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Abstract:

The adoption of Directive 2007/60/EC of the European Parliament and of the Council on the assessment and management of flood risks on 23 October 2007 certifies the importance of flood risk analysis methods and the recency of flood protection problems. The Directive signifies that flood risk analysis methods are gaining ground in EC Member States and thus also in the Czech Republic (CR). It can be stated that procedures of flood risk analysis in the Czech Republic have been developed since the catastrophic floods of 1997. The applications involved are in line with European and worldwide trends.

For the coming period the Czech Republic has prepared flood risk analysis tools which have been verified in hundreds of case studies. Currently, the Directive 2007/60/EC guideline based on past experience with flood risk analysis applications is being processed.

The paper presents flood risk analysis steps and procedures for the development of flood danger and flood risk maps. Methods related to flood risk management plans and for flood protection measure assessment are briefly mentioned as well. The above-mentioned techniques are documented via practical applications at pilot localities in the Czech Republic.

Keywords: flood, risk analysis, danger, hazard, vulnerability

1. Introduction

Experience from extreme flood events in the Czech Republic during recent years has shown the necessity for a systematic approach to flood protection. Procedures based on the theory of risk management appear to be very effective. These methods enable identification of endangered areas and the consecutive effective design of flood protection measures (FPM). FPM conception should be based on land use in threatened areas and assessed by cost benefit analysis or with respect to other aspects (e.g. environmental, social, etc.). The aim of such multicriterial assessment is the assignment of priorities for the allocation of funding for flood protection arrangements.

The principles included in the Directive [ES, 2007], which is calling for the development of effective tools for appointing priorities for the taking of technical, financial and political decisions in flood risk management, are already in use in the Czech Republic. The Directive [ES, 2007] calls for three stages of flood risk management (see also chapter 3):

1. Preliminary risk assessment.
2. Creation of flood hazard, flood danger and risk maps for various scenarios.
3. Development of flood management plans.
2. Current methods for flood protection measure design in the Czech Republic

The basis for the floodplain protection issues in the Czech Republic are so-called flood extent maps developed and maintained according to legislative instructions [TNV 752932], [Decree No. 236/2002] and [Act No. 254/2001]. Floodplains are administratively determined areas which could be inundated during a flood event. Floodplain boundaries are delimited for maximum water levels on the basis of hydraulic calculations, documentation from maximum past flood events or on alluvial soil areas. The selected flood scenarios correspond with appropriate return periods, which in the CR are minimally prescribed as being 5, 20 and 100 years ($Q_5$, $Q_{20}$, $Q_{100}$). In some cases the floodplain documentation contains so called “active zones” represented as sub-areas with restricted activities inducing unfavourable flood conditions or extensive flood damage. At present, the philosophy of active zones is being superseded by the current view on flood risk analysis methods. Consequently, the trend is tending towards the replacement of active zones by risk analysis methods in terms of Directive [ES, 2007] (see chapter 3.2). Nowadays, floodplain boundaries are available as a part of thematic maps (Flood extent maps 1:10 000) [T.G.M. WRI, 2009]. Floodplain documentation serves as fundamental information:

- as a decision making tool for governmental institutions,
- for urban planning,
- in the design of flood protection measures (structures),
- for flood emergency plans [TNV 752931].

More detailed data in comparison with floodplain documentation are represented by “runoff studies”. Their aim is the comprehensive assessment of flood protection of a given area and the indication of the course design floods could take. Runoff studies usually contain recommendations on variants of possible flood protection measures and assessments of their efficiency. A further level is a feasibility study which, in comparison with runoff studies, focuses on more detailed technical solutions and on cost estimates for flood protection arrangements. The feasibility study is often used as part of an application for financial allocations and is based on the elaboration of more detailed designs. Flood protection measures are involved to the same extent in general water management audits and plans for urban areas. Recently, the studies involve the following risk based methods:

- The risk matrix procedure serves for the assessment of floodplains from the viewpoint of flood hazard, vulnerability, danger and risk. The method enables the identification of areas and structures where the acceptable risk has been exceeded and following on from this, the design of flood protection measures.
- The method based on flood loss estimates serves for an assessment of the economic effectiveness of the flood protection measures proposed.

A more detailed description of the methods mentioned is shown in chapter 3 in relation to the implementation of the Directive [ES, 2007].

During the implementation of the Directive [ES, 2007], contemporarily used flood risk assessment methods will be used. At present it is planned that the detailed description of these methods will be part of the Guidelines [Drbal et al., 2008] which have recently been elaborated (see the following chapters).

