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Risk Assessment and Cost Benefit Analysis of risk mitigation strategies

METHODOLOGY

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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 defense 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* (see section 0 for definition) 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. A scheme of the process of risk assessment and planning and evaluation of risk mitigation strategies is shown in Figure 1.

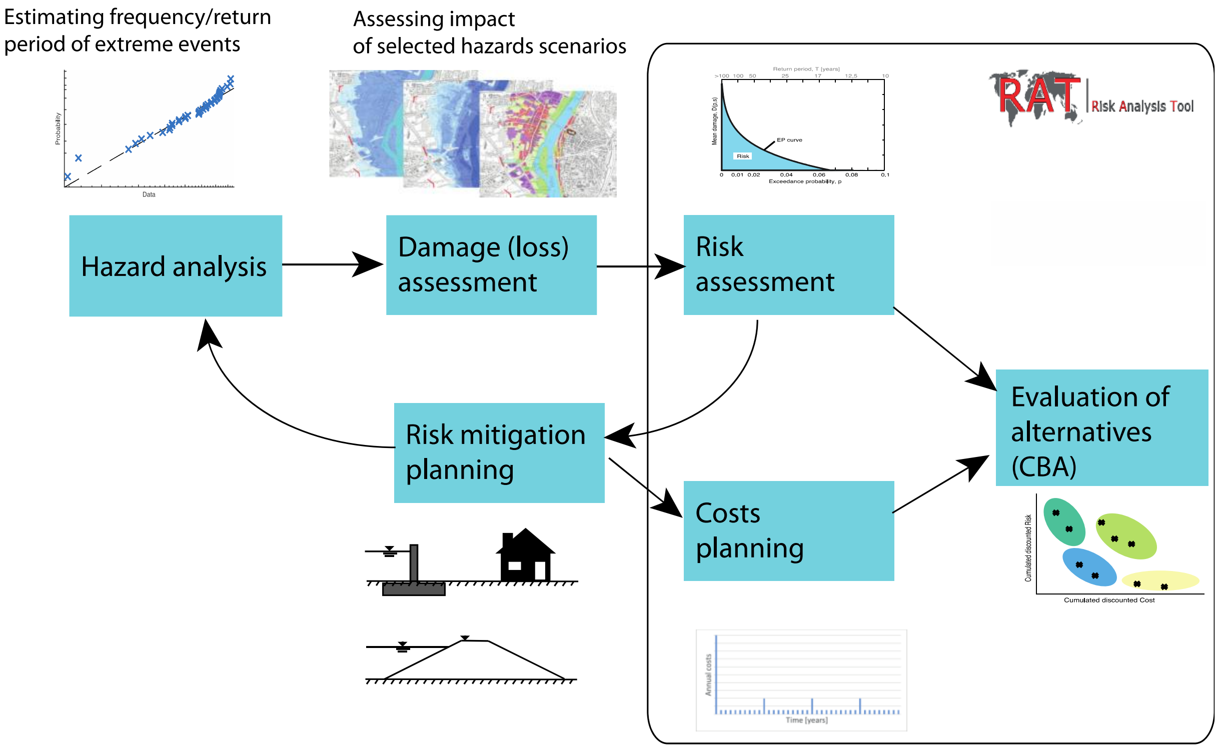

Figure 1. Process of risk analysis and risk mitigation planning.

To facilitate the analysis, the risk assessment and the Cost Benefit Analysis (CBA) were implemented in the RAT software (Excel based) developed in the ERA Group of TU Munich that is freely available.

This document describes the methodology for risk analysis and cost benefit analysis implemented in the RAT that consists of the following steps:

- Estimation of the residual risk for each risk mitigation strategy based on selected scenarios of the hazard event. The scenarios represent different intensities of the hazard event and are characterized by their return period (exceedance probability) – Section 2.1

- Quantifying the uncertainty in the risk estimation - Section 2.2
- Including the possibility of cascading hazards (such as landslides induced by flood/earthquake, failure of flood protection measures) into the risk assessment through modeling of subscenarios - Section 2.3
- Prognosis of investment and maintenance costs of the risk mitigation strategies – Section 3
- Discounting of the risk and costs – Section 4
- Comparison of alternative risk mitigation strategies (CBA): The strategies are compared based on the discounted residual risk and costs. The optimal strategy is identified as the one that minimizes the sum of discounted residual risk and cost over the whole planning horizon, i.e. which provides the optimal balance between the costs for its implementation and the residual risk – Section 5

Contents

1. Definitions, terminology

Hazard is a phenomenon that can potentially lead to damage. The occurrence of the hazard is inherently random, therefore the time of the occurrence and its intensity are considered in probabilistic way.

Risk is the expected damage caused by the analysed hazard in the area of interest over a certain time period. The risk is dependent on the hazard probability and intensity, on the elements at risk and on the preparedness of the society, i.e. on the risk mitigation strategy in place. The annual risk is typically denoted as the **expected annual damage (EAD)**[1] .

Risk mitigation STRATEGIES are here defined as different combinations and/or dimensions of mitigation measures. For example, four alternative flood mitigation strategies can be: (a) a dike system design for a 100-year event, (2) a dike system designed for a 200-year event, (3) a dike system design for a 100-year event combined with measures increasing the resilience of buildings in the flood plain for the case that the dike systems fails/is overtopped. (4) keeping the current flood protection system (providing a protection from a 100-year event for a small part of the town only).

Damage occurs as a consequence of a hazard event. It is for example the costs of repairing the buildings and infrastructure destroyed by the event. It is not known, when the damage occurs and it is thus expressed in the probabilistic way as the expected annual damage (= Risk).

Costs are expenses that are to be spent for implementation, operation and maintenance of a risk mitigation strategy over the planning period, independent whether a hazard event occurs during this time or not. The expenses (i.e. how much and when must be spent) can be planned with relatively high certainty (in contradiction to damage).

A hazard SCENARIO is a possible realization of a hazard. In the risk assessment methodology described in this document it is assumed that the scenarios represent different intensities of the hazard event and are characterized by their return period (exceedance probability). For example, for flood risk assessment, a 50-, 100- and 300- year scenarios can be considered.

SUBSCENARIOs can be used for assessing the mean damage for a given hazard scenario in cases, where the event can have very different impact depending on some secondary hazard (such as collapse of a defence structure, failure of safety system in industrial plant

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[1] alternatively also called “Average Annual Loss”

that would lead to secondary contamination, blockage of a bridge in case of flood etc). Subscenarios can be used for modelling so called cascading hazards.

The return period of a certain scenario/hazard intensity represents the average time interval between two events with such (or greater) intensity. For example, a 100-year event would on average happen 10 times in 1000 years, but it does not mean that it would happen regularly every 100 years, or only once in 100 years. In any given 100-year period, a 100-year event may occur once, twice, more, or not at all. Figure 2 illustrates the probability that 0,1,2,3 or more than 3 events equal or greater than the 100-year event occur in a certain time interval.

