Technische Universität München

RAT | Risk Analysis Tool

Risk Assessment and Cost Benefit Analysis of risk mitigation strategies

EXAMPLES

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Society is exposed to numerous hazards such as floods, storms, landslides or earthquakes. To mitigate the impact of such hazards on the society, different types of mitigation measures can be implemented, such as defence structures that aim at protecting the built up area from the hazard, measures increasing the resilience of the buildings and infrastructure or warning systems and emergency plans. In most cases, many alternative *risk mitigation strategies* are potentially applicable. To select the best mitigation strategy, Cost-Benefit Analysis (CBA) is standardly implemented, that allows identifying a strategy that provides the optimal balance between the costs for implementation and maintenance of the risk mitigation and the residual risk.

The methodology for risk assessment and for CBA is described in the document RAT-Methodology. This document provides application examples on:

- Selection of an optimal flood risk mitigation strategy
- Analysis of the uncertainties in Risk estimation (extension of the previous example)
- Accounting for subscenarios in the Risk estimation

All examples were implemented using the (Excel based) RAT software developed in the ERA Group of TU Munich that is freely available. The presented examples are partly taken from (Neumayer, 2016).

Contents

1. Example 1: Selection of an optimal flood risk mitigation strategy

The first application example aims at identifying an optimal flood protection strategy against river floods in a hypothetical town in Germany.

Three alternative risk mitigation strategies are evaluated:

- Strategy S0: preserve the actual state of protection against a 40-year flood event
- Strategy S1: construction of dykes designed for a 100-year flood event
- Strategy S2: construction of dykes designed for a 100-year flood event + detention basin

The best strategy is selected using Cost Benefit Analysis, as the strategy minimizing the discounted lifetime sum of risk and cost, following Sec. 5 of RAT-Methodology. The planning horizon is 100 years, the discount rate is 2%.

1.1 Risk estimation

For each risk mitigation strategy, multiple flood scenarios are considered:

- The discharges for individual scenarios were taken over from the Bavarian Hydrological Service and the local water authority, as well as the estimate of the discharge where the first damages occur (estimate of the capacity of the river bed).
- A hydraulic model was then used to determine the flooded area and water depths under each scenario for flood protection strategies S0 and S1, i.e. with and without the dykes.
- Based on that, the flooded objects were identified and the damage on each object was estimated using available vulnerability curves (that show the mean damage on an object of given category as a function of water depth in the location).
- Finally, the total damage for each scenario for strategy S0 and S1 was estimated as the sum of damages on all flooded objects.
- For strategy S2, the modeling of the effect of new detention basin on the flood discharges was not possible because of time limitations. Therefore very rough estimates were made assuming that implementation of the detention basin transforms a 100-year event to an event with peak discharge in town corresponding to today's 50-year event, a 200-year event to an event with peak discharge corresponding to a 100-year event etc.

The results of these investigations are summarized in Table 1, which is the input table for the RAT software. It can be seen that the dyke system (strategy S1) significantly reduces the damages for the 50-year and the 100-year event, but for larger events the dykes would be overtopped and the damage is expected to be the same as under the actual state (strategy S0). Note that this assumption is very likely simplifying the reality: (a) The failure mechanism of the dykes is not modeled in detail, the fact that for example only the dykes on one side of the river would fail and thus only part of the town would be flooded is not considered. This might lead to overestimation of the damage. (b) The so-called levee-effect is not taken into account, which describes the fact that the damage potential in a settlement where dykes are built actually increases due to the feeling of safety – people are not aware of the flood danger anymore and don't take appropriate preventive actions, more construction is allowed in the flood plain etc. This might, on the contrary, lead to underestimation of the damage.

Table 1: Mean damages [€] per scenario and strategy used as input data for the risk estimation in RAT software.

Scenario	***Return Period [years]***	***Annual Exceedence probability***	***Mean damage for [€]***		
			Strategy S0	**Strategy S1**	**Strategy S2**
No damage scenario	**40**	0.025	0	0	0
50-year event	**50**	0.020	187 343 750	4 950 000	0
100-year event	**100**	0.010	330 600 000	9 050 000	4 950 000
200-year event	**200**	0.005	394 550 000	394 550 000	9 050 000
500-year event	**500**	0.002	771 712 500	771 712 500	394 550 000
1000-year event	**1000**	0.001	-	-	771 712 500

Figure 1 shows the Exceedance Probability (EP) curves for the analyzed risk mitigation strategies as generated based on the inputs of Table 1 - they show the mean damage associated with scenarios of different exceedance probabilities. As explained in Sec. ##2 of the methodology, the area under each curve corresponds to the residual risk associated with the strategy.

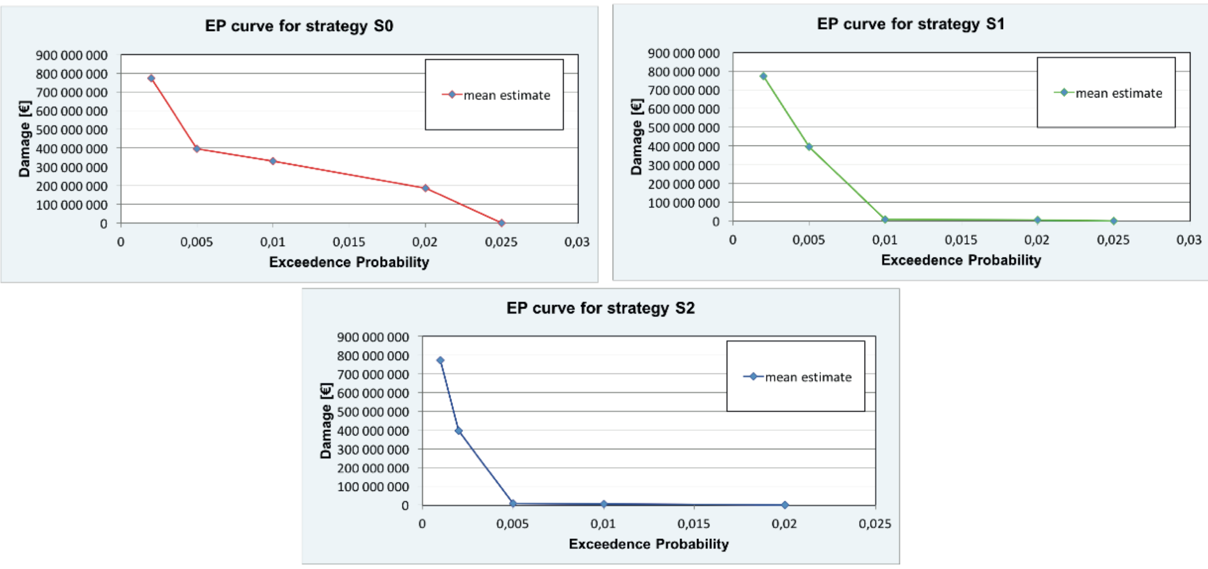


Figure 1. EP curves for the evaluated flood mitigation strategies (generated with RAT).

The reduction of risk achieved with building of a dyke system (strategy S1) is displayed in Figure 2 with the red shaded area. The additional risk reduction associated with building the detention basin on top of the tyke system (strategy S2) is illustrated with the green shaded area in Figure 2.

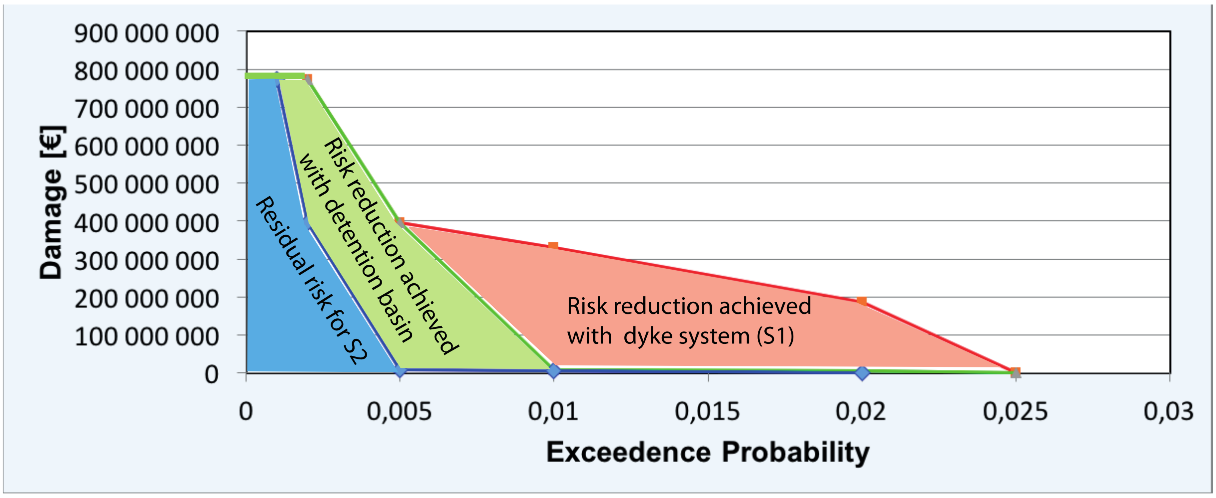


Figure 2. Risk reduction achieved with strategies S1 and S2.

