Large-scale assessment of flood risk and the effects of mitigation measures along the Elbe River

Jean-Luc de Kok · Malte Grossmann

Abstract The downstream effects of flood risk mitigation measures and the necessity to develop flood risk management strategies that are effective on a basin scale call for a flood risk assessment methodology that can be applied at the scale of a large river. We present an example of a rapid flood risk assessment methodology for the Elbe River. A 1D hydraulic routing model is extended by including the effect of planned (regulated and unregulated) and unintended retention (dike breaches) on the peak water levels. We further add an inundation model for dike breaches due to dike overtopping and a macroscale economic approach to assess the flood damage. The flexible approach to model the effects of measures by means of volume storage functions allows for rapid assessment of combinations of retention measures of various proposed dimensions and at multiple locations. The method allows for the comparison of the flood risk at the scale of the main river trajectory, which has not been possible for the Elbe River to date. The model is applied to a series of exemplary flood risk mitigation measures to show the downstream effects and the additive effects of combinations of measures on the flood risk along the river. We further demonstrate the increase in the downstream flood risk resulting from unilateral decisions to increase the dike height at upstream locations. As expected, the results underline the potential effectiveness of increased retention along the river. The effects of controlled retention at the most upstream possible location and largest possible extent generate the most pronounced reduction of average annual damage. As expected, the effect of uncontrolled retention with dike relocations is significantly lower.

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1 Introduction

During the flood catastrophe of August 2002, the Elbe River and its tributaries were heavily affected in terms of damage (IKSE 2004a). Efforts to improve flood risk management have increased as a result (Petrow et al. 2006). For example, the International Commission for the Protection of the Elbe (IKSE) formulated a flood action plain (IKSE 2004b), in which potential measures such as the reactivation of retention capacity in the floodplains, increased storage capacity in upstream reservoirs, improvement of the existing river dikes, and flood preparedness are proposed. Within the concept of integrated floodplain and river basin management, it is not only the reduction of flood risk that guides the future development of the floodplains. Other goals to be taken into consideration are, for example, the restoration of the ecological function of floodplain habitats, the improvement of the nutrient retention capacity of the floodplains or the capacity of the river as an important waterway for transport.

The Elbe pilot Decision Support System or Elbe DSS is an integrated tool aimed to promote the discussion on integrated river basin management by enabling the analysis and comparison of different long-term strategies that take multiple river functions into account. The DSS is described in detail by De Kok et al. (2008) and Berlekamp et al. (2005). In order to take into consideration the inherent trade-offs between goals and possibly conflicting interests of different stakeholders, the effects of different interventions on different goal indicators such as flood risk have to be considered simultaneously. This article reports on the approach chosen to integrate a rapid flood risk assessment approach into this model system. The application in an interactive decision-support system (DSS) calls for flexible models that are easy to set up and adapt to changing user demands. Comprehensive 2D hydrodynamic models are well able to capture the dynamic aspects of a flood, but the data requirements and computational load make these models less practical for application in a large-scale risk assessment, particularly when multiple scenarios have to be analyzed and compared interactively, for example during sessions with stakeholders (Apel et al. 2006). An ongoing development is the application of 1D models combined with volume storage functions derived from GIS analysis for large-scale risk assessment (De Roo et al. 2000; ICPR 2001; Zerger 2002; Förster et al. 2005; Knebl et al. 2005; Apel et al. 2006; Lindenschmidt et al. 2006), but the majority of these studies pertain to only a small section of the whole river trajectory. As the intention of the Elbe DSS was to apply existing models as much as possible, the choice was made for an existing 1D hydraulic model as the basis for large-scale flood risk assessment.

The large extent of the Elbe floodplains and the absence of any previous economic evaluation at the scale of the river required the development of an innovative rapid assessment approach. We therefore combine the 1D model with a macroscale approach for damage assessment that is based on the method originally developed for assessing flood risk for the Rhine Flood Action Plan and Rhine Atlas (ICPR 2001). Macroscale approaches have been used for risk assessment on a large scale with scarce data in several studies (Penning-Rowsell et al. 2003; Meyer and Messner 2005; Messner et al. 2007). See Meyer and Messner (2005) and Messner et al. (2007) for a review of applications. Of the federal states along the Elbe, the State of Sachsen has recommended a damage assessment method which is also based on the Rhine Atlas Method (LTV 2003). The state of Mecklenburg

followed a different approach, which is an adaptation of the so-called German mesoscale approach (Messner et al. 2007). This approach was also recommended for flood risk assessment along the Elbe River in the IKSE Action Plan (IKSE 2004b), but it has not been elaborated since. An abridged version of this approach has also been used by Förster et al. (2005) for their assessment of the mitigating effects of a number of large retention polders at the mouth of the Havel River. Other federal states do not give a recommendation for a river flood damage assessment method. Currently, efforts are under way to further improve the basin scale analysis of the flood risk in the Elbe River (e.g., VERIS Elbe 2008).

The aim of this article is to examine the usefulness of the combined flood risk assessment approach, which has been used in the Elbe DSS. This approach comprises four steps: the generation of artificial flood events based on statistical analysis of hydrological data, the routing of the flood event along the river including the effect of controlled retention and dike breaches, inundation modeling, and modeling of the expected damage. We demonstrate possible applications of the method by analyzing various risk mitigation measures discussed in the IKSE action plan as case examples. The measures consist of various combinations of dike heightening and operation of (un)controlled retention polders along the river.

This article is organized as follows. Section 2 introduces the study area and the risk mitigation measures that we consider. The methodology is outlined in Sect. 3. We begin with the routing of flood events and inundation model, followed by a presentation of the approach for flood damage assessment. The outcomes of the flood risk assessment are presented in Sect. 4. The article ends with the conclusions section, elaborating on the effectiveness of measures, potential bottlenecks of the method, and room for future research.

2 Case study description

The German part of the Elbe catchment (Fig. 1) covers an area of 97,175 km^2 and has 18.5 million inhabitants. The Elbe River has characteristics of a lowland river with large floodplains downstream of Dresden. Approximately 80% of the floodplains along this river stretch are protected by dikes. The generally desired design standard for dikes protecting settlements is a recurrence interval of 100 years plus a 1 m freeboard. Protection standards in rural areas are generally lower, for example LTV (2003) recommends a recurrence interval of 25 years for single buildings and infrastructure, and 5 years for agricultural areas. In 2000, over 470 km of dikes required maintenance (IKSE 2004b). The actual freeboard varied between −1.70 and +1.30 m. The flood of August 2002 was due to extreme rainfall in the Elbe catchment, and was estimated to have resulted in 6.2 billion € damage in the state of Sachsen, 1 billion € in Sachsen-Anhalt, 0.2 billion € in Brandenburg, 0.2 billion € in Niedersachsen, 0.04 billion € in Mecklenburg Vorpommern, and 0.004 billion € in Schleswig-Holstein (IKSE 2004a). Twenty-one dike breaches occurred along the Elbe River. The peak discharges in the Elbe River during the flood are estimated to have had a recurrence interval of 200 years (IKSE 2004b). The technical condition of about 45% of the 1,200-km long Elbe dikes was considered to be insufficient (IKSE 2004b). This partially explains the large number of dike breaches. To what extent upstream dike breaches lowered the downstream water levels is not known exactly, but it can be assumed that some areas escaped inundation in this way (Apel et al. 2006). The purpose of the IKSE action plan (IKSE 2004b) is to develop a comprehensive flood risk management strategy for the river. The proposed measures include amongst others, reactivation of the

retention capacity along the river floodplains and reconstruction of dikes to the desired safety standard. Dike shifting has been proposed and discussed mainly as a nature conservation measure (cf. Meyerhoff and Dehnhardt 2007), but realignment may also prove beneficial by shortening the dike line. Since the flood of 2002, both the IKSE and the German federal states have commissioned a series of studies to evaluate potential sites for dike relocations and retention polders (Fig. 1).