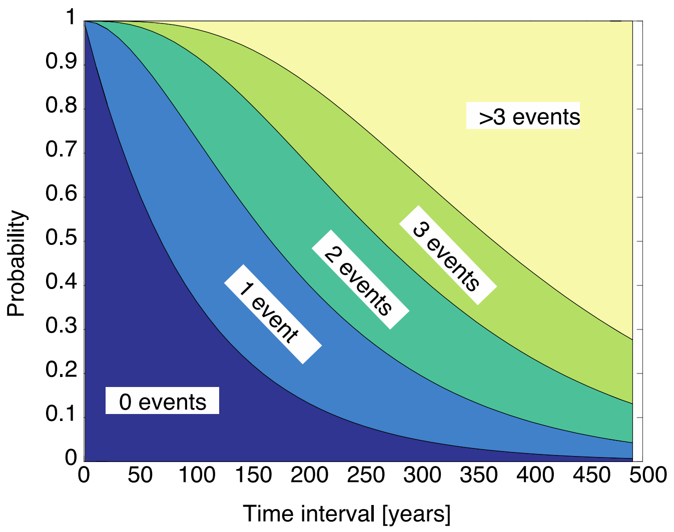


Figure 2. Probability of occurrence of 100-year (or larger) event(s) in a given time interval.

The annual **exceedence probability** of a certain scenario/hazard intensity is the probability, that in a given year, the observed hazard (e.g. flood, earthquake, landslide) will be equal or greater than the scenario/hazard intensity. For example, the exceedance probability of a 100-year flood is 0.01, meaning that there is a probability of 0.01 that in the next year (or any year in the future, assuming their is no change in the frequency of the event) a flood that is equal or larger than the 100-year event occurs.

2. Risk assessment

Risk is defined as the expected (annual) damage caused by certain hazard(s). Since the hazard can materialize in many different forms, it is necessary to take all the possible hazard scenarios into account. The expected damage is then calculated as a damage associated with each scenario multiplied with the probability of each scenario (in the given year), summed over all possible scenarios. The scenarios must be defined as mutually exclusive and exhaustive events. In other words, they must represent all possible realizations of the hazards (be exhaustive) but, at the same time, they cannot overlap in order to avoid double counting of certain realizations.

In the methodology described in this document (as also implemented in the RAT software), the scenarios represent different intensities of the hazard event. This is a common approach used in the field of natural hazard risk assessment, but it can also be applied to other types of problems. In fact, the hazard can occur in an infinite number of scenarios (intensities). The annual risk (EAD) in year t can thus be expressed as:

$$R_t = \int_0^\infty D_t(v,s) f_{V,t}(v,s) dv \qquad (1)$$

where V describes the intensity of the analyzed hazards. V can be a multidimensional vector or parameters; overview of parameters describing the intensity for different types of hazards are summarized in Table 1. $f_{V,t}(v,s)$ is the probability density function (PDF) of the annual maximum intensity of the hazard given that risk mitigation strategy s has been implemented. $D_t(v,s)$ is the damage-intensity curve representing the mean damage caused by the hazard with intensity v in the analysed area given that risk mitigation strategy s has been implemented. An example PDF and damage function is shown in Figure 3. It can be seen that the mean damage increases with the hazard intensity, but the probability of high intensity events is relatively low.

Table 1. Parameters that are typically used for characterizing the intensity of selected hazards

Hazard type	**Descriptive parameters for hazard intensity** V
River flood	Annual maximum peak discharge and/or the volume of flood wave
Coastal flood	Annual maximum water level and/or wave height
Landslide, rockfall	Area affected by the landslide and/or the landslide volume
Earthquake	Peak ground acceleration
Drought	Drought indexes and/or drought duration

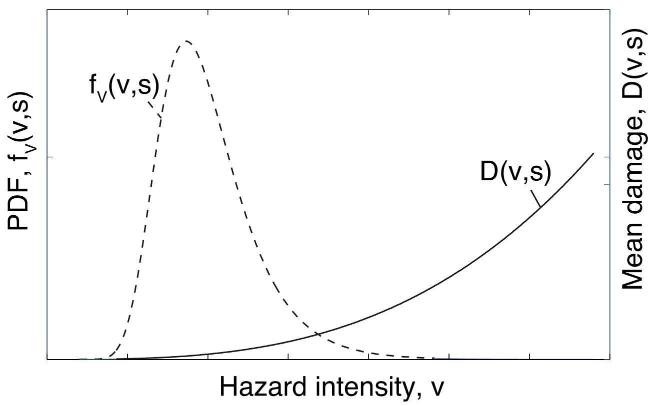


Figure 3 Probability Density Function (PDF) of different hazard intensities and damage function expressing the mean damage for given intensity.

Because the PDF is a derivative of the Cumulative Distribution Function (CDF), $f_{V,t}(v,s) = \frac{dF_{V,t}(v,s)}{dv}$, equation (1) can be rewritten as (Arnell, 1989):

$$R_t = \int_0^1 D_t(v,s)dF_{V,t}(v,s) = \int_0^1 D_t(p,s)dp \qquad (2)$$

where $D_t(p,s)$ is the Exceedance Probability (EP)[2] curve, which expresses the damage as a function of exceedance probability p. $F_{V,t}(v,s)$ is the CDF of the hazard intensity that expressed the "non- exceedance probability of the hazard intensity and it is thus related to p as follows:

$$p = 1 - F_{V,t}(v,s) \qquad (3)$$

An example EP curve, which is a broadly used representation of risk used in engineering, insurance etc., is shown in Figure 4. The annual risk (EAD) equals an integral over this curve.

[2] Alternatively called "Risk Curve", "Damage-Probability Curve" or "Loss Exceedence Curve"

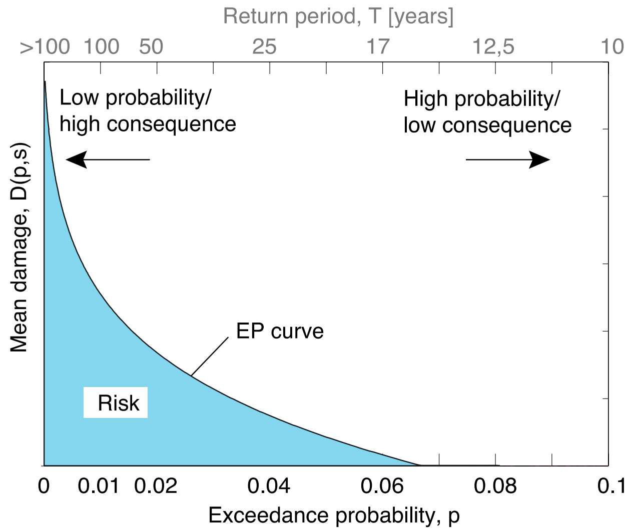


Figure 4. Exceedance Probability (EP) curve for the single analyzed hazard in the area of interest

On the left of the EP curve one can see the low probability / high consequence scenarios, on the right side the high probability / low consequence scenarios. The shape of the EP curve is site specific as it is shown in Figure 5. The relative contribution of low and high probability scenarios can be observed by comparing the areas under the respective EP curves. The two sites shown in Figure 5 have a similar annual risk (EAD), but in one area the risk is mostly associated with small but frequent damages, while the other area is protected from high probability events (with return period smaller than 50 years) and the risk is thus associated with events with lower probabilities but high consequences.

