 https://doi.org/10.1051/e3sconf/20184006014

The German National Flood Protection Programme: Evaluating the impact of supra-regional flood protection measures on extreme floods using hydrodynamic modelling

Carina Schuh* and *Marcus* Hatz

Federal Institute of Hydrology (BfG), Department of Water Balance, Forecasting and Predictions, 56068 Koblenz, Germany

Abstract. After the disastrous flood events of June 2013 in the German Elbe and Danube catchments, the German government together with the federal states decided on the joint elaboration of a nationwide flood protection programme (NHWSP, 2015-2027+). Within the frame of this programme, the government supports the realization of large-scale retention measures for the improvement of supra-regional flood prevention. For scientific monitoring, the Federal Institute of Hydrology (BfG) was mandated to conduct a two-part preparatory *ad hoc* study (2014-2015) and a subsequent research project (2015-2019) evaluating the collective impact of the planned retention measures on flooding processes and flood peak reduction in the Danube, Elbe, and Rhine basins. Findings from the *ad hoc* study provided the government with first elements of evidence for taking its decision on the elaboration of the NHWSP programme, and supported the development of a modelling strategy for the accompanying research project. By using extensive sets of hydrodynamic models, the research project takes into account the complex interrelations between supra-regional flood formation, flooding process, and retention control concepts when evaluating flood reduction on catchment level. It is expected to technically substantiate the government's NHWSP programme by refining the criteria for identification and prioritization of measures.

1. Introduction

In the recent past, many countries have experienced major river floods beyond historic records: Czech Republic and Germany in 2002, the United Kingdom in 2007, Australia and Bangkok in 2011, New York in 2012, Germany in 2013, and the United Kingdom again in 2015/16. Climate change is likely to exacerbate the increasing trend of heavy precipitation events and related flooding in the near future, and at the same time, vulnerabilities of modern societies and metropolitan areas in particular are constantly rising due to population growth and the increase in socio-economic activities in flood-prone areas [1-3].

* Corresponding author: schuh@bafg.de

The economic impact of a major flood event can be significant on national level. In Japan or the Netherlands, for instance, about half the population and three quarters of its economic assets are located in flood-prone areas [4, 5]. In France, a major flooding of the Seine river in the Paris-Île-de-France region is projected at up to €30 bn excluding macroeconomic impacts [3], and the disastrous floods of 2002 and 2013 in Germany together caused the state a direct damage of about €20 bn [6]. Given the impact of major flood events for the national state, its level of protection and resilience should also take a more than local, larger-scale approach [3]. As a matter of fact, major flood disasters have already acted as catalysts for changing flood risk management policies on national level [1].

The Netherlands, for instance, after being hit by extreme discharges in 1993 and 1995, adopted a new "living with water" strategy promoting the idea to accommodate extreme events rather than fight them with heavy infrastructure. As a deliberate alternative to the former technocratic approach, the project "Room for the River" now supports 39 river-widening measures to allow for higher river discharges and to improve the spatial quality along the Dutch river systems [4, 7].

These two consecutive extreme flood events at the Rhine led to a paradigm shift in Germany, too. The guidelines on prospective flood protection, published right in 1995 by the national working group on water (LAWA), now turned away their focus from the mere technical approach. Instead, natural retention concepts such as dyke relocation or floodplain restoration eventually found their way into German flood protection policy [8]. In Germany, the federal system stipulates that flood risk management (within the framework of the EU Floods Directive) is decentralized and mainly in the responsibility of the federal states. Coordination of water management issues across federal state borders is done by the national working group on water (LAWA) composed of state representatives, and by national and international river basin communities. Both commissions play a vital role in coordinating catchment-wide flood risk management (e.g. through the setup of flood action plans), but the recent past has shown that more binding agreements between the various policy and planning areas are required to ensure the actual realization of large-scale flood protection measures [9].

In 2012, the United Kingdom implemented the concept of partnership funding after facing similar difficulties regarding the insufficient realization of measures. It is a hybrid system based on national prioritization and funding, but at the same time allowing local input so that both national and local priorities can be addressed together [10, 11]. In 2015, the flood risk management system got further reinforced by a 6-year spending programme by the government for the realization of 1,400 defence and mitigation measures [12]. Despite all investments so far, after facing the extreme events of winter 2015/2016, the government was forced to revisit its flood control concepts and, hence, launched a 25-year plan to investigate best practices for the reduction of flood risk on catchment scale [13].