Table 3 summarizes the annual residual risk for evaluated flood protection strategies, which is calculated as the integral of the EP curves displayed in Figure 1 following Eq. ##3 in the Methodology. As expected, strategy S2 is associated with the lowest (residual) risk, as it offers the highest protection standard.

Table 2. Results of risk estimation using the RAT software – annual risk (expected annual damage) for evaluated flood protection strategies.

Strategy	Annual Risk [€/year]
S0	8 163 772
S1	4 384 194
S2	2 019 994

The risk is assumed to be constant over time, i.e. it is assumed that the conditions such as frequency of extreme flood events or the damage potential do not change in the future. This is not likely to be true (e.g. due to climate change, socio-economic development in the flood plain or due to changing land use in the catchment), but it is a common assumption made in the planning of flood protection measures.

To account for the time value of money, the future risk is discounted. When the (nominal value of) risk is assumed to be constant in each year of the planning horizon, the discounted values decrease with time, as is illustrated in Figure 3.

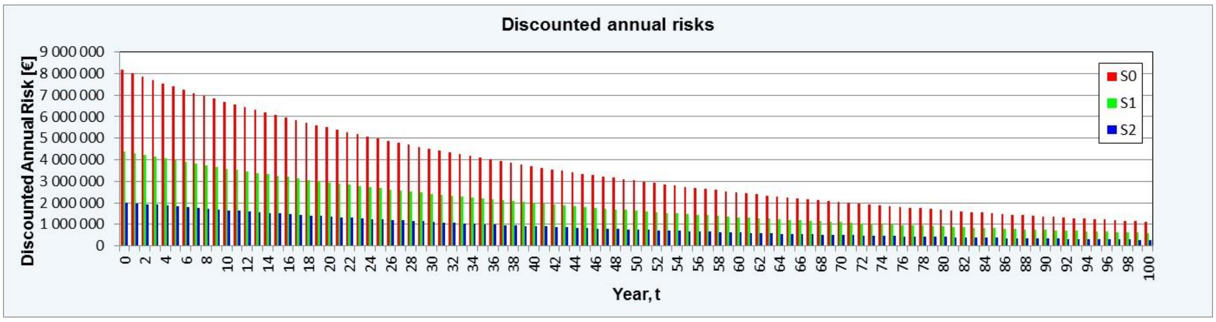


Figure 3. Discounted annual risk distribution over the planning horizon - comparison of strategies (RAT software output).

Table 3 summarizes the cumulated discounted risk over the whole planning horizon (i.e. the sum of annual discounted risk shown in Figure 3) for evaluated flood protection strategies. This serves as the input for the Cost Benefit Analysis described later in Sec. 0.

Table 3. Results of risk estimation using the RAT software – sum of discounted residual risk (expected annual damage) over the planning horizon for evaluated flood protection strategies.

Strategy	Cumulated Discounted risk [€]
S0	360 008 883
S1	193 335 718
S2	89 078 395

1.2 Cost estimation

Strategy S0 represents the preservation of the actual state of protection. Therefore no investment costs are necessary, only annual maintenance costs, as shown in Table 4. Strategy S1 and S2 are associated with an extension of the actual protection measures. Hence investment costs as well as annual maintenance costs have to be considered.

Table 4. Costs of individual flood protection strategies

Strategy	Investment costs [€]	Annual maintenance costs [€]
S0	0	500 000
S1	100 000 000	750 000
S2	155 000 000	1 025 000

Figure 4 shows a distribution of the undiscounted annual costs for all evaluated strategies in time. It is obvious that the costs are dominated by the investment costs that are by several orders of magnitude higher than the operation and maintenance costs. The graph can thus alternatively be shown in a logarithmic scale (Figure 5).

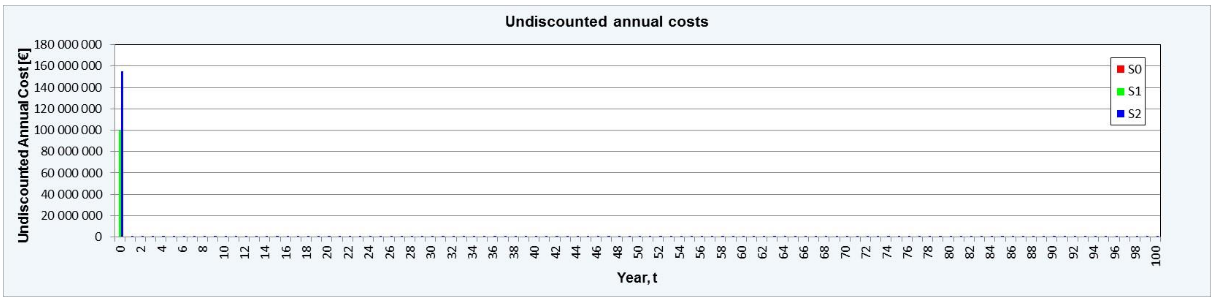


Figure 4. Distribution of undiscounted cost over the planning horizon – comparison of strategies (RAT software output).

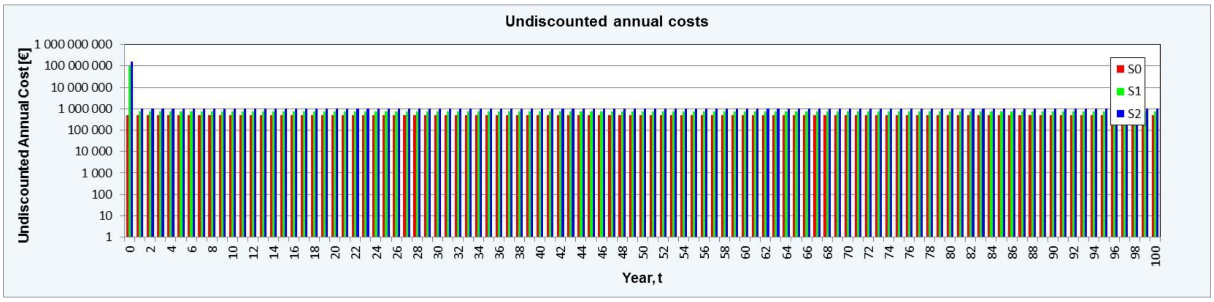


Figure 5. Distribution of undiscounted cost over the planning horizon in log-scale.

Finally, Table 5 summarizes the results of the cost estimation for evaluated flood protection strategies, i.e. the cumulated discounted cost over the whole planning horizon (sum of annual discounted cost shown in Figure 5).

Table 5. Results of cost estimation using the RAT software – sum of discounted cost over the planning horizon for all evaluated flood protection strategies.

Strategy	Cumulated discounted cost [€]
S0	22 049 176
S1	132 323 764
S2	199 175 810

1.3 Comparison of the risk mitigation strategies – Cost Benefit Analysis

The results of the comparison of the three evaluated strategies are summarized in Table 6. Strategy S2, i.e. building both the system of dykes and detention basin minimizes the cumulated discounted risk and costs. Figure 6 shows the results in a graphical form as a Risk vs. Cost graph (see section 5 of the Methodology).

Table 6. Cost Benefit Analysis using the RAT software – Comparison of strategies.

Strategy	Cumulated Discounted Risk [€]	Cumulated Discounted Cost [€]	Sum (Risk + Cost) [€]
S0	360 008 883	22 049 176	**382 058 059**
S1	193 335 718	132 323 764	**325 659 481**
S2	89 078 395	199 175 810	**288 254 205**

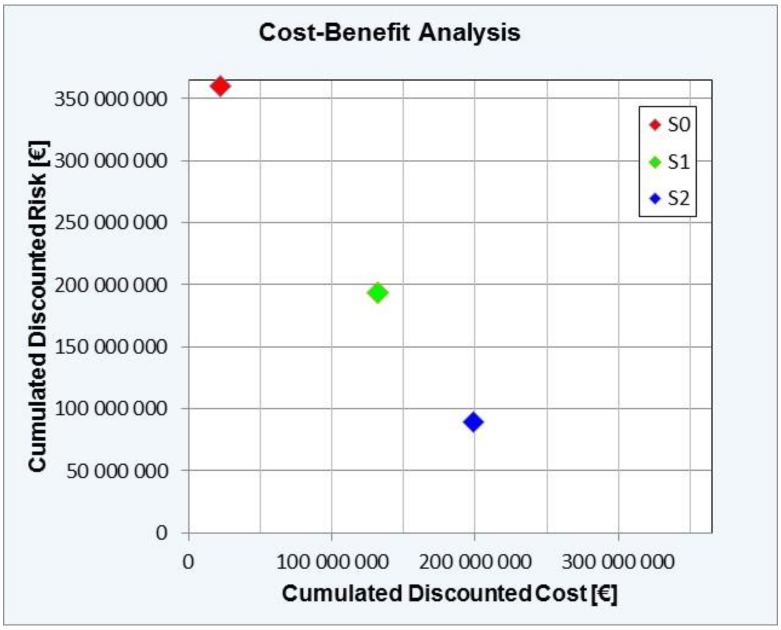


Figure 6. Cost Benefit Analysis using the RAT software – Comparison of strategies in the Risk vs. Cost graph.