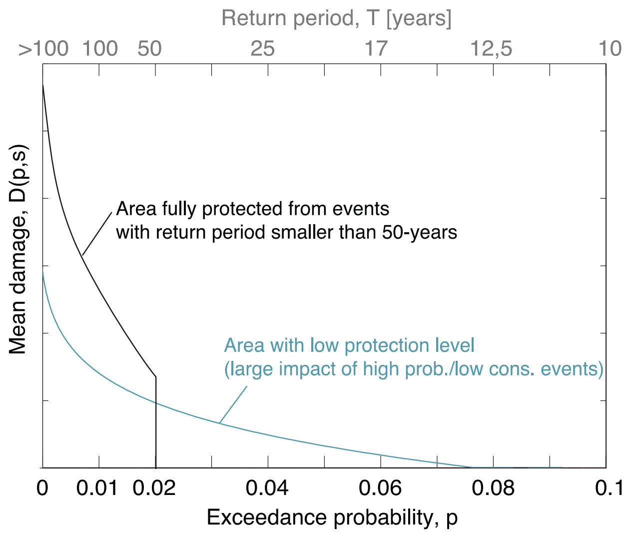


Figure 5. Exceedance Probability (EP) curves for different areas of interests.

The index t in equations (1) and (2) denotes that the frequency of extreme events (described by the PDF) as well as the damage associated with events of different intensity (described by the damage function $D_t(v, s)$ can change in time. The frequency of extreme events can be influenced e.g. by climate change or changes in land use and agricultural production in the catchment that influence the hydrological behaviour of the system. The damage can vary with time e.g. due to development of the urban area that leads to increasing damage potential or due to development of technologies used in construction and equipment of buildings (e.g. the increasing use of materials and equipment vulnerable to flooding). As a result, the risk (EAD) can be changing with time as is illustrated in Figure 6.

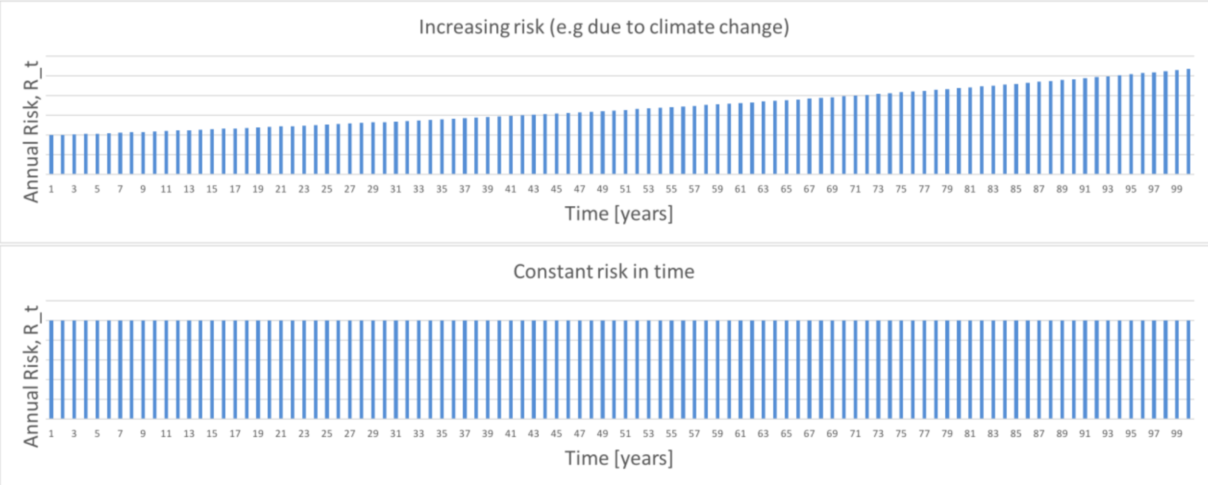


Figure 6. Change of risk (EAD) in time throughout the planning horizon.

2.1. Approximation of the annual risk with scenarios

In most applications, the damage curve in Eq. (1) and (2) cannot be determined within the analysis, because assessing the damage for all possible hazard intensities is associated with too much effort. The procedure of damage estimation is depending on the hazard type but in principle the extent of the event must be determined, the affected assets must be identified and a vulnerability model applied to assess the impact of the event on the assets. For example for the case of flood, a hydrodynamic model is applied to estimate the flooded area and depth, based on that the type and number of flooded assets is determined and afterwards, the vulnerability models are applied to estimate the total mean damage for the analysed hazard scenario. Such analysis is demanding and therefore only a limited number of hazard scenarios can be analysed in practice.

The annual risk (EAD) is thus typically approximated with a few selected scenarios such as a 30-year, a 100-year and a 300-year event. Each of the N analysed scenarios is characterized by its return period T_i, the corresponding exceedance probability $p_{T_i} = \frac{1}{T_i}$, the hazard intensity v_{T_i} and the mean damage associated with the scenario D_{T_i}, as is illustrated in Figure 7.

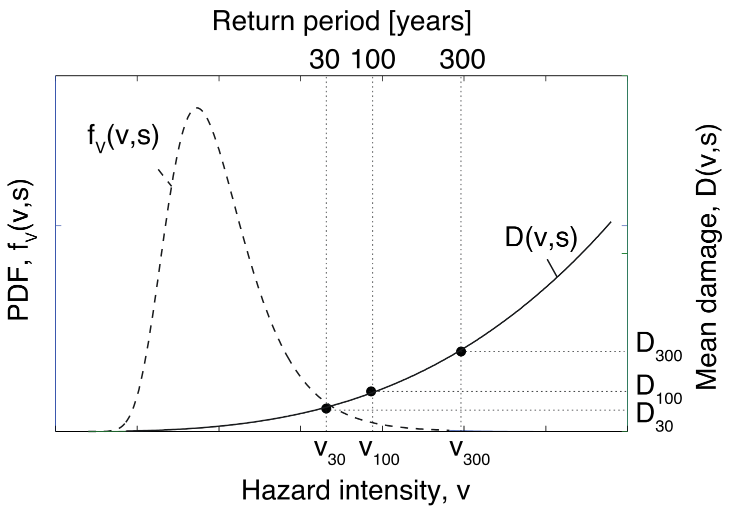


Figure 7. Approximation of annual risk (EAD) using selected scenarios – the selected scenarios are shown with dots.

Using these scenarios, the integral of Eq. (2) is approximated using a trapezoidal rule as

$$R \approx \sum_{i=1}^{i=N-1} \left(p_{T_i} - p_{T_{i+1}}\right) \frac{\left(D_{T_{i+1}} + D_{T_i}\right)}{2} + p_{T_N} D_{T_N} \qquad (3)$$

Note that the scenarios must be ordered from the most frequent to the least frequent one, i.e. for example $T_1 = 30$ years and $T_4 = 1000$ years for $N = 4$ scenarios.

