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Sensitivity analysis of flood damage calculations for the river Rhine

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1 Introduction

The river Rhine originates in the Swiss Alps and flows through Austria, Switzerland, France and Germany into The Netherlands, where it eventually drains into the North Sea and the Lake IJsel. The river basin area is about 197.000km^2, shared by nine countries and inhabited by about 58 million people (ICPR, 2001; ICPR, 2008). Especially since the 19th century, the Rhine has been developed into an important traffic route and is today one of the world's most trafficked and used waterways. It is thus also referred to as artery of Europe. It connects one of the world's largest sea harbours in Rotterdam, the Netherlands, with the world's largest inland harbour in Duisburg and other industrial complexes in Germany, France and Switzerland. Every year, about 200.000 vessels cross the Dutch-German border, transporting about 200 million tons of goods (ICPR, 2008).

To aid shipping and industrialization, the main river channel has undergone severe changes and has been rectified and canalized. From the original 8000km^2 of flood plains, less than 15% remained (ICPR, 2008). Moreover, the undertaken canalization and rectification of the riverbed caused an acceleration of flood wave propagation in the Rhine canal (Lammersen et al., 2002). These developments have led to an increasing risk of flooding and the ICPR estimates that about 10 million people live at risk from extreme flooding (ICPR, 2001). Safety levels along the river vary and range from 1/200 per year in the Upper Rhine and parts of the middle Rhine to 1/500 per year in the lower Rhine to 1/1250 per year in the Netherlands.

Two major floods occurred in 1993 and 1995 along the Rhine that caused substantial economic damages (Kron and Thumerer, 2002) and the evacuation of about 250.000 people in the Netherlands. In response to these flood events, the International Commission for the Protection of the Rhine (ICPR) adopted the 'Action Plan on Floods' in January 1998 at the 12th Conference of Rhine Ministers. Amongst others, this action plan formulates the target to reduce flood risk (defined as probability x damage), by 25 per cent in 2020 compared to the level in 1995.[1] In this context, the ICPR expert group on flood risk (HIRI) currently works on developing a method that allows an evaluation of this target with the help of quantitative indicators. Prerequisite of such a flood damage evaluation method is its applicability to the whole trans-boundary Rhine basin in a cost effective manner.

The so-called Damage Scanner model, which has been adapted to the river Rhine (te Linde et al., 2010), can provide such a basin wide evaluation of current and future flood risk, taking both socio-economic development and climate change into account, as well as of various adaptation strategies.

When performing flood damage analyses in trans-boundary river basins, usually a common flood damage assessment method needs to be chosen and agreed upon by various stakeholders (ICPR, 2001; Silva and Reuter, 2006). However, different damage assessment methods are used and preferred by riparian countries (Meyer and Messner, 2005) that can yield substantial differences in terms of absolute damages due to existing uncertainties and methodological differences in flood damage modelling. When deciding on a common method, it is thus important to understand how different damage assessment methods and their results compare to each other. This refers in particular to the Damage Scanner, the evaluation carried out in the project *'Waterveiligheid in de 21e eeuw'* (WV21) and the Rhine Atlas damage model. Such a

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[1] http://www.iksr.org/index.php?id=123&L=3

comparison can help to improve the acceptance of a chosen method and respective findings in organizations such as the ICPR and thus to support cooperation in trans-boundary flood risk management.

A first inventory of potential damages along the Rhine was undertaken by the ICPR in 2001 with the so-called Rhine Atlas model (ICPR, 2001). In the meantime, new and improved information became available, e.g. on the extent and water depths of possibly inundated areas in the Dutch delta (www.risicokaart.nl). It is thus also of interest to evaluate potential flood damages taking these new insights into account.

Flood risk is expected to increase in the future due to ongoing developments in risk prone areas, as well as the effects of climate change on river discharges and flood probabilities (Belz et al., 2007; te Linde et al., 2010). Non-structural flood plain measures, such as flood proofing of buildings, are possible ways to address the projected increase in flood damages and risk (ICPR, 2002; Kreibich et al., 2005). However, relatively few studies exist that quantified the effectiveness of such measures, especially with respect to climate change adaptation. It is thus of interest to see how non-structural flood mitigation measures can be incorporated in the Damage Scanner model to evaluate their effectiveness in terms of flood damage and consequently risk reduction.

To gain insights into the sensitivity of flood damage calculations in the Rhine basin and the effectiveness of non-structural flood mitigation measures, the present report will address the following aspects: the report starts with a general introduction into flood damage assessment and its uncertainties (Section 2). Section 3 compares the variations in potential flood damages for the Rhine delta, resulting from different information on inundated areas, namely the Rhine Atlas inundation map and the so-called ‘Risikokaart’. A comparison between potential damages applying the Damage Scanner model and the figures provided by the WV21 study is given in section 4. Section 5 provides insights into the applicability of a uniform damage model for the entire Rhine basin. This is done by evaluating the influence, different damage models have on the estimation of relative flood damage developments over time. In section 6, we discuss different approaches to incorporate non-structural flood mitigation measures in the Damage Scanner model and evaluate the effectiveness of such measures. Section 7 provides an evaluation of observed flood damage developments between 1990, 200 and 2006. This is done on the basis of the CORINE data sets.

2 Flood damage assessment and uncertainty

In order to assess the risks of extreme flooding along the river Rhine from the *Lake of Constance* to the Dutch delta, the so-called ‘Damage Scanner’ has been set-up. This flood damage model is a simplification of the detailed HISS SSM model (Klijn et al., 2007) and capable of assessing potential flood damages for projected future land use. This approach makes use of so-called stage-damage functions. Stage-damage functions are based upon maximum flood damages (in €/m2) per land-use type and describe the fraction of the maximum possible damage that occurs at a given flood depth. The use of stage-damage curves is a widely accepted technique for estimating direct flood damages (Merz et al., 2007; Smith, 1994). Such curves can be established by fitting curves through empirical data on damage and their corresponding flood depth of historical flood events (e.g. the HOWAS database, see Merz et al., 2004). Alternatively, the functions can be derived synthetically using expert judgement (Penning-Rowsell et al., 2005).

Even though a considerable research effort has been made in recent years, it has been acknowledged that the scientific field of flood impact assessment still lags behind the more developed fields of hydrology and hydraulics (Buchele et al., 2006; Merz et al., 2010). Several studies have demonstrated the large uncertainties associated with flood damage assessments (Merz et al., 2004; Apel et al., 2008; Merz et al., 2009; Freni et al., 2010). De Moel and Aerts (2010) have observed differences of up to a factor 4 between different damage models. Their results are in line with the findings of Apel et al. (2009) who also showed a large variation between different damage models.

In the following paragraph a number of issues are addressed concerning damage calculations using this standard approach in order to frame the results correctly. More specifically, the uncertainty of stage-damage curves, and therefore the resulting damage estimate, is addressed and the uncertainty in changes of absolute and proportional damage estimates are compared.

2.1 Uncertainty in stage-damage curves

Merz et al. (2004) show, based on post-flood surveys, that damage to individual buildings and depth-damage relations resulting from such data exhibits considerable uncertainty. This is also apparent when the shape of damage curves and their associated maximum damages of the Rhine Atlas (IKSR, 2001) are compared with the damage curves of the Damage Scanner (Klijn et al., 2007). This is illustrated in Table 1 and Figure 1.

Table I: Maximum damages for land use classes of the Rhine Atlas and the Damage Scanner.

Rhine Atlas	Max. damage (€/m^2)	**Damage Scanner**	Max. damage (€/m^2)
Residential	311	Residential – high density	910
		Residential – low density	400
Industry	349	Commercial	600
Infrastructure	268	Infrastructure	190
Agriculture	7	Agriculture	20
Forest	1	Nature / Forest	20
Other	0	Grassland	10
		Building lot	130
		Recreation	30

Table 1 shows that the maximum damages for comparable land use types is significantly higher in the Damage Scanner compared to the Rhine Atlas. For instance, the residential category of the Rhine Atlas has a maximum damage of 311 €/m^2 whilst the maximum damage of the Damage Scanner is 910 €/m2 for high density urban areas and 400 €/m^2 for low density urban areas. Likewise, the industrial land use class has a maximum damage of 349 €/m^2 in the Rhine Atlas compared to 600 €/m^2 in the Damage Scanner. While these urban land use classes have maximum damages that differ roughly a factor 2, the differences between agricultural land use and nature areas is even larger, with a factor of 2.8 and 20, respectively.

There are a number of reasons that can explain the large differences in terms of maximum damage values between the Rhine Atlas and the Damage Scanner model. While the Rhine Atlas always uses depreciated asset values, the Damage Scanner uses replacement costs, for instance for household inventory and residential building structures (Briene et al., 2002).[2] Damages to cars, which can make a significant contribution to total damages, are not considered in the maximum values of the Rhine Atlas (ICPR, 2001), while replacement values are included in the Damage Scanner (Briene et al., 2002). Whether the valuation approach of the HIS-SSM has been changed from replacement costs to depreciated values for the more recent version of the HIS-SSM, could not be established. The very large difference for agricultural areas can be explained by the fact that the Damage Scanner takes into account that in grid cells with an agricultural land use, there are also buildings with inventory present, and not just crops. Besides, the Damage Scanner also implicitly comprises approximately 5 per cent of indirect damages as a surcharge on direct damages. Indirect damages refer to losses resulting from business interruption during a flood event and can make up a substantial share of total flood damages (Gauderis, 2007).

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[2] Whether replacement or depreciated values should be used for flood damage assessment depends on the purpose of the flood damage assessment. Replacement values describe the 'value at risk' and can provide useful information e.g. for insurance companies. However, using replacement values overestimates potential flood damages from an economic point of view, since "old goods, which are damaged during a flood event are substituted by new, more productive or better performing ones" (Penning-Rowsell et al., 2003). Using depreciated values takes into account that durable consumer goods lose value over time, which is in line with national accounting and should thus be used for public policy appraisal (Merz et al., 2010). See Merz et al. (2010) and (Messner et al., 2007) for more detailed discussions on this subject.

An additional source that leads to differences in calculated damages are the depth-damage functions. Figure 1 displays the shape of the damage curves of the Rhine Atlas and the Damage Scanner. These curves are used to calculate the fraction of the maximum damage (damage factor) occurring in a grid cell, based on the respective inundation depth. Looking at the urban damage curves (solid red lines), it becomes apparent that the curve of the Damage Scanner is steeper compared to the one of the Rhine Atlas. For instance, at 4m water depth, the Rhine atlas curve gives a damage factor of about 0.4, whilst the Damage Scanner curve gives a damage factor of about 0.8. Besides, both models differ in their assumption at which water level the maximum damage is reached. According to the Damage Scanner, maximum damage of all land use types is reached at a water level of about 5m. In contrast, the Rhine Atlas damage model assumes that a water level of 5m results in 70 per cent to 80 per cent of maximum damages for residential and commercial areas.

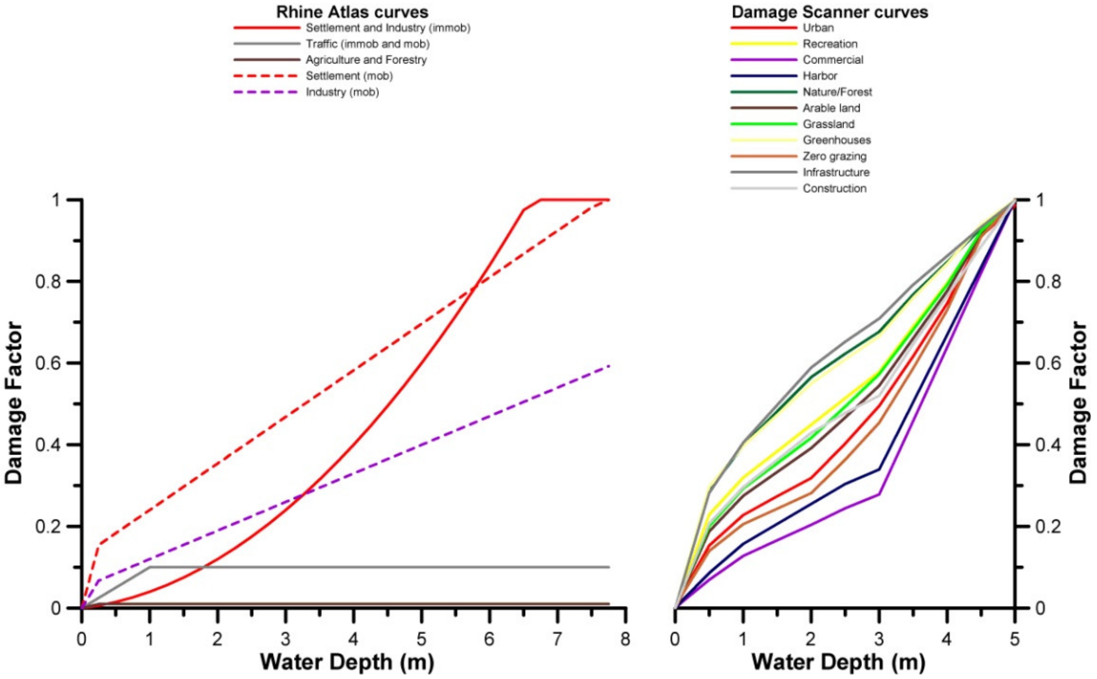


Figure 1: Damage curves for the Rhine Atlas and the Damage Scanner

Because of the above mentioned differences, flood damages, estimated for the same area but using both models can differ substantially (see also Section 5). Between the two, the Rhine Atlas gives much lower results compared to the Damage Scanner. (Thieken et al., 2008) compared several models in terms of residential damages against two observed flood events in Germany in 1993 and 2002. They concluded that the Rhine Atlas damage model tends to underestimate flood damages. The Damage Scanner was not included in this comparison.

