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Lessons learned from the Big Floods, 1999–2013: The Bavarian Flood Action Programme 2020plus

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Abstract

Flood protection is an integral part of society's development. Meeting a growing vulnerability in the context of geopolitical and global changes, existing systems of natural hazard management must be reviewed on a regular basis. This is illustrated well by Bavaria's recent history. The lessons from the big floods in the period of 1999–2013 led to a fundamental modification of Bavaria's integral flood protection strategy. The concepts of flood risk management, resilience and dealing with extreme flood events which exceed standard structural design limits came to the fore. Management of flash floods and other floods, handling of potential retention areas, the inclusion of insurance, resettlement, and the burden of maintenance are further challenges which are briefly addressed in this paper.

Keywords: Bavaria; Danube; EU Floods Directive; Flood protection; Maintenance; Resilience; Risk management; Torrents

1. Introduction

1.1. Water as a public good and a basic public safety issue

Water resource management touches upon basic safety issues: drinking water and nutrition, water as a hygiene factor, water as an eco-system and especially as a natural hazard posing a direct threat to humans (as well as to all the aforementioned water issues).

As a gravimetric element, it links all of society with an array of circumstances upriver and downriver alike. Water comes to everyone. Everyone can benefit from good management and suffer from poor management. That is why water management in general and especially flood protection are special

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essential public services, and a component of the basic protection strategy falling under a state's fundamental responsibility. That is why, above all else, the duty of those involved in politics and administration is to derive strategies to the best of their knowledge and abilities, that will be fair and preventative in nature, in the spirit of sustainable policies.

Doing so, however, involves both centralised and decentralised components. A state's water management is subject to both national and international frameworks (in this case, German and European), as well as regional and local ones. Within the scope of good governance, execution of the strategy will always have components that are both of a sovereign/public nature, i.e. resting on the state and community, as well as of a private sector nature, i.e. private industry, institutional and individual. The reality, of course, is always on site.

1.2. Outstanding characteristics of EU water policy

Attempts to provide flood protection are as old as hydraulic engineering itself. Bavaria has been investing in natural hazard management for more than 200 years within the scope of strategic state water management. There have always been floods, yet the striking frequency of the events from 1999 to 2013 after nearly 30 years of having only a few flood events has revealed weak points. Not only has the number of protective structures been increasing due to ongoing investments, but also our technological society has apparently grown more sensitive, with damage constantly rising year on year as put forward by insurance organisations and statistics (MunichRe, 2014). The time series on which flood protection structural design is based are comparatively brief, with uncertainties additionally being cast due to climate change predictions.

What is helpful is the great amount of knowledge gained as a consequence of the establishment of European norms. To that end, the EU Water Framework Directive (2000) and EU Floods Directive (2007) have yielded integral approaches representing an outstanding basis for sustainable water management. However, that does not mean that we have learned all we need to know – on the contrary!

2. Brief description of Bavaria

Bavaria is a water region, and more than 100,000 km of streams and rivers flow through it (Table 1). Bavaria is internationally active in water management.

The State of Bavaria actively fosters mutual water policies in Europe as a member of international water commissions (Danube, Elbe, Rhine, Lake Constance) and consortia (Arge Alp, Arge Alpen-Adria). Moreover, Bavaria's water economy recognises its obligation to pass on its knowledge and experience not only within the context of these international organisations, but also in bilateral projects with states and regions interested in the model shaped in Bavaria of integral state water management based upon sustainability criteria. This obligation is simultaneously an opportunity: an opportunity to implement practice-proven Bavarian environmental technology in order to improve environmental and living conditions in these regions, thereby garnering mutual experience while also securing and enhancing Bavaria as a home for business and science.

Table 1. Key numbers concerning the Bavarian water region.

- Area of Bavaria 70,550 km^2
- Gross Domestic Product (GDP) (as of 2013): €488 billion[1]
- Residents (as of 31 December 2011): 12,595,891
- Administrative communities: 2,056
- total length of all bodies of water (rivers): approx. 100,000 km, of which first-order (large, trans-regionally important) 4,200 km; second order (regionally important) 4,800 km
- Number of larger natural lakes: 150; total area: 270 km^2
- State dams and flood control basins: 25
- Hydro power plants: approx. 4,200
- Water cycle: average annual precipitation in Bavaria: 939 mm (south max: 2000 mm, north min. 450 mm), runoff 422 mm, evaporation 517 mm
- Highest point: Zugspitze at 2962 mNN (metres above sea level); Lowest point: Main 102 mNN, Danube 280 mNN
- Public water supply (as of 2010): percentage connected 99.1%, potable water protection areas approx. 3,250, i.e. ~4.6% of Bavaria's area (national territory in Germany: ~12%)
- Waste water disposal: 96.4% of residents have a connection to the 2,669 waste water treatment plants (as of 2010)
- Hundreds of hydrography measurement points along surface waters and in the ground water for monitoring level qualitatively and quantitatively

3. Flood cluster 1999–2013

The period from the 1960s to the 1990s is considered in Europe as well as in Bavaria to be a period with few flood events. There were, of course, extreme local events of HQ100[2] dimensions, but no sweeping catastrophic floods. That changed in Bavaria with the flood of 1999, where heavy rain in the Alpine foothills caused heavy damage, e.g. along the Danube after the dyke breach near Neustadt. In 2005, billions of euros of damage were caused again due to rain, this time in the western Alpine region. In early June 2013, vast areas of Bavaria, this time both the Alpine region and northern Bavaria were hit by a massive flood event causing around €1.3 billion of damage (Figure 1). The last flood was an extreme event with regard to its duration, geographic coverage and exceedingly high peak discharges. At some locations, the peak discharges were the highest ever recorded and reached or even surpassed the structural design limits of the flood protection systems.

As is often the case, this large-scale event occurred in the 'third wave':

- In May 2013, 25 days of rain with an aggregate high level of relatively constant rainfall led to a high level of pre-saturation in the soil. Local flooding was then followed by flood water on a moderate scale.
- Then came further intensive rainfall throughout all of eastern Bavaria from 30 May to 3 June, especially in the Alps, at times corresponding to a rain event well over a 100-year event for durations of 72–96 h.

The water level rose sharply, especially in the southern Danube basin, at times above the level of a 100-year event. Thus, only a relatively short period of time after the floods of 1999, 2002 and 2005,

[1] Billion = $\times 10^9$.

[2] HQ100 describes a flood with a recurrence probability of 100 years: 'a 100-year flood'. This is the standard design flood in Bavaria.