Figure 8 shows the comparison of the true EP curve and approximation following Eq. (3). It can be observed that in the intervals representing the events with return periods smaller than 300 years, the approximated curve slightly overestimates the true risk, while in the interval representing low probability (RP>300 years) / high consequence events, the risk is slightly underestimated because the damage associated with the 300-year event is assumed to be representative for all these events. However, the approximation depicted in Figure 8 can be considered very accurate.

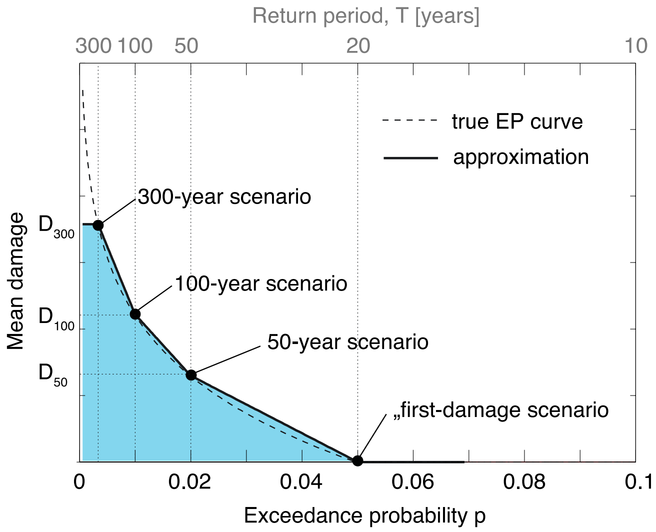
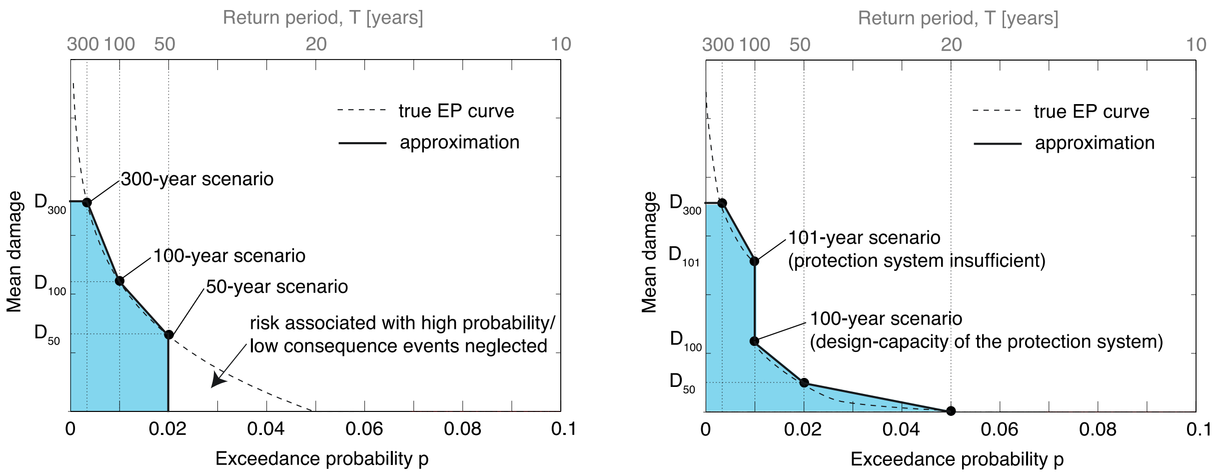


Figure 8. Approximation of annual risk (EAD) using selected scenarios: comparison of true and approximated EP curve.

The quality of the approximation depends on the selection of the scenarios. These must be selected in a way that they accurately represent the whole EP curve. A high number of scenarios does not necessarily mean an accurate approximation, if they are not selected wisely. Additionally, inclusion of high number of scenarios is typically impossible because of the high modeling requirements associated with mean damage estimation for each of the scenario. The annual risk (EAD) can be reasonably approximated with even a small number of scenarios, if the following recommendations are followed:

- Include a "first damage scenario" corresponding to the hazard intensity from which the damages start (see the 20-year scenario in Figure 8). This is very important for covering the high probability low consequence scenarios that can have high contribution to the annual risk (EAD) even if the damage associated with these scenarios is not so high (but their probability is). If "first damage scenario" is not included and the analysis starts with the 50-year scenario, the risk associated with events with return period of 20-50 years is neglected and the annual risk (EAD) is significantly underestimated, as is illustrated in Figure 9(a). The "first damage scenario" often does not require extensive analysis for mean damage estimation as the other scenarios, its return period (exceedance probability of such scenario) can often be determined based on available information and engineering judgement. Its inclusion is therefore "cheap" in terms of effort.
- If high probability/low damage events have significant role in the analysed area (i.e. the protection level in the area is low), consider additional 1-3 such scenarios, since these can have significant impact on the annual risk (EAD).

- Include 100-year scenario, if this is the reference scenario in the analysed type of hazard. This scenario is commonly used in hazard maps and for communication.
- Include (at least) one scenario representing an extreme event (with a return period ≥ 300 years). The contribution of such scenarios to the annual risk (EAD) is again site-specific. In areas with high protection level, the low probability/high consequence scenarios have high impact and more of them should be considered. On the other hand, in areas with low protection, the risk is mostly associated with high probability /low consequence events and considering one extreme event scenario is sufficient.
- Include scenarios that take into account sudden changes (jumps) in the damage function. For example, if a part of the analysed area is protected from a 100-year event, the exceedance of such event will be associated with sudden increase of the damages, as is illustrated in Figure 9(b). To correctly model this fact, a 100-year scenario and a 101-year or 200-year scenario should be included in the analysis.



(a) (b)

Figure 9. Selection of scenarios for annual risk (EAD) approximation: (a) neglecting of "first damage" scenario leads to underestimation of annual risk, (b) approximation of a "jump" in the EP curve with 100-year and "101-year" scenario.

2.2. Uncertainty in the Risk estimation

The risk estimation process is associated with significant uncertainties and errors. The EP curve introduced in previous sections represent the mean damage caused by the hazard scenario of given exceedance probability. Estimation of the mean damage, however, is associated with numerous uncertainties, for example:

- Uncertainty in estimation of the size (intensity) of the N-year event. In other words, uncertainty in determining the return period (and exceedance probability) of an event of given intensity. The frequency of extreme events is typically determined based on historic data or based on simulated events. The length of the historic data and the accuracy of the simulations are, however, limited. The more data are available, the better is the estimate of the intensity of a given event, as is illustrated in Figure 10 (a) for a 100-year event. However, even with 100 years of observations, the uncertainty on assessing the intensity of a 100-year event is significant. The uncertainty increases with the return period of the events: for low probability events, the uncertainty on estimation of their intensity is very high, as is depicted in Figure 10 (b).