2.2 Absolute versus proportional increases

In general, it can be said that absolute flood damage estimates are inherently very uncertain because of uncertainties in, amongst others, the stage-damage relations. Many studies therefore aim not to assess the absolute damage correctly, but rather use flood damage models to assess how flood damage changes between different situations. For example, they are often used to estimate the effect of climate change, land use change, or certain management measures.

De Moel and Aerts (2010) find that when assessing the change in flood damage not as an absolute number (i.e. an increase of 2 million euro) but as a percentage of a reference situation (i.e. a 10% increase in damage compared to the current situation), the results between different model are more similar. When assessing the proportional changes in flood damages due to e.g. changes in inundation depths, the difference between the Rhine Atlas and the Damage Scanner is about a factor 1.2 instead of 4. This indicates that statements concerning proportional damage increases (or decreases) can be made with a much more satisfying degree of certainty compared to statements concerning an absolute change in flood damage.

3 Differences in potential damages – Rhine Atlas inundation map versus ‘Risicokaart’

For the Dutch Delta area, there are mainly two different inundation maps available that can be used for large scale flood damage assessment. One inundation map is provided by the ICPR (2001), which has been used to calculate potential damages for the Rhine Atlas. In recent years, an improved and updated inundation map based on hydrological modelling results became available in form of the so-called *Risikokaart* (www.risikokaart.nl).

3.1 Rhine Atlas inundation map versus ‘Risicokaart’

The two inundation maps are depicted in Figure 3 and 4. A comparison between the two inundation maps shows, that the extent of inundated areas as well as water depth levels is much larger for the Rhine Atlas inundation map. For the Rhine Atlas map it was assumed that all dike rings could be potentially entirely flooded. This assumption proved to be unrealistic for many dike rings according to the hydrological modelling undertaken for the development of the ‘Risicokaart’.

Furthermore, the inundation map shown in the Rhine Atlas includes many areas that face no risk of extreme flooding from the river Rhine, such as the province of Zeeland in the south of the Netherlands. Also dike ring 14 (Zuid Holland) is not at risk from extreme floods of the Rhine but mainly from coastal storm surges in combination with high, but not extreme, river discharges of the Rhine. Thus, when evaluating flood damages resulting from extreme floods along the Rhine, we adjusted these areas, accordingly. Figures 5 and 6 show again both inundation maps but then only for those dike rings that face flood risk from extreme floods along the river Rhine, only. Table II and Figure 2 show the selected dike rings. If not indicated otherwise, this selection will be used in the present report.

Table II: List of selected dike rings facing flood risk from the Rhine

Number	Name	Number	Name
10	Mastenbroek	42	Ooij en Millingen
11	IJsseldelta	43	Betuwe, Tieler- en Culemborgerwaarden
15	Lopiker- en Krimpenerwaard	44	Kromme Rijn
16	Alblasserwaard en Vijfheerenlanden	45	Gelderse Vallei
22	Eiland van Dordrecht	47	Arnhemse- en Velpsebroek
23	Biesbosch	48	Rijn en IJssel
24	Land van Altena	49	IJsselland
37	Nederhemert	50	Zutphen
38	Bommelerwaard	51	Gorssel
39	Alem	52	Oost Veluwe
40	Heerewaarden	53	Salland
41	Land van Maas en Waal		

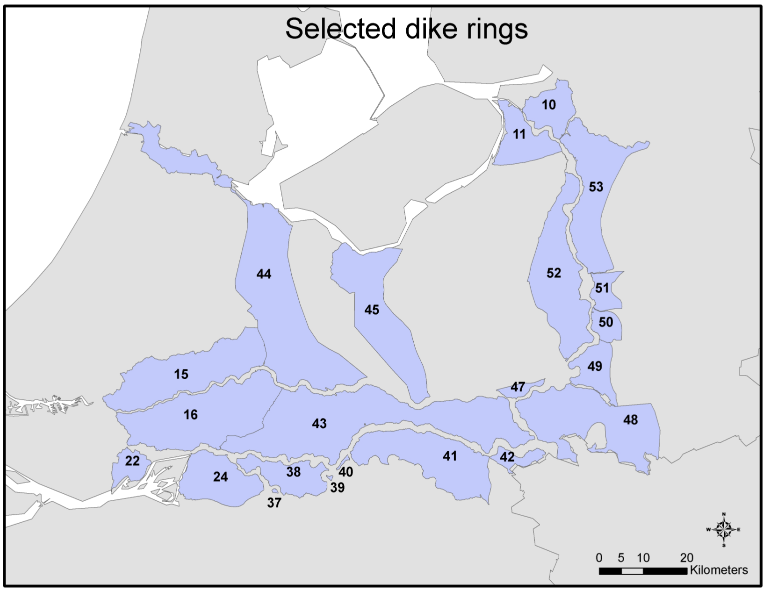


Figure 2: Selection of dike rings facing risk from extreme flooding along the Rhine

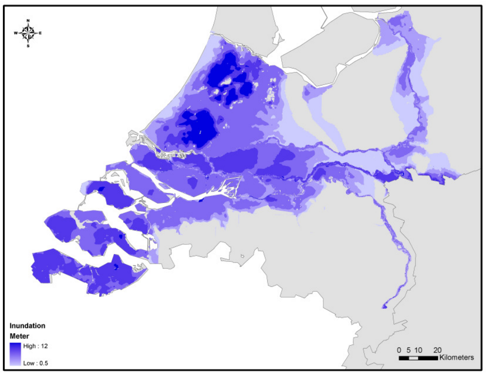


Figure 3: Rhine Atlas inundation map

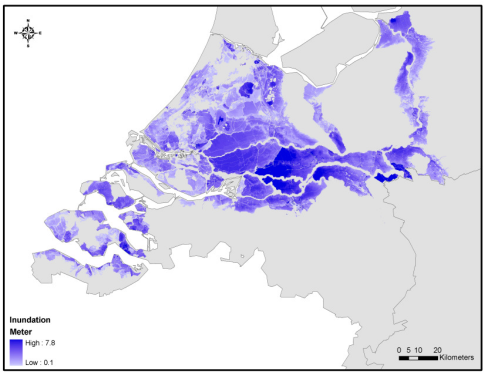


Figure 4: Risicokaart

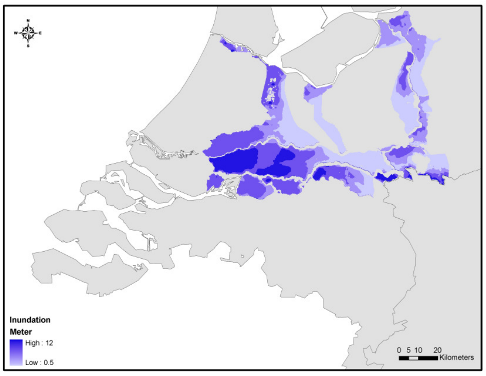


Figure 5: Rhine Atlas river dike rings

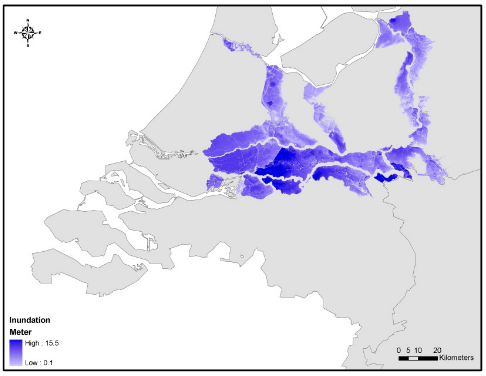


Figure 6: Risicokaart river dike rings

The four inundation maps depicted in Figure 3 to 6 were used as input for the Damage Scanner model to compare potential damages. Given their large differences in terms of inundated areas as well as water depths, substantially different damage values are derived. An overview of potential damages for the year 2000 is provided in Table III.

Table III: Potential flood damages for the Rhine Atlas inundation map and the Risicokaart.

	Potential Damage (Million Euros)*	
Inundation map	Extent Rhine Atlas	Extent River Dike rings
Rhine Atlas	628,000 (Figure 3)	147,000 (Figure 5)
Risicokaart	188,000 (Figure 4)	108,000 (Figure 6)
Difference Factor	3.3	1.3

* Please note: because the Damage Scanner model is used for all four calculations, the differences in potential damages are due to variations in the inundation maps, only.

As can be seen from the difference factors for the two flood extents, the variations in terms of absolute damages between the inundation maps is much smaller, when only river dike rings are included in the analysis. This can be explained by the fact that also according to the hydrological modelling undertaken for the Risicokaart, some river dike rings could almost be entirely flooded, as it is assumed for all dike rings in the Rhine Atlas approach. For larger dike rings such as Zuid Holland (Nr. 14), the assumption that the whole dike ring could be filled with water is unrealistic, leading to the much larger differences between the two inundation maps, when the full extent is included in the analysis. Differences in calculated damages between the two inundation maps can be up to a factor 3.3.

To conclude, the comparison between the two inundation maps thus shows that potential flood damages were largely overestimated in the Rhine Atlas due to the unrealistic extent and too high water depths of the considered inundation map.

3.2 Flood extent map of the Rhine Atlas and corresponding damages

As mentioned above, the Rhine Atlas inundation map (Figure 3) depicts potentially flooded areas that do not face flood risk from the river Rhine, or flood risk resulting from a combination of coastal storm surges and high river discharges. These areas are for example Zeeland or the province of Zuid Holland. Dike ring 14 (Zuid Holland) has by far the highest damage potential in the Netherlands, as it comprises the Randstad with the cities of Rotterdam, Amsterdam and The Hague and thus the 'economic heart' of the Netherlands. Therefore, including this area in a damage and risk assessment for extreme floods along the river Rhine, would dominate the damage and risk assessment. In this context, the questions was raised whether the damage figures provided in the Rhine Atlas (Table IV) really reflect all the depicted inundated areas (Figure 3), or, if a selection was made of areas that actually face flood risk from the Rhine.

Table IV: Potential damages (Mill. €) according to the Rhine Atlas (Source ICPR, 2001)

Section of the Rhine	**Sum**
High Rhine	38,3
Upper Rhine	11.978
Middle Rhine	1.687
Lower Rhine	20.333
Rhine Delta	130.886
Sum	164.9

The Rhine Atlas itself does not provide precise information, which areas were included to derive at the damage figure of 130.886 Million Euro for the Rhine Delta (Table IV). In contrast to the Rhine Atlas inundation map (Figure 3), the map overview depicted in the Atlas itself indicates a smaller area, and e.g. excludes the province of Zeeland. The map is misleading, though, as it shows potentially flooded areas up to the Dutch border, while only river courses are shown in the Netherlands (Figure 7).

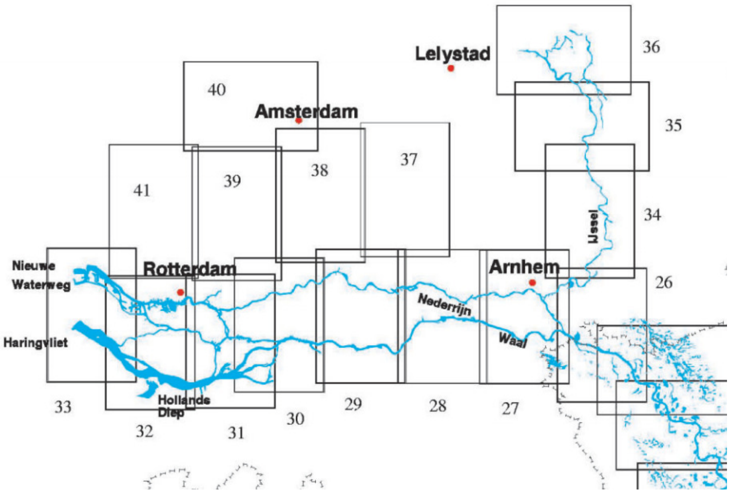


Figure 7: Map overview provided by the Rhine Atlas. (Source: ICPR, 2001)

To gain insights into this aspect, potential damages for 2000 were calculated using the Rhine Atlas inundation map in combination with the Rhine Atlas damage model. The aim of this exercise thus was, to replicate the damage calculations of the Rhine Atlas. It should be noted, though, that resulting damages will not exactly match the figures provided in the Rhine Atlas. The main reason for this is that adjustments were included in the Rhine Atlas to represent population density (IKSR, 2001). As the exact key for these adjustments is not provided in the documentation, this could not be replicated.

