quite unique up to date, still holds a couple of simplifications which keep it from being set to action in Germany. These simplifications include: The uncertainties of river water levels might be low for Dutch lowland rivers, but it is not in mountainous influenced areas like the Upper Elbe or the Iller.

1.3.2 Transfer of PC-Ring to the Severn Estuary in the UK

In 2003 another Dutch / British research group set up a PC-Ring based project to analyze the Severn Estuary in the UK. This area, again with coastal background, is influenced by one of the world's highest tidal ranges varying between 9 and 15m. (Buijs 2003) This project was the first conversion of the proprietary Dutch software to a different area and a new failure mechanism was included: failure of wave return walls. Despite a quite weak data fundament, the conclusion could be drawn, that overtopping and failure of wave return walls are the weakest points in this area.

2. OUR APPROACH

The transfer of the Dutch PC-Ring to the Elbe River in Saxony gives a first example for probabilistic river dike analysis in Germany. A couple of adaptations have to be made to transfer the software, developed for a delta, to fit the characteristics of a mountainous influenced lowland river. The hydraulic part will be explained in chapter 2.1. The geotechnical adaptations will be briefly mentioned in 2.2 and discussed in the accompanying paper "RELIABILITY ANALYSIS FOR RIVER EMBANKMENTS USING ANALYTICAL METHODS AND FINITE-ELEMENTS" [Möllmann, Vermeer, Westrich]

2.1 Dike stress *S* and its uncertainties

The main stress component that hits a single dike is the hydraulic head and in exposed positions, the flow velocity. Most geotechnical failure analyses need these parameters as input. For additional parameters, like ice, human failure or secondary catastrophes only unsecure databases are available. At least for wind effects, cause for a superposing hydraulic head, an additional input parameter set is implemented. The most promising method to model the dike stress S (W.L. & V) which depends on dozens of different parameters is the Monte Carlo (MC) Simulation. By calculating numerous variations for a given flood event with randomized input parameters, a reality near W.L. probability distribution is constructed.

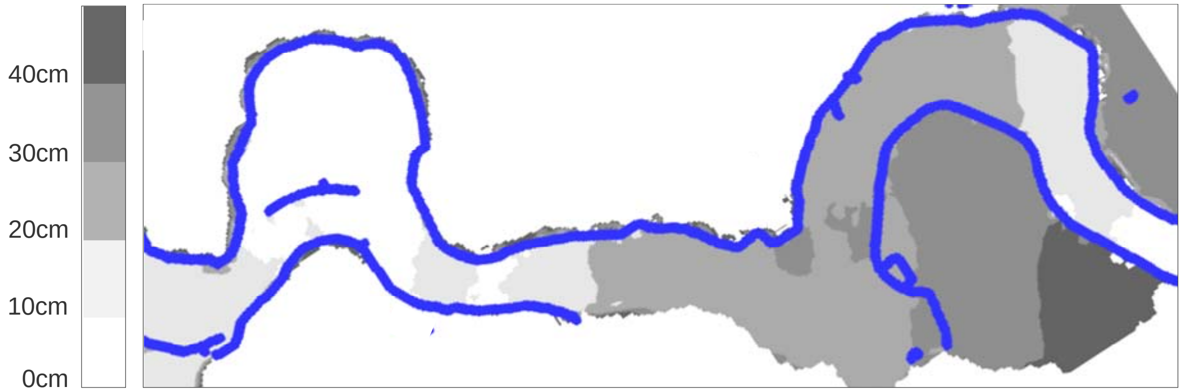

FIGURE 2 – Example: standard deviation of 68 simulated water levels between and behind dikes

However, the MC method is very time-consuming if applied to 2D hydrodynamic models, as they are necessary for meandering rivers. Reliable predictions for the standard deviation correlate with the total number of calculations. Some hundred cycles are a minimum requirement for a large scale investigation, like the case study project. Therefore, the applicability of the MC method depends on the performance of the 2D-HN-model. An independently developed adaptive mesh generator is used to produce resource saving 2D-meshes with a defined quality standard. It applies newly developed adaptive algorithms with a minimum amount of geometrically reliable cells per km² which enable fast calculation cycles. Quality is ensured by validation on high resolution reference models (Merkel 2008).

2.1.1 Dike load - Calculated with a 2D Model

Hydraulic simulations as shown in figure 2 have to be performed with a 2D-HN model which is based on adaptive meshing algorithms for better performance. Calculated with "*FLUMEN 2.0",* a single calculation for the 140km² reference area needs less than 3 hours on common desktop computers. The mesh is based on laser scan data and land use break lines. All break lines had to be generalized to a minimum number of points with specified minimum distance to the next neighbors. A couple of new algorithms are implemented here. These include a "minimum fix point distance" filter, break line generalization filters, minimum angle for cutting lines and minimum triangle filters. Parts of the model might be substituted by inline 1D–HN models for a further speed up. Additional break lines, generated from specific flow distributions, enable an automatic mesh densification in zones of strong flow inhomogenities.