2. Setup and overall aim of the NHWSP programme

As a direct consequence of the disastrous flood events of June 2013, the German government together with the federal states decided on the joint elaboration of a nationwide protection programme against extreme floods (NHWSP) (2015-2027+). June 2013 accentuated again that, as a result of the federal system, the implementation of measures usually targets a rather local to regional scale. Larger, supra-regional flood prevention (e.g. across federal state borders) has been more difficult to enforce on regional scale due to the large demand of land for such measures and potential conflicting interests locally. With the NHWSP programme, the government aims at accelerating the realization of priority, supra-regional flood protection measures [14]. Under the auspices of the Federal Ministry for the Environment, a first list of more than 80 large-scale flood protection measures to be funded by the programme was compiled and agreed upon by the state representatives. It encompasses the realization of controlled retention (retention reservoirs, polders) greater than $5 \cdot 10^6$ m³ capacity as well as uncontrolled retention (dyke relocation) greater than 100 ha area, or, alternatively, several contiguous areas of less than 100 ha, but lumped together into a composite measure. The list of fundable priority measures is followed up and updated on an annual basis as the federal states concretize their individual flood control concepts. The particular thresholds for measures, selected in the first place to limit the number of measures registered in the programme, will be revised based on hydraulic criteria, amongst others, as the NHWSP programme proceeds. Following the idea of partnership funding, the German state supports the federal states' investments in the measures by up to 60%, allocating a total budget of about €5.4 bn for the period 2015-2027 and beyond [6, 15].

For scientific monitoring, the Federal Institute of Hydrology (BfG) was mandated to conduct a two-part preparatory *ad hoc* study (2014-2015) [16] and a subsequent research project (2015-2019) evaluating the impact of the listed flood prevention measures. In the first part of the *ad hoc* study, a rough estimate of the maximum impact to be expected from the projected retention reservoirs was calculated. The estimate was based on the theoretical maximum effect (TME) of each polder, i.e. its maximum retention capacity. Right after the June 2013 floods, this pre-analysis provided the government with first elements of evidence for taking its decision on the elaboration of the NHWSP programme. In the second part of the *ad hoc* study, polder effects were evaluated using hydrodynamic modelling. As hydrodynamic models were not available at BfG mostly for river sections outside federal waterways (Fig. 1a), the concept of TME was applied again to those polders outside model coverage. While part 1 of the *ad hoc* study considered five out of 10 German catchments, part 2 was limited to the larger Danube, Elbe, and Rhine basins. The model-based approach is considered an improvement over the analyses in part 1 of the study because flooding process and polder control are accounted for when estimating the polder impacts on flood discharge. The expertise from this part of the *ad hoc* study supported the development of the modelling strategy applied in the subsequent research project.

The research project currently carried out at BfG derives from both findings and limitations of the *ad hoc* study and focuses on the Danube, Elbe, and Rhine basins, too. Using numerical modelling in virtually all river sections, it aims at investigating the collective impact of the planned flood protection measures on flooding processes and flood peak reduction. The project is the first attempt in Germany to study the impacts of flood protection measures on catchment scale following the same nationwide approach. This way, findings are expected not only on the effect of large sets of flood protection measures within a catchment (i.e. in most cases across federal state borders), but also inter-catchment comparison will be possible to a certain degree. The research project is meant to technically substantiate the government's NHWSP programme by gradually refining the criteria for identification and prioritization of measures, i.e. by sharpening the understanding of supra-regional effectiveness.

3. Findings from the *ad hoc* project phase (2014-2015)

To estimate the theoretical maximum effect (TME) of measures, it was assumed that all polders in the catchment can be controlled in an optimal way to cap peak discharge. The consideration of polder effects was done for 3-4 historic flood events at two river gauges, one in the upper and one in the lower part of the catchment. Accordingly, the maximum retention capacities of the polders to be implemented upstream of the respective gauge were added up and deducted from peak discharge at the gauge. As shown in Fig. 1a, TME was estimated to range between 24 and 160 cm water level reduction. Owing to the applied volumetric approach, the size of the reduction corresponds directly to the available retention capacity in the catchment and the shape of the hydrograph. Given the same retention capacity in the catchment, water level reductions were comparatively small in cases of elongated flood waves (e.g. Danube at Achleiten 1999: -70 cm) and higher in case of steep waves (e.g. Danube at Achleiten 2013: -160 cm). In other words, the highest retention capacity in the catchment does not necessarily lead to highest peak water level reductions, as shown distinctly for the Elbe and Rhine basins in comparison to the Danube (Fig. 1a).