When calculating potential flood damages using the Rhine Atlas damage model as well as the entire Rhine Atlas inundation map (Figure 3), we arrive at potential damages for the Dutch Delta of 167.899 Million Euros. Damages aggregated for the river dike rings, lead to 35.327 Million Euros, only. Given the significant differences to the value of 130.886 of the Rhine Atlas it can be assumed that not all areas shown in Figure 3 were included to arrive at this value. However, it is certain that the damage figures provided in the Rhine Atlas reflect a much larger area than the dike rings facing flood risk from the river Rhine. It is, for instance, clear that dike ring 14 (Zuid Holland) has been included in the Rhine Atlas damage figure: without its large amount of potential damages (81.600 Million Euros), it is not be possible to arrive at the damage amount of about 130.886. An overview of calculated damages using the Rhine Atlas inundation map and the Rhine Atlas damage model on a dike ring level is provided in Table V.

Table V: Potential damages (in million Euros) on a dike rings level using the Rhine Atlas inundation map in combination with the Rhine Atlas damage model

Number	Name	Damages (Million Euros)
9	Vollenhove	15.5
10	Mastenbroek	500
11	IJsseldelta	340
14	Zuid-Holland	81600
15	Lopiker- en Krimpenerwaard	4110
16	Alblasserwaard en Vijfheerenlanden	7580
17	IJsselmonde	11600
18	Pernis	168
19	Rozenburg	476
20	Voorne-Putten	5480
21	Hoekse Waard	2270
22	Eiland van Dordrecht	2030
23	Biesbosch	13.3
24	Land van Altena	984
25	Goeree-Overflakkee	1150
26	Schouwen Duivenland	1840
27	Tholen en St. Philipsland	598
28	Noord-Beveland	215
29	Walcheren	4970
30	Zuid-Beveland	3070
31	Zuid-Beveland	812
32	Zeeuwsch Vlaanderen	7960
33	Kreekrakpolder	0.90
34	West-Brabant	4260
34-a	Geertruidenberg	52.6
35	Donge	1550
36	Land van Heusden/de Maaskant	4470
36-a	Keent	0.07
37	Nederhemert	0.07
38	Bommelerwaard	1580
39	Alem	0.07
40	Heerewaarden	10.7
41	Land van Maas en Waal	2520
42	Ooij en Millingen	486
43	Betuwe, Tieler- en Culemborgerwaarden	4150
44	Kromme Rijn	4920
45	Gelderse Vallei	869
47	Arnhemse- en Velpsebroek	341
48	Rijn en IJssel	2210
49	IJsselland	97.3

50	Zutphen	628
51	Gorssel	69.4
52	Oost Veluwe	422
53	Salland	1480
Total		**167899**

To identify which areas have been included in the damage figure provided in the Rhine Atlas is difficult to assess, since we cannot fully replicate the calculations. To gain further insights, we selected all dike rings that should be within the boxes of the map overview provided in the Atlas (Figure 7). The thus selected dike rings are shown in Figure 8. Based on this selection, we arrive at potential damages of 142.397 Million Euros.

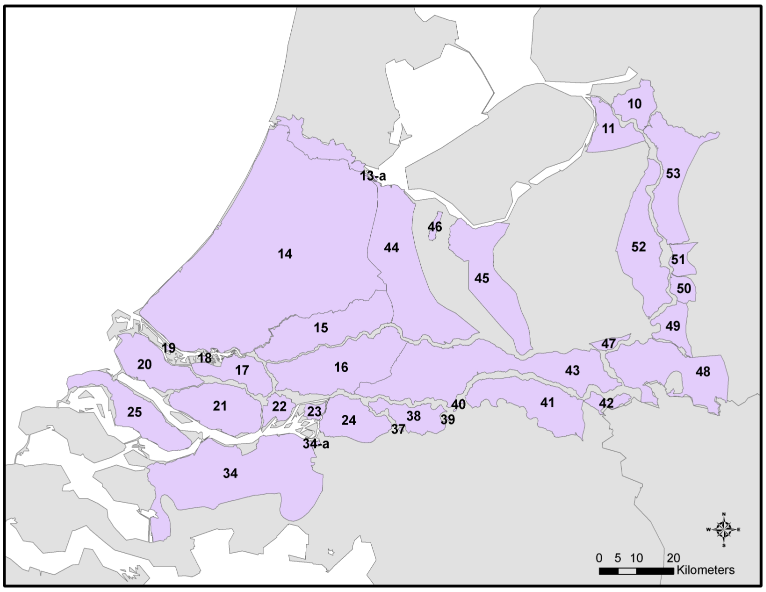


Figure 8: Dike rings selected on the basis of the Rhine Atlas map overview (Figure 7) and corresponding potential damages

To conclude, it can be stated that the Rhine Atlas largely overestimates potential flood damages for the Dutch Delta, as far as extreme floods from the river Rhine are concerned, by including dike ring 14 (Zuid Holland).

4 Differences in potential damages: Damage Scanner versus WV21

4.1 Introduction

Next, we compare the damage calculations of the *'Waterveiligheid in de 21e eeuw'* (WV21) project with the results we obtained using the Damage Scanner.

Current safety levels in the Netherlands are based on the works of the Delta Commission conducted in the 1960s. Since the amount of assets and the number of inhabitants in flood prone areas has increased continuously since then, these safety levels are currently being updated. To gain insights into current assets at risk, the WV21 project carries out an analysis on potential flood damages in Dutch dike rings on the basis of new information on potentially flooded areas. This information is derived from both the Risicokaart and the *'Veiligheid Nederland in Kaart 2'* (VNK2) project. The HIS-SSM software (version 2.5) is used to calculate damages on the basis of detailed and partly object-based information. Such detailed information is currently not available for all areas along the Rhine and also not for future projections. To gain insights into the differences between the two damage assessment methods, the following paragraph will provide a comparison between the Damage Scanner approach and the values derived in the WV21 study for the Dutch dike rings.

There are mainly two sources that can explain differences in terms of calculated damage between the two models, namely the damage evaluation method (1) and the applied land use data (2).

1) <u>Damage Evaluation Method</u>

Instead of applying the HIS SSM directly, we use the concept of the Damage Scanner, which calculates damages on the basis of land use types. Even though the Damage Scanner is derived from the HIS SSM model, it has been shown that the two methods can lead to noticeable differences in calculated damages, especially for smaller dike rings (Klijn et al., 2007). These differences result from the fact that detailed and partly object based damage data, as used in the HIS SSM are averaged for the entire country for each land- use type in the Damage Scanner.

2) <u>Land use data</u>

We calculate damages on the basis of land use types. In contrast to the HIS SSM applied within the WV21 project, we use different land use information in the Damage Scanner, namely CORINE 2000 that was reclassified into the thirteen land use classes of the Damage Scanner. In this reclassified land use database, a land use class representing 'high urban density' areas was introduced using the LandScan population data base (te Linde et al., 2010).

4.2 Results

The results of the comparison between the figures of the WV21 project and the application of the Damage Scanner are provided in Table VI. The left column provides the damage values of the WV21 project on the level of individual dike ring. The second column provides the damage calculations using the Damage Scanner model in combination with the Risicokaart (version nlprof090708). The differences (in per cent) between the two calculations are also provided. It can be seen that very large differences between the two calculations are observed for some dike rings, such as dike rings 34 (West-Brabant), 49 (IJsselland) or 51 (Gorssel). Dike rings, highlighted in orange, are those that differ by more than a 100 per cent.

The third column provides the damage calculations using the Damage Scanner model in combination with the WV21inundation map. These inundation maps are partly based on the *Risicokaart* but also on the results of the *'Veiligheid Nederland in Kaart 2'* (VNK2) project. Differences (in per cent) compared to WV21 damage figures are also provided. Since the same inundation map is used for both calculations now, the values are better comparable. As can be seen from Table VI, all the large deviations shown in the second column are greatly reduced.

Given the methodological differences between the Damage Scanner and the WV21 project (see above), we consider the variations in calculated damages as very reasonable. The magnitude of differences in damage calculations are in line with findings of Klijn et al. (2007), who also compared the HIS-SSM to the Damage Scanner and deviations of similar size.

Table VI Comparison of potential flood damages of the WV21 project and the Damage Scanner

WV21 (zonder systeemwerking (zs))		**DS* / Risicokaart**			**Difference**	**DS* / Inund. Toetspeil (zs)**	**Difference**
Dike ring	**Million Euro**	**Dike ring**	**Name**	**Million Euro**	**(in %)**	**Million Euro**	**(in %)**
10_1	1998	10	Mastenbroek	1716	-14.1	2001	0.12
11_1	978	11	IJsseldelta	1206	23.3	1259	28.69
15_1	11212	15	Lopiker- en Krimpenerwaard	10780	-3.9	12394	10.54
21_1	1271	21	Hoekse Waard	1479	16.4	1551	22.11
22_1	4832	22	Eiland van Dordrecht	5226	8.2	3896	-19.36
24_1	2026	24	Land van Altena	3108	53.4	2645	30.53
34_1	480	34	West-Brabant	1033	115.1	524	9.19
35_1	3087	35	Donge	4499	45.8	4105	32.98
36_1	11797	36	Land van Heusden/de Maaskant	13242	12.3	13553	14.88
38_1	4915	38	Bommelerwaard	5908	20.2	5321	8.26
39_1	27	39	Alem	4	-85.4	5	-81.86
40_1	145	40	Heerewaarden	44	-69.6	113	-22.09
41_1	4958	41	Land van Maas en Waal	10709	116.0	6356	28.21
42_1	977	42	Ooij en Millingen	1509	54.4	1104	13.02
43_1	20746	43	Betuwe, Tieler- en Culemborgerwa	27162	30.9	20355	-1.88
44_1	14188	44.0	Kromme Rijn	11124	-21.6	11853	-16.46
44_2	6						
45_1	8741	45.0	Gelderse Vallei	8804	0.7	8480	-2.98
45_2	520						
46_1	96	46	Eempolder	74	-23.3	115	19.38
47_1	2203	47	Arnhemse- en Velpsebroek	2230	1.2	2408	9.32
48_1	4876	48.0	Rijn en IJssel	12124	148.6	6021	23.49
48_2	806						
49_1	239	49	IJsselland	1853	674.9	335	40.16
50_1	1069	50	Zutphen	1807	69.0	1145	7.09
51_1	117	51	Gorssel	270	131.7	121	3.99
52_1	1229	52	Oost Veluwe	1707	38.9	1320	7.42
53_1	5400	53	Salland	5312	-1.6	5507	1.99
Total	108940			132930	22.0	112490	3.3

*DS stand for Damage Scanner

5 Applicability of a uniform damage model for the entire basin

As discussed earlier in Section 2, different damage models can yield substantial variations in terms of absolute damages due to existing uncertainties and methodological differences in flood damage modelling. Even though a considerable research effort has been made in recent years, it has been acknowledged that the scientific field of flood impact assessment still lags behind the more developed fields of hydrology and hydraulics (Buchele et al., 2006; Merz et al., 2010). Even though further efforts are currently undertaken to reduce the uncertainty of flood impact assessment and especially the estimation of direct economic damage (Kreibich et al., 2010; Thieken et al., 2008), it can be assumed that considerable uncertainty will remain in coming years.

Acknowledging the uncertainty of absolute flood damage assessment, it is important to gain insights into the robustness of relative estimates of flood damage developments over time. However, while many studies have addressed the uncertainties originating from projections of socio-economic development and also climate change (Aerts et al., 2008; Bouwer et al., 2010), little attention has been devoted to the influence of uncertainties of flood damage assessment methods on relative estimates of flood damage developments over time.