The number, exact location, area, and retention volume of potential sites are the subject of public debate and constant review. Within the Pilot Elbe DSS, the proposed sites and dimensions from four data sources were included (Merkel et al. 2002; Ihringer et al. 2003;
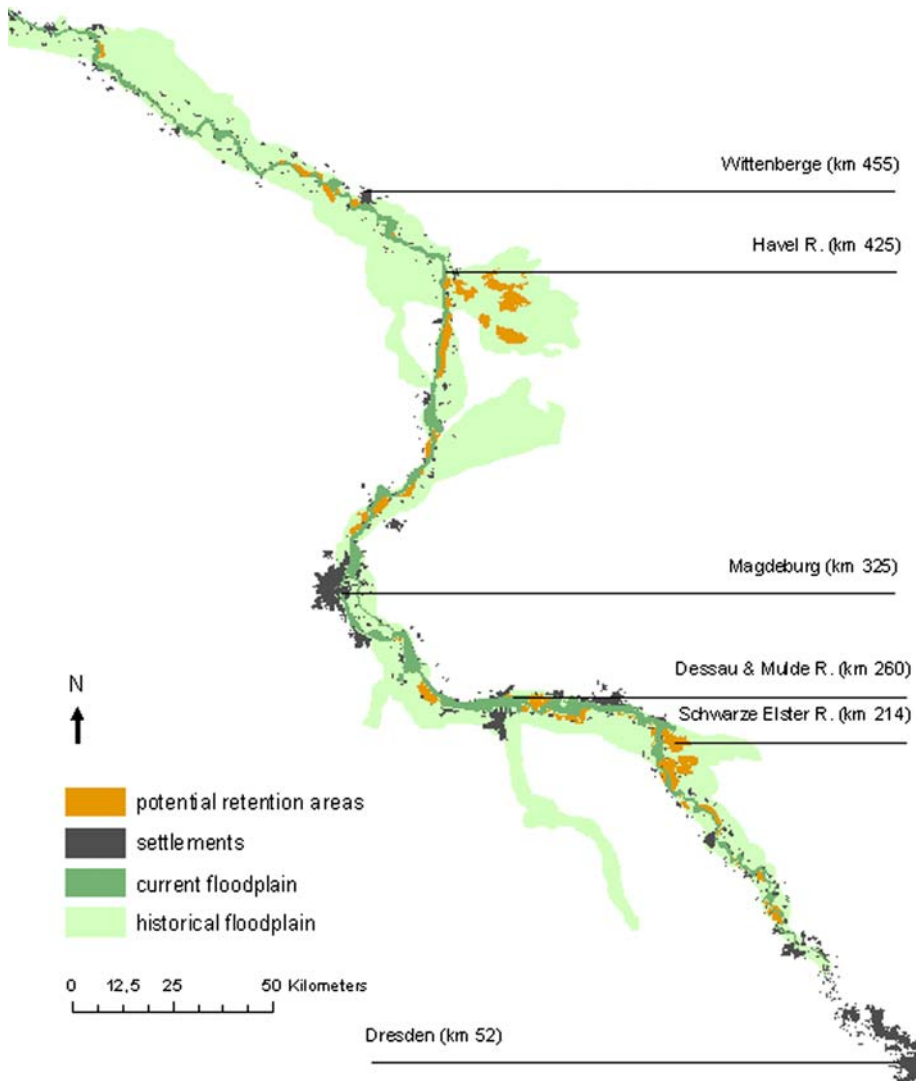

Fig. 1 Map of the study area showing the location of the potential retention areas

IKSE 2004b; Förster et al. 2005). In the case of divergent information on dimensions for a site, the larger alternative was chosen for this study.

For analytical purposes, this article concentrates on six combinations of measures (see Table 1), which were chosen to illustrate the magnitude of effects that could be achieved.

The strategies are compared to the baseline scenario that describes the status of the flood protection system for the year 2000 (IKSE 2001). Recent improvements of the dikes since the flood are not included in the database. The first strategy looks at effects of dike heightening, the following two strategies compare retention effects of dike relocation measures of different magnitude, and the last three strategies compare the retention effects of controlled polders of different magnitudes and locations.

Strategy D S+1: implementation of the design standard of a 100-year recurrence interval with an additional freeboard of 1 m for all dikes in Sachsen for which this protection standard is stated. The total length of the modified dikes is 60 km in the river stretch between Elbe km 60 and 180. The purpose is to compare the upstream damage with possible increases in the flood damage downstream.

Strategy DR I: dike relocation (uncontrolled operation) of all 60 potential sites is included in the database irrespective of their designation for dike relocation along the river stretch Elbe km 117–536. The total floodplain area is 34,658 ha with a storage capacity of 738 million m^3. The purpose is to examine the potential effects of a dike relocation program which is much larger than the 15,000 ha analyzed in Merkel et al. (2002) or otherwise currently under discussion.

Strategy DR II: dike relocation (uncontrolled operation) of the 33 potential sites identified in the IKSE action plan (IKSE 2004b) in the river stretch Elbe km 120.5–536. The total area is 9,432 ha with a storage capacity of 251 million m^3. The purpose is an assessment of a flood risk mitigation program of a realistic dimension as is currently being discussed.

Strategy POL A: controlled operation of all the 31 potential sites for retention polders identified in IKSE (2004b) along the river stretch Elbe km 117–427 with a total area of 25,576 ha and a total storage capacity of 494 million m^3. The polders in Sachsen-Anhalt are dimensioned according to Ihringer et al. (2003) and the polders on the Havel are included and dimensioned according to Förster et al. (2005). The purpose is an assessment of the hypothetical maximum attainable damage reduction through the retention effect.

Strategy POL P: controlled operation of only the largest five potential sites for retention polders identified in Ihringer et al. (2003) near Prettin-Mauken, Elbe km 180, with a total area of 4,557 ha and a storage capacity of 138 million m^3. The purpose is to assess the contribution of the largest upstream sites to the maximum attainable damage reduction of alternative POL A.

Table 1 List of the risk mitigation strategies that were compared

Strategy	Type	River stretch (Elbe km)	Capacity or magnitude
D S + 1	Dike heightening	60–180	+1 m along 60 km
DR I	Dike shifting	117–536	738 million m^3
DR II	Dike shifting	120.5–536	251 million m^3
POL A	Controlled retention	117–427	494 million m^3
POL P	Controlled retention	180	138 million m^3
POL H	Controlled retention	427	112 million m^3

Strategy POL H: controlled operation of the eight existing retention polders at the mouth of the River Havel near Elbe km 427 with a total area of 9,909 ha and a capacity of 112 million m3. The purpose is to illustrate the effect of a set of major retention polders in the middle reaches.

3 Methodology

The approach is based on four consecutive steps: generating flood events, modeling dike overtopping and inundation, flood damage assessment, and assessment of the flood risk (Fig. 2).

3.1 Generating flood events

Due to limitations in the availability of quality discharge data, the large-scale risk analysis in the Elbe DSS takes an artificial flood event at the gauge station of the city of Dresden, 56 km downstream of the Czech-German border, as the starting point. Daily average discharge data for the gauge stations of the Elbe River have been collected since 1853 and were subject to a detailed statistical analysis (Helms et al. 2002a, b) aimed at the regionalization of the hydrological parameters along the German section of the river. For longer time periods (e.g., 1936–1995, 1903–1995), the data quality was considered insufficient due to human modifications to the river and changes in the basin hydrology (Helms et al. 2002a). Instead, for the period 1964–1995, the more reliable and hydro-logically consistent discharge data have been used. A regionalized flood frequency analysis of these data resulted in longitudinal sections for the yearly peak discharges along the river stretch Elbe km 0–536 (Helms et al. 2002a). The 1964–1995 flood frequency analysis has also been used to generate an artificial flood event with a 100-year recurrence interval for the gauge station at Dresden (Merkel et al. 2002; Helms et al. 2002b).
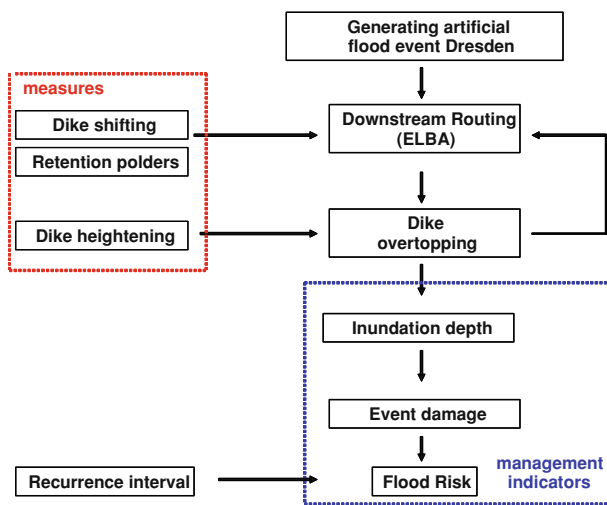

Fig. 2 Methodology for flood risk assessment

In order to obtain the flood events with a different recurrence interval, the discharge values for the 100-year event are rescaled on the basis of the ratio of the peak discharges. This is justified by the fact that the peak discharge is the most relevant parameter for dike overtopping and inundation. There exist also a number of major tributaries along the Elbe River, the outflows of which play an important role. The generation of consistent discharge data for the tributaries is a hydrological challenge beyond the scope of the pilot DSS. Therefore, the contributions of the three main tributaries, the Schwarze Elster, the Mulde, and the Saale, have been generated artificially corresponding to the statistical analysis of the Elbe data (Helms et al. 2002a) and are rescaled proportionally to the discharge for the main channel.