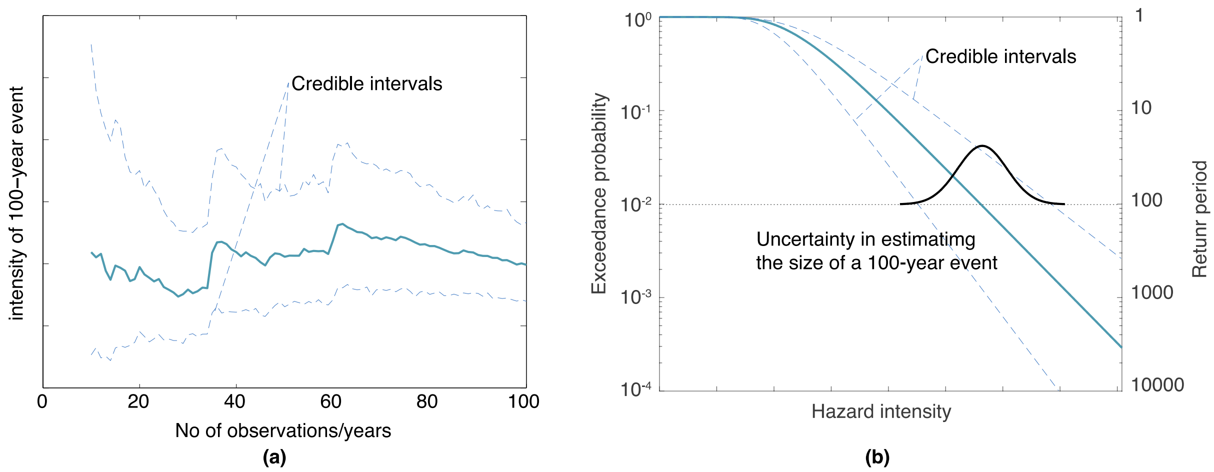


Figure 10. Uncertainty in determining the intensity / frequency of extreme events: (a) Uncertainty in estimation of a 100-year event as a function of the length of historic data. (b) Increase of uncertainty of prediction for low probability events.

- Uncertainty in estimating the effect of the hazard scenario on the society, i.e. determining the extent of the area affected by the events, the location of the exposed assets, the local impact of the event on the assets etc. This uncertainty combines the uncertainty in the physical model of the process (such as of the hydrodynamic model utilized for modelling the extent of a flood event), the uncertainty in parameters of the model as well as the uncertainty in the topographic and geographic data utilized in the model.
- Uncertainty in estimating the vulnerability of the exposed assets, i.e. the damage caused by the event on individual assets. Such analysis requires categorization of the assets based on their construction system or functionality and application of vulnerability curves[3] that determine the mean damage on a given category of asset for given hazard type and local intensity. The uncertainty is associated with the uncertainty in the vulnerability curves themselves, the correlation between the vulnerability of the individual assets as well as with the uncertainty on the characterisation and categorization of the assets based on available data.

[3] alternatively called damage curves or damage models. These curves are typically derived based on historic damage data or using synthetic approaches (modeling the damage extent and estimating the reconstruction costs).

Ideally, all these uncertainties (uncertain errors) should be evaluated and aggregated in order to assess the total uncertainty on estimated annual risk (EAD) as shown in Figure 11(a). Also the correlations between the errors of different scenarios with different magnitudes should be carefully considered. A detailed description of uncertainty analysis that would lead to quantifying the uncertainty, however, exceeds the scope of this document and, in most cases, it is not possible to carry out a detailed uncertainty analysis within the planning of flood mitigation measures. In spite of that, the analyst should be aware of these uncertainties and include them in the analysis e.g. by estimating the upper and lower credible limits on damage associated with the analysed scenarios as depicted in Figure 11(b). The analyst should not only consider the size of the individual uncertainties described above, but also their interaction (correlations). For example, incorrect vulnerability curves that tend to over- or under-estimate the damage for the analysed area lead to correlated error for all analysed scenarios (i.e. they over- or under-estimate the damage for 100-year scenario as well as for 300-year scenario). Similarly, if the probabilistic model used for modelling the hazard intensity (i.e. the PDF shown in Figure 3 and Figure 7) is incorrect, it is likely to under- or over estimate the exceedance probability / intensity for all analysed scenarios.

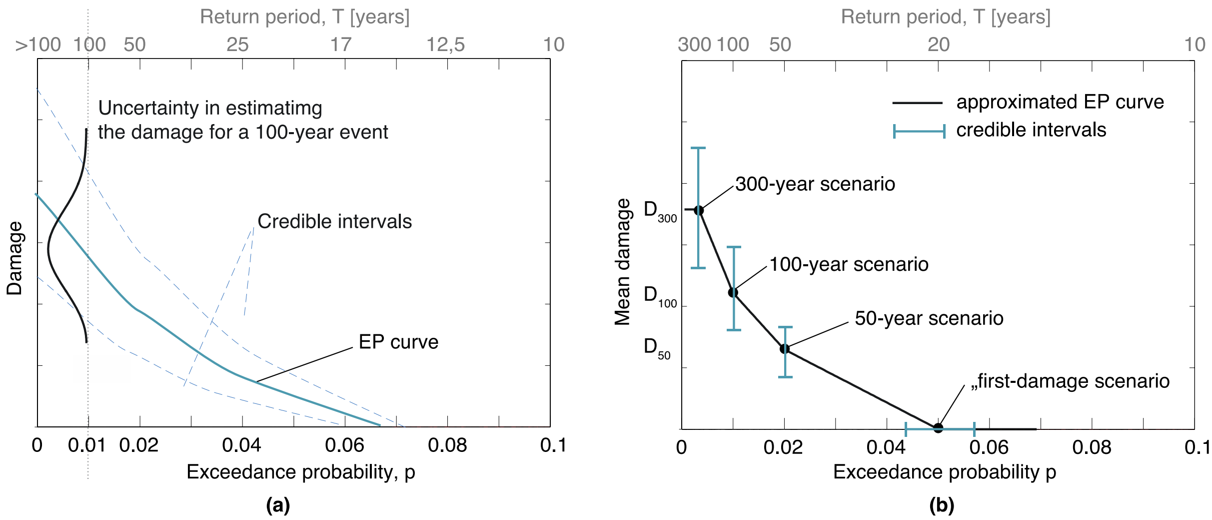


Figure 11. Uncertainty in risk estimation: (a) EP curve with credible intervals (b) Uncertainty in Damage estimation for selected scenarios used in risk approximation.

2.3. Modelling uncertainty in damage estimation using subscenarios

In many cases, the impact of an event can depend on secondary hazards that determine its severity. Examples are a collapse of a defence structure, blockage of a bridge during a flood event or failure of safety system in a flooded industrial plant that would lead to secondary contamination of the flood water. An event with the same intensity can thus have very different consequences depending on whether this secondary hazard is materialized or not.

For example, a 50-year flood event would have minor impact on the analysed area, if the existing dike system stays intact. However, if it fails, the resulting damage can be enormous.