3.1 Preliminary risk assessment

The aim of preliminary assessment of flood risk is the definition of localities where more detailed risk based methods should be applied. The initial basis for preliminary flood risk assessment will in particular be the existing documentation for flooded areas for selected floods with return periods of $N = 5, 20, 100$. This documentation gives a first idea for preliminary research in the area of interest and for the delimitation of potentially dangerous water courses in the Czech Republic. When combined with other sources, such as the Register of census districts and structures [CSO, 2009] and ZABAGED [COSMC, 2009], it will be possible to preliminarily estimate the endangered property and number of affected inhabitants in existing areas with the potential for flooding. Based on the preliminary assessment a list of the most endangered localities will be created and subsequently the selection will take place of a final set of areas where more detailed risk analysis is needed.

3.2 Maps of flood hazard, danger and risk

For the construction of flood hazard, danger and risk maps a semi-quantitative method based on a so-called “risk matrix” which serves for the spatial evaluation of corresponding quantities has been chosen. The procedure originates from the original Swiss method [FOWM, 1997] adapted and tested for the conditions in the Czech Republic. The method follows these steps (see Fig. 2):

1. Quantification of flood hazard and evaluation of flood intensity based on the water depth and velocity in flooded areas.
2. Determination of flood danger using the risk matrix.
3. Definition of areas with unacceptable risk using data about the vulnerability of objects within the studied locality.

Tab. 1 – An example of selected land use zones [Drbal et al., 2008]

<table>
<thead>
<tr>
<th>Land use</th>
<th>Acceptable risk (see Tab. 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>(2) Low</td>
</tr>
<tr>
<td>Public services</td>
<td></td>
</tr>
<tr>
<td>Transportation and utility</td>
<td></td>
</tr>
<tr>
<td>Industrial and manufacturing</td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td></td>
</tr>
<tr>
<td>Sport and recreation</td>
<td>(3) Medium</td>
</tr>
<tr>
<td>Water area</td>
<td></td>
</tr>
<tr>
<td>Parks and open space, gardens, woods</td>
<td>(4) High</td>
</tr>
<tr>
<td>Arable land, meadow, pasture land</td>
<td></td>
</tr>
</tbody>
</table>
With this method the flood hazard is expressed via so called flood intensity $IP$ [m$^2$/s]. This is understood to be a measure of the destructive ability of the flood and is defined as a function of water depth $h$ [m] and velocity $v$ [m/s]. Using previously carried out experiments and expert assessment [FOWM, 1997] the flood intensity is expressed as follows:

$$IP(h, v) = \begin{cases} 
0, & h = 0 \\
h, & h > 0 \text{m}, \quad v < 1 \text{m/s} \\
h \cdot v, & v \geq 1 \text{m/s}
\end{cases}.$$  \hspace{1cm} (1)

It is possible to classify the obtained $IP$ values according to the extent of damaged property, humans and animals in the flooded area (Fig. 1 and Tab. 2). The values of the flood intensity $IP$ in combination with appropriate base maps can be presented in the form of flood hazard maps.

![Fig. 1 – Categories of flood intensity by [FOWM, 1997] and Tab. 2](image)

### Tab. 2 – Possible damage for categories of flood intensity by [FOWM, 1997] and Fig. 1

<table>
<thead>
<tr>
<th>Hazard</th>
<th>$IP$ Categories</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$h &lt; 0.5$ m or $v \cdot h &lt; 0.5$ m$^2$/s</td>
<td>Humans and animals outside buildings are slightly endangered. Minor damage is possible.</td>
</tr>
<tr>
<td>Medium</td>
<td>$0.5 &lt; h &lt; 2$ m or $0.5$ m$^2$/s &lt; $v \cdot h &lt; 0.5$ m$^2$/s</td>
<td>Humans and animals outside buildings are endangered; those indoors are only slightly endangered. More extensive damage to buildings possible (total destruction is not expected).</td>
</tr>
<tr>
<td>High</td>
<td>$h &gt; 2$ m or $v \cdot h &gt; 2$ m$^2$/s</td>
<td>Humans and animals endangered both indoors and outdoors. Threat of total collapse of buildings.</td>
</tr>
</tbody>
</table>

Based on the calculated flood intensity $IP$ the flood danger can be evaluated using the so-called risk matrix (see Fig. 2). The lines in the matrix correspond to $IP$ categories; the
columns to the return period of flood scenarios. For such derived hazard values appropriate recommendations according to Tab. 3 are taken into account. In the Czech Republic the method described is applied for the minimum number of relevant flood scenarios: \( Q_5, Q_{20}, Q_{100} \). The resulting danger is assumed to be the maximum danger obtained in individual flood scenarios according to formula (4).