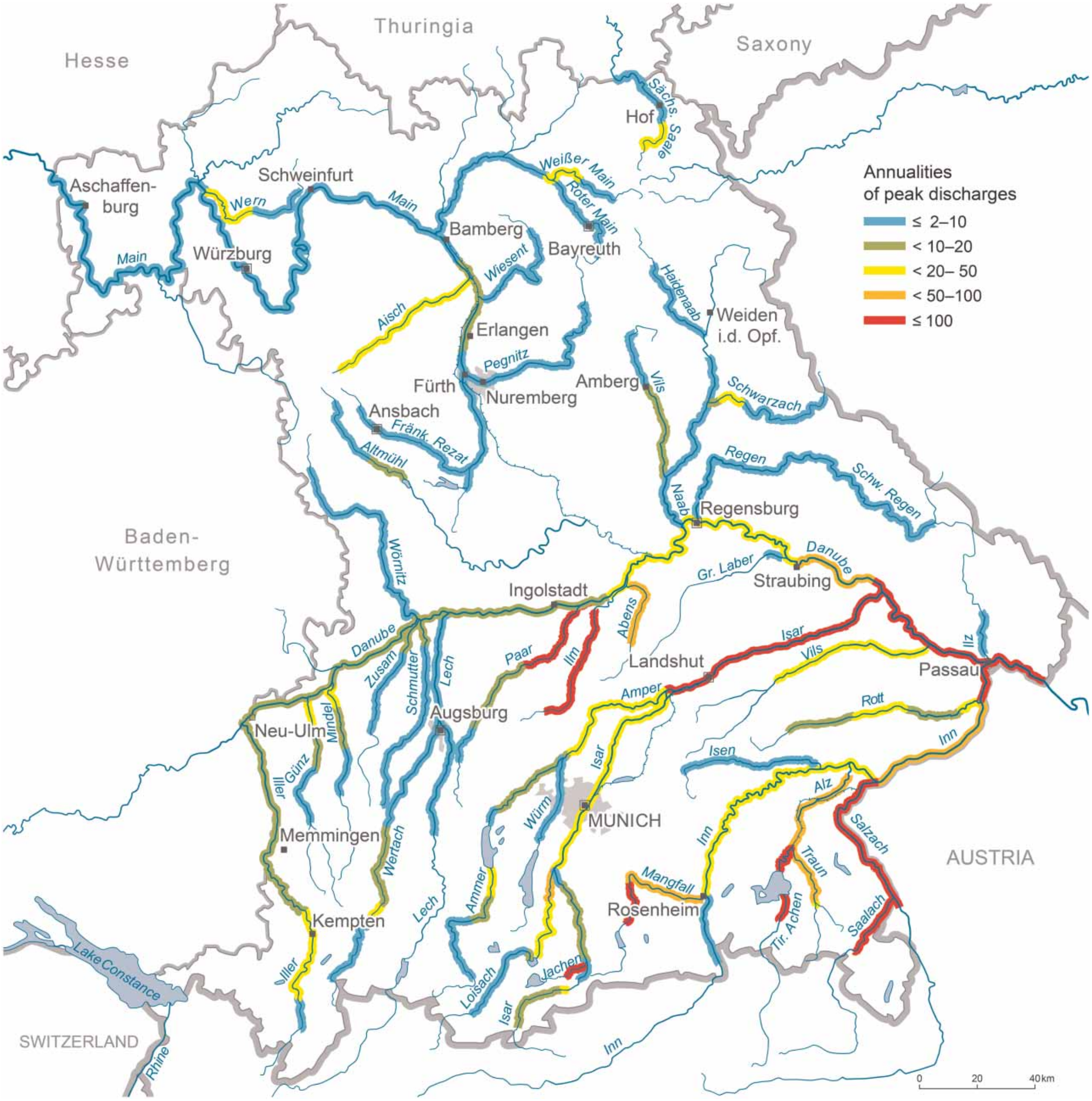

Fig. 1. Affected river sections in the May/June 2013 flood.

another catastrophic event occurred. While the geographical focal points of the events do vary greatly, this series of events can indeed by classified as a flood cluster which may even be marked by weather changes caused by climate change.

4. Lessons learned following the large-scale floods of 1999–2013

Despite all the damage and problems, the existing flood protection installations in place in Bavaria fundamentally proved themselves. The investments made over past years were well placed. This made it possible to prevent damage of a much larger scale; the Bavarian administration estimates the ratio of investment in flood protection to damage prevention to be ~1:4 to 1:7. Even when taking capital costs into consideration, the financial calculation remains positive, not to mention the prevented human suffering – floods traumatise people in a significant manner.

An assessment of flooding consequences reveals a few significant characteristics:

- In 2005 and 2013, many systems – especially dykes – were subjected to significant overload (flood discharge >> structural design discharge). Many of these systems successfully withstood this overload due to high safety design margins. Other systems, although overrun, still withstood the overload and significantly helped the mitigation of the damage. Several systems, however, did fail and were completely eroded.
- All flood protection systems meeting today's flood design standards and providing protection against a 100-year event withstood the 2013 events. However, this was frequently the case with full exhaustion of safety heights and occasionally structural damage to the system.
- Damage was largely incurred along river sections that were not yet protected or not sufficiently protected: either because installations were not yet developed to HQ100 or because the river was calculated to withstand the HQ100 discharge (and was then overloaded by an HQ 300–500). The worst damage was the result of sudden and/or complete (eroding) failure of flood protection installations.
- In 2005 and 2013, the controlled retention areas (especially state reservoirs) made a large contribution to damage prevention. At approximately 100 million m^3, the Sylvenstein Dam alone helped prevent billions of euros of damage in Munich.
- The collaboration between all parties (administrations and crisis intervention staff) throughout the course of the event was excellent. Good weather forecasts and solid preparation contributed to that end.
- There were minimal cases of deficits in flood predictions and flood warnings, where real conditions 'overran' model scenarios, or where catastrophic events destroyed river gauges or cut-off power supplies, thereby cutting off communication.

The extreme flooding seen in June 2013 once again explicitly underscored the importance of having modern and effective flood protection in order to protect the population and avoid economic damage, additionally illuminating how decisive a society's systemic ability to react is. In the aftermath of the flooding, the tremendous solidarity and willingness to help, seen throughout Bavaria and Germany was remarkable. €8 billion in assistance came for the federal and state government for rebuilding.

Statements that can be made as a first conclusion based on recent experiences include the following:

- Statistically calculated flood events (design discharge) occur irregularly, yet they certainly do occur. Timely investment and preparation avoids enormous consequential costs.
- Mega events that far exceed HQ 100 can occur. Despite all endeavours carried out with technical protection systems and preventative measures, safety against flooding is always only possible to a limited extent. A residual risk will always remain and cannot be remediated regardless of the expenditure made.
- This residual risk can only be reduced through individual action: assuming individual responsibility in making provisions and correct action in a crisis situation can make a significant contribution to

reducing damage. Modern integrated flood protection and flood risk management is therefore a duty spanning across multiple departments and fields (development planning, settlement policy, location and risk mitigation in business and agriculture, the insurance industry).

- After events of this nature, it is necessary to fully evaluate and improve the flood prediction models implemented. Interfaces are found in precipitation forecast based on location and volume, discharge measurement during extreme events and cross-border collaboration.
- The interplay among the four principle factors contributing to river discharge (precipitation, runoff, channel hydraulics and wave superposition) is partially non-linear and cannot be determined with intuitive cause and effect presumptions. This is especially recognised in the philosophical dispute between 'natural' vs 'technical' flood protection.
- Instead of pure protection, it is important to think about the *resilience* of protection systems in the face of extreme events. The focus here is on systemic and precise overload stability (system and subsystems).
- Flooding has illustrated once again that flood protection systems not only have to be well planned and executed, but also well maintained. Ensuring they are in a solid, functional state is a permanent task of growing dimensions.
- Quality in flood protection is yielded by the sum of the qualities found among the personnel involved.

Based on this information, several fundamental positions and insights will be examined in detail for the purpose of illustration.

4.1. Universal strategy in dealing with flooding

For more than 200 years, state flood protection has been actively carried out along Bavarian rivers in line with modern criteria (Wiebeking, 1817). New information and technical advancements have triggered more and more adjustments in the fundamental protection strategy. After the flood during Pentecost 1999, the Bavarian Cabinet enacted the 'Flood Water Action Programme 2020 – for sustainable flood protection in Bavaria'. It lays out a specialised strategic orientation for flood protection, as well as a framework for finances and time for implementation. The Action Programme 2020 (AP 2020; see: http://www.lfu.bayern.de/wasser/hw_aktionsprogramm_2020/index.htm) follows an integral, pioneering protection strategy consisting of three (equal) fields of action:

- natural retention;
- technical flood protection; and
- prevention and extended precautionary action against flooding.

This means that it represents a new level of quality in integral protection strategy all over Bavaria. It spells out investments of €115 million per year, to a total €2.3 billion. This has made it possible to protect an additional population exceeding 400,000 residents along first-order and second-order bodies of water against 100-year floods. Many of these measures have already proven their value multiple times and avoided enormous damage on multiple occasions. Several of the implemented measures displayed their effectiveness in an impressive manner during the flooding of June 2013.

This three-pillar strategy continues to be current and also facilitates the implementation of recent knowledge gains. The enhancements described below largely pertain to enhanced system observations, the inclusion of complex, non-linear factors and better quantification of influential factors that are frequently only made possible by modern computing.