2. Example 2: Analysis of uncertainties in Risk estimation

Risk estimation is associated with significant uncertainties, as discussed in the Sec. ## 2.2 of the methodology. These were, however, not explicitly considered in the previous example. This section focuses on analysis of different sources of uncertainty.

2.1. Uncertainty in damage estimation

Estimation of the mean damage for individual scenarios is associated with significant uncertainty. This uncertainty stems for example from the uncertain estimation of the extent of the flooded area, location of the exposed objects or from the uncertainty in estimating the vulnerability of the different objects (see Sec. ## 2.2. of the Methodology). This uncertainty is also referred to as an (uncertain) error in the estimation (i.e. the difference between the true value and the estimated damage).

Quantification of such uncertainty (error) is a complex task and it extends the scope of this document. A simple assumption is thus made here, that the damage for each scenario lies most likely in an interval of +- 50 % above/below the mean estimate. It is assumed that the lower and upper estimates define a 90 % credible interval, i.e. an interval where the true value of the damage lies with a 90 % probability. It is assumed that this interval includes all uncertainties in the extent of the flooded area, location of the exposed objects or the vulnerability of the objects.

The lower (optimistic) and upper (pessimistic) estimates are inserted in the RAT software for each scenario, as shown in Table 7. Figure 7 shows the EP curves for mean, lower and upper estimate for each of the evaluated risk mitigation strategy. The mean estimate of the damage and annual risk remains the same as in the example in Sec. 1.1, but the lower and upper estimates are added.

Table 7: Including lower and upper estimate in RAT software to account for uncertainty in damage estimation.

Strategy	**Scenarios**			**Damage per (sub)scenario [€]**			**Annual Risk [€/year]**		
Name	Description	Return period [years]	Exceedence probability	lower estimate	mean estimate	upper estimate	lower estimate	mean estimate	upper estimate
S0	No damage Scenario	40	0.025	0	0	0	**4 081 886**	**8 163 772**	**12 245 658**
S0	50-year event	50	0.020	93 671 875	187 343 750	281 015 625			
S0	100-year event	100	0.010	165 300 000	330 600 000	495 900 000			
S0	200-year event	200	0.005	197 275 000	394 550 000	591 825 000			
S0	500-year event	500	0.002	385 856 250	771 712 500	1 157 568 750			
S1	No damage scenario	40	0.025	0	0	0	**2 192 097**	**4 384 194**	**6 576 291**
S1	50-year event	50	0.020	2 475 000	4 950 000	7 425 000			
S1	100-year event	100	0.010	4 525 000	9 050 000	13 575 000			
S1	200-year event	200	0.005	197 275 000	394 550 000	591 825 000			
S1	500-year event	500	0.002	385 856 250	771 712 500	1 157 568 750			
S2	50-year event	50	0.020	0	0	0	**1 009 997**	**2 019 994**	**3 029 991**
S2	100-year event	100	0.010	2 475 000	4 950 000	7 425 000			
S2	200-year event	200	0.005	4 525 000	9 050 000	13 575 000			
S2	500-year event	500	0.002	197 275 000	394 550 000	591 825 000			
S2	1000-year event	1000	0.001	385 856 250	771 712 500	1 157 568 750			

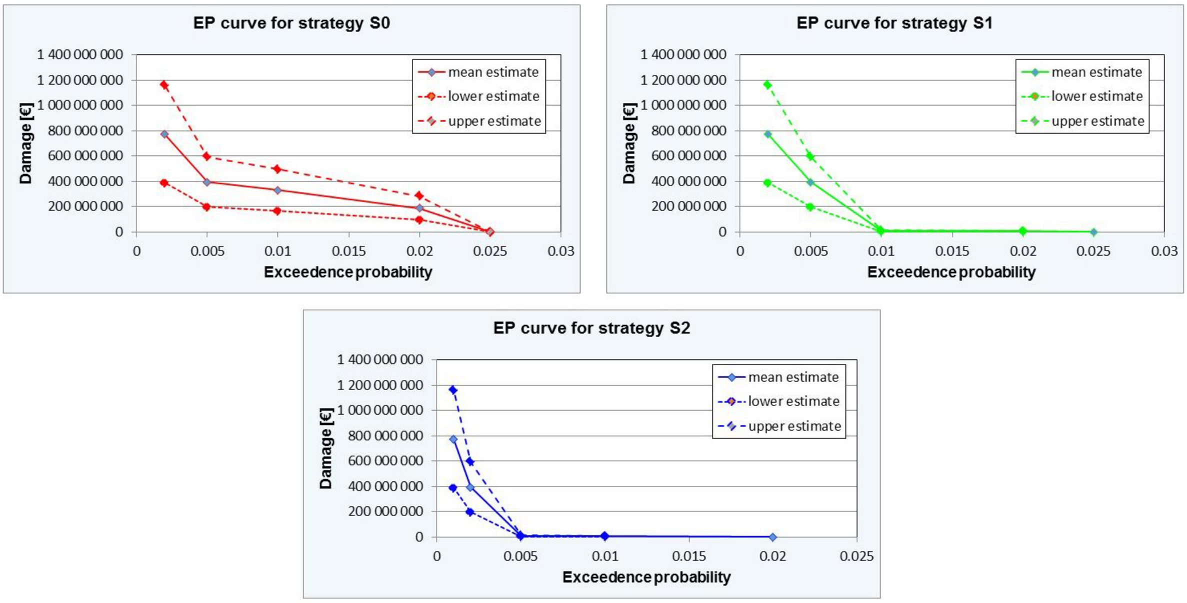


Figure 7. EP curves for the evaluated flood mitigation strategies including lower and upper estimate (generated with RAT).

It should be noted that the estimation of the annual risk assumes that the error/uncertainty in the damage estimation is fully correlated between the evaluated scenarios. I.e. it assumes that if the damage is underestimated by 50% for the 100-year scenario, it is underestimated by 50% also in case of all other scenarios. Only if this is true, the lower and upper estimate of annual risk represents the 90% credible interval of annual risk estimate. If the error of damage estimation for individual scenarios is not fully correlated, the lower and upper estimate of the annual risk represent a credible interval with probability higher than 90%.

Finally, Figure 8 shows the comparison of the risk mitigation strategies in the risk vs. Cost graph, Table 8 summarizes the results. For mean and upper (pessimistic) estimate of the risk, strategy S2 (i.e. building both dykes and a detention basin) is recommendable. However, in case of the lower (optimistic) estimate of the risk, keeping the current state is the best solution, as it provides a sufficient protection level.

Taking into account the uncertainty, still strategy S2 should be recommended, but the uncertainty analysis shows that there is a certain chance, that the strategy S2 is too conservative and thus not cost-effective.

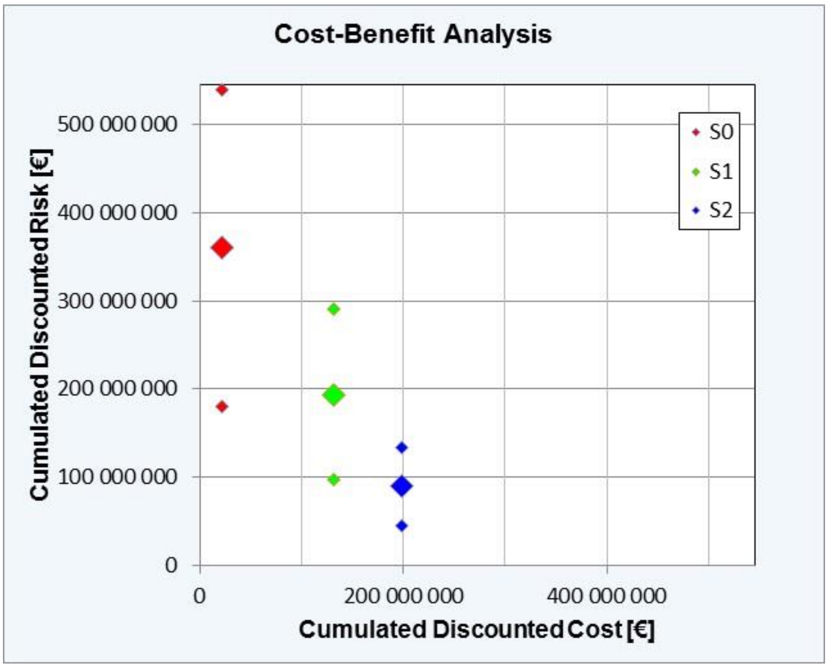


Figure 8. Risk vs. Cost graph incl. lower (optimistic) and upper (pessimistic) estimate of risk accounting for uncertainty in damage estimation (from RAT software).