Gaining insights into the robustness of such relative estimates is important, because they provide crucial information for flood risk management. They indicate the order of magnitude of projected changes in exposure and allow to evaluate the damage and thus risk reducing effect of various adaptation strategies (Aerts et al., 2008). This is especially important, because many investments in flood control and mitigation measures take 20 to 30 years to design, plan and implement (Dircke et al., 2010; Maaskant et al., 2009) and are designed for long life spans as well. Furthermore, flood risk management, and thus flood risk assessments should be carried out at the basin-wide scale. Such a basin-wide approach is supported and stimulated by governmental organizations such as the International Commission for the Protection of the Rhine (ICPR) and the EU (Directive 2007/60/EC), because measures taken upstream can have a significant influence on flood risk downstream. When performing flood damage analyses in trans-boundary river basins, usually one flood damage assessment method needs to be chosen and agreed upon by various stakeholders (ICPR, 2001; Silva and Reuter, 2006). However, different damage assessment methods are used and preferred by riparian countries (Meyer and Messner, 2005) that can yield substantial differences in terms of absolute damages. When choosing a common method, it is important to understand to what extent different damage assessment methods influence estimates of relative changes in flood damages over time. This can, for instance, help to improve the acceptance of a chosen method and respective findings in organizations such as the ICPR and thus support cooperation in trans-boundary flood risk management.

To gain insights into this aspect, we compare the Rhine Atlas and the Damage Scanner model in terms of absolute and relative estimates of flood damages developments over time. Both models are used to calculate potential flood damages for 1990, 2000 and two land-use projection for 2030. Subsequently, the calculated absolute flood damage figures are used to estimate relative change over time.

Two land use projections were derived from a land use model known as the *Land Use Scanner* (Hilferink and Rietveld, 1999). The model uses socio-economic scenarios to simulate future land-use patterns on the basis of spatial claims (expected quantity of land use change), suitability and policy maps. Information on land-use claims were derived from the EURURALIS projections (Verburg et al., 2008; Verburg and Overmars, 2009). For a more detailed description on the downscaling approach and the development of the land use projections, the reader is referred to Te Linde et al. (2010).

The two land use projections reflect two contrasting futures of possible changes in land use. The Global Economy scenario (GE) assumes a world with high economic and population growth, international economic integration and a strong influence of private interests. A weak government is assumed that enforces little environmental regulation. The GE scenario results in a land-use projection that sees a large increase in urban land-use. No restrictions in terms of urban development are applied to areas at risk of flooding, due the weak role of the government assumed for this scenario. In contrast, the Regional Communities scenario (RC) assumes a world with little economic and population growth and a strong regional focus. In this world, a strong government is foreseen that enforces strict environmental regulations such as spatial zoning in flood prone areas. The RC scenario leads to a land use change projection that sees far less urban development, which is considerably restricted in areas at risk from flooding. While none of these two scenarios is particularly likely, we aim at reflecting the possible bandwidth of future changes in land use by having chosen two most diverging scenarios in terms of urban development.

Information on possibly inundated areas up to the Dutch border was derived from the Rhine Atlas. For the Netherlands, the information provided by the Risicokaart was used as input parameter. The thus created inundation map for the entire Rhine channel shows flood extent and depths for extreme discharge events, ranging from 1/200 years at the Upper Rhine to 1/1250 years in the Dutch delta area (te Linde et al., 2010).

5.1 Absolute estimates of flood damage developments over time

A comparison between the two models in terms of absolute damage estimates again demonstrates that flood damage models can yield substantially different results. An overview on potential damages along the Rhine according to the Rhine Atlas and the Damage Scanner model for 1990, 2000 and the two socio-economic scenarios (2030), as well as their difference factor, is provided in Table VII. Since only dike rings facing risk of extreme flooding from the Rhine were included in this analysis (see Figure 2), the damage values for the Rhine Atlas model presented in Table VII are significantly lower compared to the figures provided by the ICPR (see Table IV).

Table VII: Basin wide potential flood damages (in million Euros) for different time steps for the Damage Scanner and the Rhine Atlas model

	1990	2000	2030 RC	2030 GE
Rhine Atlas model	74591	77749	86982	108158
Damage Scanner model	290883	300463	323608	380684
Difference factor	3.8	3.8	3.7	3.5

In line with results of previous studies (de Moel and Aerts, 2010), both models differ significantly in terms of absolute damages by a factor ranging from 3.8 for 1990 to 3.5 for 2030 for the GE scenario.

5.2 Relative estimates of flood damage development over time

Given these large differences in terms of absolute damages estimates, it is of interest to evaluate, how the two models compare when looking at relative damage developments over time. We thus assess how the two models compare when looking at the relative change in flood damages (in per cent) for the periods 1990 to 2000 and 2000 to 2030 (GE and RC).

5.2.1 Residential and commercial areas

We first compare the relative change in potential damages for residential and commercial areas for the entire Rhine, because these two land-use types are usually the most important in flood damage assessment, given their large contribution to total flood damages (de Moel and Aerts, 2010). For the two models applied in the current study, they contribute about 97 per cent to the total damages of the Rhine Atlas and about 79 per cent to the total damages of the Damage Scanner model for the year 2000. Table VIII provides an overview on the relative change (in per cent) in potential flood damages for residential and commercial areas, as estimated by the two models. The two urban residential classes (high and low density) reflected in the Damage Scanner were aggregated to one figure.

Table VIII: Estimates of relative changes (in %) in flood damages over time using the Rhine Atlas Damage model (RA) and the Damage Scanner (DS).

	Residential		**Commercial**	
	DS	RA	DS	RA
1990 -2000	-0.13	-0.16	21.66	21.64
2000 - 2030 RC	10.20	12.98	9.42	9.37
2000 - 2030 GE	35.83	40.9	36.52	36.85

Even though both models show large differences in terms of absolute damages, Table VIII shows that relative estimates of flood damage developments over time are much more comparable. For residential areas, the Rhine Atlas model foresees a higher relative increase in flood damages for the two socio-economic scenarios compared to the Damage Scanner. The largest difference is observed for the GE scenario. Here, the Rhine Atlas foresees a relative increase of about 40 per cent, whereas the Damage Scanner estimates a change of 36 per cent. For commercial areas, both models show only very minor differences for all time steps.

5.2.2 Complete model comparison

Next, we again evaluate how the two models compare, when looking at the relative changes in flood damages (in per cent) for the periods 1990 to 2000 and 2000 and 2030 (GE and RC), but then including all land-use classes in the analysis. As can be seen from Figure 9, both models show considerable differences when estimating the relative change (in per cent) in flood damages along the Rhine for 2000 and the two socio-economic scenarios for 2030. When comparing the two damage models, the RA model estimates consistently higher relative increases in potential flood damage compared to the DS. In general the RA model gives relative estimates about 1.4 times higher than the DS model (e.g. 11.9% divided by 8.4% for RC scenarios).

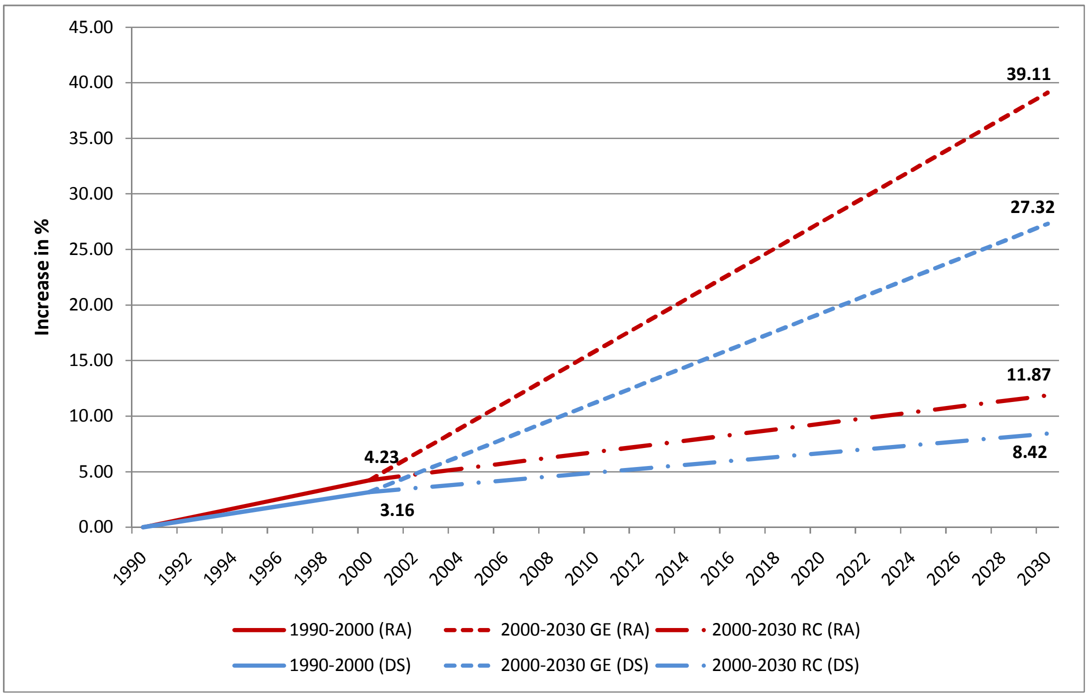


Figure 9: Relative increase (in per cent) in potential flood damages along the Rhine according to the Rhine Atlas (RA) and Damage Scanner (DS) models

This difference in behaviour can be explained by the relative share of respective land-use classes to the total damage of each model. Table IX shows the total damage and share of each land-use class to the total damage for 2000. As mentioned above, it can be observed that in the RA model, about 98 per cent of the total damage results from urban land-use classes (residential and commercial). In the DS model this number is considerably lower (79 per cent). The different contribution of urban land-use classes to total damages is also reflected by the ratio of maximum damages across the assigned land uses *within* each of the two models (see Table I). In the RA model, the difference between the maximum damage of residential and agricultural land use is e.g. about a factor 44 (311 €/m^2 divided by 7 €/m^2), whilst in the DS model the difference between low density residential areas (which comprises most of the residential area) and agriculture differs only a factor 20 (400 €/m^2 divided by 20 €/m^2).

Table IX: Relative share of respective land-use types to total damages (2000) for the Damage Scanner and Rhine Atlas model.

Rhine Atlas			**Damage Scanner**		
Land use	Total damages	Per cent total damages	Land use	Total damages	Per cent total damages
Residential	58248	74.92	Residential	187707	62.47
Commercial	17919	23.05	Commercial	49359	16.43
Infrastructure	1231	1.58	Infrastrcuture	6339	2.11
Nature /Forestry	6	0.01	Nature	7626	2.54
Agriculture	346	0.45	Agriculture	44487	14.81
			Construction / Mines	2840	0.95
			Recreation	2104	0.70
Total	77750	100.00	Total	300463	100.00

This difference in the contribution of respective land-use classes to the total damage is crucial in explaining the different model behaviour when estimating relative changes in flood damages over time. The GE scenario, for instance, which represents a 'strong growth scenario', results in a large shift from agricultural to residential (low density) grid cells.[3] This change in land use has a different effect in both models. While the loss of agricultural area has hardly any effect on the total damage in the RA (given its minimal contribution of 0.45 per cent to the total damages), the loss of agricultural areas has a significant effect in the DS, as it comprises ~15% of the total damage. The difference in model behaviour is probably best illustrated by looking at what happens when a single cell changes from agriculture to residential land-use. In the RA model the potential damage of such a cell will increase 44 times (see above), whilst in the DS model it increases only 22 times. Because of this, the relative increase in potential damages is considerably larger in the RA model compared to the DS model.

Even though both models differ consistently in terms of relative estimates of flood damage developments over time, the observed variation is considerably smaller, compared to the differences in absolute damage estimates (See Table VII) and uncertainties reflected by the two socio-economic scenarios. The latter differ by more than a factor 3 (e.g. 39.1 per cent (GE) divided by 11.9 per cent (RC) for the Rhine Atlas model.

The relative change in flood damages over time, but then only for Dutch dike rings facing risk from extreme floods along the Rhine (Figure 2), is provided in Figure 10. It is interesting to notice that the Dutch dike rings showed a larger increase in potential flood damages for the (observed) period between 1990 and 2000 than the area along the Rhine as whole (see also Section 7). An extrapolation of the observed trend between 1990 and 2000 for the Netherlands would almost correspond to the GE scenario (see Figure 10), which represents a high growth scenario. An extrapolation of the trend between 1990 -2000 for the entire basin would rather correspond to the RC scenario (see Figure 9), which represents a low growth scenario.