To represent these secondary hazards in the risk estimation, the so called subscenarios should be taken into account. The subscenarios are always considered with respect to a given basic scenario, e.g. the 100-year event. Each subscenario is characterized by its conditional probability of occurrence (for given basic scenario) and by the mean damage that it causes. The damage for a scenario with return period T_i and intensity v_{T_i}, which is then used in the risk approximation following Eq. (3), is calculated by weighting damages associated with each subscenario, as

$$D_{T_i} = \sum_{j=1}^{j=M} \left[p_{S_j}(v_{T_i}) * D_{S_j}(v_{T_i}) \right] + \left(1 - \sum_{j=1}^{j=M} p_{S_j}(v_{T_i}) \right) * D_{S_0}(v_{T_i}) \quad (4)$$

where M is the number of subscenarios considered, $p_{S_j}(v_{T_i})$ is the conditional probability of jth subscenario given the basic scenario with intensity v_{T_i}, $D_{S_j}(v_{T_i})$ is the damage associated with this subscenario and $D_{S_0}(v_{T_i})$ is the damage associated with the basic scenario, i.e. with the case that none of the subscenarios materializes.

The damage associated with each subscenario can be estimated using physical models estimating the extent of the events, similarly to evaluation of damage for basic scenarios. Including subscenarios to the analysis thus requires additional evaluations of the models (e.g. in case of bridge blockage or dike failure during flood event, additional runs of the hydrodynamic model can be required) or even additional models, if cascading hazard of other nature are to be considered (such as flood induced landslides, secondary contamination etc.). Additionally, determining the conditional probabilities of the subscenarios is a complex task. For example, for subscenario representing the dike failure, a reliability analysis of the dike system is needed.

Considering the modelling efforts, it only makes sense to include the subscenarios if they have significant contribution to the mean damage (as a rule of thumb at least 10%), i.e. if they have high conditional probabilities of occurrence and/or high expected damages. For more information on modelling the subscenarios, especially when more phenomena are to be considered, the reader is referred to (Špačková et al., 2014).

3. Cost estimation

Costs are expenses for implementation, operation and maintenance of a risk mitigation strategy over the planning period, independent whether a hazard event occurs during this time or not. It consist of the initial investment costs, maintenance & operation costs and re-investment costs after the end of the lifetime of the measures, if this falls before the end of the planning horizon. The timing of the costs can be planned with relatively high certainty and is not related to occurrence of a hazard event (unlike damage). To give example, expenses for maintenance works on the flood defence system that must be carried out regularly even if no event occurs are considered as costs. On the contrary, cleaning and reconstruction of the defence system after a flood event is classified as damage because the timing of these works is related to the occurrence of flood event that can only be predicted probabilistically.

Examples of costs for different types of risk mitigation strategies are shown in Figure 12. In the upper panel, a large protection system is built at the beginning of the planning horizon. The system has a lifetime of 100 years, only maintenance works are thus required for the rest of the planning horizon. In the middle panel, the same system is built, but later (in year 10) and before this investment, an existing protection system is maintained, which is connected with larger maintenance costs, because of its poor state. The two strategies thus differ only in the timing of the investment. The lower panel represents a strategy where a cheaper protection system is implemented that only has a lifetime of 40 years and must be thus regularly renewed.

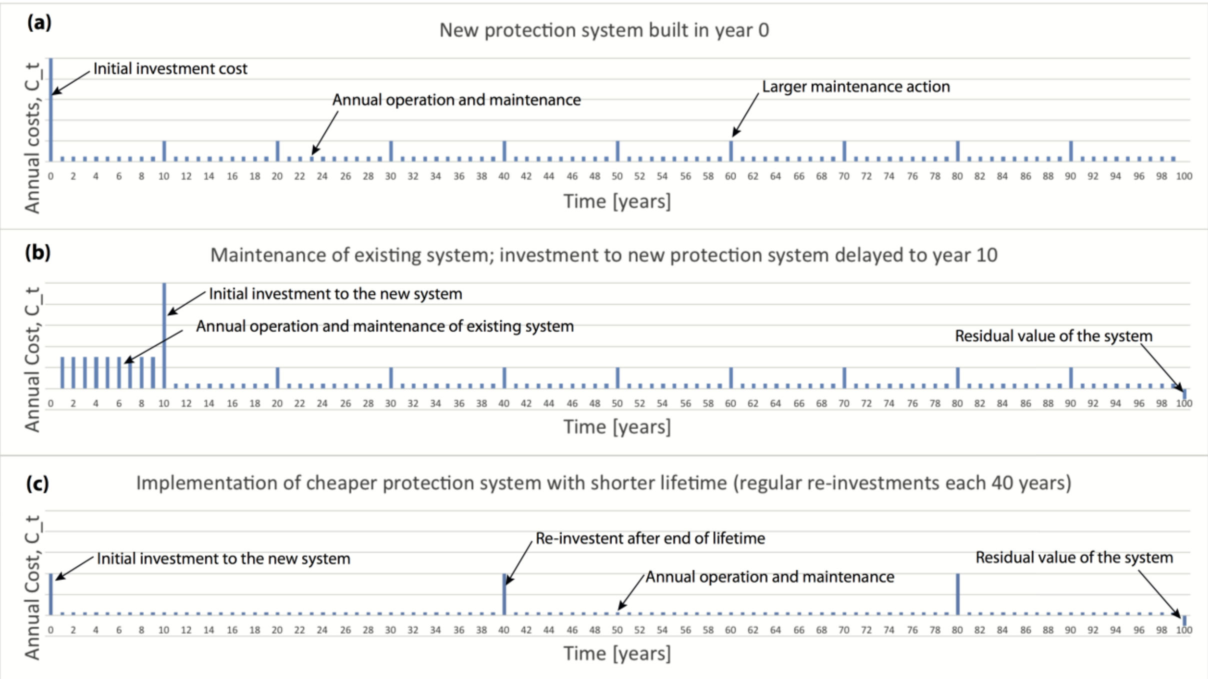


Figure 12. Examples of costs for different types of risk mitigation strategies.

Note that the planning horizon of all strategies that are to be compared must be the same**.** In Figure 12 the planning horizon of 100 years is used. It must be ensured that all the compared systems are in place for the whole planning horizon (therefore the system in panel c must be renewed in yeas 40 and 80). If the state (and remaining lifetime) of the systems at the end of the planning horizon differs, this can be included as the residual value of the system as is shown in Figure 12: The systems in panel b and c have lifetime going behind the planning horizon and a residual value of the system is thus included. It should be however noted, that due to the time value of money considered through discounting, the relevance of the expenses made late in the planning horizon is low.

4. Discounting the future risk and cost

Discounting is a process used for taking into account the time value of money, i.e. the fact that receiving money now rather than later is associated with greater benefit to the beneficiary. Analogously, spending the same amount of money later rather than now is less painful for the payer.

The present value of risk and costs cumulated over the whole planning horizon of T years is calculated as:

$$R = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t} \quad (5)$$

$$C = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (6)$$

where R_t and C_t are the annual risk and costs in year t, respectively, and r is the annual discount rate.