The areas between the line graph is filled with terrain adapted Delaunay conform cells. Finally the whole model was calibrated with vessel based water level measurements from the 2 major floods previously mentioned. Further validation for the adaptive algorithms is based on the W.L. and velocity comparisons to a 2D model with highest possible resolution.

2.1.2 Set-up for the Monte Carlo Simulation (MCS)

Although the MCS has an attribute to be a brute force method, the setup requires some deeper thoughts to ensure a minimum amount of samples and meaningful results. A calibrated 2D master model is the basis for all variations. Its settings are assumed to be the average values for the further examinations. In a single calculation all parameters are randomly variegated within their specific probability distribution. 1200 randomly generated input jobs are generated and calculated as batch jobs. (See 2.1.3. for further information). The results are then combined to two georeferenced grid files. One shows the average water level and another one the standard deviation. These files serve as input for the geotechnical analysis of chapter 2.2. Multivariate statistics help to find the major contributions to all uncertainties.

2.1.3 Water levels and Velocities

For every parameter typical variation rules had to be defined. These are based on own data analysis, data providers information and an extensive literature research. The following deviation values for the most important parameters are common 95% confidence intervals.

2.1.3.1 Discharge

It is hard to define a clear discharge vs. recurrence interval relation. More than a dozen different research groups examined the gauge in Dresden during the last decade and the results for HQ100 ranged between 3500m³/s and 4800³/s +/- 10% for the 95% confidence interval. Different statistical methods, different timeline length, bed development and a couple of newer extreme events were the main reasons. Even if we chose studies that seam reliable to us, the calculated water levels vary more than 30 cm for the 95% confidence interval.

The date of occurrence influences the water level additionally. Due to the changing vegetation throughout a typical year, the week of occurrence plays a significant role on friction parameters and the resulting water levels. The problem is simulated as follows: The daily values for “dike wetted or not wetted” since 1951 have been sorted in 53 probability classes. The time of occurrence is then randomly chosen according to a filtered class distribution of figure 3. See Chapter 2.1.3.3 for further information.

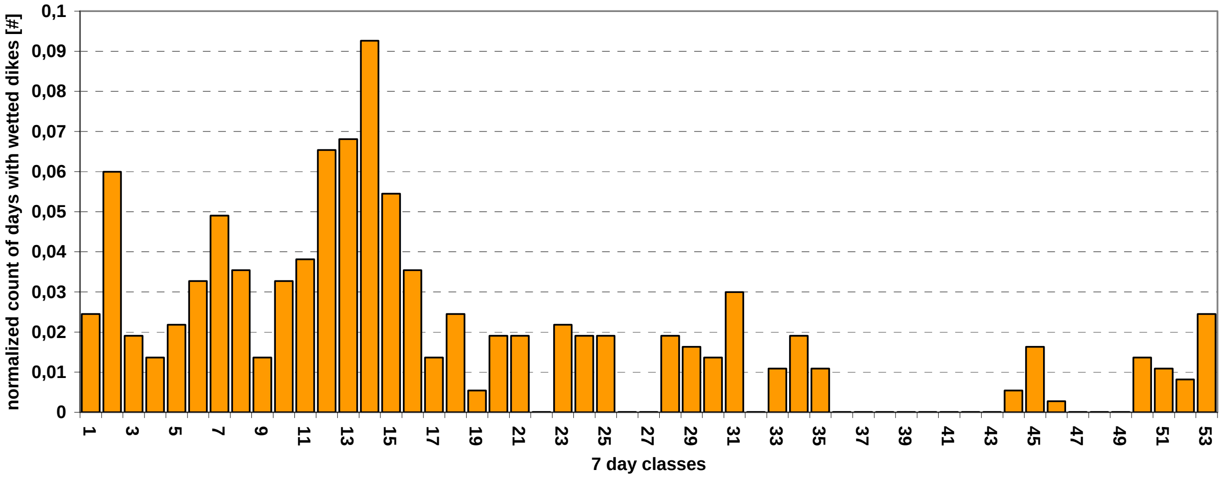

FIGURE 3 - Overbank flooding in 7 day classes – normalized counts 1951 - 2005

2.1.3.2 Topographic Information

Laser scan based digital elevation models, advertised with theoretical accuracies of up to +/- 5cm on asphalt were proofed as far worse than 20cm throughout an average project area in several studies. This equals one sand pack layer along the dikes. Ultrasonic sounders for vessel based bed measurement produce even rougher results. (See especially BAFG 2005 for further information)

All together we came to the conclusion that an average DEM error for the wide spread laser distance sensor generation between 2001 and 2004 can be estimated with +/- 25cm for the 95% confidence interval. This is valid after the elimination of systematic errors caused by flight path, sensor mount and GPS uncertainties. The main reason is the land use dependent reflection characteristic of the laser beam. (Göpfert 2007). For the simulation therefore a random elevation error correction was implemented based on polygons with land use information.