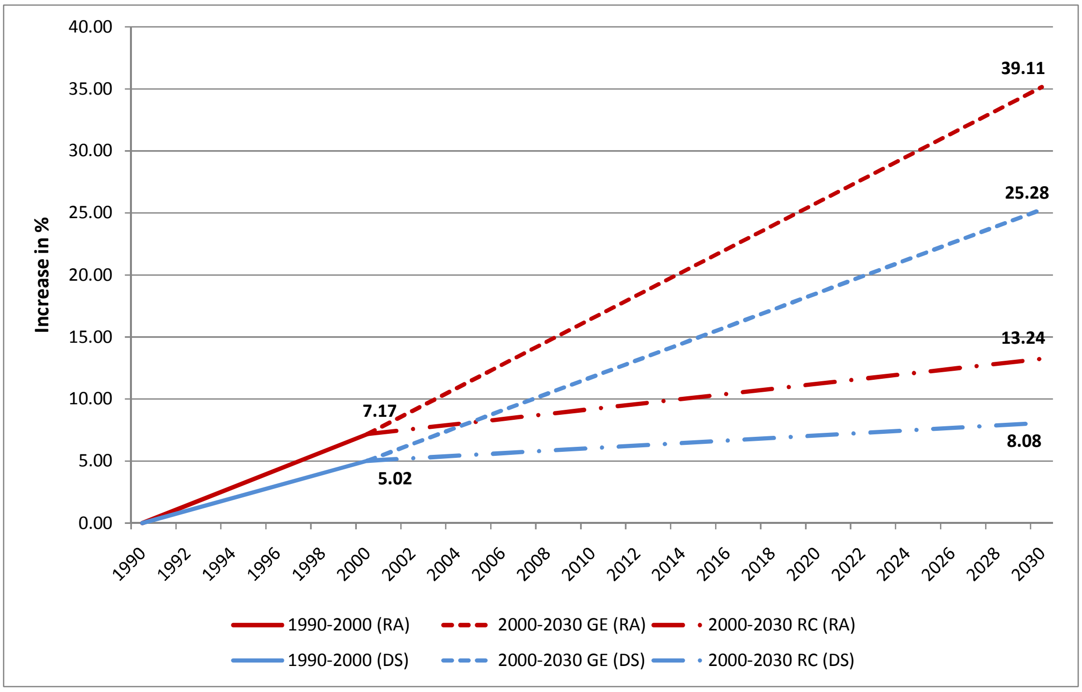


Figure 10 Relative increase (in per cent) in potential flood damages for Dutch dike rings (Figure 2) according to the Rhine Atlas (RA) and Damage Scanner (DS) models

5.3 Discussion and conclusions

Following from these observations, we can conclude that when estimating relative changes in potential flood damages over time, both models give much more similar results compared to absolute estimates. While estimates of absolute flood damage differ by up to a factor 3.3 between the two models applied, relative estimates vary by about a factor 1.4. The fact that both models produce similar results indicates that they can provide valid estimates of flood damage developments over time. Moreover, we find that the uncertainty resulting from the applied damage models is considerably smaller compared to the uncertainty of different socio-economic (land-use) scenarios.

While more similar than absolute estimates, also relative estimates still differ consistently between the two models. This variation is the result of the different shares that respective land-use classes contribute to total damage of each model. It is thus important to have good understanding of how different sectors (land-use types) contribute to overall flood damages in the studied area. As long as the applied damage model is a realistic representation of that share, the choice of the damage model and function is of minor importance. If a realistic representation has been established, a damage model can be chosen or designed that can provide robust estimates of the development of potential flood damages over-time for different land-use projections.

6 Non structural flood mitigation measures

6.1 Introduction

Traditionally, (increasing) risk of flooding in Europe was almost exclusively tackled by maintaining or reducing the probability of flood events by means of flood protection measures. Flood management policies thus focussed on large-scale engineering of flood defence infrastructure, which were designed and implemented by governmental agencies. (Buchele et al., 2006; ICPR, 2002; Messner et al., 2007). This approach has been increasingly questioned for a number of reasons. An exclusive reliance on technical flood prevention measures can lead to a false sense of security among the population at risk and can foster further economic development in risk-prone areas. This is problematic, because flood protection infrastructure can fail, what could lead to potentially catastrophic consequences if a high concentration of people and capital is located in flood-prone areas (Aerts et al., 2008; Maaskant et al., 2009). Another reason to reconsider traditional flood management strategies is the potential magnitude of the increase in future flood risk. If present trends of global warming and socio-economic development continue, then worldwide disaster losses will keep increasing at a higher rate than average economic growth, which would require additional risk reducing measures (Bouwer et al., 2007). Moreover, future investments in flood defence measures might be economically suboptimal in many places in terms of their costs and benefits. Except for large areas protected by main dikes, such as polders in the Netherlands, it is often a relatively small group of people that benefits from comprehensive flood defence infrastructure while the costs are commonly borne by the society as a whole through tax money (Umweltbundesamt, 2006).

Against this background, flood mitigation measures, such as flood proofing of houses or spatial zoning, have received renewed attention as a possible strategy to reduce potential flood damages and consequently risk. A number of studies demonstrated that private flood mitigation measures can significantly reduce flood damage (defra, ; ICPR, 2002; Kreibich et al., 2005; Kron and Thumerer, 2002; Olfert, 2008). In 1993 and 1995, two major flood events with recurrence intervals larger than 50 years occurred along the middle and lower Rhine, causing substantial economic damages. Even though both events were of comparable size, the flood in 1995 caused only half of the damages. The reduction in losses was mainly attributed to the precautionary behavior of citizens.

> *"The economic losses from the second event (US$ 320m) were only about half as big as those from the first (US$ 600m), although the two events were of comparable size. One of the main reasons for this difference was the fact that the previous flood event was still fresh in people's minds, i.e. they knew what to do when the water rose again, and they had learnt some lessons and had taken appropriate action (e.g. replacing oil burners and tanks with gas heating."* (Kron and Thumerer, 2002)

A similar finding was reported for the floods along the Meuse in 1993 and 1995 (Wind et al., 1999).

Generally, it is assumed that flood mitigation measures are especially effective in areas with frequent flood events and low water depths (ICPR, 2002; Kreibich et al., 2005). The report *'Non structural flood plain management: Measures and their effectiveness'* published by the ICPR in 2002 evaluates the effectiveness of specific flood mitigation measures. For each measure, such as flood proofing constructions, implementation of building codes, spatial zoning or securing hazardous substances, the damage reduction potential is provided. According to the ICPR report, flood adapted building use e.g. could reduce flood damages by 30 to 40 %, while the use water resistant materials for buildings and their installations (flood adapted interior fitting) could reduce flood damages by 15 to 35 %. However, the figures of the ICPR report have been criticised because it cannot be established, how they have been derived (Kreibich et al., 2005).

Empirical data on the effectiveness of flood mitigation measures are provided by Kreibich et al. (2005). In the aftermath of the 2002 flood in Germany, 1248 households were interviewed, amongst others on the amount of suffered damages and undertaken precautionary measures. A comparison of suffered direct damages to building structures and contents between households with and without precautionary measures was undertaken. The analysis revealed that the implementation of precautionary measures had a significant damage reducing effect. It was found that flood adapted use, flood adapted interior fitting and the installation of electrical utilities in higher storeys were the most effective measures, once flood water had entered a building. Since the mentioned measures aim at reducing damages once flood water enters the building, they are also referred to as 'wet flood proofing' (WFP). Flood adapted building use, flood adapted interior fitting and the installations of heating and electrical utilities in higher storeys reduced mean damage ratio of buildings by 46%, 53% and 36%, respectively. Flood adapted use and flood adapted interior fitting could reduce the mean damage ratio for contents by 48% and 53% respectively.

In the following paragraphs it will be discussed, how several flood mitigation measures can be incorporated in the Damage Scanner. Two different methodological approaches will be discussed and compared to each other, namely the 'Global Approach' (GA) and the 'Modeled Approach' (MA). Furthermore, we will assess the effectiveness of flood mitigation measures to address the projected increases in potential flood damages and risk along the River Rhine. Again, information on possibly inundated areas up to the Dutch border was derived from the Rhine Atlas and from the *Risicokaart* for dike rings in the Netherlands (see Figure 6).

6.2 Incorporation of flood mitigation measures in the Damage Scanner model

6.2.1 Global approach

The easiest way to take the potential effect of flood mitigation measures into account is to apply a global reduction factor (further referred to as '*Global Approach*') to the calculated damages.

Wet flood proofing of new urban areas (GA)

Wet flood proofing of property aims to reduce damages to building structures and content in the case flood water enters a building. An adapted building use and adapted interior fitting have been found to be effective measures to reduce potential flood damages (ICPR, 2002; Kreibich et al., 2005). In combination with a building code, flood management policies could require that all residential areas that are newly built in flood prone areas need to have such measures in place.

Taking the empirical findings of Kreibich et al. (2005) as a guideline, we applied a global reduction factor of 45 per cent on all newly projected residential areas according to the two land-use scenarios. In a first step, damages corresponding to all newly projected residential areas were extracted from the total damages for both the GE-scenario and the RC-scenario. Subsequently, a global reduction factor of 45 per cent was applied on the extracted residential damage figures.

Following this approach led to a reduction in potential damages along the Rhine by 3.01 per cent for the RC scenario and 7.96 per cent for the GE scenario (See Table X).

Wet flood proofing of all urban areas at risk (GA)

To assess the full potential of wet flood proofing, we also assumed a situation, in which all urban areas at risk of flooding would be flood proofed. Instead of applying a global damage reduction factor of 45 per cent on newly projected areas, only, all residential areas at risk from flooding were taken into account. Even though such a scenario seems unrealistic, it can provide interesting insights into the full potential of flood proofing the existing building stock.

Following this approach led to a reduction in potential damages along the Rhine by 28.65 per cent for the RC and 30.07 per cent for the GE scenario (See Table X).

Figure 11 shows the developments of basin-wide potential flood damages between 1990, 2000, and the two socio-economic scenarios (2030). Moreover, Figure 11 shows the damage reducing effect of wet flood proofing new residential areas and wet flood proofing all residential areas. It is shown that according to the Global Approach, both measures can significantly reduce potential flood damages. According to the Global Approach, wet flood proofing of all residential areas would lead to an overall decrease in potential damages for both scenarios.

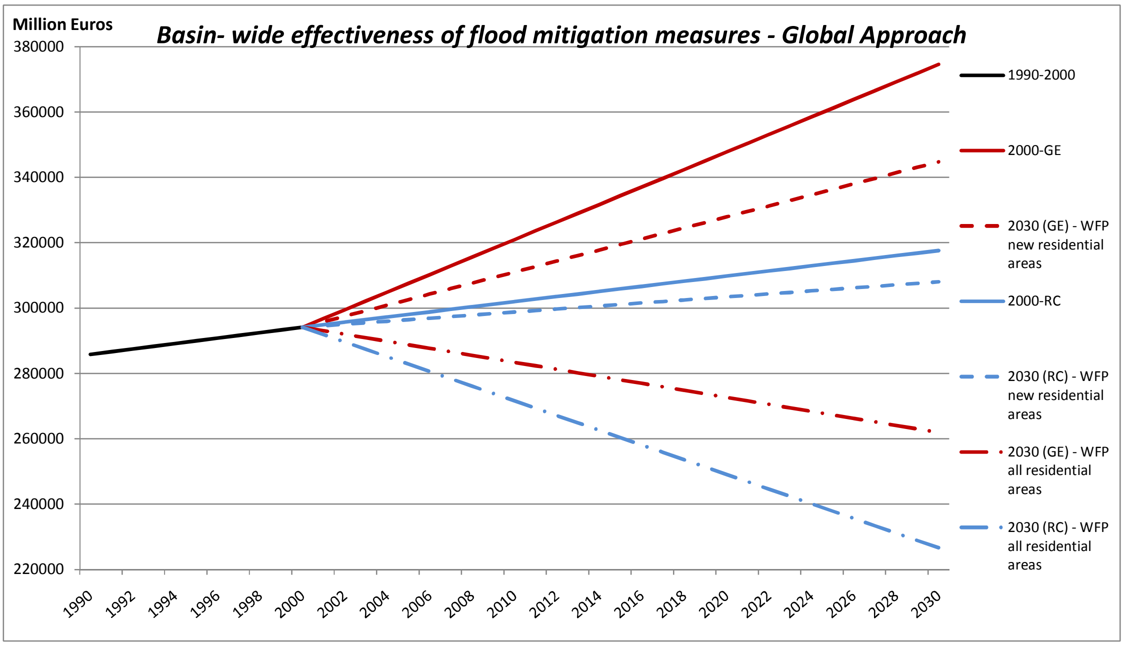


Figure 11: Basin-wide effectiveness of flood mitigation measures – Global Approach

6.2.2 Modelled approach

Applying the ‘Global approach’ described in section 6.2.1 has an important limitation. It is not possible to take the location specific information on water depth into account. However, considering local water depth levels is crucial, when evaluation the potential of flood mitigation measures, because it is assumed that flood mitigation measures are especially effective in areas with frequent flood events and low water depths (ICPR, 2002; Kreibich et al., 2005). Commonly, it is suggested that wet flood proofing can only be effective up to water level of about 2 meter. (ICPR, 2002).