In order to route the flood hydrographs downstream along the main channel, the German Federal Institute of Hydrology developed the 1D translation–diffusion model ELBA (Fröhlich 1998; Busch et al. 1999). This empirical model was developed for quick routing of flood events along rivers such as the Elbe River. The model has been calibrated for seven sections along the Elbe River. In the model, three discharge regimes are distinguished, which can be superimposed. The hydrograph is separated into 1 h pulses, which are multiplied with a dimensionless system function for routing along the river sections:

$$h(t) = \frac{L}{2t\sqrt{\pi Dt}} \exp\left[-\frac{(ut-x)^2}{4Dt}\right],$$ (1)

where $h(t)$ is the system function, L is the length of the modeled river section in km, u is the translation coefficient in km h^{-1}, D is the diffusion coefficient in km^2 h^{-1}, and t is the time step in hours. The model parameters were determined for the seven river sections in the trajectory downstream of Dresden for three discharge regimes. For parameter values, we refer to Helms et al. (2002b).

3.2 Inundation modeling

The peak water levels in the main channel were determined by means of stage–discharge relationships which are available every 500 m. These have been determined with the 1D steady-flow hydraulic model HEC-6 (Otte-Witte et al. 2002) for discharge values up to the peak discharge with a recurrence interval of 100 years. The functions have been extrapolated to cover discharges with a recurrence interval in the range of 100 to 1,000 years. The information on the dikes is based on the 2001 status report on the Elbe dikes (IKSE 2001), which comprises the design flood recurrence interval and an additional freeboard value for each dike section. GIS analysis was used to generate a georeferenced map of the positions of each dike section (Jankiewicz et al. 2005). The dike segments and floodplain area were allocated to the river kilometrization for every 100-m stretch of the main channel using the closest distance function. The dike height above sea level was derived from the water level corresponding to the design recurrence interval plus the given freeboard. This approach was chosen to calibrate the dike heights to the river kilometrization and the corresponding discharge–stage functions. The wide floodplains of the lowland Elbe are compartmentalized into areas protected by dikes and natural areas of high ground. Seventy-one compartments of the floodplain with corresponding dike segments on both sides of the river were delineated by extrapolating the water level corresponding to a 200-year peak discharge from the main channel into the floodplain. While the compartmentalization is obvious for many areas, in the very wide floodplains in the vicinity of confluences with

tributaries such as the Havel, the compartmentalization is more difficult to implement because the barrier effects of structures such as road embankments are unclear.

In the case of overtopping of the dike, the most upstream overtopped dike cell with the lowest recurrence interval is assigned as the overtopping location for the inundation of the protected area. In view of the computational efficiency, the inundation process is not modeled within the Elbe DSS but determined on a 100×100 m grid by means of pre-computed volume storage functions. The flooding volume depends on the water level in the main channel, the inflow rate at the location of the dike breach, and the capacity of the protected area, and is directly translated into inundation depths, using the volume storage functions and the available elevation data (BKG 2003). The inundation depths in the areas of the floodplains not protected by dikes are determined directly from the water level and elevation data.

The probability of a dike breach due to overtopping depends on the duration of the overtopping and the overtopping height (Apel et al. 2006; Kamrath et al. 2006). Analysis of the dike failure probability for the Rhine river (Apel et al. 2006) showed that this probability approaches 100% in the case that the overtopping time is more than a few hours and/or the overtopping height exceeds 10 cm. Here, the flood events are described with a 1-day time step and it is assumed that these conditions are met for all dike overtopping locations, with a dike breach as certain consequence.

The effect of dike overtopping on the downstream peak water levels is included in the analysis. This makes it possible to analyze flood events at the scale of the complete modeled trajectory. The retention effect of dike overtopping instances on the downstream peak discharges is relevant. For example, in the case of a mean inundation depth of 2 m, the stored flood volume in the floodplain protected by dikes can exceed 100 million m^3, which is an order of magnitude larger than the capacity of most proposed retention polders (see Sect. 2). For a large-scale risk analysis, it is therefore essential to include this effect if one wishes to compare the potential damage between different locations and consider the analysis as an event at the river scale.

In order to include the consequences of the potential dike failures on the peak discharges in the main channel, the shape of the flood event is corrected by assuming an inflow based on the simple weir overflow equation (Chen 1995):

$$q_{\text{inflow}} = \frac{2}{3}B(2g)^{1/2}h^{3/2}, \tag{2}$$

where q_{inflow} is the inflow rate in m^3 s^{-1}, B is the width of the dike breach in m, g is the gravitational acceleration in ms^{-2}, and h is the head difference in m between the water level in the main channel and the lowest point of the dike breach, which was assumed to follow the overtopping. During the 2002 flood, the dike breaches that occurred along the Elbe River varied in size between 20 and 200 m, with the most frequent value being ca. 20 m. A log-normal distribution with a mean of 64 m was fitted to dike breach width data for the Elbe 2002 flood from Gocht (2002) and Horlacher et al. (2005), and this mean was used for all dike overtopping locations. Apel et al. (2004), on the basis of case reports, assume that the range of breach width on the lower Rhine is 100–400 m, whereas Kamrath et al. (2006) assume a breach width ranging from 50 to 150 m. A standard value of 3 m was used for the head difference, approximating the lowest dike height according to the IKSE tables (IKSE 2001).

Within the Elbe DSS, the effects of three types of flood risk mitigation measures can be modeled (Table 1). The first is the heightening of dikes by section and the other measures are reactivation of the floodplain retention capacity by dike relocation or the construction

of flood retention polders. Both retention options are conceptualized as retention polders with the difference that the flooding process of dike relocations is uncontrolled, whereas the retention polders are flooded in a controlled way. In the first case, the retention polders are considered to be always open and flood freely with the rising flood wave up to the maximum capacity. In the case of controlled operation, the polders are assumed to be opened at the optimum time to lower the peak discharge to the maximum extent possible. The effect of retention polders on the peak discharges in the main channel is modeled in a way similar to the modeling of the dike breaches with the help of volume storage functions.

3.3 Damage assessment

The damage assessment is based on a modification of the method that was originally developed for assessing the flood risk for the Rhine Flood Action Plan and Rhine Atlas (ICPR 2001). Key characteristics of this method are (a) the application of relative damage functions and (b) a macroscale approach for describing the value of elements at risk. Relative damage functions describe the flood damage as a percentage of the value of the element at risk as a function of the inundation depth. In contrast to object-oriented approaches, macroscale damage assessment methods are characterized by a very high level of aggregation of the data describing both the spatial distribution and the value of the elements at risk. We use the CORINE land cover data (EEA 2002), which were derived from remote sensing data, to characterize the spatial distribution and data from national accounting to estimate the value of the elements at risk. While details will be presented below, the principle of the macroscale method is that the total values of the elements at risk for an administrative region are divided by the area of the corresponding land use class in that administrative area to derive the specific value densities. The method thus makes the implicit assumption that the values of elements at risk are completely homogeneous regarding their characteristics and distribution within the corresponding land use class.