In part 2 of the *ad hoc* study, water level reductions were computed using hydrodynamic modelling. For retention reservoirs in river sections outside federal waterways, were BfG did not maintain models, the concept of TME was applied. As anticipated, modelled effects (ME) of polders were shown to be much smaller than the calculated TME. For the investigated flood events, they range between 1 and 63 cm, which, in relation to their TME, results in a degree of efficiency of only 3-76% (Fig. 1a).

a	Retention capacity		Peak water level reduction	
	Total * [10^6 m³]	Modelled [% of total]	Theoretical max. effect (TME) [cm]	Modelled effect (ME) [cm]
Danube	177	24	70 - 160	17 - 35
Elbe	405	78	24 - 95	1 - 63
Rhine	229	69	45 - 81	2 - 42
			24 - 160	1 - 63
Degree of efficiency (ME/TME)			3% - 76%	

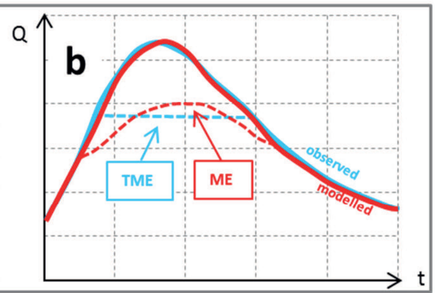

Figure 1 : (a) Summary of retention capacity and estimated peak flow reductions in the investigated basins (* data from 10/2014; differs from retention capacity investigated in the current research project), (b) schematic representation of the evaluation methods applied in the *ad hoc* study: theoretical maximum effect (TME) and modelled effect (ME) at a predefined gauging station.

One of the key factors influencing the effect of the retention reservoirs was found to be flood formation. In the Danube basin, which is characterized markedly by several large tributaries, measures are planned both along the Danube and its main tributaries (e.g. the Inn river). This way, the contribution of tributaries to the flooding process was shown to have a considerable impact on the achievable water level reduction at the gauges under consideration. At the Rhine, irrespective of polder control assumptions, lowest water level reductions were simulated for the event of 1988 (Kaub: -7 to -14 cm, Rees: -2 to -9 cm) despite the fact that the polders were filled to a high degree (up to 92% of total retention capacity). Here, the large tributaries of Main and Moselle superimpose and raise the Rhine peak, partly counterbalancing the effect of retention observed at the two stations.

Another key aspect in determining polder effectiveness was found to be polder control in conjunction with the selection of flood events to be simulated. The floods investigated in the Elbe basin were mostly 20- to 50-year floods, except for 2002 (approx. 1/200), so that polder activation was assumed at 1/50 or below (i.e. far below design levels). Given these imaginary control assumptions, the extreme flood peak in 2002 could not be capped since the Elbe polders were activated and filled too early, resulting in no water level reduction at all at Wittenberg station. Consequently, when investigating extreme floods and large-scale measures within the NHWSP programme, polder control will have to be more realistic, i.e. activation at 1/100 or above. Also, the flood events for simulation will have to be in the same order of magnitude as the polders' activation level or even higher to adequately test the effectiveness of a set of consecutive polders along larger river sections.

Despite its limitations, the findings of the *ad hoc* study as precursor of the current research project allow first conclusions on the possibilities and requirements of a large-scale flood prevention programme such as the NHWSP. Based on this pre-analysis, the projected prevention measures are able to reduce the water level by several decimetres over large river sections. However, supra-regional effectiveness of prevention measures cannot be assessed exclusively by the number, size, or retention capacity of the measures. In fact, an efficient flood prevention concept on catchment scale has to take into account the complex interrelations between flood formation, flooding process, supra-regional interferences, as well as the retention control concept (polder usage) both along the main stream and its tributaries. The modelling strategy of the current research project answers these requirements widely: it is based on nearly full model coverage, simulates a much larger number and more extreme flood events, assumes a representative polder control, and equally takes into consideration the effect of uncontrolled retention measures. This way, it is expected to further consolidate the knowledge on the most critical aspects to account for when drawing up a supra-regional flood control concept.