4.2. Flood risk management

For many generations, people spoke of ‘flood clearing’. This term is no longer suitable in light of current knowledge regarding the systemically established limits to active protection against natural hazards. Flood risk management is aimed at organised/systematic and balanced handling of flooding that significantly reduces damage with tailored utilisation and action in consideration of the residual risks. Specifically, effective handling of flood water means more than simply setting up technical protective structures. Rather, it is necessary to develop an integral strategy and also to take into consideration aspects like effectiveness, efficiency and suitability against the background of probability (and unpredictability) of rare extreme events and the resulting overload on protection systems. Another aspect to flood risk management of this kind is that various fields collaborate in a cross-border and multi-disciplinary manner. Examples of the fields involved here include water management, land use, nature conservation, local hazard control and disaster prevention.

Flood risk management encompasses all phases before, during and after flooding. It can therefore be understood as an ongoing cycle dependent upon time (Figure 2).

Thus, addressing flood risk is not a one-time task, but rather a process consisting of various phases that have to be run through on a regular basis.

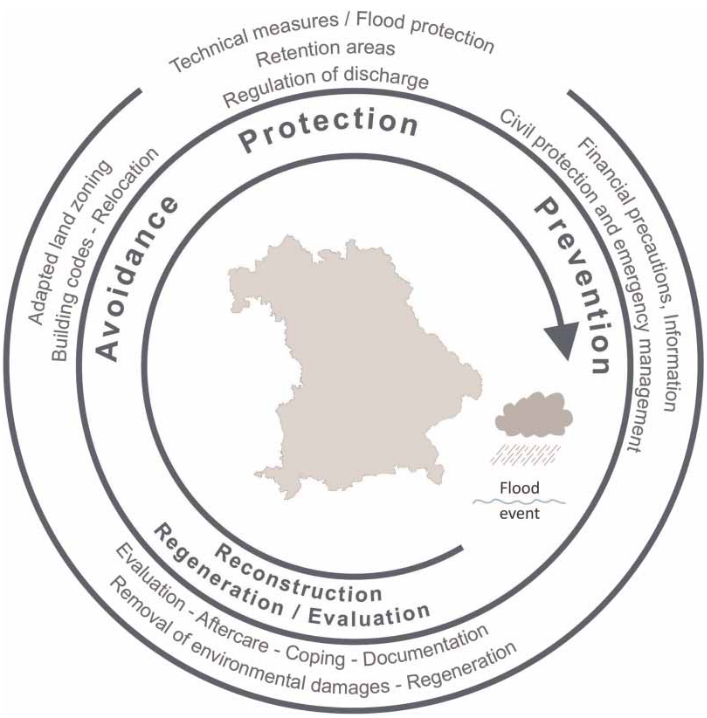

Fig. 2. Flood risk management cycle.

The revision to the first flood risk management plans for Bavaria stipulated in the EU Floods Directive (2007) was designed to introduce and permanently establish systematic flood risk dialogue. Only those who are aware of the hazards and risks will be capable of implementing effective provisions and acting correctly in the event of a serious incident. This applies for all actors – from state, city and community governments, to those responsible for infrastructures covering several regions, to industrial and commercial operations, and each individual citizen.

The foundation for constructive risk dialogue consists of maps visualising the hazards and risks to the public in a comprehensible manner. Risk dialogue is carried out on a local level between cities and communities, water management agencies and district administration offices in their capacity as disaster prevention agencies.

4.3. Tailoring the strategy to Bavaria – from AP 2020 to AP 2020plus

In light of the flood events in June 2013, Bavaria re-adjusted the cornerstones of flood water protection in Bavaria with the current 'Flood Water Protection Action Programme 2020plus' (AP 2020plus). AP 2020plus is a logical continuation of AP 2020 based on flood risk management. This is expressed in Figure 3, which integrates AP 2020plus with the risk management cycle.

4.3.1. Organisational adjustments. To start, the terms 'risk' and 'risk cycle' better reflect legislative developments from the EU Floods Directive (2007), which was implemented into national law in 2010.

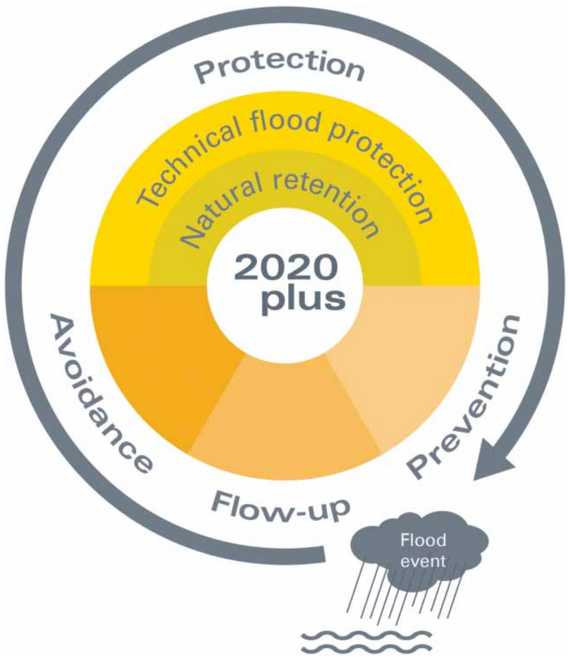

Fig. 3. Elements of the Action Programme 2020plus.

Another element of AP 2020plus is better financing and staffing. In the future, there are plans to provide €150 million instead of €115 million for implementation of AP 2020plus. Additionally, plans were passed in February 2014 for a special programme for flood protection on the Danube featuring an aggregate €600 million. When accounting for the higher expenditures made to date (compared to the €115 million/year planned), this means that the AP 2020 and AP 2020plus financial volume for flood protection is increasing from €2.3 billion to €3.4 billion. Moreover, reductions in flood protection staffing have been halted, with an initial 150 new positions created – to be staffed up to 2022.

One of the big challenges for the future consists of the large inventory of flood protection installations and dams, as well as structures designed to protect against torrent hazards. The replacement value for state hydraulic engineering structures in Bavaria is estimated at €10 billion. These installations require regular monitoring, maintenance and, when necessary, restoration. This overall required effort grows with each new structure.

4.3.2. Technical/operational improvements. Additionally, AP 2020plus lays out technical/operational improvements and enhancements in all fields of flood risk management. Select examples are:

- further improvements in notification and warning services (www.naturgefahren.bayern.de) including improvement in flood forecasting;
- investing in risk dialogue (in line with implementation of the EU Floods Directive);
- adoption of design and construction of protection systems also based on resilience criteria;
- determination of flooding regions in further river sections.

The following will address and detail the core points in the technical/operational adjustments to protective measures.

4.3.3. Overload and systemic reinforcement of resilience. The June flooding displayed once again the catastrophic consequences of dyke breaches, especially along the Danube. The affected dykes there were not designed to accommodate a 100-year event and were overloaded. However, this particular example also makes it clear that flood protection has its limits and that there will always be a residual risk. Overload can occur anywhere any time, regardless of the statistical flood parameters used to design and build protective structures; an even larger event can occur at any time. In addition to 'the ability to resist external influences', the term resilience also has more complex characteristics. Over time, systems typically develop through growth and are stable up to a certain point. After this point a sudden decline occurs, if the decline is not prevented via early intervention and renewal – an allegory for the upkeep of installations. When systems transgress their threshold, they fall into a new stable state: a dyke is flooded, eroded and 'disappears'. Ultimately, all systems are comprised of superordinate and subordinate sub-systems. The resilience in each sub-system corresponds to the superordinate and subordinate sub-systems, i.e. it is influenced by them while also influencing them (Walker & Salt, 2006).

The lesson to be learned here for flood protection is that, in the event of overloading, there will be further influences, such as ageing of systems, sub-optimal control and criminal acts rendering it impossible to completely prevent damage. However, it makes a huge difference whether an installation totally fails and collapses in the event of overload, or survives the overloading and thus continues to provide a partial protection function. Taking a dyke as an example: the damage is much lower when the water level behind the dyke (polder) rises only slowly with lower momentum, giving additional warning time. In addition, after flood wave peak(s), overflow into polders ceases quickly when dykes are still in place. Ultimately, the degree of protection is maintained during subsequent flood waves, and the polder is not left defenceless.