Table 8: Cost Benefit Analysis using the RAT software – Comparison of strategies accounting for uncertainty in damage estimation.

Strategy	Cumulated Discounted Risk [€]			Cumulated Discounted Cost [€]	Sum (Risk + Cost) [€]		
	lower estimate	mean estimate	upper estimate		lower estimate	mean estimate	upper estimate
S0	180 004 441	360 008 883	540 013 324	22 049 176	**202 053 617**	**382 058 059**	**562 062 500**
S1	96 667 859	193 335 718	290 003 576	132 323 764	**228 991 623**	**325 659 481**	**422 327 340**
S2	44 539 197	89 078 395	133 617 592	199 175 810	**243 715 008**	**288 254 205**	**332 793 402**

2.2. Uncertainty in estimating the extreme discharges

In analysis of river floods, the discharges associated with each flood scenario (e.g. the 100-year discharge) are estimated based on historic discharge records or using rainfall data with rainfall runoff models. The uncertainty associated with such estimate depends on the amount and quality of data and of the model (see Sec. ## 2.2. of the Methodology), with less data, the uncertainty is higher, and it also increases for scenarios with long return periods. For example, estimating a 1000-year discharge based on 100 years of discharge observations is a very tricky job. Quantifying these uncertainties is thus important for making good decisions about the flood protection.

The extreme discharges in the analysed area are estimated based on 44 years of discharge measurements. The annual discharge maxima are summarized in Annex 1 and they are plotted in Figure 9. Gumbel distribution is fitted to the annual maxima using Bayesian method, assuming a uniform prior. The posterior joint PDF of the location and shape parameter of the Gumbel distribution are plotted in Figure 10.

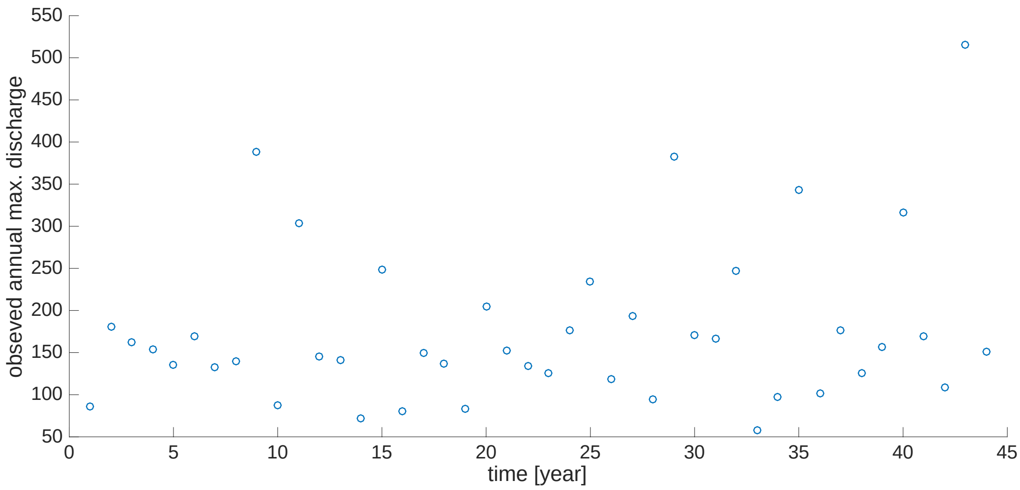


Figure 9. Observed annual max. discharges in the study area (44 years of observations).

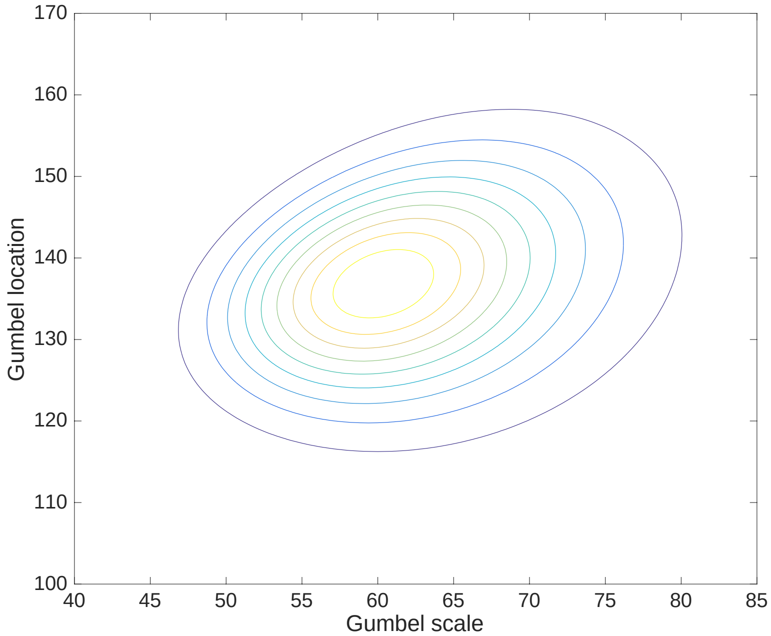


Figure 10. Posterior joint PDF of parameters of the Gumbel distribution fitted to the observed annual discharges.

Figure 11 shows comparison of the fitted Gumbel CDF with the cumulative frequency plot representing the data. Parameters of the fitted distribution in Figure 11 are determined using the Maximum a posteriori (MAP) estimation, i.e. as the maximum of the posterior joint PDF shown in Figure 10. The extreme discharges with 50-, 100- and higher return period determined based on this Gumbel distribution are summarized in Table 9.

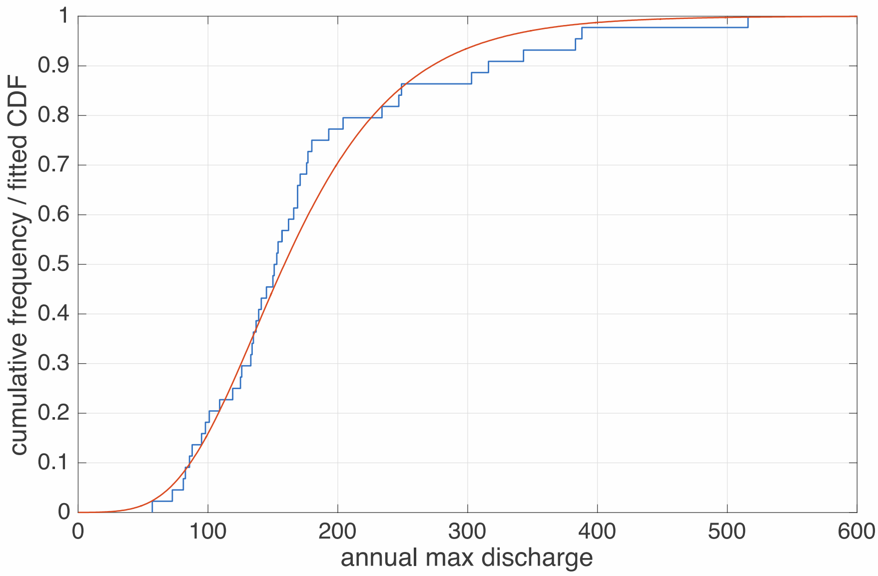


Figure 11. Cumulative frequency plot of the observed annual max discharges compared with the fitted Cumulative Distribution Function (CDF) – based on MAP estimate.

The posterior joint PDF of the location and shape parameter of the Gumbel distribution plotted in Figure 10 is further used to determine the uncertainty on the estimation of the extreme discharges. Figure 12 shows the results of estimating the extreme discharge for different return periods. It should be, however, kept in mind that the uncertainty estimated in this example underestimates the total uncertainty, because we do not consider the uncertainty in the probabilistic model used for representing the extreme discharges (the Gumbel distribution is considered to be the right one).

