Utilization of Risk Analysis of Hydraulic Structures for Efficient Allocation of Means

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Abstract. Efficient allocation of available means presuppose detailed knowledge about risks, costs and benefits within the area of interest. The societal demand for increased safety of hydraulic structures, as components of the critical infrastructure, requires considerable investment. To evaluate the effectiveness of potential measures in an environment influenced by epistemic and aleatory uncertainties, risk analysis and cost-benefit analysis are used in practice. The above described approach is now fully implemented when considering natural floods and structural flood protection measures, and also presented in the paper. For potential failures of dams and other important hydraulic structures however the procedure becomes rather more complex to comprehend the effect of designed measures on different failure modes. After introducing governing theoretical principles used for the natural flood vs structural measures analysis, the paper presents examples of application of combination of cost-benefit and risk analysis in the framework of the authors' work as Strategic Expert of the Ministry of Agriculture of the Czech Republic for the different stages of the flood prevention program. The last part of the paper focuses on dam safety and the application of risk analysis as a support tool for decision making processes. It describes the practice applied in the Czech Republic and comments on the advantages and disadvantages of the current approach while suggesting further possible improvement.

1. Introduction
Recognition of the potential of natural floods to threaten economic development and disrupt economic activity is part of Directive 2007/60/EC of the European Parliament and of the Council [1] on the assessment and management of flood risks. The Directive was implemented by an amendment to the Water Act into Czech legislation in 2010 [2] and became the basis for the Flood Risk Management Plans for transnational river basins [3], [4], [5]. In the Czech Republic, the fourth stage of the Flood Prevention Programme is currently underway [6], which allows for the continuation of the implementation of effective flood prevention measures in floodplains, including increasing the safety of hydraulic structures where the potential for a flood caused by failure of the structure (dam breach) is part of the course of natural floods.

The paper presents in detail the risk analysis and following cost-benefit analysis of the proposed technical flood control measure, which are applied as part of the process of feasible project selection, i.e. allocation of resources of the program, according to the Methodology for the Assessment of Flood Control Measures [7]. The fundamental principles of risk analysis can also be applied in the evaluation of the deterministic value of the so-called safe water level of the reservoirs, which is the basis for the
evaluation of the safety of hydraulic structures during natural or special floods. Depending on the approach applied, the solution is then more or less stochastic and the paper deals with this part only marginally.

2. Cost-benefit analysis of the flood control measures

Cost-benefit analysis is applied to evaluate the economic efficiency of the proposed flood protection measure in absolute and relative terms. The obvious benefit of the flood protection measure is the difference in flood risk, or its capitalised form, of the flooded area before and after the implementation of the measure under consideration. Flood risk therefore enters the analysis either on both the Costs and the Benefits sides or on only the difference of risk on the Benefits side. It is necessary to include in the Costs side the maintenance costs of the new measure and, where appropriate, penalties for the elimination of a storage volume of the floodplain which was “removed” due to the assessed project. The resulting absolute and relative efficiency, or the payback period of the investment of the proposed flood control project, then serves as a basis for the decision-making process. However, despite the appealing objectivity of the method, it should not be used as a decisive criterion, as it does not include components of the phenomenon in question that cannot be expressed in financial terms for ethical reasons (life loss, environmental amenity loss, etc.). The absolute and relative effectiveness of the measure are defined by the following equations:

$$AE = \frac{R(\text{before}) - R(\text{after}) - OC(\text{inc. penalties})}{FDR} - I \quad (1)$$

$$RE = \frac{R(\text{before}) - R(\text{after}) - OC(\text{inc. penalties})}{I + FDR} \quad (2)$$

where: \( R(\text{before}) \) denotes average annual risk before implementation of the proposed project ($/year); \( R(\text{after}) \) denotes average annual risk after implementation of the proposed project ($/year); \( I \) is the investment costs ($); \( OC \) represents operating costs ($/year) and \( FDR \) is the financial discount rate (for first three stages of the Flood Prevention Programme in Czech Republic the value 0.03, i.e 3% was used).