The resilience of one single sub-system or of the superordinate system (e.g. river section, body of water) can be improved through constructive measures on various planning levels, with construction details to the aggregate system (Figure 4). The following mutually complementing options come into consideration.

- Structural safety: selection of fundamentally overloadable and therefore resilient construction methods and structures, e.g. flood protection walls, anti-erosion dykes (e.g. sheet piling and geotextiles) and dyke sections designed to allow overflow. When it comes to dams, these kinds of relief systems

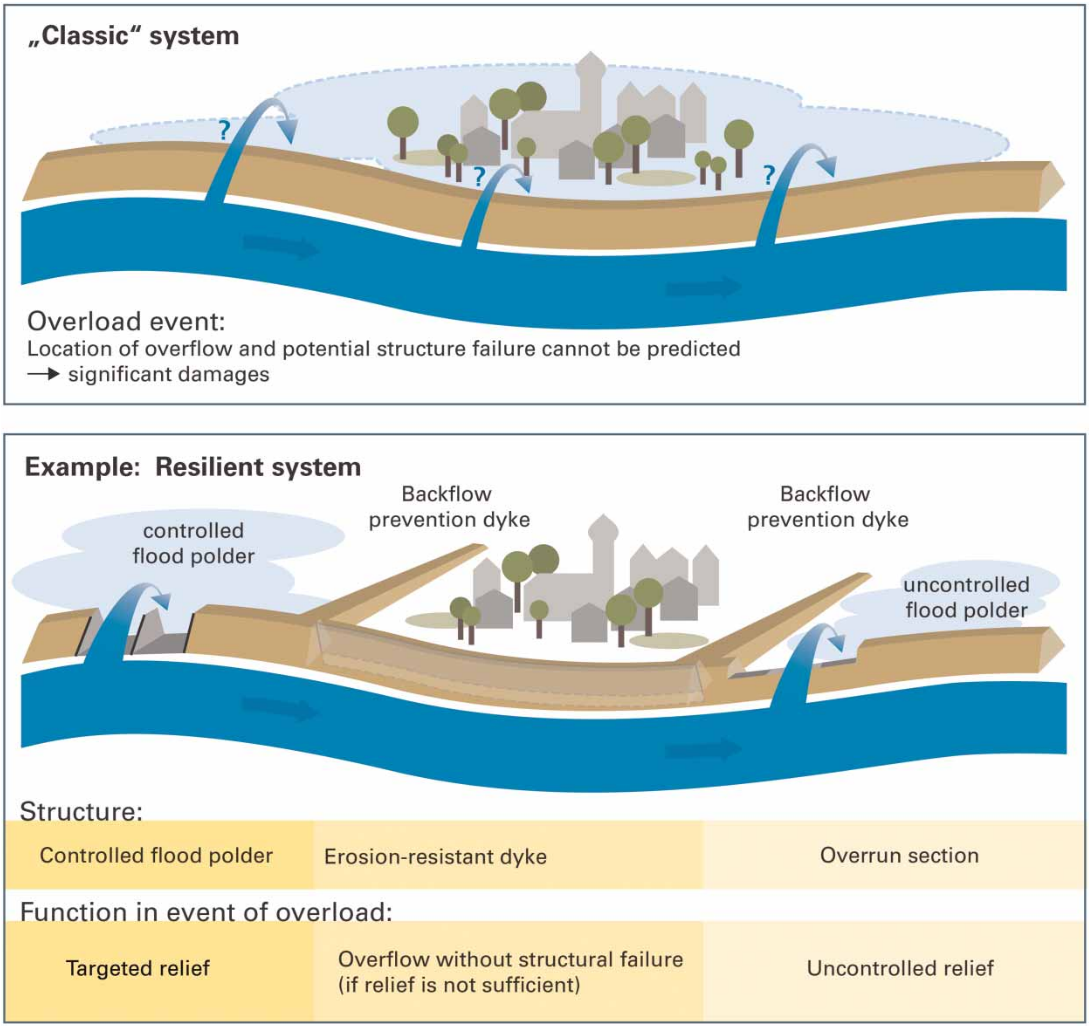

Fig. 4. Principal outline for potential components of resilient protection systems.

(spillways) have long been standard due to their better ability to take on damage. However, this also includes redundant power supply, capacity for manual operation and sufficient personnel with regards to numbers and training.

- Systemic safety: conceptualisation of overloadable and therefore resilient protection systems; the resilience of the individual structures is complemented with supplemental elements, such as natural retention spaces, relief sections, flood polders and further dykes (transversal dykes). This makes it possible to either retain a design flood longer, or at least to provide partial relief due to volume reduction.
- In combination with the 15% climate increment on the HQ100 design discharge introduced throughout all of Bavaria back in 2005, safety has significantly increased in situations involving design flood levels and beyond.
- The residual risk remaining can be further reduced with management measures. It can be reduced in these areas with further prevention measures, e.g. through personnel planning in disaster prevention organisations, voluntary adjustment to utilisations and elemental damage insurance. Warning systems include stable forecast models, anti-flood measuring and monitoring systems as well as the preparation of individual decision channels in the event that central management is lost (contingency strategy for management, etc.).

It is under these conditions, and only under these conditions, that the elevated degree of utilisation necessarily yielded by the improved protection level will not result in greater systemic susceptibility.

4.3.4. Installation safety and resilience. Flood protection installations are generally complex systems built using cement, steel and/or earthworks requiring substantial expenditure for planning, construction and operation. Before these structures are built, extensive planning and legal procedures are usually carried out and financial issues are clarified, generally involving contributions from the communities and cities being protected.

Upon completion of the installations, the citizens in question expect an extremely high level of protection, in most cases absolutely fail-safe protection against flood hazards. Since safety installations only seldom have to display their suitability for use, and when they do it is during flood events, it is not possible to perform a long, staged 'trial back-up' to observe the structure's performance and discover potential weak points requiring improvement (one exception to this being dams and flood detention reservoirs subjected to systematic load increases under 'normal' discharge conditions via a trial back-up programme).

Thus, flood protection installations need to be constructed such that they deliver a high degree of inherent safety. This can be achieved through the selection of building materials, through reserves in load assumptions, through sufficient freeboard measurement, and through subsidiaries for hydrological parameters (e.g. in Bavaria, 15% increment on HQ100), etc. This makes it possible to render earthwork structures, at risk of being overrun in the event of overload, resilient with surface erosion protection or with additional sealing within the dyke (earth/soil concrete, diaphragm wall, sheet pile wall), thereby providing protection against sudden structural failure. The relief options laid out in the relevant norms regarding protection of the aggregate system against sudden failure (intake structures) are generally 'secured by sealing them with sand bags' (not intended when designed and thereby robbed of their function). This makes resilience all the more important, i.e. the ability of flood protection installations to provide protection against failures in the sense of the threat of overload. Damage to installations and protective materials is unavoidable even when subject to loads accounted for in the design. What is important here is that sudden failure in protection systems and the corresponding catastrophic consequences can be hindered and that the flood levels remain under control.

In contrast to classic flood protection installations, dams and large river barrages represent a constant potential hazard with their high permanent water level above the surrounding terrain. That is why these large-scale water installations are built with particularly reliable design, equipped with safety margins laid out in the current applicable norms (design discharge, freeboard, failure in outlet culverts (n-1 case)) or are retrofits of older installations as needed, operated by specialist personnel and carefully monitored. Timely assessment of measured values and observations, separation between in-house and third-party monitoring, annual safety reports on the current state of the installation including any changes, as well as detailed checks of the entire installation approximately every 15 years guarantee a high level of safety in Bavaria's dams and water reservoirs.