4. Modelling strategy of the research project (2015-2019)

4.1. Nationwide approach

Up until today, a total of 53 controlled and 30 uncontrolled retention measures (including several small, contiguous areas) were registered in the NHWSP programme for funding, providing a total retention capacity of 964 million m³ and more than 32,000 ha of newly retrieved floodplain area (data from 01/2018). The measures are widespread within the catchments and located both along the main stream and along first or higher order tributaries. To evaluate all measures to a nationwide equally high standard, extensive sets of coupled numerical, mainly hydraulic models were put together by BfG and the state water management authorities for the purpose of the research programme. Where possible, hydraulic modelling is preferred to hydrologic modelling to ensure that results are obtained all along the river course instead of lumped at predefined stations. In some cases, models are technically coupled, whereas in others, model outputs from upstream parts of the catchment are entered into the subsequent model downstream for further processing. In most cases, BfG is in charge of simulating the main streams (Danube, Elbe, and Rhine) as well as larger first order tributaries (all usually federal waterways) whereas the federal states take on responsibility for the modelling of most tributaries, partly reaching far into the upper catchment. This is reflected in the applied modelling techniques: the majority of measures (mostly located along the main streams) are computed using 1D SOBEK models available at BfG. Where BfG does not maintain models, 2D modelling and hydrologic modelling is applied by the states. In the Elbe and Rhine basins, a considerable number of measures are located far in the upper catchment where suitable models could not be provided within the duration of the research project. In these cases, the retention effect will have to be estimated and discussed qualitatively or based on the TME approach (Elbe: 24% of controlled retention [$120 \cdot 10^6$ m³]; Rhine: 10% of controlled [$23 \cdot 10^6$ m³] and 47% of uncontrolled retention [2,400 ha]).

Not only the modelling techniques are combined, but also do BfG, the federal states and the river basin commissions share responsibility for the conceptual set-up of the study, the implementation of the modelling and the subsequent interpretation of results. The modelling strategy allows for the separate consideration of impacts resulting from the type of retention (controlled or uncontrolled retention) as well as resulting from the location of the retention measure (along main stream or tributary). The scenarios are assessed for five characteristic flood events of the recent past (original records) as well as for 12 additional synthetic flood events. The synthetic flood events are generated using the selected historic events and scaling them up to events of return periods of 200-500 years. The upscaling is performed by increasing the original flood hydrographs of all model boundary conditions (inflows) upstream of a selected station by a consistent factor, while the boundary conditions (inflows) downstream of the station are left unchanged. This way, the natural character of the flood formation is preserved upstream of the investigated station. The synthetic events aim at representing catastrophic floods at the order of magnitude of characteristic design discharges or slightly above, extending over large areas along most of the main river sections and tributaries. Consequently, the modelling concept needs to address the interaction of large-scale flood formation and retention measure impacts as well as unanticipated effects such as dyke overflow or failure.

4.2. Example: modelling strategy in the Danube basin

The Danube, second largest river in Europe (2,860 km), originates in southwest Germany and crosses the state of Bavaria from West to East over 380 km. The Danube's larger southern tributaries mostly originate in the Alps, and their catchment is about three times larger than that of the northern tributaries (Fig. 2a) [17].