3. Risk and capitalised risk

Flood risk as integrate of a product of flood damage and the probability of flood damage is usually defined by the following relationship:

$$R = \int_{Q_a}^{Q_b} D(Q) f(Q) dQ \approx \int_{Q_a}^{Q_b} D(Q) f(Q) dQ \quad (3)$$

where: \( R \) represents average annual risk, i.e. the potential flood damage over a year averaged over a very long period; \( D(Q) \) represents flood damage caused by the discharge of a certain value \( Q \); \( f(Q) \) is probability density function of the discharge \( Q \); \( Q_a \) minimum value of the discharge when the flood damages is no longer a zero; \( Q_b \) discharge value with probability of occurrence close to zero.

Capitalization of the risk, i.e. quantification of its total value in $, can be done, for example, by using the perpetual annuity method, which is also accepted by the European Investment Bank. While the probability of occurrence of a given flow can be determined by the hydrological situation at the hydraulic structure or in the area of interest, the extent of damage must be determined for individual discharges by numerical modelling of the passage of a natural or special flood.

4. Flood hazard and loss functions

The characteristics of a natural or special flood in the area of interest are usually determined in relation to the value of the peak discharge for which the probability of exceedance is known. With few exceptions, the problem is solved as a steady state problem and in rural areas a solution using ID
numerical models with a 3D terrain model is sufficient. In urbanized areas, 2D models with vertically integrated Reynolds equations are used. The use of a complete 3D numerical model, regardless of the type of solution (turbulence, DNS or other models), is quite exceptional due to the extreme computational complexity for determining the extent of the flood and its characteristics.

The solution is usually implemented for natural floods for flows with a probability of exceedance of 0.2; 0.05; 0.01 and 0.002. For special floods, the extent of flooding is calculated based on the characteristics of the breach wave from the dam or other hydraulic structure depending on the selected failure mode. This results in maps of depths and flow velocities in the area in question, which can then be used to quantify the damage corresponding to a given flow or probability of occurrence, depending on the land use. The following figures are examples of flood extent assessments for natural and special floods respectively.

Figure 1. Flood extent for discharges $Q_5$, $Q_{20}$, $Q_{100}$ and $Q_{500}$ in the Veseli nad Luznici Town [8]
The probability of a special flood is the probability of a natural flood causing a rise above the safe water level in the profile of the dam (hydraulic structure). If the dam is assessed using a fully probabilistic approach, this can be used and the probability of failure or accident can be considered as the probability of a special flood.

Based on the calculated flood characteristics, flood hazard maps are produced for a given location, which consider the appropriate combination of depths and velocities for a given potential exposure. Thus, the hazard curves vary depending on the entities under consideration. An example of a hazard curve for buildings and its application to the area of interest is presented in the following figures.

Figure 2. Flood extent of the special dam breach flood of the Boskovice Dam [9]

Figure 3. Flood hazard curve for building according to DHCZ USBuRe [10]
Damage quantification is carried out using loss functions of individual entities, where the respective loss is related to the unit area, and the flood characteristics are averaged for the whole objects. An example of a loss function for buildings is presented in the following figure.

**Figure 4.** Map of flood hazard for buildings according to DHCZ USBuRe prior to the flood control project [12]

**Figure 5.** Loss functions for different categories of buildings based on the inundation depth [11]
Depending on the nature of the proposed measure on the hydraulic structure or in the area of interest, the difference in potential damage before and after the implementation of the measure can be quantified. The following figures represent the resulting potential damages for the project of securing the spillway capacity of a dam to the $Q_{10000}$ level, and the implementation of a complex of measures on one side of the stream with a design level of protection at $Q_{20}$.

![Figure 6](image)

**Figure 6.** Potential flood damage before and after implementation of the dam safety enhancement project reducing the probability of special flood from 0.01 to 0.0001 [9]

![Figure 7](image)

**Figure 7.** Potential flood damage in the urbanized area before and after flood control project with the designed level of protection equal $Q_{20}$ (20 years return period) [9]

5. Conclusions
The paper summarizes the issue of using risk analysis of natural and special floods as a basis for cost-benefit analyses of possible flood control measures. The specific data requirements and procedures needed to obtain the difference in the value of flood risk before and after the implementation of a proposed project, which represents the economic benefit of the proposed project, are presented. The results of the cost-benefit analysis allow for an economically efficient allocation of available resources, although it does not cover all aspects of the phenomenon under study. Although the system currently used can be considered as heavily generalised, it should be stressed out that the costs of the analysis increases significantly with the level of detail and therefore reduces the usability of the analysis.
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