To be able to take local water depth levels into account, the depth-damage functions within the Damage Scanner model were adjusted in the so-called *'Modelled approach'*. It was assumed that damage potential in residential areas can be reduced by 45 per cent up to a water level of 2m through flood proofing. Figure 12 show the original and the adapted damage function of the Damage Scanner for residential areas (high density).

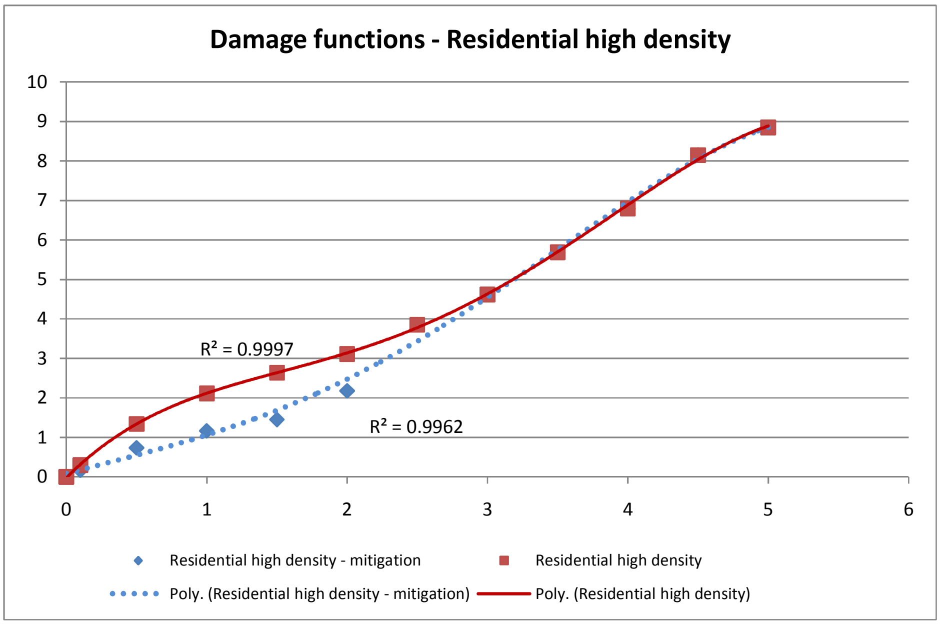


Figure 12: Original and adjusted depth-damage function for residential areas (high density). The adjusted curve represents the implementation of flood proofing measures.

By taking location specific information on water depth into account, a more realistic estimation of the effectiveness of flood mitigation measures can be provided compared to the 'Global approach'.

Wet flood proofing of new residential areas (MA)

In a first step, the adjusted damage functions for residential areas (high and low density) were applied to all newly projected residential areas both for the RC- and the GE scenario. This resulted in a reduction of potential damages along the Rhine by 1.12 per cent for the RC and 1.49 for the GE scenario.

Wet flood proofing of all residential areas (MA)

In a second step, the adjusted damage functions for residential areas (high and low density) were applied to all residential areas. Following this approach resulted in a reduction in potential damages along the Rhine by 7.05 per cent for the RC and 7.11 for the GE scenario.

6.2.3 Comparison 'Global approach' versus 'Modelled Approach'

In the previous paragraphs we evaluated the effectiveness of two mitigation measures, namely wet flood proofing new residential areas and wet flood proofing of all residential areas, using the 'Global Approach' and the 'Modelled Approach'. A comparison between the two approaches shows again, how important it is to take the location specific information on water depth into account. Table X provides an overview on the reduction potential of the two mitigation measure, according to the two methodological approaches. It is shown that the 'Global Approach' largely overestimates the effectiveness of flood mitigation measures, by ignoring the location specific information on water depth. The more residential areas are included in the analysis, the larger the overestimation of the 'Global Approach'. While the 'Global Approach' estimates that wet flood proofing of all residential areas would reduce potential damages by about 30 per cent, the same mitigation measure leads to a reduction of about 7 per cent only, according to the 'Modelled Approach'. This is, because residential areas with water levels above 2 meters are taken into account in the 'Global Approach', while they are exempted in the 'Modelled Approach'. Besides, high water levels of more two meters result in large potential damages in the damage model. Thus, also the application of a global reduction factor of 45 per cent on these large damage amounts has a large effect, accordingly.

Table X: Reduction in potential damages along the river Rhine according to the Global Approach and the Modelled Approach

	Wet flood proofing			
	RC Scenario		***GE Scenario***	
	New residential areas	All residential areas	New Residential areas	All Residential areas
Modelled	-1.12	-7.05	-1.49	-7.11
Global	-3.01	-28.65	-7.96	-30.07

Dry proof residential areas at locations with water depths below 1m

Moreover, the effectiveness of so-called dry flood proving (DFP) was evaluated. 'Dry flood proofing' refers to measures that prevent surface or flood water from entering a building during a flood event. Dry flood proofing can be achieved by sealing the structure of a house with water proof coatings or installing watertight shields over doors, windows, and other openings (FEMA). The effectiveness of these measures is especially dependent on water depths, but also flood duration and flow velocity (Keijser, 2008). If water levels rise to high, also the pressure on the buildings' structure increases and can eventually lead to a collapse. As a general rule, it is recommended to undertake dry flood proofing only to a water depth of about 1m. If water levels outside of the building rise above a critical level, the house needs to be flooded with clean water or flood water needs to be allowed to enter to avoid a collapse (Kreibich et al., 2005).

The costs of dry flood proofing depend on the size, condition and use of the building as well as the flood proofing height (FEMA).

To gain insights into the potential effectiveness of dry flood proving, all residential areas were selected that showed a water depth of 1 meter or lower. A situation was assumed in which all residential areas at locations with water depths lower than 1m would be dry proofed. Thus, no damage would occur in residential areas that show water levels lower or equal than 1 meter. Even though such a scenario seems be unrealistic, it provides insights into the full potential of dry flood proofing.

Following this approach resulted in a reduction in potential damages by 5.63 per cent for the RC and 5.46 for the GE scenario. It is interesting to notice that dry flood proofing residential areas at areas at water depth levels lower or equal than one meter has a similar effect compared to wet flood proofing of all residential areas. Figure 13 shows the development of basin-wide potential damages for 1990, 2000 and 2030 (RC- and GE-Scenario) and the damage reducing effect of three mitigation measures discussed (Modelled Approach).

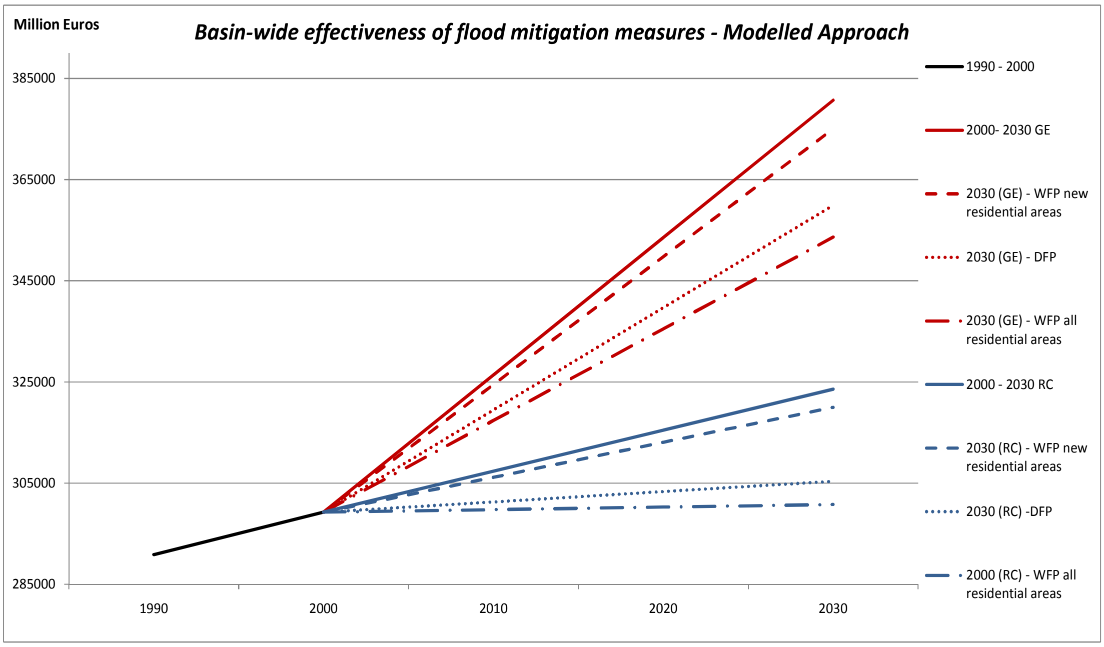


Figure 13: Basin-wide effectiveness of flood mitigation measures – Modelled Approach

The same information, but then only for Dutch dike rings facing risk from extreme floods along the Rhine (Figure 2), is provided in Figure 14.

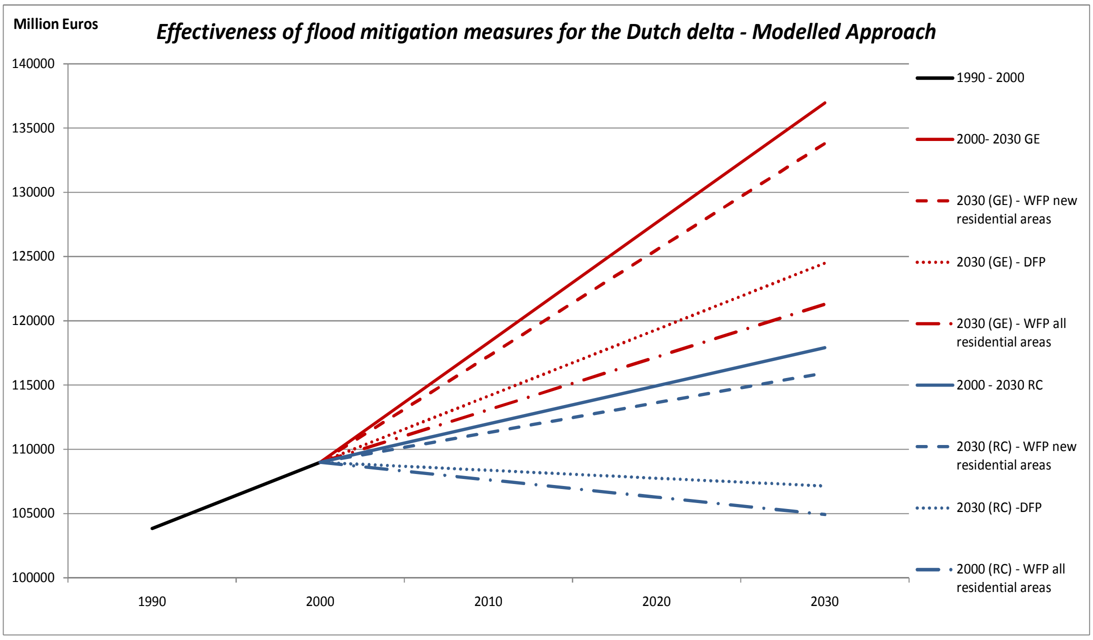


Figure 14: Effectiveness of flood mitigation measures for the Dutch Delta – Modelled Approach

6.3 Relation between inundation depths and the effectiveness of flood mitigation measures for dike rings facing risk from extreme flooding of the Rhine.

As discussed above, it is generally assumed that flood mitigation measures are especially effective in areas with frequent flood events and shallow water depths (ICPR, 2002; Kreibich et al., 2005). While all dike rings in the Netherland have very high safety standards, ranging from 1/1250 years to 1/2000 years, water depth levels vary considerably. Table XI and Table XII provide the mean inundation depth occurring at residential grid cells according to the two socio-economic scenarios. Only water levels at residential grid cells were taken into account to derive mean water levels, as these areas are of interest with respect to flood mitigation measures. Subsequently, the damage reducing effect of wet and dry flood proofing was evaluated for both the RC and GE scenario, again on the level of individual dike rings (Table XI and XII). As could be expected from the variations in water depths, also the damage reduction potential of flood mitigation measures varies considerably between the dike rings.

An example of mean water levels and the effectiveness of dry flood proofing (DFP) is provided in Figures 15 and 16. Figure 15 depicts the mean water depth level occurring at residential grid cells according to the GE scenario of the selected dike rings (see section 3). It can be seen that mean water depth levels range from about 0.5 meter (dike ring 52) to about 4.6 meter (dike ring 42). The damage reducing effect of dry flood proofing is depicted on a dike ring level in Figure 16. It is shown that DFP can reduce potential dike rings by up to 56 per cent (dike ring 51).