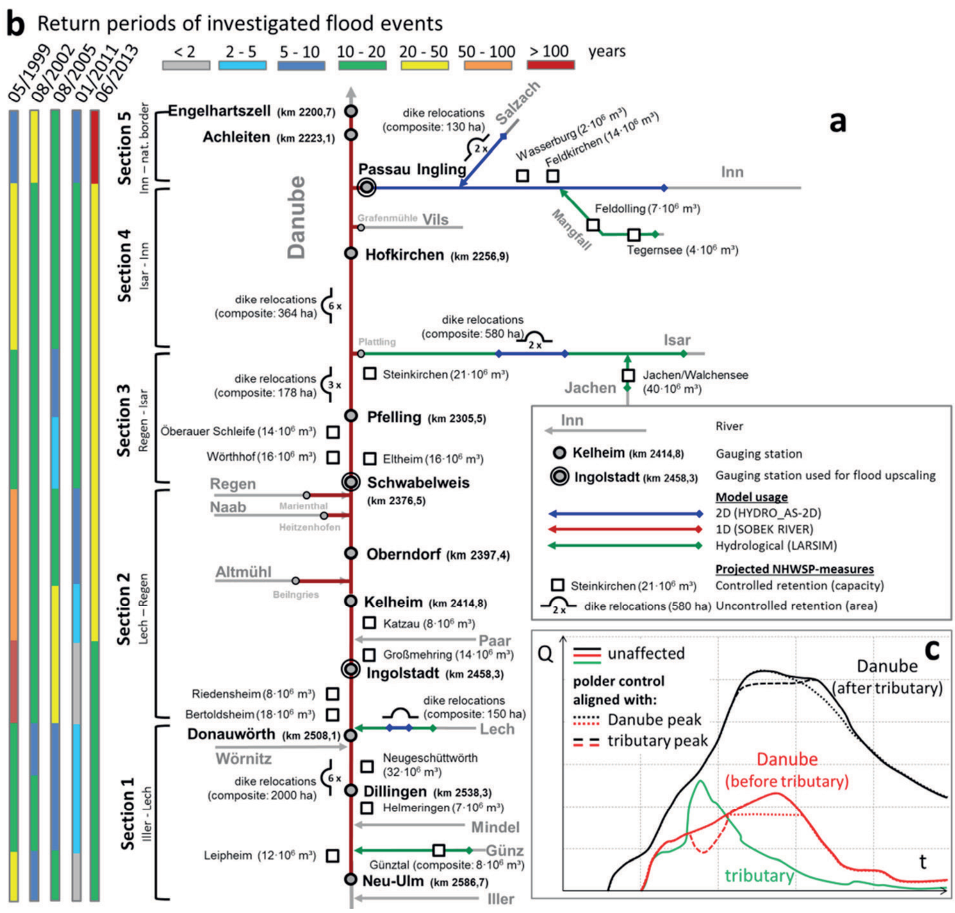

Figure 2: (a) Model layout for the Danube basin including planned retention measures, (b) overview of historic flood events and their return periods, and (c) comparison of hydrographs for different polder control scenarios (schematic; modified after [18])

 https://doi.org/10.1051/e3sconf/20184006014

Along the Danube, the particular contribution of the tributaries, that is flood formation, is one of the most important catchment characteristics influencing the effectiveness of retention measures (see chapter 3). Consequently, to be able to react to different types of flood formation, the state water management authorities are planning to place large retention measures in every hydrologically coherent river section, i.e. between the outlets of two influential, flood-relevant tributaries each (Fig. 2a). The retention reservoirs are designed almost exclusively for usage in case of discharges above the respective design levels, i.e. mostly 100-yr flood events [18].

The Danube (including the estuaries of larger tributaries) is modelled by BfG using a newly updated 1D SOBEK River model for the Bavarian Danube from Neu-Ulm to the Austrian border. The modelling of measures along the tributaries, on the other hand, is performed by the Bavarian Environment Agency (LfU) using HYDRO_AS-2D and LARSIM models, either separately or in combination (Fig. 2a). Model results generated by LfU are then entered into SOBEK for the simulation of the complete river system.

For the evaluation of the measures' collective impact, five characteristic historic flood events of the recent past were selected, covering the various types of flood formation as well as return periods (Fig. 2b). To be able to investigate the combined effect of several voluminous retention reservoirs over larger parts of the river system, the events of 1999, 2005, and 2013 are scaled up to events of return periods between approx. 200 and 500 years, respectively. Dyke overflow or failure is not considered in the model, since it would superimpose the effect of the planned retention measures. Instead, the magnitude of the synthetic floods was selected in a way that allows the assumption that the simulated water level does not exceed the height of dykes plus freeboard (mostly 1/100 level + 1 m). Where dyke overflow is still inevitable, it will be assessed qualitatively with regard to the present level of protection. To create extreme flooding along as many river sections as possible, Ingolstadt and Schwabelweis, respectively, were chosen as stations for generating synthetic floods along the Danube, and Passau Ingling was chosen as station for upscaling the events along the Inn river (Fig. 2a).