For the implementation of this approach, a selection of elements at risk to be considered has to be made and three harmonizing sets of data have to be generated: (a) the value density of each element at risk, (b) a map of the spatial distribution of the elements at risk, and (c) a specification of the damage functions describing the damage as a function of the inundation depth. Because we apply the damage functions developed for the Rhine Atlas Method directly, we develop new estimates of the specific value densities on the basis of statistical data for the former East German federal states of Thüringen, Sachsen, Sachsen-Anhalt, Brandenburg, and Mecklenburg. The reason is that no effort has been made to date to develop the value densities required for the application of this method for the East German states. The specific value densities can be expected to diverge from the Western German values because of the post-socialist transformation of the regional economy in Eastern Germany. We further compare our method with four alternative adaptations of the Rhine Atlas methodology to the Elbe River Basin in order to give some indication of variability of results associated with different possible implementations of the method. The considered elements at risk and the corresponding CORINE land use classes, value densities, and damage functions of all the damage assessment approaches are summarized in Table 2 and discussed in more detail below.

The classification of the elements at risk follows the classification of stocks and flows typically accounted for in the expenditure approach of national accounting. The expenditure approach measures the total expenditure on final goods and services produced in the domestic economy within a year. A stock variable is measured at one specific time and represents a quantity existing at that point in time, which may have been accumulated in

Table 2 Summary of the considered elements at risk, the corresponding aggregated land use classes, value densities, and stage damage functions for the five variants of the damage assessment method

Elements at risk	CORINE land cover classes[a]		Value density [€ m⁻² of CORINE land cover class]					Damage function [% as a function of inundation depth h in m]
	(I) DSS	(II–IV)	(I) DSS	(II) IKSR adj.	(III) LTV	(IV) IKSR unadj.	(V) IKSE	
Constructed assets								
All buildings	U, I, T		73					$Y = \min(90; 2h^2 + 2h)$
Urban areas		U		186	145	233	104	$Y = \min(90; 2h^2 + 2h)$
Industrial areas		I		189	207	246	25	$Y = \min(90; 2h^2 + 2h)$
Traffic areas		T		250	200	250	25	$Y = \min(10x; 10)$
Traffic infrastructure	U, I, T, A, G, F		1.77				0.35	$Y = \min(10x; 10)$
Traffic infrastructure		A, G		7		7		$Y = \mathrm{if}(x > 0; 1; 0)$
Machinery and equipment, inventories and consumer durables								
Urban aggregate		U		44	40	55	9.23	$Y = \min(100, 11.4h + 12.625)$
Household	U, I, T		15					$Y = \min(100, 12h + 16.25)$
Producing	U, I, T		3	63	72	82	0.58	$Y = \min(7h + 5; 100)$
Commercial	U, I, T		26					$Y = \min(11x + 7.5; 100)$
Traffic	T			2	2	2	0.58	$Y = \min(10x; 10)$
Livestock	U, I, T	G	0.4				0.06	$Y = \min(x*50; 100)$
Vehicles	U, I, T		4.4					$Y = \mathrm{if}(X > 0; \min(22.667*(\mathrm{LN}(x)) + 36.345; 60); 0)$
Agriculture		A, G			0.4			$Y = \mathrm{if}(x > 0; 1; 0)$
Cropland	A		0.06	0.1		0.1	0.1	$Y = \mathrm{if}(x > 0; 50; 0)$
Grassland	G		0.03	0.05		0.05	0.1	$Y = \mathrm{if}(x > 0; 50; 0)$
Forest	F		1	1	1	1	0.025	$Y = \mathrm{if}(x > 0; 1; 0)$

[a] Aggregated CORINE land cover classification: *U* urban fabric, *I* industrial, *T* traffic, *A* arable, *G* grassland, *F* forest

the past. The capital stock is the total value of equipment, buildings, inventories, and other assets in the economy. The stock of capital is increased by the flow of new investment and depleted by the flow of depreciation. Of all stocks, we only consider the stock of consumer durables of households, tangible fixed assets (constructed assets, and machinery and equipment), and inventories of producers (industrial, commercial, and agricultural sector). Currently, only information on the stock of tangible assets is available from the official statistics (Statistisches Bundesamt 2003), so that separate estimates for consumer durables and inventories had to be made. The data on tangible fixed assets are subdivided into constructed assets and machinery and equipment. Constructed assets are further subdivided into buildings and traffic infrastructure, and machinery and equipment are further subdivided into machinery, equipment, and vehicles. In addition, we developed estimates of the stock of consumer durables, the inventories (or standing crop) of the agricultural sector (livestock, grassland, arable land, forest) and the inventories of the commercial and producing sector. For all value estimates, the net concept is applied, which means that the consumption (depreciation) of fixed capital accumulated since the time of investment is deducted. The net concept is the correct concept for flood damage assessment because the damage to the economy would be overestimated if full replacement (or gross) values are used (Penning-Rowsell et al. 2003).

We used data on the net value of fixed assets at the level of the federal states (Statistisches Bundesamt 2003). The value for constructed assets are subdivided into buildings and traffic by assuming a specific net value of 50 € m^{-2} for traffic (road and railway) infrastructure (cf. Meyer 2005) and attributing the remaining asset value to building stock. The values for machinery and equipment and vehicles of the producing and commercial sector are split according to the shares taken from the statistical data for Germany (Statistisches Bundesamt 2005a). According to these data, the share of vehicles is 22% of the total machinery and equipment. Of the residual, 85% is allocated to the commercial and 15% to the producing sector. Separate estimates were developed for inventories and consumer durables based on literature values. The inventories are estimated to be 25% and 15% of the value of machinery and equipment for the commercial and producing sector, respectively (cf. Meyer 2005). Livestock, arable crop, grassland, and forest field inventories are valued using standard values of 1,000 € per head of livestock unit, 600 € ha^{-1} for cropland, 300 € ha^{-1} for grassland, and 1,000 € ha^{-1} for forest land. The total value of household consumer durables is calculated using literature values for the net value per residential floor area[1] combined with statistical data on total residential building floor area and residential land use area for each federal state (Statistisches Bundesamt 2005b). This gives an average of 200 € ha^{-1} for residential building floor area and 21 € ha^{-1} for residential land use.

The value densities are calculated from the area of the corresponding cadastral land use classes and later adjusted to the CORINE land cover classification, which is used to describe the spatial distribution of elements at risk. The CORINE land cover data (EEA 2002) provide readily available land use information on a 100-m grid derived from satellite remote sensing and comprises 44 classes of land use. Areas smaller than 25 ha and line objects wider than 100 m are generalized. For the Rhine Atlas Method, the land use classes were aggregated into six classes: urban fabric (u), industrial areas (i), traffic areas (t)

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[1] Using a net value of 7500 € per unit from IKSE (2004b) for Eastern Germany and the statistical data on number of units and total floor area (Statistisches Bundesamt 2005b) yields an estimate of 102 €m^{-2}. Meyer (2005) uses a net value of 350 €m^{-2} for Western Germany, ICPR (2001) 392 €m^{-2} for Western Germany. Adjusted for Eastern Germany using the long-term difference in average annual household expenditures of a factor 0.82, this yields values of 287 and 321 €m^{-2}. We use an average value of 200 € m^{-2} of residential building floor area.

(airports, harbors, and rail yards), forests (f), arable land (a), grassland (g), and other land use classes. For the Elbe DSS, the land use is further aggregated into only four flood-risk relevant classes with the following percentage cover in the area at risk considered in the model: land with buildings (urban fabric, industry, and traffic) (9.1%), grassland (59.2%), arable cropland (10.2%), and forest (19.5%). The allocation of the elements at risk to these land use classes is summarized in Table 2.

The value densities are calculated by first dividing the total value of elements at risk by the area of the corresponding cadastral land use classes from the official statistics (Statistisches Bundesamt 2004). The elements at risk associated with residential housing, commercial, industrial, and traffic sectors are divided by the respective cadastral land use area. We consider the aggregate of residential and commercial land use classes as urban fabric. These values are corrected to account for the relative share of these land use classes in the aggregated CORINE land cover class they correspond to. The scale factor is 0.75 for built up areas (urban fabric, industrial, and traffic) of which the share of residential land use is roughly 60% and of commercial and producing sectors is roughly 40%. The scale factor for linear traffic elements as a share of the total area share is 0.04 and 1.00 for all other land uses.