2.1.3.3 Friction

For roughness parameters, as the most important adjusting screw for HN-models, the situation is a little bit more complicated. An areas Strickler coefficient k_{str} (= 1 / mannings n) is influenced by a lot of different effects. These values are normally processed by simulation of more or less well documented flood water levels.

Unfortunately vegetation, which is the major contribution to this parameter, changes a lot during the year. As the most impressing example serves corn which sometimes might reach a k_{str} of $4m^{1/3}{}_{/s}$ (See Hartlieb 2006). After harvesting, Stricklers k_{str} has the value typical for bare acres which might be around 25 $m^{1/3}{}_{/s}$. The rest of the year the friction influence ranges in between these extremes. Due to lack of reliable literature values for theses annual cycle, we assumed a relation between the yearly biomass balances. It describes the growth of crops or grass as well as leaves and therefore has a strong correlation to friction values. After the characteristics of the biomasses annual curve is fitted to the minimum and maximum friction values of a specific land use we obtain figure 4.

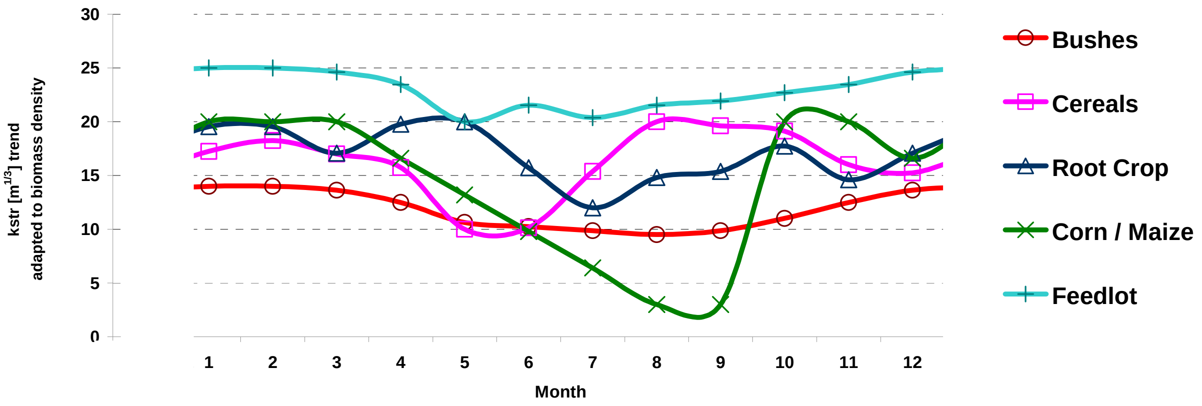

FIGURE 4 - Specific roughness parameters throughout a typical eastern German crop cycle. Assumption based on biomass integration. (Manning’s n equals 1 / kst in this presentation)

The simulation of a friction variation I in our program then is performed by choosing the time *t(I)* during a typical year when the hypothetical event takes place, for all land use polygons (according to the description in 2.1.3.1). For every land use polygon J, we take the roughness coefficient as it was obtained by the models calibration to a certain historical event (in our case August 2002 & April 2006). Then we convert these parameters according to figure 4. Finally these values are randomly modified within the vegetation type’s usual normal distributed bandwidth.

$$k_{str,I}(J) = k_{str,Calibration}(J) + \Delta k_{str,Timeshift,Global} + \Delta k_{str,Random,Local}(J)$$

2.1.3.4 Morphological aspects

For normal situations erosion and sedimentation are well examined (Faulhaber 2007) and the balance is almost zero in our example section. But bed forms occur.

Within the Elbe example section ripples with a size of up to 30cm and an average grain diameter d_{50} ~ 2mm can be found. The development of bed forms and their flow resistance during flood events with the characteristics of 2002 and 2006 are examined (fig. 5) and translated in a 95% confidence interval for the mainstreams Manning / Strickler coefficient. This parameter has a strong correlation to a flood event's duration. Several research projects examined resistance due to bed forms. Einstein, Engelund, van Rijn and others were compared to approximate these effects.