Figure 13 shows the effect of discounting on the costs on the example of risk mitigation strategy from Figure 12b. The upper panel corresponds to the undiscounted costs shown in Figure 12, the lower panel shows the costs after considering their time value. It is obvious that the expenses made later get less important.

Figure 13. Comparison of undiscounted and discounted costs of the strategy shown in Figure 12b.

5. Cost-Benefit Analysis (CBA)

CBA is a method for comparing the alternative strategies based on the cumulated discounted residual risk and costs associated with each of them. The optimal strategy is identified as the one that minimizes the sum of discounted residual risk and cost over the whole planning horizon, as calculated in Eqs. 5 and 6, i.e.

$$\min_{i}[R(S_i) + C(S_i)] \quad (7)$$

where S_i is the ith strategy.

The CBA is typically depicted using a so called risk vs. cost graph which is shown in Figure 14. Each cross represents one alternative risk mitigation strategy and the position of the cross on the graph is determined by the cumulated discounted residual risk and cost over the whole planning horizon, which is associated with the strategy. Figure 14 illustrates, how the risk mitigation strategies can be characterised using the Risk vs. Cost graph. With increasing protection standard, the residual risk decreases and the costs increase. The optimal strategies that minimize the sum of risk and cost following Eq. 7 are the ones in the left lower corner. The "cost-constrained strategies" provide a lower protection standard but are cheaper, so their implementation may be necessitated by a limited budget. "Conservative strategies", on the contrary, do not provide cost-effective risk reduction: increasing the protection standard from the one associated with the optimal strategies to the conservative ones does not pay off (the additional risk reduction is lower than the additionally invested cost). Finally, the "clearly suboptimal strategies" all have a superior alternative that provides both lower risk and lower costs at the same time.

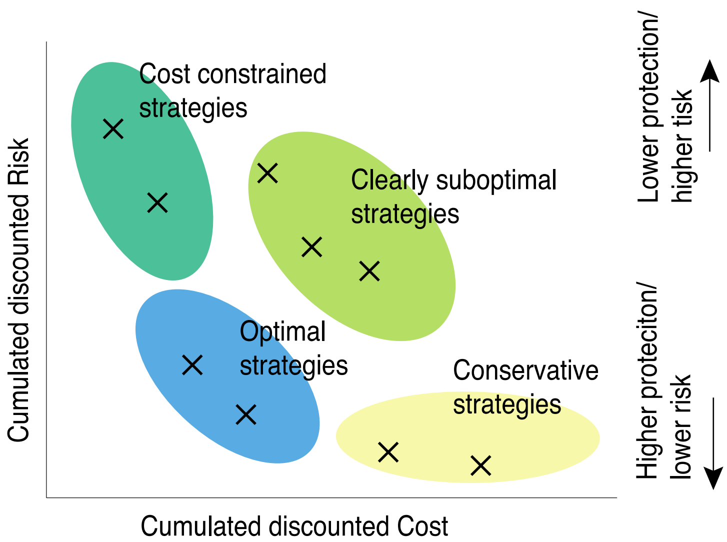


Figure 14. Risk vs. cost graph: characteristics of the strategies

An example of comparison of five different risk mitigation strategies is illustrated in Figure 15: S_1 and S_2 protect the area of interest from a 50-year event, S_3 and S_4 from a 100-year event and S_5 from a 200-year event. The strategies S_1 and S_2 are both designed for the same protection standard but have different cost and also residual risk. The reason for the difference in residual risk can be the difference in probability of failure of the system in events with return period smaller than 50 years and also the difference in consequences in case of event larger than the 50 year event. It can also be seen from the Figure 15 that the strategy S_2 is clearly suboptimal to S_1 since it has both higher risk and cost.

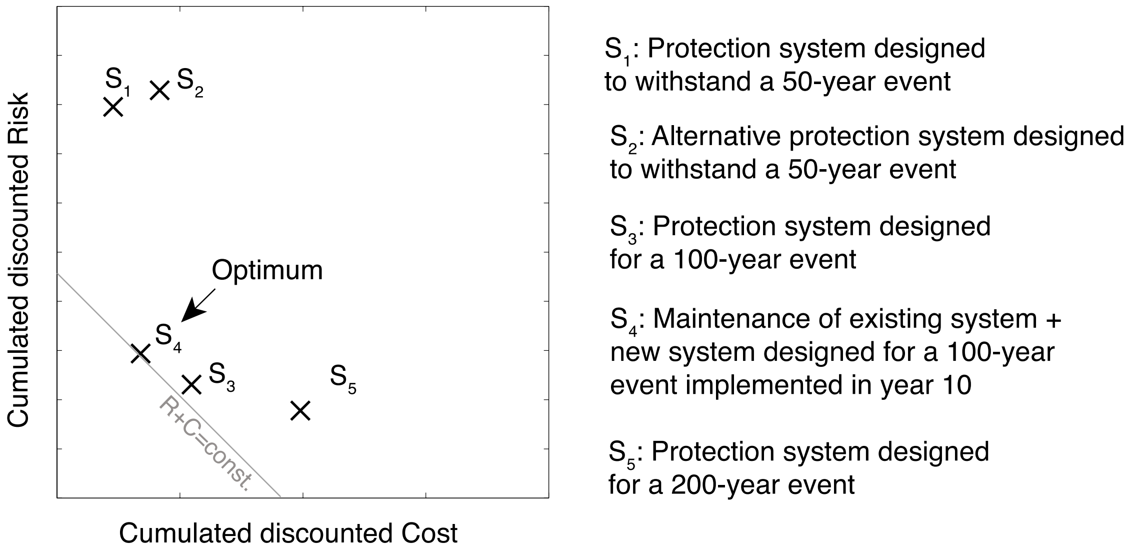


Figure 15. Risk vs. cost graph: Cost Benefit analysis of alternative risk mitigation strategies.

The strategies S_3 and S_4 are both designed for the same protection standard, they differ in the timing of the investment. Due to the discounting, the costs of strategy S_4, where the large investment is delayed, is lower in spite of the possible higher maintenance costs of the existing system (see Figure 13). The risk is however higher than in case of S_3, because the existing protection system is more likely to fail and/or has a lower protection standard.

In Figure 15, the strategy that minimizes the sum of risk and costs following Eq. 7 is strategy S_4. It can be seen from the grey line that represents the subset of the space, where the sum of risk and costs is constant (R+C=const). Since all other strategies lie on the right side from this line, S_4 is strategy that has lowest sum of risk and cost. It can, however, also be seen that strategy S_3 is not significantly worse, both can therefore be considered as good solutions.

5.1. Treating uncertainty in the CBA

The estimation of residual risk (and to smaller extent also of cost) associated with the different risk protection strategies is associated with significant uncertainty, as was discussed in Sec. 2.2. Illustration of this uncertainty in the risk vs. cost graph is shown in Figure 16. The uncertainty in the risk assessment dominates; the uncertainty in estimation of the cost is typically lower.