We compared our method with four slightly different methods of adapting the Rhine Atlas Methodology to the conditions of the Elbe Basin. These are: (1) application of a correction factor as described by the Rhine Atlas Method (ICPR 2001) to adjust value densities from the conditions of Western Germany to the conditions of Eastern Germany[2], (2) the ad hoc adaptation of the Rhine Atlas Method as proposed by LTV (2003) for use in the federal state of Sachsen, (3) a direct transfer of the values for Western Germany as used in the Rhine Atlas Method (ICPR 2001) without any adjustment to density values as compared to Western Germany, and (4) utilization of the specific value densities proposed in the IKSE Action Plan (2004b) with an adaptation to the CORINE land cover data[3]. The value densities and their allocation to the different aggregations of CORINE land cover data are summarized in Table 2.

The stage-damage functions to determine the percentage damage as a function of the inundation depth for each value component are also summarized in Table 2. Other factors describing the flood hazard besides inundation depth, such as velocity, inundation duration, or contamination with oil or factors influencing the susceptibility of assets, flood proofing, and disaster preparedness are not considered here (cf. Merz et al. (2004); Büchele et al. (2006)). The damage functions are taken from ICPR (2001) and are based on a statistical evaluation of the empirical data on flood damage from the HOWAS database (see Merz et al. (2004) for a critical appraisal) of around 2,000 damage incidences from flood events in Germany. The damage functions were estimated separately for buildings and their content (machinery and equipment plus inventory and consumer durables) and consist of an evaluation of the damage for inundation depths exceeding the ground floor level of the

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[2] We use the difference in capital intensity of production measured per employee of a factor of 0.77 between the Eastern and Western German federal states and a difference in average annual household expenditures of a factor 0.82 factor to adjust property density values for urban and industrial categories. This procedure further assumes a share of residential land use in the urban fabric of 60%.

[3] The specific value density is 225 € m⁻² for residential land use and 25 €m⁻² for non-residential land use. We assume a share of residential and non residential land use of 60% and 40%, respectively, in urban areas and apply a factor of 0.74 m²/m² to correct from cadastral to CORINE land use. The value for transport infrastructure is calculated from 10 €m⁻² and a share of transport infrastructure in the total area of 4%. The value for household consumer durables is calculated from the stated specific value of 7500 € per household unit as described above. The value of inventories is calculated using the proposed 8% share of total producing and commercial fixed assets. All other data are taken directly from the source.

property, a damage maximum, and a choice for the functional form describing the flood damage for inundation depths in between. Following ICPR (2001), an exponential functional form was chosen for buildings and a linear function for equipment and inventories.

Finally, the total damage (D_{total}) in € per flood event scenario for every 100×100 m grid cell is obtained from

$$D_{total} = \sum_{clc=1}^{n} \sum_{e=10}^{n} \sum_{h=0}^{n} (r(h)/100)_e * A_{h,clc} * V_e * f_{clc} * s_e, \qquad (3)$$

where $A_{h,clc}$ is the area (in m^2) of land use class clc inundated with a depth of h in m, V_e is the specific value density of the element at risk e in € m^{-2}, $r(h)$ is the relative damage at inundation depth h in %, f_{clc} is the factor to correct the value density of the cadastral database to CORINE land cover in m^2 per m^2, and s_e is the share of the value component in the total area of the aggregated land use class in m^2 per m^2.

3.4 Flood risk assessment

The damage model was applied to assess the flood damage for individual flood event scenarios, but it was also used to calculate the expected average annual damage as an integrated indicator of flood risk. The change in expected average annual damage is the correct way to estimate the monetary effect of a mitigation measure in a cost-benefit analysis (Penning-Rowsell et al. 2003, NRC 2000).

In the context of the risk-based approach, flood risk is understood to be the product of the flood hazard (i.e., extreme events and associated probability) and the resulting damage. Ideally, a flood risk analysis should take into account all relevant flooding scenarios, their associated probabilities, and possible damage. From these, both a risk curve, i.e., the full distribution function of the flood damage, and the annual expectation value of the flood damage can be derived.

In the Elbe DSS, the flood risk is calculated from a limited number of flood event scenarios by repeating the damage assessment for a series of flood events with recurrence intervals of 2, 10, 20, 50, 100, 200, 500, and 1,000 years at the gauge station of Dresden (Elbe 56 km):

$$\langle EAD_{tot} \rangle = \{(1 - P_1)D_1 + \cdots + (P_{n-1} - P_n)D_n + \cdots + P_N D_{max}\}, \qquad (4)$$

where $\langle EAD_{tot} \rangle$ is the expected average annual value of the flood damage in €, P_1 is the exceedance probability of the lowest peak discharge causing flood damage with a recurrence interval of 2 years, P_n is the exceedance probability of flood event with a recurrence interval of n years, D_n is the corresponding total flood damage in €, and D_{max} is the maximum flood damage for event N (a 1,000-year event). Since this approach requires repeating the calculations for a series of flood events, it is necessary that the damage assessment is carried out with a rapid hydraulic model, if it is to be included in a DSS framework.

4 Results

4.1 Comparison of the damage assessment methods

First, we compared the estimates for the potential total damage for the five variations of the damage assessment methodology (see Sect. 3.3). For this purpose, we used the water levels

Table 3 Comparison of the potential total damage estimate for five variants of the macroscale damage assessment method for a water level corresponding to HQ 200

	(I) DSS	(II) IKSR-adj	(III) LTV	(IV) IKSR-unadj.	(V) IKSE
Million €	3706	5346	4488	6642	2487
Million € per ha[a]	0.013	0.019	0.016	0.023	0.009

[a] Inundated model area is 2,866 km^2

corresponding to a HQ 200 peak discharge along the trajectory and extrapolated these into the floodplains under the assumption of absence of the dikes. The results of this comparison are shown in Table 3.

The total damage estimate varies by a factor of 2.2 and ranges between 2,480 and 6,640 million €. The distribution of the flood damage over the inundation depth classes follows a similar pattern for all variants. The total flooded area is 286,648 ha. This yields an average damage of 0.01 to 0.02 million € ha^{-1}. This estimate is low compared to the estimate of roughly 7,607 million € (IKSE 2004a) total damage in the German part of the Elbe Basin in the year 2002 which, for an inundated area of approximately 300 km^2, corresponds to an average damage density of 0.25 million € per ha. A comparison of the contribution of the damage categories to the total damage is presented in Table 4. These are compared to the relative shares reported for Sachsen and Sachsen-Anhalt for 2002 (IKSE 2004a).

The predominance of damage to buildings and their content with shares of total damage between 70% and 95% is reflected in all model approaches and the observed damage. In comparison to the observed damage, the model results underestimate the damage to traffic infrastructure and do not consider the damage to the flood protection system.

We conclude that the estimate we developed from the available statistical data yields results that are of a similar order of magnitude compared to the ad hoc approaches of LTV (2003) and the method of adjustment proposed by the ICPR (2001). The uncorrected transfer of data from Western Germany yields higher damage because higher values are assumed for all fixed asset categories and the adjustment proposed by the IKSE yields lower values because lower values are assumed.

4.2 Flood risk in the baseline scenario

Next, we present results for the analysis of flood damage along the river trajectory for the baseline scenario without measures for flood events with various recurrence intervals (Fig. 3).