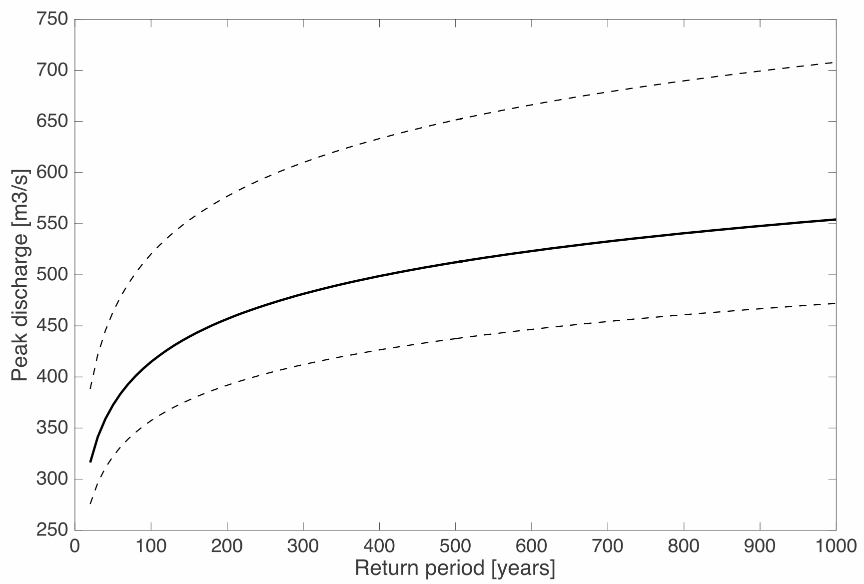


Figure 12. Uncertainty in estimation of extreme discharges: MAP estimate and 95% credible interval (equal-tailed).

The Maximum a posteriori (MAP) estimate of extreme discharges as well as the lower and upper limit of the 95 % credible interval for selected scenarios are summarized in Table 9. The no damage scenario corresponds to a peak discharge of 358 m3/s, which has a return period of 40 years according to MAP estimate. The return period of this discharge, however, is also uncertain and its 95% credible interval is (14,102) years.

Table 9: Extreme discharges in the analysed area – Maximum a posteriori (MAP) estimate and lower and upper limit of 95% credible interval.

Scenario	***Return Period [years]***	***Annual Exceedence probability***	***Discharge [m³/s]***		
			Maximum a posteriori (MAP)	**95% credible int.**	
				Lower limit (optimistic)	**Upper limit (pessimistic)**
No damage	**40**	0.025	358	-	-
50-year event	**50**	0.020	372	322	464
100-year event	**100**	0.010	415	357	520
200-year event	**200**	0.005	457	392	577
500-year event	**500**	0.002	512	438	651
1000-year event	**1000**	0.001	554	472	708

The damages estimated for individual scenarios, as presented in Table 1 and Table 10, were determined using hydrodynamic simulation and damage assessment. The damage curves showing the total mean damage in the analysed area for all analysed flood protection strategies as a function of discharge are plotted in Figure 13.

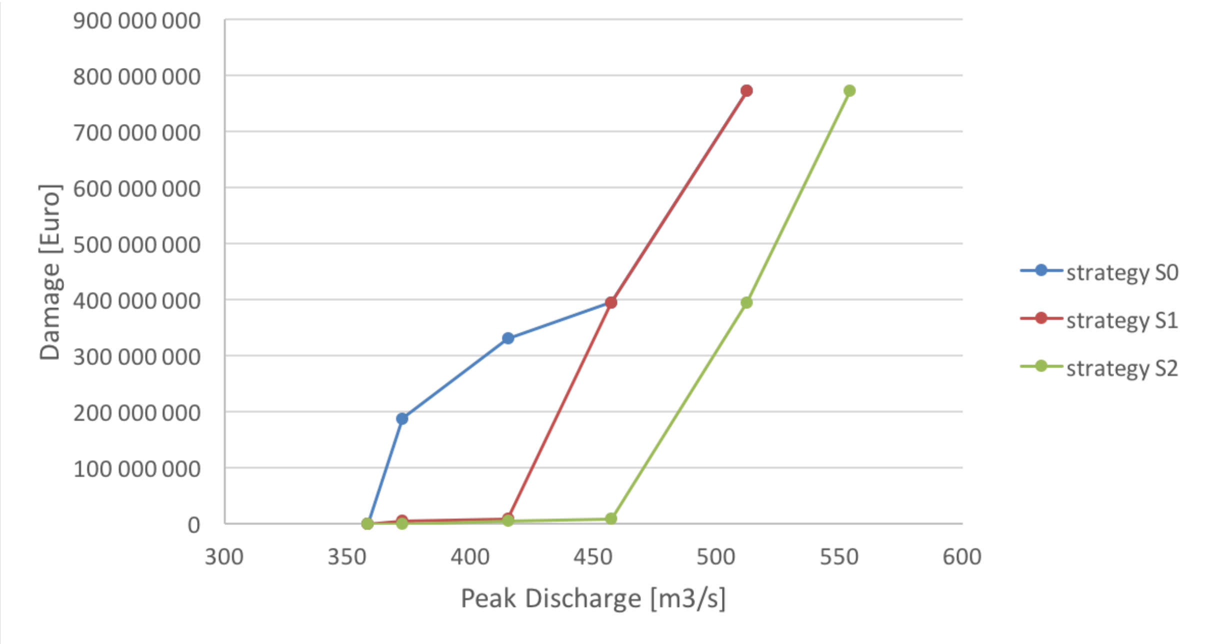


Figure 13. Damage curve as function of peak discharge.

Using the damage curves in Figure 13, the damage associated with other discharges than those analysed in detail using the hydrodynamic model can be approximated without conducting additional hydrodynamic simulations. The damage for the upper (pessimistic) and lower (optimistic) estimate of extreme discharges are summarized in Table 11 and Table 12.

In Table 12 presenting the lower (optimistic) estimate of frequency (and intensity) of extreme discharges it can be seen that the "no damage" scenario has a return period of 102 years and therefore also the damage associated with 50- and 100- years scenarios is equal to 0. The damages for the scenarios with higher return period were estimated using interpolation of the damage curve from Figure 13.

It is assumed that the dikes in strategy S1 and S2 are designed to withstand a peak discharge of 415 m^3/s, which corresponds the 100-year discharge estimated with the MAP estimate. In the optimistic estimate (Table 12), such discharge has a return period higher than 200 years and the 200-year scenario is thus associated with very low damage. In the pessimistic estimate (Table 11), such discharge has slightly higher return period than 50 years. The 50 – and 100-year scenarios are thus already associated with significant damage.

Table 10: MAP estimate of Damages [€] per scenario and strategy (compare with Table 1).

Scenario	***Return Period [years]***	***Peak discharge [m3/s]***	***Damage for [€]***		
			Strategy S0	**Strategy S1**	**Strategy S2**
No damage scenario	**40**	358	0	0	0
50-year event	**50**	372	187 343 750	4 950 000	0
100-year event	**100**	415	330 600 000	9 050 000	4 950 000
200-year event	**200**	457	394 550 000	394 550 000	9 050 000
500-year event	**500**	512	771 712 500	771 712 500	394 550 000
1000-year event	**1000**	554	-	-	771 712 500

Table 11: Pessimistic estimate - Upper limit of Damages [€] per scenario and strategy.

Scenario	***Return Period [years]***	***Peak discharge [m3/s]***	***Damage for [€]***		
			Strategy S0	**Strategy S1**	**Strategy S2**
No damage scenario	**13**	358	0	0	0
20-year event	**20**	388	240 650 000	0	0
40-year event	**40**	445	376 280 000	376 280 000	0
50-year event	**50**	464	442 550 000	442 550 000	0
100-year event	**100**	520	826 570 000	826 570 000	442 550 000
200-year event	**200**	577	1 217 450 000	1 217 450 000	826 570 000
500-year event	**500**	651	1 724 900 000	1 724 900 000	1 217 450 000
1000-year event	**1000**	708	-	-	1 724 900 000

Table 12: Optimistic estimate: Lower limit of Damages [€] per scenario and strategy.

Scenario	***Return Period [years]***	***Peak discharge [m3/s]***	***Damage for [€]***		
			Strategy S0	**Strategy S1**	**Strategy S2**
No damage scenario	**102**	358	0	0	0
50-year event	**50**	322	0	0	0
100-year event	**100**	357	0	0	0
200-year event	**200**	392	253 970 000	6 860 000	0
500-year event	**500**	438	365 620 238	365 620 238	6 860 000
1000-year event	**1000**	472	-	-	365 620 238

Quantifying the uncertainty in Risk assessment

The lower (optimistic) and upper (pessimistic) estimates are inserted in the RAT software for each scenario, as shown in Table 13. The mean estimate of the damage and annual risk remains the same as in Table 2, but the lower and upper estimates are added.

Table 13: Including lower and upper estimate in RAT software to account for uncertainty in estimated frequency/intensity of extreme events.