When abnormalities in installations are recognised, punctual counter measures are implemented in order to maintain the overall high safety level. The State of Bavaria makes considerable expenditures to that end. Dedicated retrofit projects are contracted for older rivers dams and have been implemented for the first time in order to bring those dams back into the desired state without interrupting operation or restricting functionality. One example for these kinds of measures is the successful construction measures on the Sylvenstein Dam, carried out from 1994 to date (the retrofit of a pore water pressure monitoring network in the dam's body, construction of a second spillway, dam raising by 3 m, construction of a diaphragm wall in the dam core, insertion of an inspection gallery, and construction of a new seepage measurement system inside the dam).

Big gains are consistently being made in knowledge regarding technology and systems in all fields. Paradoxically, this knowledge is also shedding light on the recognised requirements. An evolution in efficiency alone is no longer sufficient, especially when doing so removes redundancies that were indispensable to the system's resilience. This is why research and development needs to be supplemented with components for sustainable system stability.

4.3.5. Effects on discharge in large rivers. The underlying concept of Integrated Water Resources Management is to observe the whole drainage basin as an effects matrix. Through observation and calculation, we have now learned that the runoff taking place within a typical drainage basin is anything but trivial:

- Rainfall is difficult to forecast and varies in intensity, duration and pull direction.
- Runoff is influenced by the surface structure as a function of gradient, relief, vegetation and infiltration rate or surface sealing – here too, times are dependent upon vegetation, frost and rate of saturation from past rain.
- In the main channel flow and the forelands the discharge is influenced by gradient, discharge coefficients and retention capacities.
- One component that is typically non-linear consists of the estuaries of larger tributaries.

The sum of the non-linear overlapping in these four transient and dynamic components makes predicting effects extraordinarily difficult. Even generally evident assumptions such as 'more retention area is always good' and 'discharge acceleration is always bad' may be incorrect. Taking the Danube

River near Passau as an example, discharge delays due to retention can indeed lead to undesired wave overlapping with the Danube's normal wave.

Thus, it can be presumed that every river system has its own character, even when properties such as the drainage basin and runoff appear to be similar. In order to make statements regarding the effect of flood protection measures beyond the general hydro-engineering assumption, the Bavarian Danube (Bavarian watershed area of 4,047 to 77,023 km^2, HQ100 from 513 to 8800 m^3/s) was modelled, including its historical, current and potential retention space using complex two-dimensional hydraulics. This is possible today because both geo data as well as hydraulic modelling are resolvable with state of the art technology. One preliminary result of these studies – which are still underway – on a 260-km stretch of the Danube river between the Iller estuary and Straubing (Rutschmann, 2013) is that several established assumptions have been confirmed and that new knowledge has been generated:

- Reactivation of natural linear retention spaces. An analysis of the natural retention areas historically present along the Bavarian Danube shows that relining retention areas during larger flood events hardly has an effect on flood water wave height. Dyke relocations yield a lower level locally (broader flow) and a certain delay in the discharge wave when there are several of them (see Section 4.3.6).
- Cultivating river barrages. Observations on pre-sinking followed by higher backwater level in river barrages (for example, Geisling and Straubing barrages) show that the additional retention volume created by pre-sinking largely fills the impounding again, with average volume/discharge conditions (m^3 retention volume/m^3/s discharge) right when the Danube's HQ100 wave arrives. It may be possible to implement tailored management strategies at various Danube backwater levels in the event of flooding as general support. However, this is no replacement for manageable flood polders. Potential effects of pre-sinking on wave overlapping taking place downstream must be observed.
- A much higher effect can be yielded (under the same retention volume) by non-linear (i.e. with intake barrier, i.e. summer dykes) and controlled retention areas in return, as they influence flood peaks in a targeted manner. An individual effect analysis at the 12 potential flood polder sites reveals that each site can make a significant contribution of approximately 30 km through local relief (peak reduction).
- Positive effects were evidenced on a trans-regional scale as well. The extent and range of the respective apex reduction are of course dependent upon multiple general conditions, including the usable retention volume, site location, and interaction between river and floodplain areas. However, the respective hydrological scenarios involving location and duration of the rains causing the flooding and the interplay among multiple relief processes are highly decisive for the trans-regional effect and vary highly in their degree of effect. The effects matrix is complicated at very the least, if not complex in a non-linear manner.

This means it will not be sufficient to create larger manageable retention options in just one Danube section in order to react flexibly to any respective flooding situation. Larger controllable retention spaces should be created in each related hydrological river section, i.e. between the estuaries of the tributaries affecting river discharge. A combination of controlled flood polders in one respective Danube section (about 50–60 km) has proved to be particularly effective. The reducing of flood wave peak(s) has to be repeated on a regular basis along its course, in order to attain a trans-regional effect.

Volume observations have clearly shown that the minimum volume required to attain a certain capping percentage in wave peaks increases significantly from section to section along the course of the

Danube. In the flood events observed, for example, attaining a reduction in the discharge peak of 10% in the Danube section between the Iller and the Lech estuaries (reference level: Donauwörth) required at least 10 million m^3, in the Danube section between Lech and Naab/Regen estuary (reference level: Ingolstadt) at least 20 million m^3, and in the section between the Regen and Isar estuaries (reference level: Schwabelweis) over 40 million m^3. This represents the minimum volume needed for optimal capping. As regards interaction with other retention effects, such as the marsh upstream from Donauwörth, significantly higher volumes may be necessary depending on the flood polder site.

The prioritisation of the individual sites based on the flood polder effect and the illumination of additional aspects provide decision-making assistance that can be used to select the flood polder sites in the next planning step. The flood polder site with top priority in the two Danube sections named above bears a high level of conflict potential in other fields, especially nature conservation. This is why it is recommended to include an additional alternative site in further planning steps.

Based on the findings from this study (Rutschmann, 2013), it is recommended to proceed as follows:

- Danube section Iller to Lech estuary. In this section, the flood polder sites Höchstädt and Schwenningen rank best in prioritisation. Feasibility studies should be contracted for these sites. They are both in the vicinity of the high population area, Donauwörth, and can be controlled even when there is extreme Lech influx when needed. At least one of these two flood polders should be implemented over the medium-term. Upstream, a marsh also quasi represents a flow polder that activates additional retention volume under extreme discharge due to increased channelling out.
- Lech to Naab/Regen estuary. The construction of the flood polder in Riedensheim was due to commence in early 2015. Additionally, feasibility studies will be performed for the Bertoldsheim flood polder site (performs best in the prioritisation) as well as for the Großmehring site (location similar to Katzau, for which a study is already available; see below). Over the medium term, at least one further flood polder should be built in addition to Riedensheim.
- Regen to Isar estuary. In order to attain an effect in this section similar to the upstream Danube sections, the flood polders of Wörthhof and Eltheim will also need to be implemented in addition to the flood polder Öberauer Schleife, which is already in planning. Hence, a feasibility study should be commissioned for both sites.

All sites suggested for future polder projects should be legally secured in a timely manner. It is also recommended to secure the remaining three sites in the most upstream Danube section as well in order to keep options open for the future.

The suggested controlled flood polders (at least one in the Iller to Lech zone, at least two in the Lech to Naab/Regen zone and all three in the Regen to Isar zone) will make it possible to establish effective elements for flood management delivering significant relief for the existing flood protection installations along the Danube, thereby reducing the residual risk. Alongside the other elements, e.g. overflow sections and erosion-resistant dykes, they should be viewed as a component for attaining resilient safety systems along the Bavarian Danube.

4.3.6. Wider verses higher. Political discourse often addresses the assumption that ‘natural’ measures, especially natural river retention, can be used to hinder flooding, or conversely that expanding the river has increased the size of flood waves. This is only true in part, as the derivations in the following will illustrate: until around 1800, the Danube flowed in constantly changing curves and streams in a riverbed that was kilometres in width (Figure 5).

This is why a channelisation was performed on the Bavarian Danube between 1806 and 1867. The corrective measures lowered the river as planned. Additionally, at the start of the 20th century, dykes were erected along the river. The flooding that used to take place throughout the entire Danube valley now only occurs to an extremely limited extent. In order to stop the continued lowering of the river bed, barrages were erected on the Bavarian Danube, which also served the purpose of energy generation. Several barrages are designed such that natural inundation can still take place when water levels are high.