The last step in the method is the overlaying of data (digital maps) concerning danger with those depicting the vulnerability of the flooded area. The vulnerability is expressed by the classes of land use in the area of interest (Tab. 1) and is derived from urban planning documentation. This indicates the application of the described method in the process of proposing flood protection measures in the context of urban planning and in the elaboration of general water management solutions in urbanised regions. The final result – a comparison of danger and vulnerability - is the identification of areas, respectively facilities in the locality, which do not fit the requirements of acceptable risk (Fig. 4).

<table>
<thead>
<tr>
<th>Danger category ( R ) by [Beffa, 2000] determined from equation (3)</th>
<th>Danger category *) determined from the risk matrix (see Fig. 2)</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R &gt; 0.1 ) or ( IP^* &gt; 3 )</td>
<td>(4) High (red)</td>
<td>Do not permit new or extend existing built up areas intended for people or animals. It is necessary to put forward designs for flood protection measures for existing buildings in order to attain an acceptable risk level.</td>
</tr>
<tr>
<td>( 0.01 &lt; R &lt; 0.1 )</td>
<td>(3) Medium (blue)</td>
<td>Building is possible with restrictions based on detailed assessment of potential flood hazards for buildings. The building of sensitive structures such as hospitals, fire departments, etc. is unsuitable. The expansion of current built-up areas is not recommended.</td>
</tr>
<tr>
<td>( R &lt; 0.01 )</td>
<td>(2) Low (orange)</td>
<td>Building is possible but land parcel owners must be warned of the potential flood hazard. It is necessary to employ special flood measures for sensitive buildings.</td>
</tr>
<tr>
<td>( p &gt; 0.0033 ) (i.e. return period ( N ) - years &gt; 300)</td>
<td>(1) Residual (yellow)</td>
<td>It is recommended to solve questions associated with flooding by means of urban planning taking into account sensitive buildings (health care institutions, fire departments, historical landmarks, etc.) and other structures with a large potential for suffering flood damage.</td>
</tr>
</tbody>
</table>

*) The danger category in conjunction with land use information and accepted recommendations represents an acceptable measure of flood risk (Tab. 1).

The method consisting in the reading of danger zones from the risk matrix (Fig. 2) is complicated to apply in computerised procedures employing GIS tools. For this reason the alternative quantity \( IP^* \) leading to the same result was introduced [Beffa, 2000]:

\[
IP^*(h,v) = \begin{cases} 
0 & h = 0 \\
0.3 + 1.35h & h > 0, \, v < 1 \, m/s \\
0.3 + 1.35h \cdot v & v \geq 1 \, m/s
\end{cases} \tag{2}
\]

Practical calculation of \( IP^* \) is carried out using GIS based on the results of hydraulic calculations - water depths and velocities for given \( N \)-year floods. The procedure for the
calculation of \( IP^* \) is necessary to repeat for all assessed flood scenarios, at least for \( Q_5, Q_{20} \) and \( Q_{100} \). The danger \( R_i \) for a given flood scenario \( i \) with a return period of \( N_i \) years is calculated using the following formula:

\[
R_i = IP^* \cdot p_i \approx IP^* \cdot \frac{1}{N_i}.
\]  

The resulting local danger \( R \) is expressed as the maximum value of the individual dangers \( R_i \) corresponding to flood scenarios represented by the return period \( N_i \):

\[
R = \max_{i=1}^{n} R_i,
\]

where \( n \) denotes the number of assessed flood scenarios.

Obtained values of flood danger \( R \) are classified according Tab. 3. The sub-regions with so-called “residual danger” (Tab. 3) can be delimited using data about real past extreme floods with high return periods (\( N > 300 \)) or by a professional estimate based on the alluvial floodplain morphology taking into account the extent of alluvial loams in the area. The preliminary estimate of the residual danger areas should be verified by hydraulic calculations and by site investigations and comparison with a digital terrain model.
The results of the described risk analysis method in the area of interest are maps of flood danger (Fig. 3) and risk maps (Fig. 4). The maps of flood danger express individual categories of flood danger and endangered areas using a colour spectrum supplemented by explanations according to Tab. 3. The categorisation of danger enables the assessment of the suitability of existing or planned land use and to recommend restrictions on activities or on the development of corresponding areas with higher danger rates. From this point of view the danger maps completed by recommendations according to Tab. 3 can be assumed to be maps of acceptable risk. The method described can be used in the process of urban planning, during the preliminary proposals for flood protection measures, etc.