Strategy		**Scenarios**			**Damage per (sub)scenario [€]**			**Annual Risk [€/year]**		
ID	Name	Description	Return period [years]	Exceedence probability	lower estimate	mean estimate	upper estimate	lower estimate	mean estimate	upper estimate
1	**S0**	13-year event	13	0,077	0	0	0	**2 295 551**	**8 163 772**	**32 317 194**
1	**S0**	20-year event	20	0,050	0	0	240 650 000			
1	**S0**	40-year event	40	0,025	0	0	376 280 000			
1	**S0**	50-year event	50	0,020	0	187 343 750	442 550 000			
1	**S0**	100-year event	100	0,010	0	330 600 000	826 570 000			
1	**S0**	200-year event	200	0,005	253 970 000	394 550 000	1 217 450 000			
1	**S0**	500-year event	500	0,002	365 620 238	771 712 500	1 724 900 000			
2	**S1**	20-year event	20	0,050	0	0	0	**1 307 111**	**4 384 194**	**26 069 550**
2	**S1**	40-year event	40	0,025	0	0	376 280 000			
2	**S1**	50-year event	50	0,020	0	4 950 000	442 550 000			
2	**S1**	100-year event	100	0,010	0	9 050 000	826 570 000			
2	**S1**	200-year event	200	0,005	6 860 000	394 550 000	1 217 450 000			
2	**S1**	500-year event	500	0,002	365 620 238	771 712 500	1 724 900 000			
3	**S2**	50-year event	50	0,020	0	0	0	**562 150**	**2 019 994**	**11 647 655**
3	**S2**	100-year event	100	0,010	0	4 950 000	442 550 000			
3	**S2**	200-year event	200	0,005	0	9 050 000	826 570 000			
3	**S2**	500-year event	500	0,002	6 860 000	394 550 000	1 217 450 000			
3	**S2**	1000-year event	1000	0,001	365 620 238	771 712 500	1 724 900 000			

Figure 14 shows the EP curves for mean, lower and upper estimate for each of the evaluated risk mitigation strategy. The mean estimates presented with the solid lines correspond to the EP curves from Figure 1.

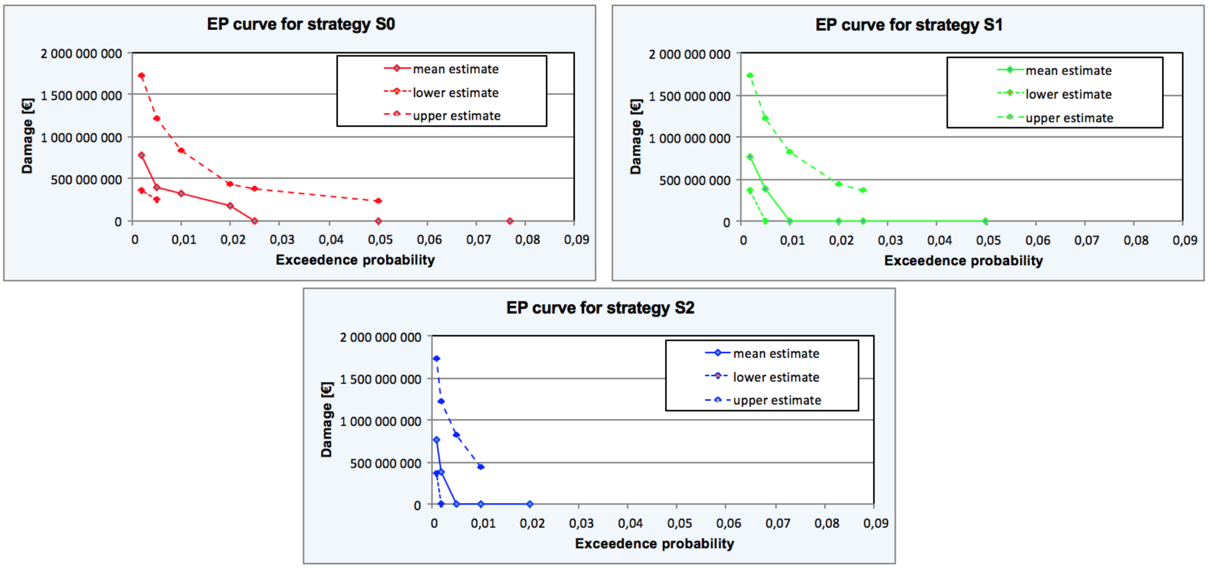
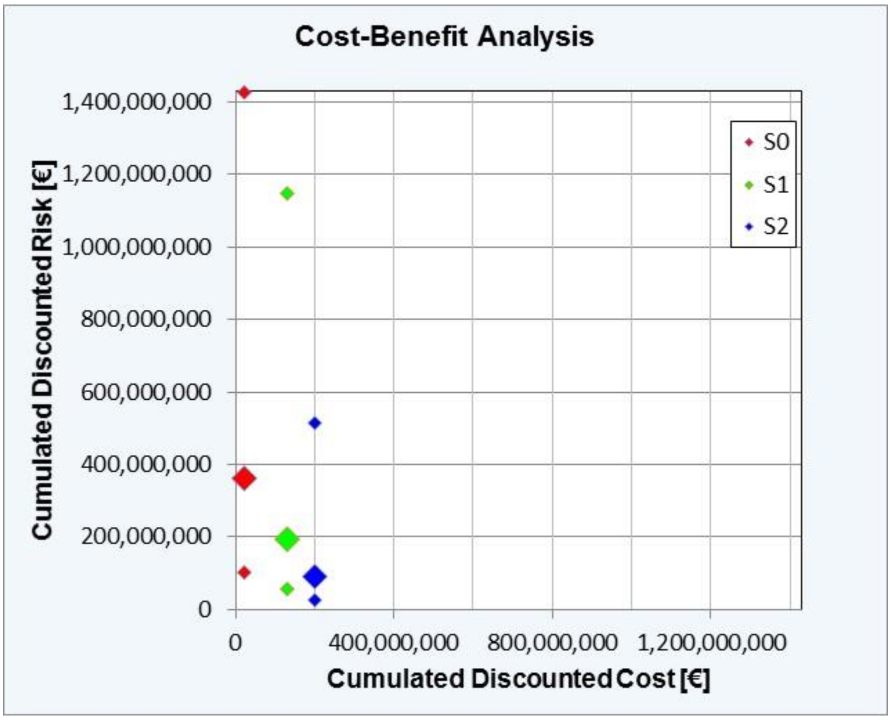


Figure 14. EP curves for the evaluated flood mitigation strategies including lower and upper estimate to account for uncertainty in estimated frequency/intensity of extreme events (generated with RAT software).



Finally,

Figure 15 shows the comparison of the risk mitigation strategies in the risk vs. Cost graph, Table 14 summarizes the results. For mean and upper (pessimistic) estimate of the risk, strategy S2 (i.e. building both dykes and a detention basin) is recommendable. However, in case of the lower (optimistic) estimate of the risk, keeping the current state is the best solution, as it provides a sufficient protection level.

Taking into account the uncertainty, still strategy S2 should be recommended, but the uncertainty analysis shows that there is a certain chance, that the implemented risk mitigation measures within S2 are too conservative.

Table 14: Cost Benefit Analysis using the RAT software – Comparison of strategies accounting for uncertainty in estimated frequency/intensity of extreme events.

Strategy	Cumulated Discounted Risk [€]			Cumulated Discounted Cost [€]	Sum (Risk + Cost) [€]		
	lower estimate	mean estimate	upper estimate		lower estimate	mean estimate	upper estimate
S0	101 230 008	360 008 883	1 425 134 995	22 049 176	**123 279 184**	**382 058 059**	**1 447 184 171**
S1	57 641 433	193 335 718	1 149 624 183	132 323 764	**189 965 197**	**325 659 481**	**1 281 947 947**
S2	24 789 904	89 078 395	513 642 386	199 175 810	**223 965 715**	**288 254 205**	**712 818 196**