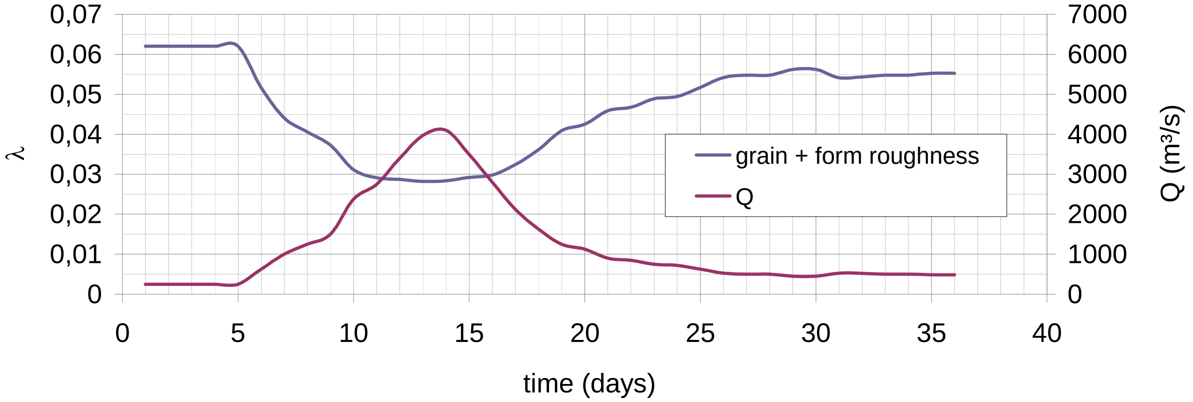

FIGURE 5 - Main bed roughness for August 2002; considering bed form development, estimated according to Vanoni & Hawang; average values for Elbe-km 121 to 180

2.1.4 Wind

Wind in general influences the water level mainly by superposing waves, or in deltas like the Rhine, by storm floods. The wind effect itself is not considered in our hydraulic analysis. It is given as an extra parameter group and calculated separately in PC-Ring by using the Brettschneider model.

2.1.5 Secondary aspects

Other aspects like the interaction between water levels and dike breaches or overtopping can be considered within a certain band width by the hydraulic model. But it is not possible up to day to characterize all parameters with influence to the flow regimes. Other hard to describe uncertainties are:

- Ice effects were seldom in the last decades, compared to the last centuries. Unfortunately there is no reliable statistic about ice drift dependency of rising water levels and dike surface erosion.
- Secondary effects caused by extreme weather conditions (e.g. land slides, storm damages, unavailability of service personal for technical measures)
- Temporary blockages of bridges and narrows by trees or abandoned ships
- Planners and Data providers errors

2.2 Dike Resistance *R* and its uncertainties

Some dozens of empirical design rules for probabilities of different failure modes like overtopping, piping, slope instability or damage of revetment have been included in PCRiver. But as usual these one dimensional functions need assumptions and simplifications. The combination of all failure mode probabilities leads to a combined failure probability which is comparable in between neighboring dike sections. Dike resistance depends on geometrical form and material distribution and their subsoil. The soil material parameters, mainly densities, void ratios, friction angles or cohesive effects influence the resisting forces. Information for soil parameters is normally available at discrete drilling profiles. Their uncertainties are inherited to the dike safety calculations. In between the drilling points all information has to be interpolated. Kriging offers good possibilities for spatial interpolation of soil parameters and their standard deviation, which increases with the distance from the drilling points.

Further information on dike resistance and failure mode combinations is discussed in the previously mentioned accompanying paper of our geotechnical project partners [Möllmann, Vermeer and Westrich].

3. CONCLUSION AND OUTLOOK

The project will be finished in Dezember 2008 and first results proofed our expectations (like fig.2 and the accompanying paper). This has to be imputed especially to the extraordinary good data sets, provided by local and federal water authorities: the LTV Sachsen, the BfG, the BAW, and the WSA Dresden.

PCRiver enables a probability based dike design in a comparative way. Due to the still not deniable rest risks from nowadays incalculable parameters, the determined probabilities enable especially a good relative comparison between neighboring dike sections. This is a good fundament for economic calculation, as a spare budget can be distributed especially to the sections were it is needed most. As the probabilistic method still has not managed the jump from academic institutions to practical planners in Germany, a monetary risk analysis is performed as an example for interested authorities and planners. As the character of the river still accounts for the usability of the concept, we are going to validate all subprojects on a second reference project, the Iller River. This more alpine influenced river with different soils and hydropower plants again adds new aspects to the insecurities.

All efforts lead to an adapted PC-Ring software package, than called PCRiver, and a second software package that enables the connection of statistically processed hydraulic data for the stress input values. The hydraulic model generator, which is not project specific, is improved due to the projects needs for resource saving high performance meshes and might also be used for operational 2D-HN-models. (*see* Merkel 2008).

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