Despite this, huge retention space has been lost along the Danube due to the river channelisation and the barrages. Today between Ulm and Straubing, around 330 million m^3 less retention volume is activated than was the case 200 years ago during an HQ100 event.

In order to evaluate the effects the river channelisation has had on the spread of flood waves along the Danube, the Bavarian Danube Valley was modelled in its historical state in order to research the effects the river correction had on the spread of high water waves. To that end, a land model was produced with the help of historical maps to reproduce the Danube from the year 1800. With the help of two-dimensional hydro-dynamic numerical simulation, various flood events were computed and the spread of high water waves was evaluated.

The studies of the historical Danube show that nearly the entire Danube Valley was available as a floodplain/retention area prior to the channelisation. The result from the calculations (base: Pentecost flood 1999) shows that the retention volume between New-Ulm and Straubing reduced by approximately 330 million m^3 compared to the historical values; however, this has had hardly any influence on the height of the flood peak, which is remarkable. Compared with the historical scenarios, however, it can be demonstrated that today's status yields a significant accelerated flood wave on the Danube, which can have effects on overlapping with flood waves from the Danube tributaries. Historically smaller events were also better dampened.

Based on the knowledge available to us today, we assume the following general properties: in larger water bodies, the dyke relocations largely reduce the local water level by removing bottlenecks and

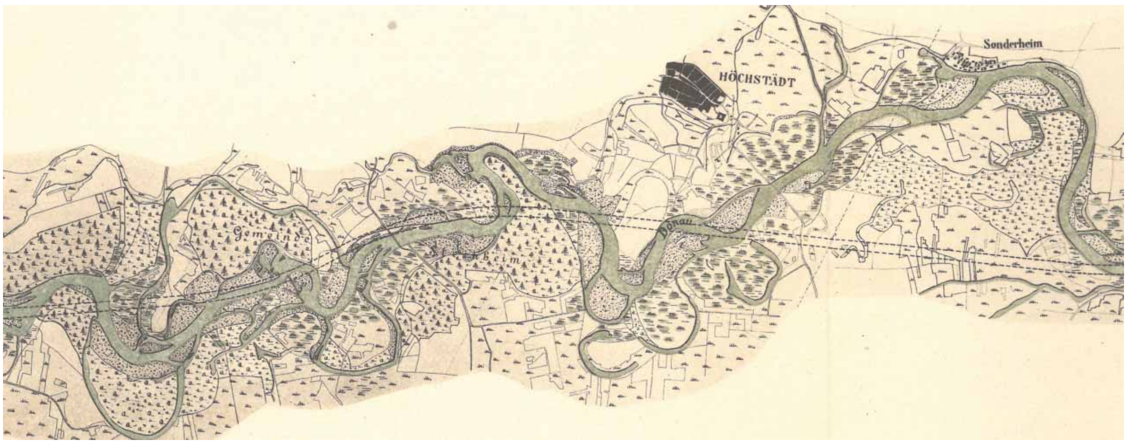

Fig. 5. Danube correction – channels planned at the start of the 19th century.

enlarging cross-sections for discharge. However, no nominal effects on an HQ100 peak are yielded downriver. Newly acquired retention space is usually inundated even in the event of smaller events and/or as flood water rises, and is therefore hardly available any more for capping and/or retaining high water peaks. In smaller rivers, these kinds of dyke relocations can also represent a component to preventative flood protection with effects on the height of the flood peak. However, the effect drops as the intensity of the flood event rises. The ratio between the volume of the flood wave and the activated retention volume is decisive for the effect on discharge reduction. The volume of the flood wave increases along with the size of the catchment area. Thus, the positive effects of dyke relocations (reduction in flood peak) decrease as the size of the catchment area increases. Thus, HQ100 protection according to plan cannot be implemented by solely relocating dykes in upstream river sections.

This is why the immediate reasons for dyke relocations are usually ecological aspects, such as targeted water meadow cultivation and synergies with nature conservation aims.

Irrespective of this, it is urgently recommended – given our anthropogenically moulded system – to retain all inundation zones (maintenance of retention areas) and relief modifications (this also includes the drying of wet zones) still available, and to reduce or stop land utilisation.

4.3.7. Flood prognosis and forecast. Timely warning of flood events avoids damage and saves lives. Since 1890, a flood warning service (HND, *Hochwassernachrichtendienst*) has worked to avert flooding and ice hazards in rivers and levels in Bavaria, as laid out in flood notification plans. The core tasks of ‘measure’, ‘report’ and ‘warn’ have remained unchanged to date. However, today’s technical capabilities are revolutionary compared to those in the beginning. Our information age expects reliable information to be available at all times, everywhere and via all media. The HND in Bavaria endeavours to meet these requirements to the best extent possible, receiving support from an optimally structured water management system to that end. Based on recent experiences, the HND was overhauled and has the following status (in 2014):

The Flood Notification Centre (HNZ, *Hochwassernachrichtenzentrale*) creates a status report for all of Bavaria, and makes this information available on the HND’s Internet site. Five regional Flood Forecast Centres (HVZ, *Hochwasservorhersagezentralen*) are each responsible for a large river zone, producing forecasts and providing warnings to the Water Management Agencies (WWA, *Wasserwirtschaftsämtern*), which have 17 office sites.

Flood warnings are only effective when they are met with prepared measure plans and those measures can be derived from warnings (e.g. flow height at gauge). Community notification plans are the focus of this work again and again, as they are the last link from a warning to protective measures and the citizens. They especially lay out relationships between level statuses and their effects and/or the protective measures to be carried out, as well as flood plans.

The flood warnings of the 17 WWAs are broken down into three warning levels: pre-warning, warning against bank transgression and flooding of agricultural zones, and warning against flooding of zones with edifices. The WWAs produce the warnings and forward them to the notification offices linked to the HND (district offices, urban municipalities), from where they are forwarded to the communities and disaster prevention organisations (fire brigades, integrated control centres). After receiving a warning, the parties affected are obligated to keep themselves informed of the flood risk. There are various information services available to that end (Internet sites, telephone messages, video text on Bavarian public broadcasting).

The trigger for the warnings can be observed transgressions of a warning level for reporting, or a prewarning issued by the HVZ and the HNZ. The decentralised warning system accounts for the local circumstances in the WWA zones and provides for on-site presence. The provision of flood information and warnings in video text, a measurement announcement service and the Internet means the authorities and the public are informed simultaneously.

The foundation for the HND consists of measured data, especially the gauges in the rivers. A total of 320 gauges are specifically used for flood warning, another 480 gauges and some 850 precipitation measurement points are used for forecast calculation via surface runoff models, as well as for other reasons. Measures for improving resilience have been undertaken, such as reinforcing the flood stability of measurement equipment beyond HQ100; data channels and equipment at the most important gauges were doubled in order to avoid outages. The data are automated centrally at a database and merged every 15 min around the clock. There are cooperation agreements with the weather services and flood warning services in neighbouring countries, and with hydro-electric power plant operators as well as with other organisations via automated electronic data exchange. The forecasts are also exchanged. External forecasts are fed into local models.

In this manner, automated hourly forecasts for the next 48 h are computed for the River Inn from the Swiss border to Passau, and on the Danube from Regensburg to Vienna through the neighbouring states of Tyrol, Salzburg, Upper Austria, Lower Austria and Bavaria, and then published on the Internet along with margins of uncertainty. The central data store means the integrity of the data can be secured. Measured data and forecasts come from one source. Their availability is secured through redundant data storage via the replication of the master database at the geographically separated flood forecast centres.

The official gauge measurement network for larger rivers encompasses around 50% of all communities, which are connected to the HND via flood notification plans. The special Storm Weather Plan put forward by the State Ministry of the Interior, in contrast, implements all communities in Bavaria; it governs the forwarding of storm warnings from the German Weather Service (DWD, *Deutscher Wetterdienst*) to the communities. Among other things, this makes it possible to send warnings in a short-term, highly effective manner regarding heavy rain events, which generally affect local and especially smaller rivers. The storm warnings from the DWD are integrated into the HND Internet site.