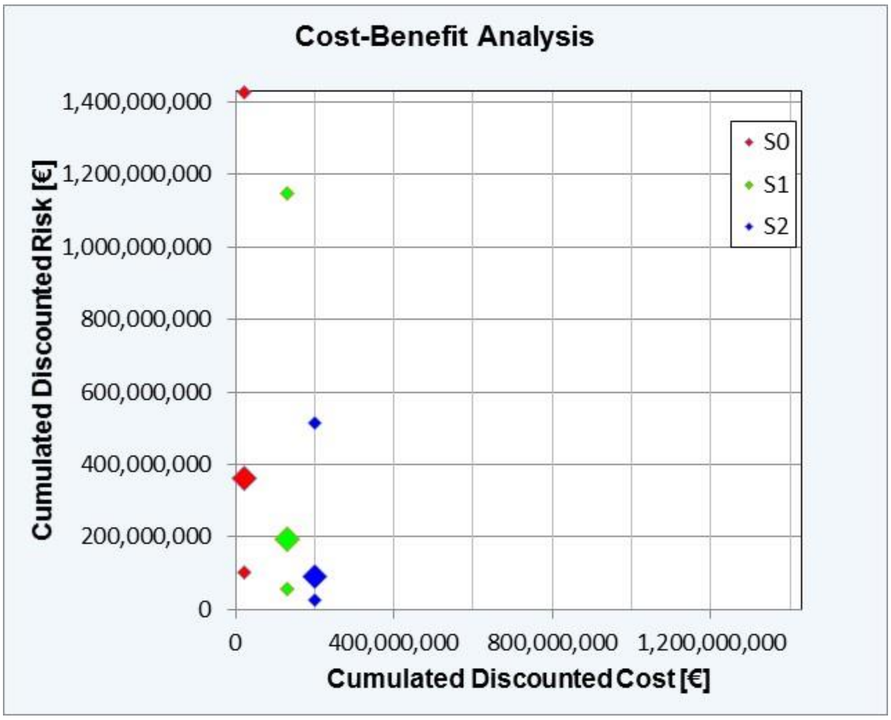


Figure 15. Risk vs. Cost graph incl. lower (optimistic) and upper (pessimistic) estimate of risk accounting for uncertainty in estimated frequency/intensity of extreme events (from RAT software).

When comparing the results with results considering the uncertainty in damage estimation presented in Sec. 2.1, the same pattern and conclusions can be made. However, the uncertainty associated with the estimate of frequency/intensity of extreme events is, in this example, significantly higher than the one resulting from uncertainty in damage estimation, as is obvious from comparison of Figure 8 and Figure 15.

3. Example 3: Flood risk mitigation planning including subscenarios

The main purpose of this hypothetical example is to show how subscenarios can be considered using RAT and how they influence the flood risk assessment.

The study area of this example is a small town located in an alpine region. Since a mountain torrent flows right through the town, it is exposed to frequent flood events. The flood events are likely to trigger debris flows, that would lead to significantly higher damage than a “normal” flood event. The possible occurrence of debris flow is thus taken into account as subscenario in the risk analysis. The probability of occurrence of debris flows during a flood event depends on the flood discharge, inclination of the river bed and available material in the catchment which can be eroded at the time of the event.

At the moment the town is protected against flood events with a 30 year return period. It should be examined now, if it is better to extend the existing protection measures in order to provide a protection of the town’s settlement areas against 100-year flood events. The planning horizon is set to T = 100 years, the discount rate r is assumed to be 2%.

Two risk mitigation strategies are evaluated in this example:

- Strategy S0: preserve the actual state of protection against 30-year flood events
- Strategy S1: protection against 100-year flood events + debris flow protection measures

3.1. Risk estimation

Multiple flood scenarios with return periods 30 to 500 years were investigated. For each scenario, the conditional probability of the occurrence of a debris flow was determined (this probability is thus conditional on the return period of the flood event). Such investigation can be very demanding and can require local investigations of the debris deposits and stochastic modeling of the debris flow initiation (e.g. using Monte Carlo simulation). Results of such study are summarized in Table 15 for the risk mitigation strategy for the actual state (strategy S0).

Table 15: Conditional probabilities of a debris flow/no debris flow given a specific scenario for strategy S0

Return Period [years]	***p(debris flow | T = t)***	**p(no debris flow | T = t)**
30	0	1
50	0	1
100	0.15	0.85
300	0.30	0.70
500	0.50	0.50

In case of strategy S1, the extension of the existing protection measures are estimated to influence the conditional probability of the occurrence of debris flows (e.g. through construction of additional transverse structures, building debris retention basins, increasing the slope stability in the upper parts of the catchment etc.). The conditional probabilities of debris flows in case of strategy S1 are summarized in Table 16.

Table 16: Conditional probabilities of a debris flow/no debris flow given a specific scenario (strategy S1)

Return Period [years]	***p(debris flow | T = t)***	**p(no debris flow | T = t)**
30	0	1
50	0	1
100	0	1
300	0.15	0.85
500	0.40	0.60

The damages are estimated to be twice as high in case of a debris flow compared to a normal flood event. The estimated damages per scenario and strategy are listed in Table 17.

Table 17: Expected damages [€] used as input data for the risk estimation

Return Period [years]	***Estimated damages [€], S0***		***Estimated damages [€], S1***	
	Debris flow	***No debris flow***	***Debris flow***	***No debris flow***
30	-	0	-	0
50	-	5 000 000	-	0
100	25 000 000	12 500 000	-	1 500 000
300	35 000 000	17 500 000	30 000 000	15 000 000
500	50 000 000	25 000 000	40 000 000	20 000 000

The inputs as well as results of risk estimation carried out with RAT are shown in Table 18. The resulting annual risk for strategy S0 is c. 369 t. Euro. Implementation of strategy S1 would reduce the annual risk to c. 156 t. Euro.

Table 18. Risk estimation incl. subscenarios in the RAT software – inputs and estimate of annual risk.

Strategy	**Scenarios**			**Subscenarios**		**Damage per (sub)scenario [€]**	**Damage per scenario [€]**	**Annual Risk [€/year]**
Name	Description	Return period [years]	Exceedence probability	Description	Probability of subscenario given a specific scenario	mean estimate	mean estimate	mean estimate
S0	30-year event	30	0.033			0	0	**369 125**
S0	50-year event	50	0.020			5 000 000	5 000 000	
S0	100-year event	100	0.010	normal development	0.85	12 500 000	14 375 000	
S0	100-year event	100	0.010	debris flow	0.15	25 000 000		
S0	300-year event	300	0.003	normal development	0.70	17 500 000	22 750 000	
S0	300-year event	300	0.003	debris flow	0.30	35 000 000		
S0	500-year event	500	0.002	normal development	0.50	25 000 000	37 500 000	
S0	500-year event	500	0.002	debris flow	0.50	50 000 000		
S1	50-year event	50	0.020			0	0	**156 167**
S1	100-year event	100	0.010			1 500 000	1 500 000	
S1	300-year event	300	0.003	normal development	0.85	15 000 000	17 250 000	
S1	300-year event	300	0.003	debris flow	0.15	30 000 000		
S1	500-year event	500	0.002	normal development	0.60	20 000 000	28 000 000	
S1	500-year event	500	0.002	debris flow	0.40	40 000 000		

Figure 16 shows the Exceedance Probability (EP) curves for the analyzed risk mitigation strategies as generated based on the inputs of Table 18 - they show the mean damage associated with scenarios of different exceedance probabilities. As explained in Sec. 2 of the methodology, the area under each curve corresponds to the residual risk associated with the strategy.

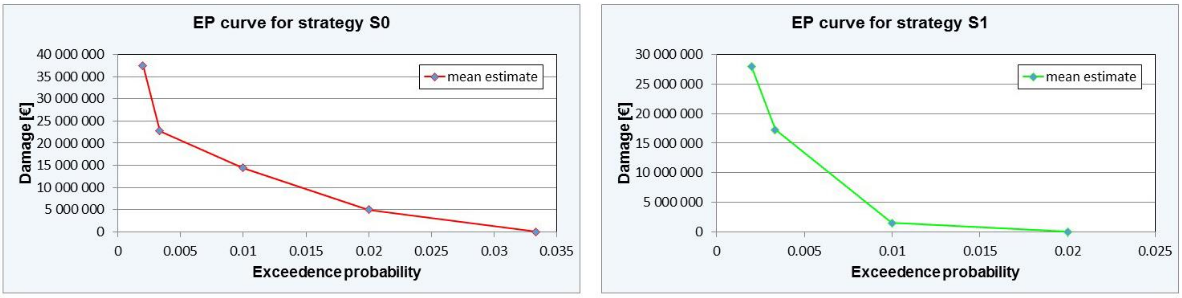


Figure 16. EP curves for the evaluated flood mitigation strategies (generated with RAT).

The risk is assumed to be constant over time. To account for the time value of money, the future risk is discounted. The discounted annual risk is illustrated in Figure 17. Table 19 summarizes the cumulated discounted risk over the whole planning horizon (i.e. the sum of annual discounted risk shown in Table 17) for evaluated flood protection strategies. This serves as the input for the Cost Benefit Analysis described later in Sec. 0.