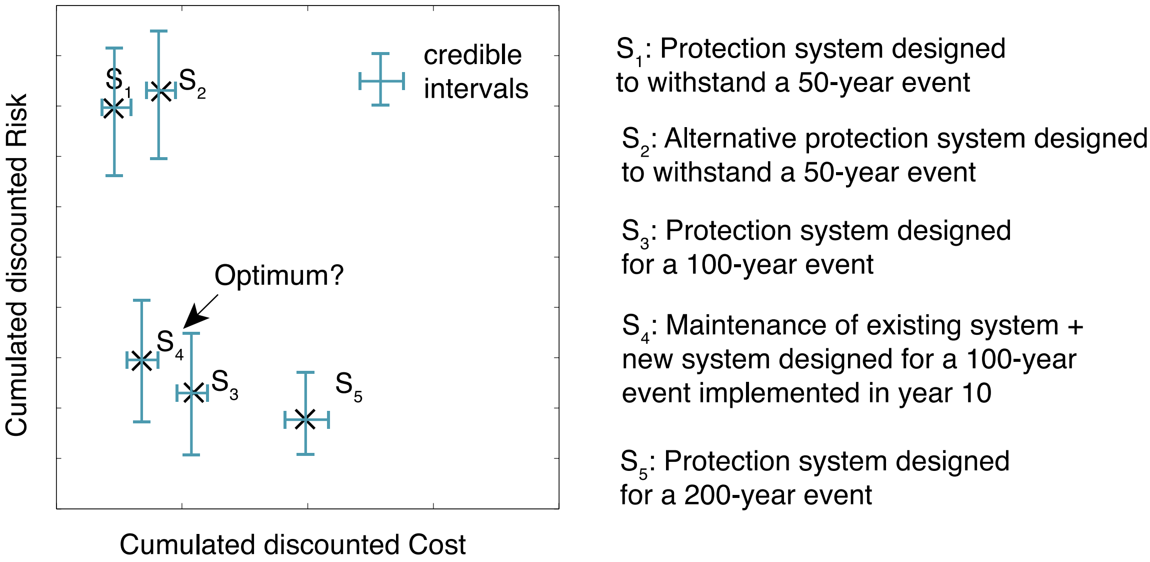
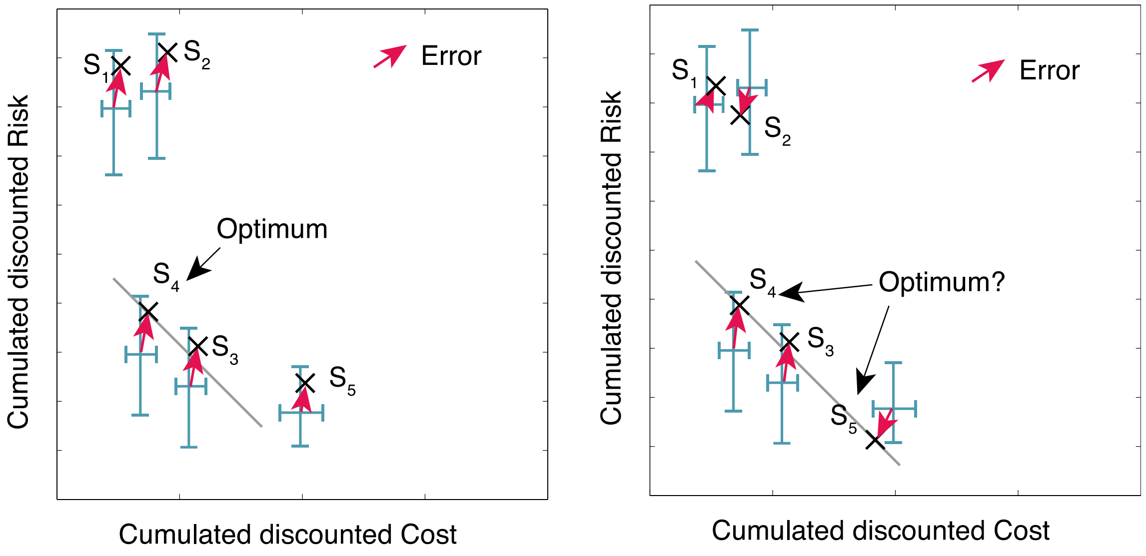


Figure 16. Risk vs. cost graph with credible intervals representing the uncertainty on risk and cost estimates associated with individual strategies.

Due to this uncertainty, the optimality of the strategy S_4 is questionable. The risk and costs associated with each strategy are uncertain and therefore the position of the crosses in the risk vs. cost graph. Figure 17 displays two possible cases of what the "true" risk and costs associated with strategies might be. In Figure 17(a), the error in the estimation of risk and costs for all strategies is assumed to be correlated, which means that the mean estimate in this case systematically underestimates the risk and costs for all strategies (the true values are above the mean estimate). In case of such systematic error, the relative position of the crosses remains (in this example) almost the same and the strategy S_4 is therefore still the optimal one (closely followed by S_3). On the contrary, in Figure 17(b), the error in the estimation of risk and costs for different strategies is uncorrelated. As a result, in some cases the true risk and costs are lower than the mean estimate (strategies S_2 and S_5), while in other cases they are higher. In this case, the optimality of strategy S_4 is no longer clear and strategy S_5 is associated with almost equal sum of discounted residual risk and cost.



(a) **(b)**

Figure 17. Effect of uncertainty in the CBA – two alternatives of what the “true” risk and costs associated with evaluated strategies might be: (a) correlated error in the estimate of risk and costs for all strategies (b) uncorrelated error in the estimate of risk and costs for all strategies.

The correlation of the error in risk and cost estimate for individual strategies thus plays a crucial role in whether the recommended strategy is a robust solution or not and it should be considered by the analyst. Generally, bias/error in the damage model, in the model of the extent of the hazard events or in the estimated frequency of extreme events is likely to lead to correlated errors for all strategies, i.e. to the situation displayed in Figure 17(a). Even in these cases, however, the optimal solution does not have to be robust as will be demonstrated in Sec. ##2 of RAT-Examples. To conclude, each case should be considered individually to ensure that the decision on the risk mitigation strategy is the best that can be made under the current knowledge.

5.2. Optimal distribution of resources in portfolio of projects / measures of efficiency

TBA (Špačková and Straub, 2015)

References

Arnell, N.W., 1989. Expected Annual Damages and Uncertainties in Flood Frequency Estimation. J. Water Resour. Plan. Manag. 115, 94–107. doi:10.1061/(ASCE)0733-9496(1989)115:1(94)

Špačková, O., Rimböck, A., Straub, D., 2014. Risk management in Bavarian Alpine torrents: a framework for flood risk quantification accounting for subscenarios, in: Proc. of the IAEG Congress 2014. Presented at the IAEG XII congress, Torino, Italy.

Špačková, O., Straub, D., 2015. Cost-Benefit Analysis for Optimization of Risk Protection Under Budget Constraints. Risk Anal. 35, 941–959. doi:10.1111/risa.12310