Within the scope of implementing the EU Floods Directive (2007), warnings are also issued for medium likelihood of flooding (at least a 1 in 100 year event), extreme events and low likelihood events, with corresponding measure plans created by the communities.

4.3.8. Heavy rain and flash floods insurance. The large floods that raise our interest in trans-regional media are usually river floods. We have a relatively high level of knowledge about these scenarios. We have prediction models, gauges and measure systems; we know the flood zones and have leveraged numeric simulations to work out all feasible hydraulic parameters, such as flow velocity, flow depth, shear stress, etc. In addition to these river floods, however, there is a flood risk that receives much less attention in the media, known as urban flash floods. What is fatal about these events is that they can arise practically anywhere, even far away from bodies of water, there are hardly any reliable options for prediction (a rain forecast, at most) and nominal pre-warning times, and they will also occur with increasingly frequency in the future as a result of climate change. They are often created by local occurrence of heavy summer rain events, at times in combination with storm and hail. These events frequently far surpass the capacities of property drainage systems, waste water systems and smaller bodies of water. Urban drainage systems are not usually big enough to account for these rare events. The strategy of measuring a rain water drainage system for a 100-year event is presumably doomed to fail. Here, new ways of channelling and retaining must be found, and the idea of private object protection must be moved more into the foreground. It is often the case that raised cellar shafts and slightly heightened door sills are sufficient to prevent the greatest damage.

According to the many years of experience of German insurance providers, half of all standard flood damage results from these kinds of localised extreme events, urban flash flooding, and is usually far from actual flowing bodies of water (DWA, 2013). This means that these flash flood events are in the same league in terms of money as the flooding of big rivers so often seen in the media.

A natural hazard insurance policy is well suited to these events, which can occur anywhere, particularly as the problem of anti-selection is not an issue here. Anti-selection means that usually only those building owners who live next to a river and experience frequent flooding take out such an insurance policy. However, if that is the only group of persons who purchase insurance, then the charge for an insurance policy would be prohibitively expensive. Purchase of a natural hazard insurance policy is voluntary in Germany. The coverage sum is largely dependent upon the property's risk level. To that end, the German insurance industry has developed a zoning system with four hazard classes. The data from water management offices, such as computed flood zones, are taken into account here. The risk in the lowest hazard level is largely determined by heavy rain events, and insurance policies are correspondingly financially affordable there. Currently however, the insurance rate in Bavaria is only approximately 21%, while it is approximately 33% in Germany as a whole.

However, it is here in particular that a social solidarity is required. State and community offices use public funds to erect suitable flood protection against high river water for regions with human settlements along rivers. However, the level of protection is usually restricted to a 100-year event (e.g. dykes and technical flood protection systems are designed for a 100-year event). State flood protection measures, however, reduce the hazard classification and the purchase of a natural hazard insurance policy becomes affordable for everyone. With an insurance policy of this kind, a private citizen hedges the residual risk, specifically the potential of failure or overload in state flood protection installations. Simultaneously, this insurance policy also covers the residual risk of flooding due to urban flash flooding. The combination of a lower risk of high river water through state flood protection installations and comprehensive insurance coverage as regards urban flash floods makes natural hazard insurance accessible for the public at large.

4.4. The burden of maintenance

4.4.1. Flood protection infrastructure: moving toward safety and prosperity, or running in circles? Valleys, rivers and river forelands were the seeds for the historical development of human settlement and the starting point of today's societies. Goods transport, water utilisation and transportation channels are all factors which led to human settlements arising in zones at risk of flooding. However, this danger was accepted, as the location also yielded an economic upswing, which led to increased prosperity. While people used to be obligated to live with flooding, capacities then emerged for correcting river runs and erecting the first flood protection installations at known focal points. This reduction in flood frequencies automatically increased the utilisation of river zones (with consequent damage potential) while the awareness for flooding hazard simultaneously dropped. However, many of these flood protection installations were never intended to protect the damage potential of modern human settlements and cities, but were rather designed to help prevent famine in the Danube region and to protect harvests against flooding, which occurred rather frequently. These installations were able to withstand flooding events for a long time. The structural change that incurred (away from agriculture), growing prosperity, the enormous boom in construction and the growth in population, however, have led to a situation bearing enormous damage potential. For example, between 1840 and 2012, the population in Bavaria grew from 3.8 million to over 12 million residents. The flood protection installations necessarily have to be raised and reinforced in order to meet today's protection level for settlement areas (HQ100). However, this retrofitting of installations automatically leads to an increase in damage potential, as there are no longer construction restrictions in these HQ100-protected zones. The damage potential rises again. Does that mean there is a need for more protection as well? It is especially when new flood protection measures are built that, in addition to the technical protection measures, further elements of flood risk management must be implemented. This is the only way to break the spiral of more and more need for protection. Even when doing this is successful, at the least a dependency on these (new) protection installations is yielded, which can no longer be reversed, as relief and settlement structures develop in an irreversible manner. For these societies, this means that each year a certain budget has to be provided to maintain the flood protection equipment that has become necessary to the people living there. Otherwise, there is a risk of collapse. Once the trigger for economic development, flood installations can become an ongoing burden. Whether they are streets or dykes, this maintenance has been consuming more funding than is available for new construction.

In summary, one must be sure that the installation of each new flood protection measure is indeed desirable today, and aware that they will quickly become essential for the region following construction, and that there will be no going back.

4.4.2. Example: resettlement. While this is only possible in individual cases, there is indeed a rising awareness for conscious decisions to no longer continue expanding flood protection in certain regions that are already settled. The experiences from the flooding in 2013, however, have demonstrated that financial decisions cannot be the sole factor here. Human suffering, trauma and psychological stress with later effects on health must also be accounted for. A typical approach here in Bavaria is to at least provide financial support for voluntary resettling to the residents in zones that cannot be permanently protected with flood protection in line with state of the art technology.

4.4.3. Example: development of maintenance strategies in torrent control in the Alpine region. The current situation in torrent control in Bavaria's Alpine region can be described briefly as follows: over the past 100 years, some 50,000 protective structures have been built along torrents and their drainage areas. Many of these structures are no longer in line with modern requirements. Their maintenance and restoration consume significant levels of resources; it is a Sisyphean task. Year on year, attempts are made to restore the existing structures with existing capacities, and to renew them as they collectively decay (Figure 6). Moreover, there is even more need for new expansion and protection measures in order to protect new and more sensitive infrastructure and to stay on top of the rising requirements from climate change and society's vulnerability. In line with the discussion of sustainable development earlier in this paper, this yields a general specification for technical development (Grambow, 2012): 'On both the level of the individual installations and on the level of entire technological systems, there should be permanent monitoring and enhancement to the technology in the direction of sustainability criteria.' General life experience reinforced academically by resilience theory, however, shows us how difficult it is to depart from a path that has already been started and solutions that are well established. There is

Fig. 6. Just one of thousands of torrent control structures that require maintenance.

danger that 'due to holding on to traditional solutions, funds are being 'sunk' and the conservation phase of a system is being stretched so much that there is no homogeneous new development loop on the other end, but rather a collapse similar to a revolution in nature' (Grambow, 2012).

Applied to the situation described above in torrent maintenance, the established solution represents the 1-for-1 restoration of structures (i.e. restoration or replacement at the same location and in the same construction model), without checking whether optimisation is an option. A crisis-like collapse then occurs when the protection systems thought to be safe gradually fail due to maintenance no longer being financially feasible. Against this background, a comprehensive research project was launched by the Bavarian water management administration with the objective of finding a way to optimise the protection systems with regard to minimisation of maintenance expenditure, and modification in framework conditions as well as long-term adjustments and further expansion requirements. In principle, there is a similar situation with regard to first-order and second-order rivers. This can presumably be applied to many further fields involving infrastructure installations (e.g. roads) in a similar manner. Once installed, our society becomes more and more dependent upon these installations. Once considered to be a 'relief' for society, for future generations it quickly becomes a dependency on 'life-sustaining systems' that can no longer be reversed, and therefore turns into a significant burden on future budgets over the long term.