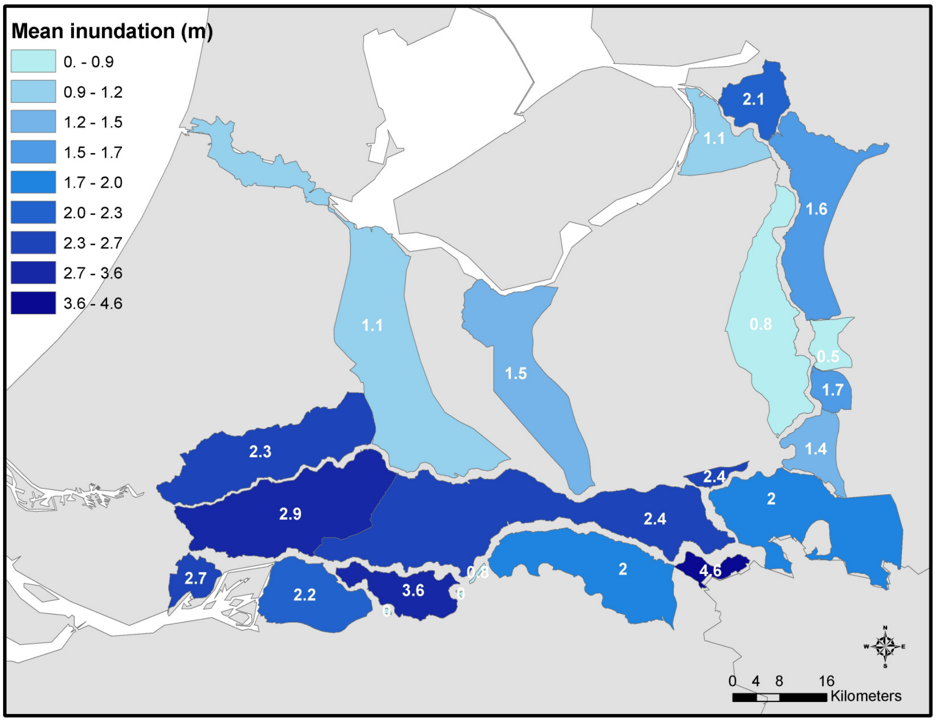


Figure 15: Mean water depth levels at residential grid cells for 2030 (GE scenario)

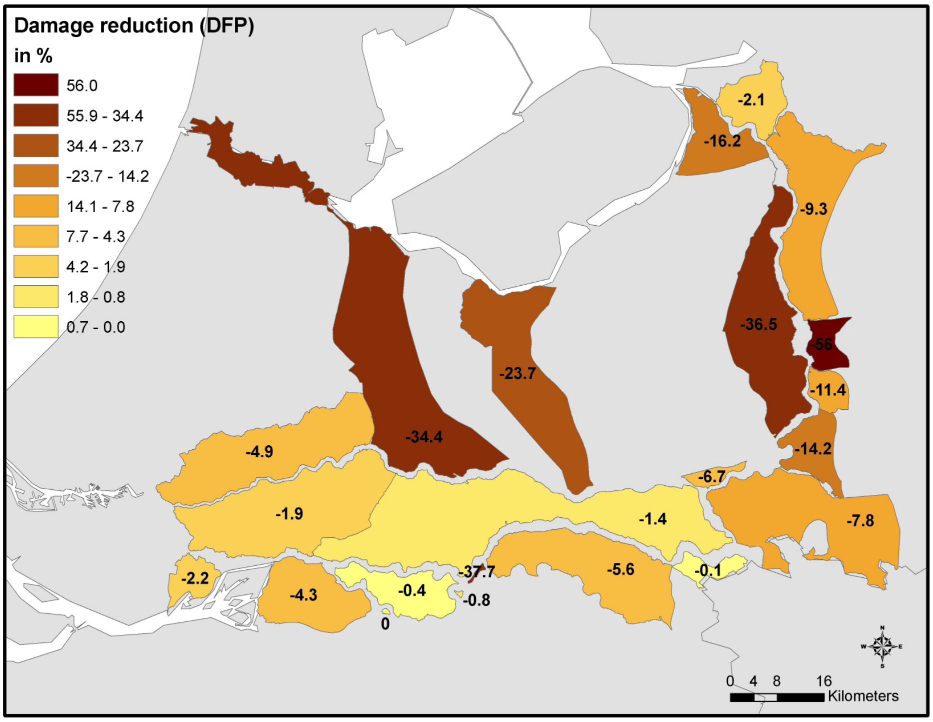


Figure 16: Damage reduction (in %) due to dry flood proofing (DFP) for 2030 (GE scenario)

A complete overview on mean water levels at residential grid cells, potential damages and the damage reduction potential for the three mitigation measures discussed above (Modelled Approach) for both the RC and GE scenario is provided in Tables XI and XII. It can be seen that flood mitigation measures can substantially reduce potential flood damages in dike rings with shallow water depths.

The relation between water depths and the effectiveness of flood mitigation measures is also exemplified by Figures 17 and 18. Figure 17 shows for each dike ring the relation between mean water depth at residential grid cells (RC scenario) and the effectiveness of wet flood proofing all residential areas. It can be seen that WFP is mostly effective for dike rings with a mean water level up to two meter. Between a mean water level of 0 and two meter, WFP all residential areas can reduce potential damages by up to 26 per cent. Figure 18 shows for each dike ring the relation between mean water depth at residential grid cells (GE scenario) and the effectiveness of dry flood proofing residential areas with water levels below one meter. It can be seen that DFP can reduce potential damages by up to 56 per cent.

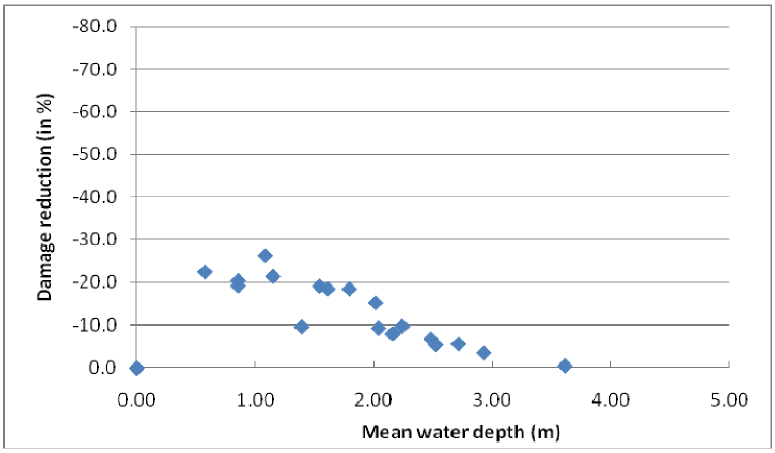


Figure 17: Relation between mean water depth at residential grid cells and the effectiveness of wet flood proofing (WFP) all residential areas (Modelled Approach) for the RC scenario.

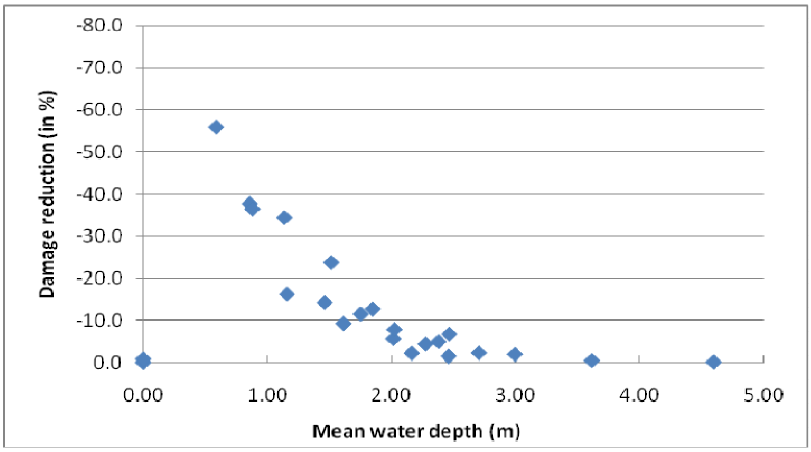


Figure 18: Relation between mean water depth at residential grid cells and the effectiveness of dry flood proofing (DFP) for the GE scenario.

Table XI: Mean water levels and damage reducing effect of three mitigation measures on dike ring level for 2030 (RC Scenario)

Name	Nr.	Mean depth res. areas	Damage 2030 (Mill. €)	WFP new res. areas	WFP all res. area	DFP
Mastenbroek	10	2.17	1831	-1.0	-8.1	-2.1
IJsseldelta	11	1.15	1299	-5.3	-21.4	-16.2
Lopiker- en Krimpenerwaard	15	2.24	12148	-2.1	-9.7	-5.5
Alblasserwaard en Vijfheerenlanden	16	2.93	14702	-0.5	-3.5	-2.1
Eiland van Dordrecht	22	2.72	6090	-0.4	-5.6	-2.2
Land van Altena	24	2.16	2697	-1.5	-8.0	-4.9
Nederhemert	37	0.00	0	0.0	0.0	0.0
Bommelerwaard	38	3.62	5376	0.0	-0.5	-0.4
Alem	39	0.00	4	0.0	0.0	-0.8
Heerewaarden	40	0.86	19	0.0	-20.4	-37.7
Land van Maas en Waal	41	2.02	10832	-1.7	-15.2	-5.8
Ooij en Millingen	42	4.58	2012	0.0	0.2	-0.1
Betuwe, Tieler- en Culemborg.	43	2.48	22334	-1.1	-6.8	-1.5
Kromme Rijn	44	1.09	11511	-3.9	-26.3	-34.9
Gelderse Vallei	45	1.54	8914	-2.6	-19.1	-24.2
Arnhemse- en Velpsebroek	47	2.53	955	-0.1	-5.4	-6.7
Rijn en IJssel	48	2.04	8800	-1.2	-9.3	-7.8
IJsselland	49	1.39	653	-1.0	-9.6	-15.0
Zutphen	50	1.80	1651	-3.0	-18.5	-11.1
Gorssel	51	0.58	181	-9.2	-22.4	-58.3
Oost Veluwe	52	0.86	1692	-7.3	-19.2	-34.2
Salland	53	1.61	4219	-1.7	-18.5	-9.7
Total			**117919**	**-2.0**	**-11.2**	**-12.8**

Table XII: Mean water levels and damage reducing effect of three mitigation measures on dike ring level for 2030 (GE Scenario)

Name	Nr.	Mean depth res. areas	Damage 2030 (Mill. €)	WFP new res. areas	WFP all res. area	DFP
Mastenbroek	10	2.17	1871	-1.1	-8.1	-2.1
IJsseldelta	11	1.16	1355	-6.3	-21.7	-16.2
Lopiker- en Krimpenerwaard	15	2.38	15874	-2.5	-8.8	-4.9
Alblasserwaard en Vijfheerenlanden	16	3.00	17523	-0.7	-3.3	-1.9
Eiland van Dordrecht	22	2.71	6202	-0.5	-5.7	-2.2
Land van Altena	24	2.28	3697	-3.1	-8.2	-4.3
Nederhemert	37	0.00	0	0.0	0.0	0.0
Bommelerwaard	38	3.62	5430	0.0	-0.5	-0.4
Alem	39	0.00	4	0.0	0.0	-0.8
Heerewaarden	40	0.86	19	0.0	-20.4	-37.7
Land van Maas en Waal	41	2.02	12066	-2.2	-15.4	-5.6
Ooij en Millingen	42	4.60	2224	0.0	0.2	-0.1
Betuwe, Tieler- en Culemborgerwaar	43	2.46	23973	-1.5	-7.3	-1.4
Kromme Rijn	44	1.14	13733	-5.7	-27.5	-34.4
Gelderse Vallei	45	1.52	10511	-3.5	-19.0	-23.7
Arnhemse- en Velpsebroek	47	2.47	1999	-0.1	-6.4	-6.7
Rijn en IJssel	48	2.02	10546	-2.4	-10.0	-7.8
IJsselland	49	1.46	683	-3.4	-12.2	-14.2
Zutphen	50	1.75	2121	-3.7	-20.8	-11.4
Gorssel	51	0.59	176	-10.2	-23.9	-56.0
Oost Veluwe	52	0.88	1807	-9.5	-21.9	-36.5
Salland	53	1.62	5145	-1.9	-20.4	-9.3
Total		**1.8**	**136959**	**-2.6**	**-11.9**	**-12.6**