The particular implementation of polder control in the study is determined individually for every simulated flood event. The polders to be realized along the Bavarian Danube are designed in a way that allows them to be used for flood reduction in the same or in the subsequent river section(s). In fact, previous investigations have shown that generally, retention reservoirs achieve the highest peak reductions at the Danube when aiming to cap the Danube peak horizontally. In some cases, however, it was found to be more effective to not align reservoir control with the actual Danube peak, but with the downstream tributary's peak [18] (Fig. 2c). Formal rules of procedure for such polder usage have not been set up yet, so that the decision of how to control the set of polders for the simulated flood events is left to the state water management authorities.

The modelling strategy for the Danube basin illustrates that, within the same nationwide methodology, specific demands arising from catchment characteristics can still be met. This way, not only could adequate research concepts be identified for the currently investigated Elbe and Rhine basins, but also can this research strategy be easily transferred to other catchments to be studied within the NHWSP programme in the future.

5. Outlook

Germany has launched its first nationwide flood protection programme to improve supra-regional flood prevention across federal state borders, hoping to avoid excessive cost for flood damages in the future by supporting the federal states' investments in large-scale flood retention today. The accompanying research project will deliver first results in autumn 2018, and subsequently feed its findings into the NHWSP programme. Of primary interest will be the effectiveness of controlled and uncontrolled retention in the catchment in terms of peak reduction along large river sections as well as impacts on the supra-regional flooding process. For example, will a set of small, contiguous measures in the upper catchment have an impact on the flooding process along the mainstream? What is the polders' range of effectiveness for different scenarios? Can we identify weak spots with insufficient protection along the river, or, vice versa, sections with excessive retention capacity?

Based on the outcomes of the simulations, the subsequent task of the research project will be to carve out and refine adequate criteria for a scientifically sound identification and prioritization of future NHWSP-measures. The project will have to work out a definition of what exactly is a measure of 'supra-regional impact'. This might involve not only the consideration of the hydraulic impact of the measures (single measure or composite of measures), but also, for instance, the number of inhabitants and industries protected by the respective measure(s) or the prospective synergies with overall ecological or environmental development plans. This way, the research project will eventually provide the government with fundamental information for an efficient supra-regional flood prevention and for an economic allocation of resources.

References

1. C. Zevenbergen, S. van Herk, J. Rijke et al., Nat Hazards, **65**, 1217–1225 (2013)
2. IPCC, Climate Change 2014: *Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2014)
3. OECD, *Seine Basin, Île-de-France: Resilience to Major Floods*, OECD Publishing (2014)
4. P. Kabat, P. Vellinga et al., Nature, **438**, 283-284 (2005)
5. OECD, *Japan, Large-scale Floods and Earthquakes*, OECD Publishing (2009)
6. LAWA, *Nationales Hochwasserschutzprogramm* (2014)
7. S. van Herk, J. Rijke, C. Zevenbergen et al., J Environ Plann Man, **58**, 554–575 (2015)
8. LAWA, *Leitlinien für einen zukunftsweisenden Hochwasserschutz* (1995)
9. BMUB, *Water Resource Management in Germany. Part 1: Fundamentals* (2013)
10. DEFRA, *Flood and Coastal Resilience Partnership Funding* (2011)
11. M. Alexander, S. Priest, H. Mees, Environ Sci Policy, **64**, 38-47 (2016)
12. DEFRA, *Reducing the Risks of Flooding and Coastal Erosion* (2014)
13. DEFRA, *National Flood Resilience Review* (2016)
14. BMUB, Fragen und Antworten zum Nationalen Hochwasserschutzprogramm, online: http://www.bmub.bund.de/themen/wasser-abfall-boden/binnengewaesser/hochwasservorsorge-und-risikomanagement/hochwasserschutzprogramm (2017)
15. BRH, *Bericht an den Haushaltsausschuss des Deutschen Bundestages* (2016)
16. BfG, *Ad-hoc-Untersuchungen zur Ermittlung der Wirkungen von Hochwasserschutzmaßnahmen des Nationalen Hochwasserschutzprogramms* (2016)
17. LfU, Einzugsgebiet Bayerische Donau, online: https://www.lfu.bayern.de/wasser/hopla_donau/einzugsgebiet/index.htm (2017)
18. M. Asenkerschbaumer, D. Skublics, P. Rutschmann, *Verzögerung und Abschätzung von Hochwasserwellen entlang der bayerischen Donau*, TUM, 2012