Table 4 Comparison of the contribution of the damage by category as a percentage of the total flood damage for three variants of the macroscale damage assessment method for a water level corresponding to HQ 200

	SN 2002[a]	ST 2002[a]	(I) DSS	(II) IKSR-adj	(III) LTV
Urban	59	30	82	94	96
Infrastructure (traffic)	14	50	13	3	3
Agriculture and Forestry	1	9	5	3	1
Emergency management	2	1	–	–	–
Infrastructure (flood protection)	24	10	–	–	–

[a] For comparison: share of total damage in Sachsen (SN) and Sachsen-Anhalt (ST) for the Elbe Flood of 2002 (IKSE 2004a)
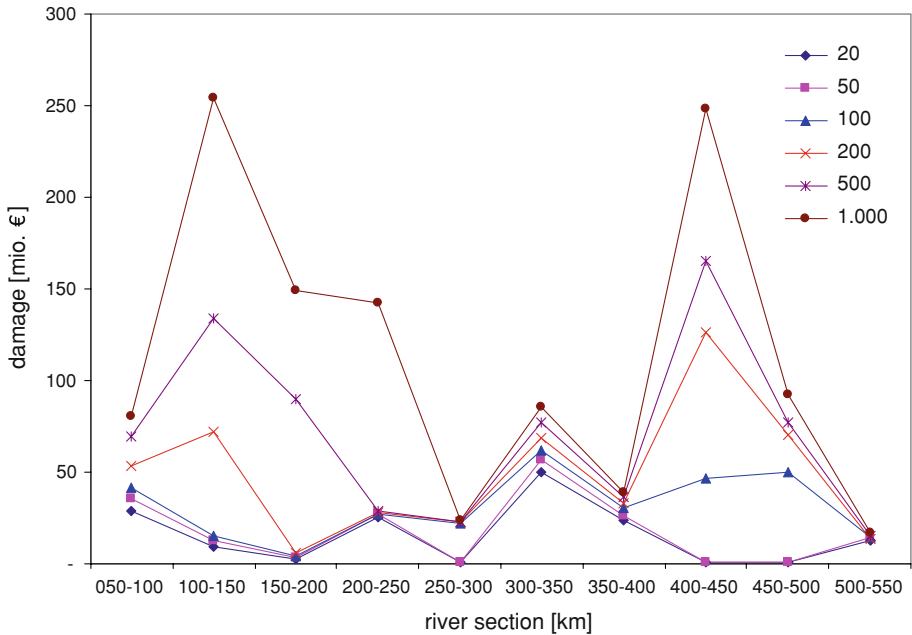
Fig. 3 Flood damage by river section for flood events of an increasing recurrence interval (baseline scenario)

The baseline scenario is based on the existing dike heights, the distribution of elements at risk in the inundated areas, and the effects on peak water levels of dike overtopping upstream of the specific site. Comparison of the damage for flood events of increasing recurrence intervals along the river trajectory leads to two observations. In river sections where damage occurs already for flood events with a recurrence interval lower than 100 years, we find concentrations of elements at risk that are not protected by dikes. We find this damage to be high especially in the vicinity of Magdeburg (km 300–350), Dessau (km 200–250) and Bleckede (km 500–550). Furthermore, the model results point to sections, where the risk of damage by a dike breach is high. These are the sections that show pronounced higher damage resulting from flood events with a recurrence interval of more than 100 years. We find that the river sections between km 100–150 and km 150–200 above Dessau and km 450–500 in the vicinity of Wittenberge have the highest flood risk emanating from a dike breach. This is in line with the expectations and the river stretches that were at risk during the 2002 flood event along the Elbe River.

The volume of water diverted by a dike breach is an important determinant of both the damage at the breach site and the damage at downstream sites, because the retention effect reduces the downstream peak water levels. A sensitivity analysis for various widths of dike breaches demonstrates this (Table 5). While the number of dike breaches remains constant, the total flooded inner dike area, the mean inundation depth, and the resulting damage increases significantly with larger width.

4.3 Effects of mitigation strategies

Next, we compared the effectiveness of various risk mitigation strategies on the peak discharge, the number of overtopped dike segments, and the average annual damage.

Table 5 Analysis of the effects of variations of the width of dike breaches on model results (for a flood event with recurrence interval of 200 years)

| | Dike breach width (m) | | | |
	20	50	100	200
Number of overtopped dike segments	13	13	13	13
Total flooded inner dike area (km^2)	192	292	359	404
Mean inundation depth inner dike areas (m)	1.6	2.0	2.9	4.9
Damage in inner dike area (million €)	168	259	438	765
Total damage (million €)	352	451	629	956

Figure 4 shows the peak discharge along the river trajectory for the baseline scenario and the different strategies (see Sect. 2) for a flood event with a recurrence interval of 500 years. Previous analyses (Helms et al. 2002a) already demonstrated the retention effect of dike relocations on the water levels along the Elbe River to be significantly lower in comparison to the retention effect of polders with controlled operation. Implementing the design standard of a 100-year recurrence interval with an additional freeboard of 1 m for all dikes in the upstream state of Sachsen causes a small increase in the peak discharge, because the retention effect of dike breaches in Sachsen is lost.
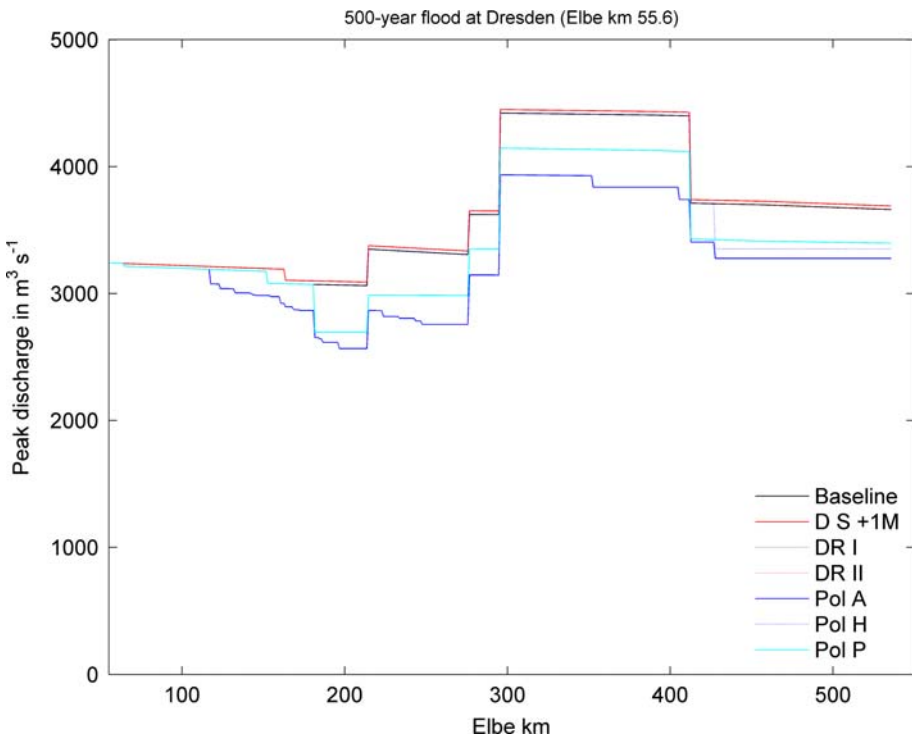
Fig. 4 Effects of the assessed mitigation strategies on the peak discharges along the river trajectory for a flood event with a recurrence interval of 500 years. The discharge curve for the DR I and DR II measures is not distinguishable from the baseline scenario

Table 6 gives a summary of effects of the flood risk mitigation strategies in terms of the avoided average annual total damage in comparison to the baseline scenario for areas protected by dikes and those not protected by dikes.

The number of overtopped dike segments and the damage for flood events with increasing recurrence intervals for the different management options are shown in Figs. 5 and 6, respectively. In Fig. 7, the distribution of the avoided annual average damage along the river is shown.

In terms of overall performance, the maximum reduction of the expected annual flood damage (EAD) is achieved by the controlled operation of the maximum potential of retention polders (POL A). This option significantly reduces the number of dike overtoppings and the associated damage for flood events with higher recurrence intervals (Figs. 5, 6). The reduction of the average annual damage is highest for the sections that have less areas protected by dikes (km 200–250, km 300–350, and km 500–550), but is also observable at sections between km 150–200 and km 450–500 that are mainly at risk from overtopping (Fig. 7). Singling out the effect of two major polder groups included in POL A, one located more upstream (POL P) and one more downstream (POL H) shows that approximately 50% of the avoided damage of the POL A measures can be traced back to the effect of the upstream polder group POL P alone (Table 6). The effect of the downstream polder group POL H on the flood risk in the downstream sections km 400–450, km 450–500, and km 500–550 is similar to that of the upstream polder group POL P.