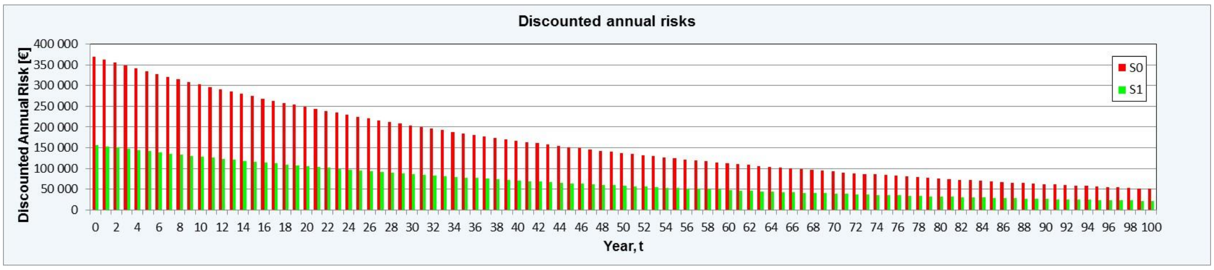


Figure 17. Discounted annual risk distribution over the planning horizon - comparison of strategies (RAT software output).

Table 19. Results of risk estimation using the RAT software –sum of discounted residual risk (expected annual damage) over the planning horizon for evaluated flood protection strategies.

Strategy	**Cumulated discounted risk [€]**
S0	**16 277 804**
S1	**6 886 693**

3.2. Cost estimation

Strategy S0 represents the preservation of the actual protection level. Therefore no investment costs are associated with strategy S0 at the beginning of the planning horizon, only annual maintenance costs of the existing protection measures. In addition it is expected that some of the existing protection measures must be replaced by new ones in approximately 50 years. For strategy S1, both investment costs and annual maintenance costs have to be considered. The detailed assumptions of the considered costs of both strategies are summarized in Table 20.

Table 20: Costs associated with the evaluated flood mitigation strategies

Strategy	**Investment costs [€]**	**Annual maintenance costs [€]**	**Reconstruction costs [€]**
S0	0	60 000	6 000 000 *
S1	9 000 000	90 000	0

* to be invested in year 50

Figure 18 shows a distribution of the undiscounted annual costs for all evaluated strategies in time.

Finally, Table 21 summarizes the results of the cost estimation for evaluated flood protection strategies, i.e. the cumulated discounted cost over the whole planning horizon.

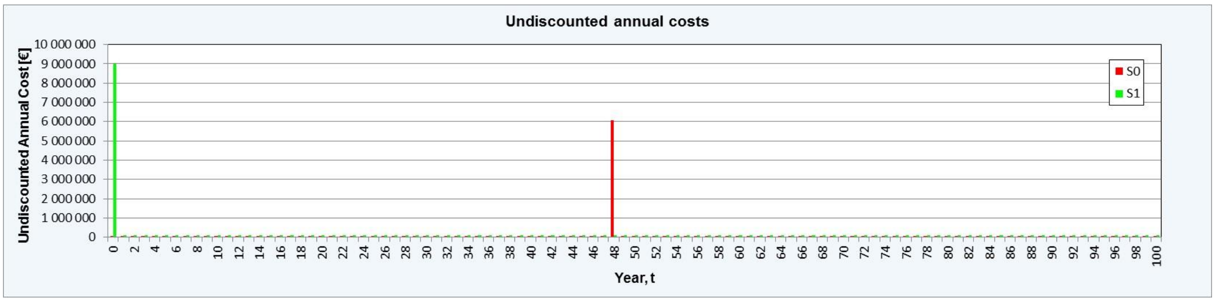


Figure 18. Distribution of undiscounted cost over the planning horizon – comparison of strategies (RAT software output).

Table 21. Results of cost estimation using the RAT software – sum of discounted cost over the planning horizon for all evaluated flood protection strategies.

Strategy	**Cumulated discounted cost [€]**
S0	**4 919 652**
S1	**12 878 852**

3.3. Comparison of the risk mitigation strategies – Cost Benefit Analysis

The results of the Cost Benefit Analysis are summarized in Table 22. Strategy S1 (i.e. extension of the existing protection system) minimizes the sum of cumulated discounted risk and costs. However, the difference to the strategy S0 (maintaining current protection level) is very small and both strategies can thus be considered similarly good in terms of the CBA. Figure 19 shows the results of the CBA in a graphical form as a Risk vs. Cost graph (see section 5 of the Methodology.

Table 22. Cost Benefit Analysis using the RAT software – Comparison of strategies.

Strategy	**Cumulated discounted disk [€]**	**Cumulated discounted cost [€]**	**Sum (Risk + Cost) [€]**
S0	16 277 804	4 919 652	**21 197 456**
S1	6 886 693	12 878 852	**19 765 544**

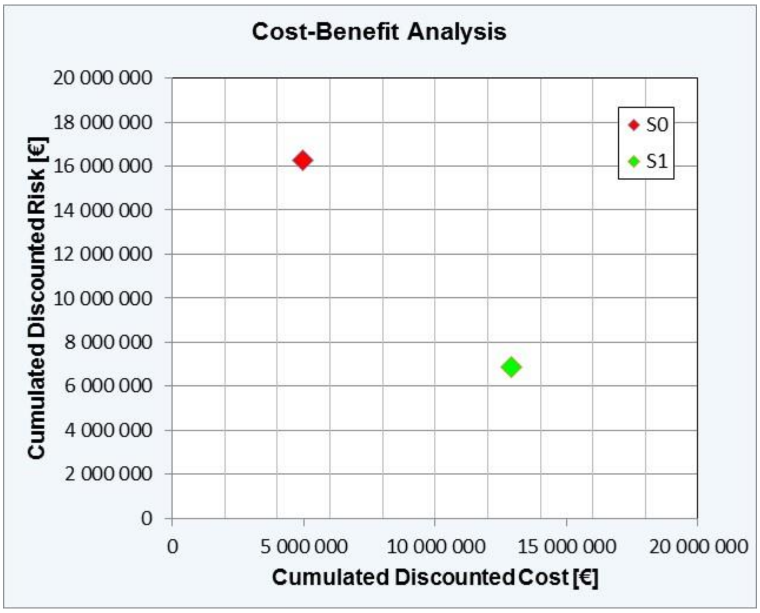


Figure 19. Cost Benefit Analysis using the RAT software – Comparison of strategies in the Risk vs. Cost graph.

3.4. Neglecting Subscenarios

Table 23 shows the results of the risk estimation of the same problem as described above, however neglecting the fact that debris flows can occur during a flood event, i.e. no subscenarios are considered.

Table 23. Risk estimation excluding subscenarios in the RAT software – inputs and estimate of annual risk.

Strategy	Scenarios			Damage per scenario [€]	Annual Risk [€/year]
Name	Description	Return period [years]	Exceedence probability	mean estimate	mean estimate
S0	30-year event	30	0.033	0	**299 167**
S0	50-year event	50	0.020	5 000 000	
S0	100-year event	100	0.010	12 500 000	
S0	300-year event	300	0.003	17 500 000	
S0	500-year event	500	0.002	25 000 000	
S1	50-year event	50	0.020	0	**125 833**
S1	100-year event	100	0.010	1 500 000	
S1	300-year event	300	0.003	15 000 000	
S1	500-year event	500	0.002	20 000 000	

Table 24 compares the results of the CBA for both cases when subscenarios are excluded and included. The residual risks of both strategies tend to be underestimated if the subscenarios are neglected. The residual risk for both strategies is underestimated by almost 20%. As a consequence, strategy S0 turns to be the one that minimizes the lifetime sum of risk and cost and it would thus be recommended, if the effect of subscenarios was not taken into account.

Table 24. Effect of including subscenarios

Strategy	Cumulated Discounted Risk [€]	Cumulated Discounted Cost [€]	Sum (Risk + Cost) [€]
S0 – incl. subscenarios	16 277 804	4 919 652	**21 197 456**
S1 – incl. subscenarios	6 886 693	12 878 852	**19 765 544**
S0 – without subscenarios	13 192 757	4 919 652	**18 112 409**
S1 – without subscenarios	5 549 043	12 878 852	**18 427 894**

It should however be noted, that including subscenarios in the analysis is worth the effort, when these have significant impact on the risk estimate (as discussed in Sec. 2.3 of the Methodology). If the probability of the debris flow in this example was lower or if the consequences were not significantly higher than in case of the “normal” flood event, the subscenarios might simply be neglected.

References

Neumayer, M., 2016. RAT – Risk Analysis Tool (Study project report). TU München, Munich, Germany.

Annex 1 – Input data for Sec. 2.2

Year	Annual max.discharge [m^3/s]
1971	86
1972	180
1973	162
1974	154
1975	135
1976	169
1977	133
1978	139
1979	388
1980	88
1981	303
1982	145
1983	141
1984	73
1985	249
1986	81
1987	150
1988	137
1989	83
1990	204
1991	153
1992	134
1993	126
1994	177
1995	234
1996	119
1997	193
1998	95
1999	383
2000	171
2001	166
2002	247
2003	57
2004	98
2005	343
2006	101
2007	176
2008	125
2009	157
2010	316
2011	169
2012	109
2013	516
2014	151