4.4.4. Reconsidering past solutions with regard to changes in general conditions. While dyke systems erected at the start of the last century were frequently intended to protect agricultural spaces and for sustaining food production (degree of protection ~ HQ30), these systems have to protect settlements and industrial zones that have grown since that time, which means they have to meet an entirely different objective (degree of protection HQ100). The changed requirements and general conditions to which torrent control has been subjected over the past decades are much more versatile today. Settlements have expanded to the scree at valley exits. The forest and vegetation situation as well as uses (e.g. mountain restaurants, ski slopes, forestry, tourism) have changed over the decades. In some places, reforestation is leading to stabilisation in mountain faces, and thus to a reduction in discharge and bedload in torrents. Short-term individual events quickly have the opposite effect, such as storm damage and avalanches. Among other things, new construction methods have developed due to changes in machinery, or were even necessary due to changes in personnel. Modern computation models permit precision in process assessment and dimensioning in protection systems. Databases and the documentation of past events also facilitate re-assessment of the current situation. Added to this are new legislative requirements in nature conservation and the two EU Directives (Water Framework Directive, 2000; Floods Directive, 2007). The knowledge that a residual risk remains for all protective measures and that our financial and personnel resources are limited requires the continuous forcing of transition away from pure hazard averting to a sustainable risk culture in natural hazard management. The list is merely an outline, yet it shows that costly 1-for-1 restoration and holding on to what are frequently historical solutions should at least be questioned and optimised (Figure 7). In this context, however, optimisation must not be placed on the same level as an increase in efficiency, which is often misunderstood. An increase is efficiency solely targeted at trimming a protective system for one reason and to prepare for a design situation in a cost optimised manner

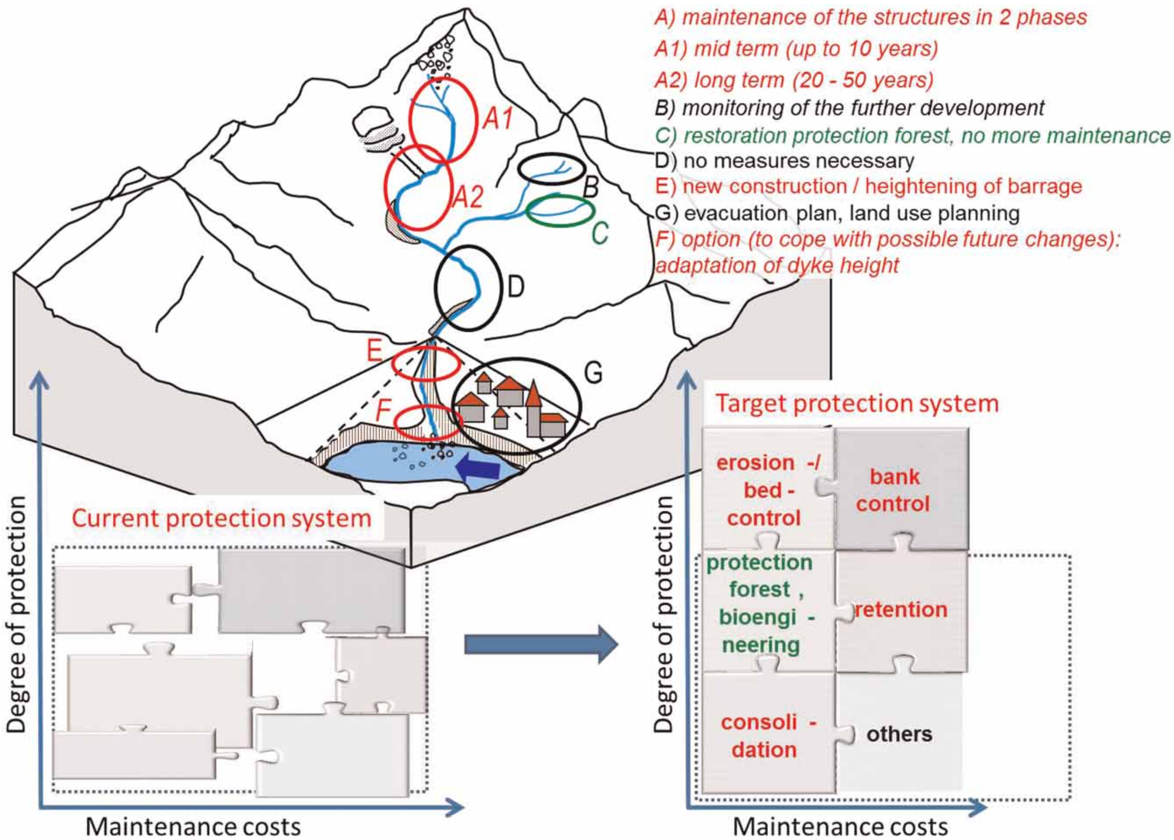

Fig. 7. Systemic visualisation of influence on maintenance costs.

which does not take critical overload properties and 'hard' system tipping points into account can never be sustainable. Optimisation of protection must consider the aggregate risk as well as costs, and lead to compliant, resilient and adaptable systems.

As an outcome from a research project on four torrent zones featuring well over 100 individual structures, research was performed regarding optimisation of maintenance and future expansion of reconstruction of the protection system in pilot studies. The objective was to derive a guide for the future maintenance strategies in the torrent catchment areas in Bavaria. The intention was not to work on specialised topics like transportation processes, driftwood, hydrology, damage analysis, monetary damage and efficiency assessment, risk analysis and assessment, geology, and hydraulics in line with state of the art technology, but rather to illuminate an integral and balanced aggregate observation that can be applied in practice.

Structures were identified in all drainage zones that are no longer needed in their respective state from a modern point of view. Simultaneously, however, weak points in the protective systems and additional need for expansion were revealed in all the studies. A 1-for-1 maintenance was therefore not the most sustainable solution in all catchment areas. There were also intensive efficiency considerations regarding the maintenance cycle for key and standard structures with simultaneous consideration of the state a structure is in (decay over time), as well as at times comprehensive drainage zone observations of historical states and even of future scenarios, like changes in wildlife and forest structures.

The implementation of this strategy must of course be accompanied in practice by intensive communication. Moreover, a sustainable master concept can only be attained with the best possible utilisation of knowledge and experiences on site.

Part of this is supplementing the process of technical rethinking with risk management measures on the demand side, i.e. via risk communication and passive and active prevention on the infrastructure and settlement side (warning and deployment plans, marking of hazard zones, restrictions in urban land-use planning). This is how modern participatory methods will become elementary components to the future torrent strategy.

5. Conclusion

Flood protection is an integral part of society's development. To meet a growing vulnerability in the context of geopolitical and global changes, existing systems of natural hazard management must be reviewed on a regular basis. In Bavaria, lessons from the big flood in 2013 have led to a fundamental modification of the existing integral flood protection strategy, the main characteristic of which concerns the handling of events which exceed standard structural design limits.

5.1. The systemic core to this approach consists of holistic scenarios and a targeted resilience strategy

Technical development will also continue throughout the course of Action Programme 2020plus, requiring adjustments in programming and even opening up new opportunities. Its 6-year cycle for adjustment and advancement in hazard maps and flood risk management plans is evidence of this fact.

Irrespective of state guarantees stipulated by society (including communal self-responsibility), sustainable and comprehensive protection can only be attained with collaboration from everyone. Here, dialogue regarding risk for the revising of flood risk management plans will attain particular significance.

In order to continue the high quality planning, building and safe operation of effective flood protection installations in Bavaria in the future, it will also be necessary to have well trained, responsible technicians and engineers in planning agencies, construction companies and public administration. The Bavarian water management administration has committed itself to these tasks and will meet this obligation with appropriate equipment and personnel.

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