Furthermore, the avoided annual average damage is, as expected, lower for the two dike relocation programs with uncontrolled retention. The dike shifting projects DR I (large scale option) and DR II (small scale option) do not reduce the frequency of dike over-topping (Fig. 5). The lack of an effect of uncontrolled retention on the peak discharge was already reported for the Elbe River (Helms et al. 2002b) and this study confirms this for even larger scale dike shifting projects such as DR I. However, an effect for flood events with lower recurrence intervals than 100 years can be shown for the dike shifting strategy DR I, which benefits especially those river sections that are to a lesser extent protected by dikes. The average annual damage for the small scale option (DR II) is not significantly reduced compared to the baseline scenario.

Raising the dikes in Sachsen to the protection level of a 100-year return period with an additional freeboard of one meter (D S+1) reduces both the number of dike overtoppings and total damage (Figs. 5, 6). Even though the number of reduced overtoppings is quite high in comparison to the other strategies, the total effect on avoided damage is not as large, because the areas protected do not contain large areas with high property value densities. A more detailed analysis of the effects along the complete river trajectory reveals that the damage reduction in the upstream sections is reduced at the cost of a slight increase of the flood damage downstream in river section between Elbe km 300–350 and km 400–500

Table 6 Avoided annual average damage (in million €) of the assessed mitigation strategies

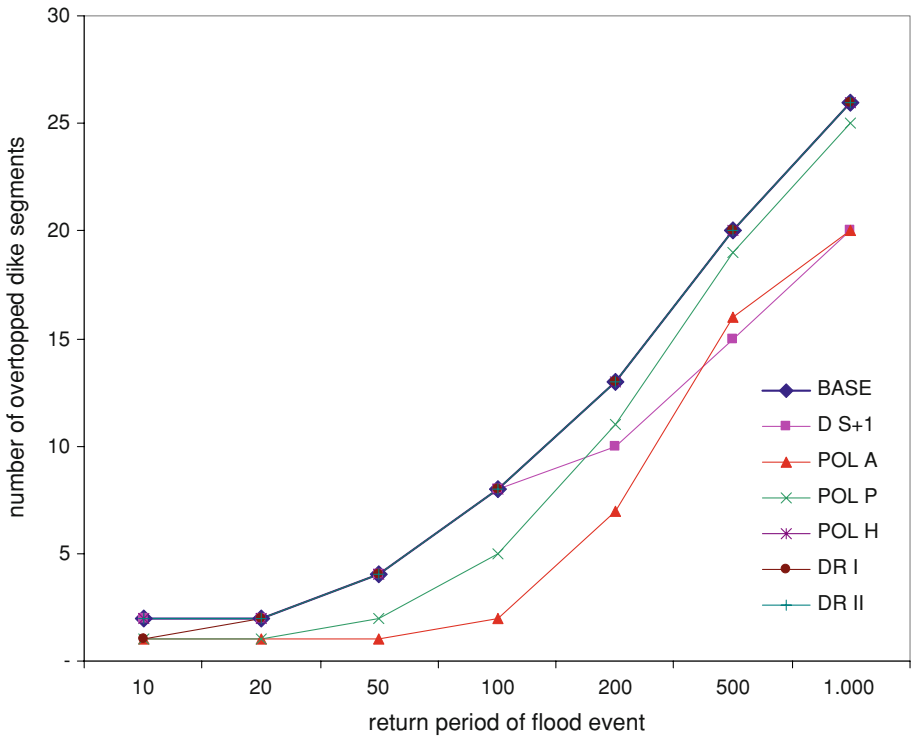|	Measure					
	D S+1	POL A	POL P	POL H	DR I	DR II
Protected by dikes	0.39	5.82	3.94	0.00	1.89	0.00
Not protected by dikes	0.00	20.15	9.44	1.36	3.82	0.64
Total	0.39	25.96	13.38	1.36	5.71	0.64

Fig. 5 Effect of the assessed mitigation strategies on the number of overtopped dike segments for flood events with increasing recurrence intervals

(Fig. 8). This effect is more pronounced, when a lower dike breach width with resulting lower unintended retention in the vulnerable middle reaches are assumed.

5 Conclusions

The need to obtain insight in the downstream effects of flood risk mitigation strategies and necessity to develop flood risk management strategies that are effective at a basin-level scale call for a flood risk assessment methodology that can be applied at the scale of the trajectory of a large river. Although comprehensive 2D hydrodynamic models are very useful for in-depth studies for the planning of structural measures or risk assessment at the scale of individual dike breaches; these models are less suitable for incorporation in an integrated model network, interactive sessions with stakeholders, or repeated use in, for example, a Monte Carlo analysis. The Elbe River served as an example to demonstrate the usefulness of a rapid, GIS-based flood risk assessment methodology. The method allowed for the comparison of the flood risk at the scale of the main river trajectory, which has not been possible for the Elbe River to date. The flexibility of the approach enables rapid assessment of various sets of retention measures of different dimensions and locations. Whereas previous studies assess the water level reductions by various retention measures (Helms et al. 2002a), this work analyzes the effects on the flood risk by taking into account the spatial distribution of the property at risk along the river. Other studies for the Elbe
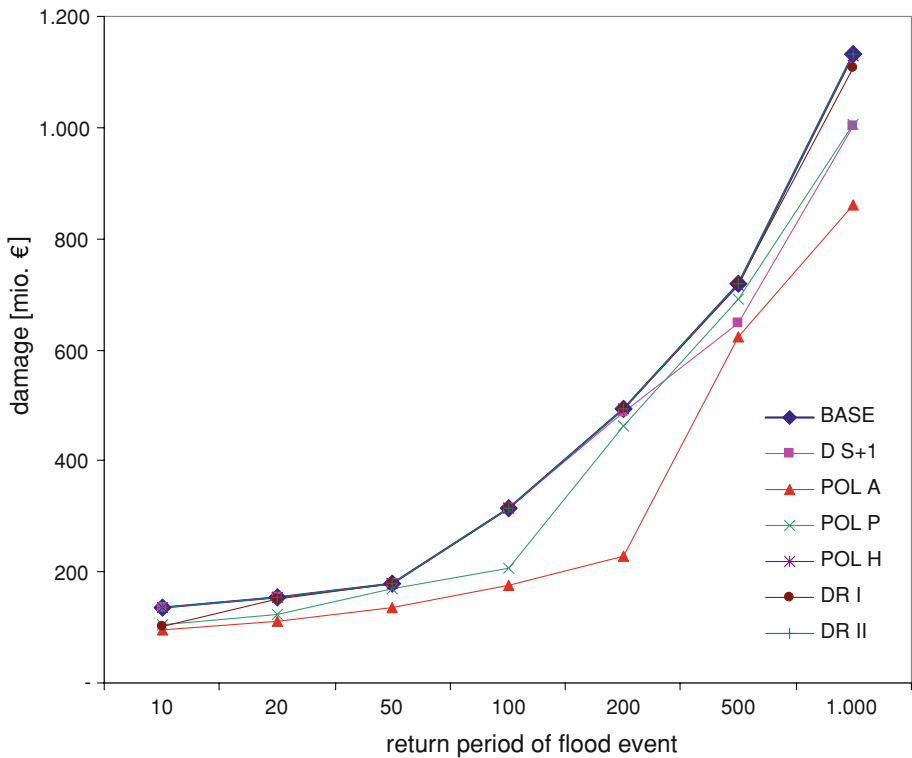
Fig. 6 Effect of the assessed mitigation strategies on the flood damage for flood events with increasing recurrence intervals

River that incorporate flood risk (e.g., Förster et al. 2005) have taken a local approach and not yet included the possible interactions of measures along the whole trajectory of the river.

The model was applied to a series of exemplary flood risk mitigation strategies that were developed from ideas discussed in the IKSE action plan (IKSE 2004b). The downstream effects and the additive effects of combinations of measures on the flood risk along the river can be observed clearly. Furthermore, the results demonstrate the increase of the downstream flood risk resulting from unilateral decisions to raise the dikes at upstream locations. As expected, the results underline the potential effectiveness of increased retention along the German Elbe River. The effects of controlled retention at the most upstream possible location and largest possible extent generate the most pronounced reduction of the expected average annual damage. The effect of uncontrolled retention (dike relocations) is significantly lower. However, the model implementation only considers the retention effects and does not consider the effect on the channel roughness of dike relocations. This is a topic for further research.