7 Observed flood damage developments

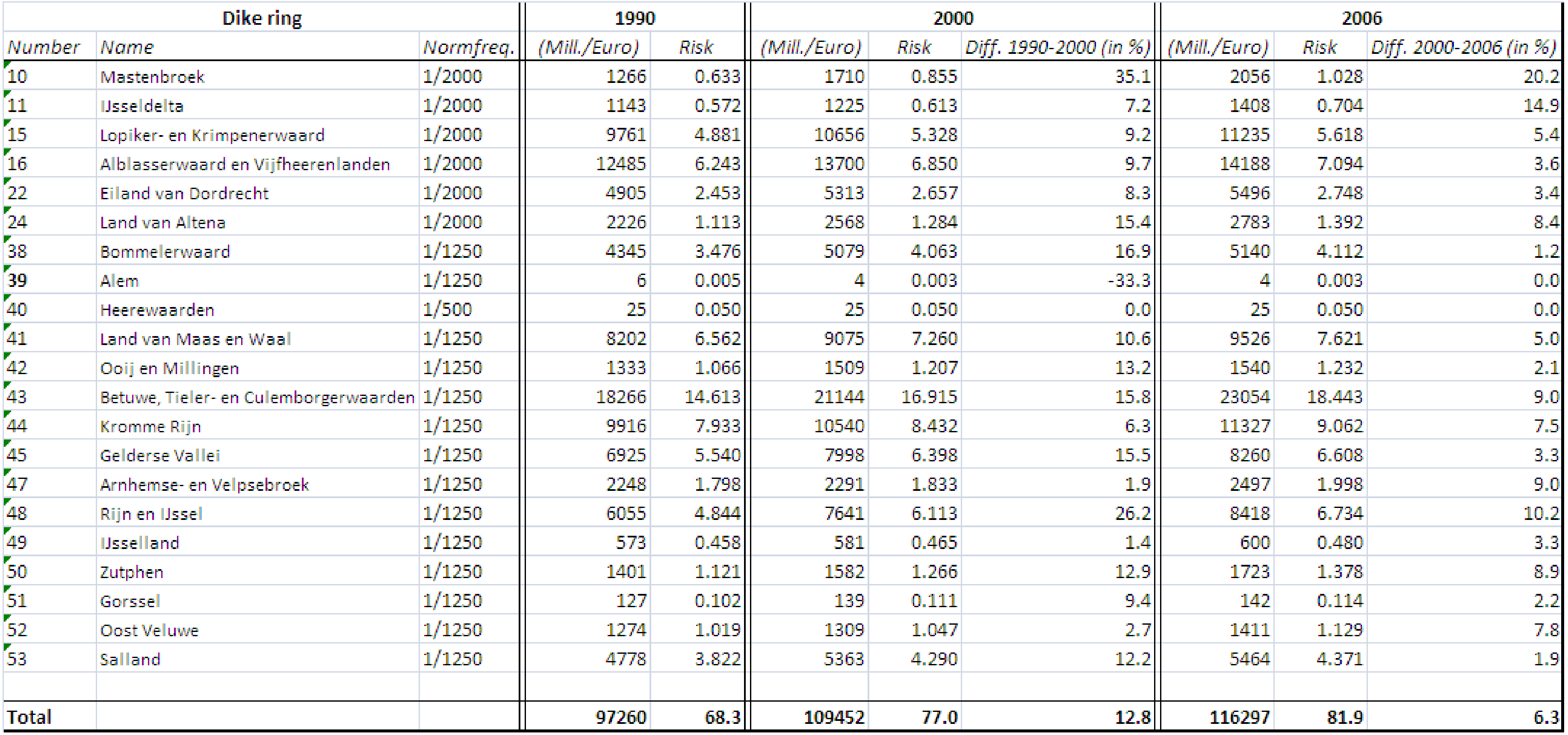
The CORINE land cover data provided by the European Environmental Agency, allows to evaluate the effect of *observed* land-use change on potential flood damages. Land cover data have been published for 1990, 2000 and 2006 (http://www.eea.europa.eu/data-and-maps). We used the CORINE land cover data to assess potential flood damages for the three time steps with the Damage Scanner. Table XIII provides an overview of potential flood damages for different sections along the Rhine for 1990, 2000 and 2006. The sections along the Rhine were defined on the basis of Te Linde et al. (2010) and represent areas with different safety levels. It can be seen that overall flood damages increased by 3.5 per cent between 1990 and 2000 and by another 1.9 per cent between 2000 and 2006. It can also be seen that the different sections along the Rhine vary considerably. While areas along the Upper Rhine show an increase in potential flood damages by about 4 per cent between 1990 and 2000 due to observed land use change, the Rhine Delta shows an increase in potential damages of almost 13 per cent for the same period.

Table XIII: Potential flood damages along the Rhine for 1990, 2000 and 2006.

Sections		**1990**		**2000**			**2006**		
	Return periods	*Damage*	*Risk*	*Damage*	*Risk*	*Diff.1990-2000 (in %)*	*Damage*	*Risk*	*Diff.2000-2006 (in %)*
Alpine A	0.005	408	2.04	413	2	1.2	413	2	0.0
Upper Rhine B	0.001	20088	20.088	20880	21	3.9	21045	21	0.8
Upper Rhine C	0.005	56323	281.615	58612	293	4.1	59941	300	2.3
Middle Rhine D	0.005	14936	74.68	15265	76	2.2	15343	77	0.5
Lower Rhine E	0.005	70884	354.42	71786	359	1.3	72376	362	0.8
Lower Rhine F	0.002	23303	46.606	24557	49	5.4	25427	51	3.5
Rhine Delta G	0.0008 - 0.0005	97260	68.3022	109452	77	12.8	116297	82	6.3
Total		**283202**	**848**	**300965**	**877**	**3.5**	**310842**	**894**	**1.9**

The same information but then on the level of dike rings in the Netherlands facing risk from extreme flooding along the Rhine is provided in Table XIV.

Table XIV: Potential flood damage and risk for the Dutch delta for 1990, 2000, 2006



Dike ring			**1990**		**2000**			**2006**		
Number	*Name*	*Normfreq.*	*(Mill./Euro)*	*Risk*	*(Mill./Euro)*	*Risk*	*Diff. 1990-2000 (in %)*	*(Mill./Euro)*	*Risk*	*Diff. 2000-2006 (in %)*
10	Mastenbroek	1/2000	1266	0.633	1710	0.855	35.1	2056	1.028	20.2
11	IJsseldelta	1/2000	1143	0.572	1225	0.613	7.2	1408	0.704	14.9
15	Lopiker- en Krimpenerwaard	1/2000	9761	4.881	10656	5.328	9.2	11235	5.618	5.4
16	Alblasserwaard en Vijfheerenlanden	1/2000	12485	6.243	13700	6.850	9.7	14188	7.094	3.6
22	Eiland van Dordrecht	1/2000	4905	2.453	5313	2.657	8.3	5496	2.748	3.4
24	Land van Altena	1/2000	2226	1.113	2568	1.284	15.4	2783	1.392	8.4
38	Bommelerwaard	1/1250	4345	3.476	5079	4.063	16.9	5140	4.112	1.2
39	Alem	1/1250	6	0.005	4	0.003	-33.3	4	0.003	0.0
40	Heerewaarden	1/500	25	0.050	25	0.050	0.0	25	0.050	0.0
41	Land van Maas en Waal	1/1250	8202	6.562	9075	7.260	10.6	9526	7.621	5.0
42	Ooij en Millingen	1/1250	1333	1.066	1509	1.207	13.2	1540	1.232	2.1
43	Betuwe, Tieler- en Culemborgerwaarden	1/1250	18266	14.613	21144	16.915	15.8	23054	18.443	9.0
44	Kromme Rijn	1/1250	9916	7.933	10540	8.432	6.3	11327	9.062	7.5
45	Gelderse Vallei	1/1250	6925	5.540	7998	6.398	15.5	8260	6.608	3.3
47	Arnhemse- en Velpsebroek	1/1250	2248	1.798	2291	1.833	1.9	2497	1.998	9.0
48	Rijn en IJssel	1/1250	6055	4.844	7641	6.113	26.2	8418	6.734	10.2
49	IJsselland	1/1250	573	0.458	581	0.465	1.4	600	0.480	3.3
50	Zutphen	1/1250	1401	1.121	1582	1.266	12.9	1723	1.378	8.9
51	Gorssel	1/1250	127	0.102	139	0.111	9.4	142	0.114	2.2
52	Oost Veluwe	1/1250	1274	1.019	1309	1.047	2.7	1411	1.129	7.8
53	Salland	1/1250	4778	3.822	5363	4.290	12.2	5464	4.371	1.9
Total			**97260**	**68.3**	**109452**	**77.0**	**12.8**	**116297**	**81.9**	**6.3**

8 Conclusions

The present report addressed several aspects of flood damage assessment along the Rhine. A general introduction on flood damage assessment methods in section 2 points out that even though flood damage assessment received growing attention in recent years, considerable uncertainties remain. This is exemplified by a comparison between the Rhine Atlas damage model and the so-called Damage Scanner. Both models are applied for damage assessments along the Rhine but differ significantly in terms of damage functions and the maximum damage values for comparable land-use types. Due to steeper damage functions and higher maximum damage values for comparable land-use types, the Damage Scanner yields substantially higher absolute potential flood damages compared to the Rhine Atlas model. Both models differ by up to a factor 3.3 (see also section 5)

A first inventory of potential flood damages along the Rhine was undertaken by the International Commission for the Protection of the Rhine (ICPR) in 2001. In the mean time, updated and improved information on possibly inundated areas became available. In section 3, we show that potential flood damage in the Dutch delta were largely overestimated due to the unrealistic information on flooded areas and water depths available at the time the Rhine Atlas was produced. Besides, it was found that the extent that the Rhine Atlas took into consideration included dike rings in the Netherlands, which are actually not so much at risk of extreme flooding from the river Rhine, but mainly from the sea (such as dike ring 14). Also this adds to the overestimation of potential damages in the Dutch delta.

A comparison between the detailed damage assessment undertaken in the WV21 and the results obtained by applying the Damage Scanner is provided in Section 4. Differences between the two approaches can be attributed to the evaluation method and the input data used. It is shown that the variations in calculated damages are reasonable given these methodological differences and in line with earlier studies comparing the Damage Scanner approach and the more detailed assessment of the HIS-SSM.

Given the considerable differences between the Rhine Atlas model and the Damage Scanner described in section 2, the question arises how the two models compare when estimating flood damage developments over time. While the two models differ by up to a factor 3.3 when looking at absolute damage estimates, we show that variations are considerably smaller when looking at relative changes over time. Here, both models differ by about a factor 1.4. This uncertainty resulting from the choice of the damage model is moreover considerably smaller than the uncertainty resulting from future land use projections (about a factor 3). Even though relative estimates are found to be more robust, they still vary consistently between the Rhine Atlas model and the Damage Scanner (about a factor 1.4). The Rhine Atlas yields consistently higher relative increases compared to the Damage Scanner. This has been attributed to the share different land-use categories contribute to total damage *within* both models. In the Rhine Atlas model, urban land use constitutes as much as 98 per cent of total flood damage, whilst in the Damage Scanner this is only 79 per cent. As a result, a shift to urban land use functions yields a much larger relative increase in the Rhine Atlas compared to the Damage Scanner. This implies that when assessing land-use change scenarios, it is crucial to apply a damage model that realistically reflects the contribution of different sectors (land-use classes) to the total damages.

Flood risk along the Rhine is projected to increase in the future due to ongoing socio-economic development in risk-prone areas and the effects of climate change on river discharges and consequently flood probabilities(te Linde et al., 2010). A possible way to cope with the projected increase in future flood risk are so-called non-structural flood mitigation measures such as wet and dry flood proofing of buildings. However, quantitative information on the effectiveness of such measures is still scarce. In section 6 we discuss two approaches how non-structural flood mitigation can be incorporated in the Damage Scanner. A comparison between the two approaches exemplifies the importance to take location specific information on water depths into account to avoid an overestimation of the effectiveness of such measures. According to the Global Approach, for which a global reduction factor is applied on potential damages, wet flood proofing of all residential areas under the GE scenario would lead to a damage reduction of about 30 per cent along the Rhine. The so-called 'Modelled Approach' is able to take the location specific information on water depths into account by an adjustment of the respective damage functions. According to the Modelled Approach, the same flood mitigation measure (wet flood proofing of all residential areas under the GE scenario) would lead to a damage reduction of about 7 per cent, only. Generally, we show that flood mitigation measures can have a significant damage reducing effect, especially in dike rings with shallow water depth.

The land cover data provided by the European Environmental Agency for 1990, 2000 and 2006 provide a good opportunity to gain insights into the development of potential flood damages due to *observed* land use change. We show that potential flood damage along the Rhine increased by 3.5 per cent in the period from 1990 to 2000 and by another 1.9 per cent between 2000 and 2006. Besides, we show that these observed trends differ significantly per area along the Rhine, ranging from 1.2 for the Alpine Rhine up to 12 per cent for the Rhine Delta for the period between 1990 and 2000.

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