The results of the flood risk assessment have to be interpreted with caution because several assumptions have to be made. Ideally, a flood risk analysis should take into account all relevant flooding scenarios, the associated probabilities, and possible damage. From these, both the full distribution function of the flood damage and the annual expectation value of the flood damage could be derived, ideally accompanied by uncertainty bounds.
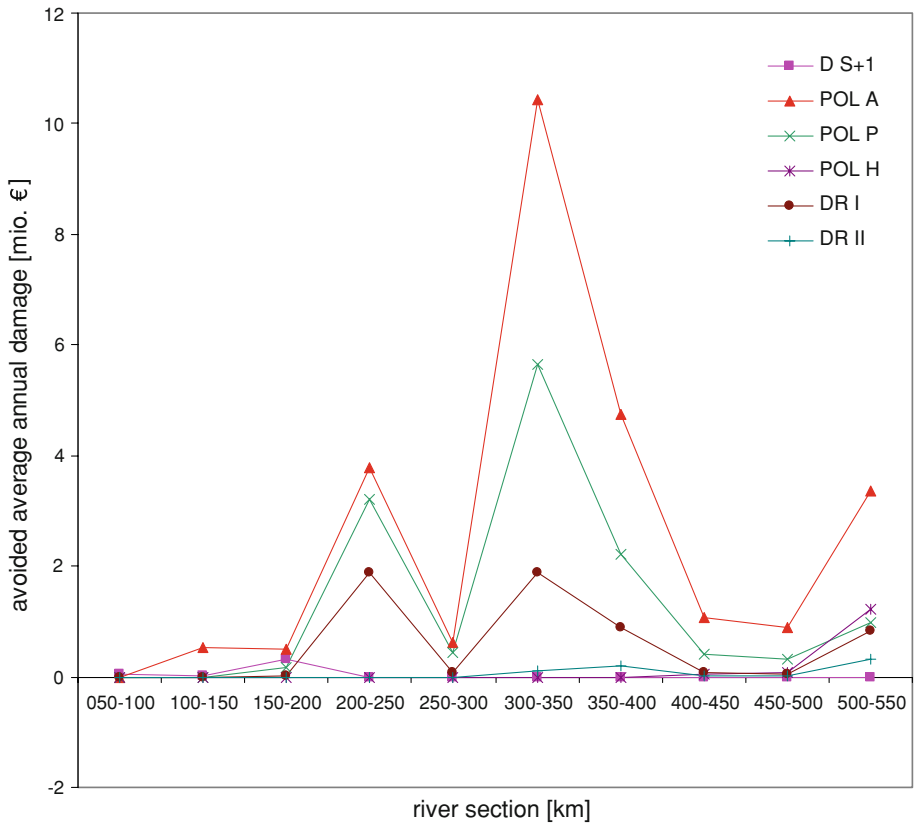
Fig. 7 Benefits of the assessed mitigation strategies: distribution of the avoided average annual damage along the river trajectory

Although the role of several uncertainty sources was examined (dike breach width, economic framework of analysis), we did not investigate these systematically in a Monte Carlo analysis. A stochastic approach to model the probability of dike breaches as a function of water level and the width of the breach (NRC 2000; Apel et al. 2006) would further enhance the analysis of uncertainty of the inundation process. For recurrence intervals beyond 200 years, the artificial flood events are based on an extrapolation of the peak discharge statistics, and the contribution of the tributaries to the discharge was assumed to be proportional to the discharge in the main channel. A conservative estimate was used for the parameters for the inflow that follows a dike breach (Eq. 2). The 1D hydraulic model (Otte-Witte et al. 2002) has been calibrated for discharges up to a 100-year recurrence interval only, which leads to an underestimation of the peak water levels for higher discharges. This, however, does not affect the general applicability of the risk assessment methodology, and the hydraulic model can easily be improved in this respect. For proper understanding, the hydrological conditions during a flood event should be varied in a Monte Carlo analysis as well to examine the role of uncertainty. The data that were used form another source of uncertainty. The dike overtopping locations and inundation patterns are sensitive to the absolute and relative dike heights, the elevation data for the floodplains and innerdike areas, and the delineation of the potentially flooded inner dike areas. The
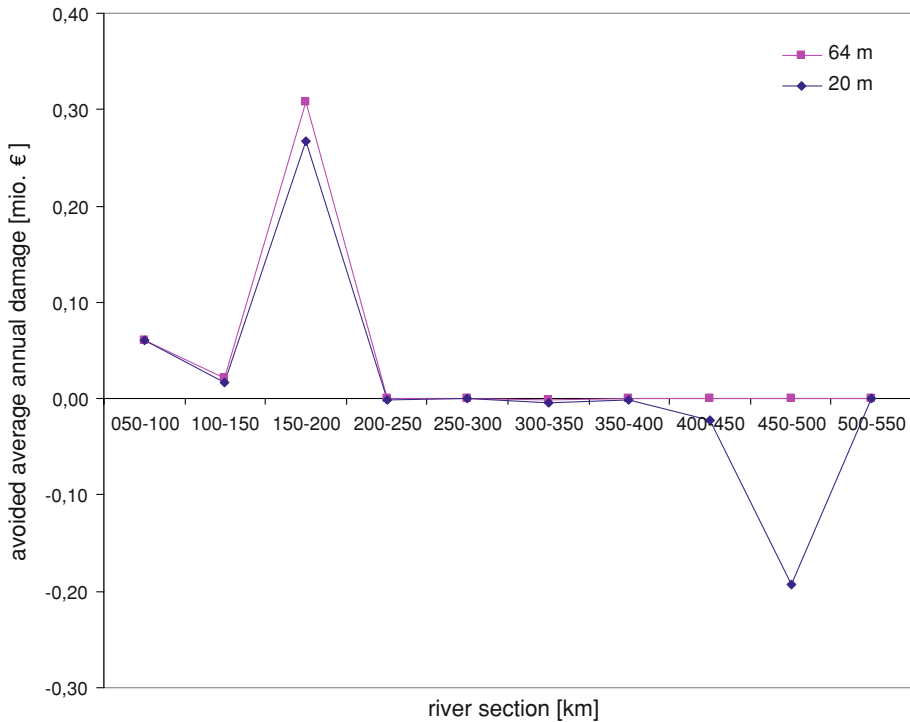
Fig. 8 Effects of dike heightening in upstream sections of the river on the avoided average annual damage along the river trajectory assuming average dike breach width of 20 and 64 m

stage-damage functions are subject to uncertainty that is very difficult to estimate (Hoekstra and De Kok 2008). The development of damage functions has, in general, received much less scientific attention than the development of models to assess the hydraulic aspects of flood hazards so that very little is known about the associated uncertainty of the methods (Merz et al. 2004; Büchele et al. 2006; Apel et al. 2004). The macroscale method, in particular, is limited by the highly aggregated description of the property elements at risk. Our comparison of different damage assessment variants indicates that the high level of spatial aggregation of our method to two land use classes (urban and agricultural) is not as much a cause for differences in the total damage, as the assumptions that are made with regard to the value density within these classes. It is unclear to what extent results of a more detailed damage model would influence the ranking of results at the scale of analysis presented here. This would be an interesting field for model comparison. Furthermore, the assessment of damage in areas classified as built-up land, such as promenades, harbors, or buildings that are outside the areas protected by dikes, proves to be a source of error. The problem is aggravated by the inherent spatial inaccuracy of the digital elevation model and the CORINE land cover data. A possible improvement of the model is a separate treatment of protected and unprotected elements at risk.

When reflecting on the assumptions made and data inaccuracies, it has to be kept in mind that the key point that matters in economic assessment of flood risk management options is not so much the absolute magnitude of the flood damage, but rather the extent to which a proposed plan will reduce that damage (NRC 2000). The results demonstrate that a

GIS-based rapid flood risk assessment approach can provide information on the relative dimensions and spatial distribution of the flood risk reduction of different combinations of measures along the trajectory of a large river. The information that can be generated with a rapid assessment method helps identifying problems and supporting discussions between and with riparians on flood risk management strategies that promise to be effective from a basin perspective and call for more detailed analysis with sophisticated models.

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