Fig. 3 - Example of a flood danger map for the river Svratka in Brno [BCM, 2008]
Risk maps (Fig. 4) combine data about the danger and vulnerability in the exposed area. The vulnerability data can be derived from urban plans and maps, and should be verified by site investigation. Based on the available urban plans, it is possible to define classes of land use (Tab. 1 – column “Land use”). The value of maximum acceptable risk is assigned to each class according to Tab. 1 column “Acceptable risk”). The maps of the areas thus classified according to land use (vulnerability maps) are “overlaid” by danger maps and are processed by GIS analytical tools into risk maps (Fig. 4) in which existing or anticipated areas with exceeded acceptable risk are highlighted using the spectrum corresponding to Tab. 3. The following logical step is a more detailed analysis of “risky areas” from the point of view of risk management and risk attenuation at an acceptable level.

The risk matrix method was first used in the CR in the locality of Hodonín in South Moravia in the year 2001 [Konvicka et al., 2002]. A more extensive analysis was carried out within the framework of the project [Dřbal et al., 2005] in the period from 2002 to 2005 along a 100 km long reach of the river Elbe (Děčín - Mělník, Nymburk, Dvůr Králové). In the year 2006 the method was verified in the Svitava, Svratka, Jihlava and Dyje river floodplains in the project [Dřbal et al., 2006]. The last extensive applications concern the general water management solutions of cities and towns like Brno, Šlapanice, Kuřim and Moravské Budějovice. In particular, the general water management solution of Brno [BCM, 2008] comprises an assessment of 13 water courses with a total length of about 87 km.
3.3 Plans for flood risk mitigation

During the development of flood risk mitigation plans, existing flood protection and feasibility studies will be used as basic documents. The first phase of the solution stems from the results from area analysis using the risk matrix method (chapter 3.2) in which recommendations for further analysis and flood protection at localities with exceeded acceptable risk are introduced. For the assessment of variants of flood protection measures according to [ES, 2007], economic, environmental and social viewpoints are taken into account. In the case of the evaluation of economic effectiveness, the following steps are used:

1. estimation of the extent of endangered and protected property in the floodplain,
2. estimation of flood losses,
3. quantification of flood risk using potential losses,
4. determination of quantitative economic criteria using cost benefit analysis.

The extent of endangered property in the floodplain is determined for the existing state and for the state after the implementation of flood protection measures. Firstly, the processing of flood hazards is carried out using maps of water depth in the floodplain for flood scenarios corresponding with at least $Q_{5}$, $Q_{20}$ and $Q_{100}$ discharges. The estimation of flood damage to properties in the floodplain is performed using so-called damage and loss curves [Drbal et al., 2008], which express the functional relation between hydraulic characteristics (water depth) and percentile flood damage or loss. Based on the potential flood losses the flood risk is expressed as follows [Říha et al, 2005]:

$$ R_I = \int_{p_1}^{p_2} D(p) \, dp, $$

where $R_I$ is the average annual economic risk in monetary units [CZK, EUR, ...], and $p$ is the exceedance probability of the corresponding $N$-year peak flood discharge. It approximately holds that:

$$ p = \frac{1}{N}, $$

$D(p)$ represents the functional dependence of potential loss [CZK, EUR, ...] on flood probability. This dependence is derived from the potential losses estimated for individual flood scenarios. A geometrical interpretation of the integral (5) is shown in Fig. 5.
The practical procedure for the calculation of average annual economical risk is as follows:

- The exceedance probability for individual flood scenarios represented by selected N-years flood discharges is estimated using formula (6).
- The hydraulic characteristics of the flood, namely water depth, are determined by hydraulic modelling of the flow in related water courses including the floodplain.
- The direct economic losses in the area of interest are derived using the loss (stage - damage) curves (Fig. 6) from hydraulic characteristics for selected flood scenarios. A graphical interpretation of the obtained function $D(p)$ can be seen in Fig. 5.
- The numerical integration of (5) enables the estimation of annual average risk.

It is desirable to implement the method described into GIS using a tailor-made application eliminating routine manual re-running of individual procedures (Fig. 6). The final value of $RI$ serves for the evaluation of the economic effectiveness of proposed technical flood protection arrangements [MA CR, 2006]. In general, the following indicators are used in the cost benefit analysis [Říha et al, 2005], [MA CR, 2006]:

- relative effectiveness,
- absolute effectiveness,
- repayment period.

The method described has been widely applied in the assessment of hundreds of anticipated flood protection measures financed from the funds of the European Investment Bank within the framework of the project [MA CR, 2006].
4. Conclusions

It can be stated that the present methods of flood risk analysis in the CR are in accordance with the Directive [ES, 2007]. From this viewpoint the Czech Republic is well prepared for the implementation of the Directive, and long-term experience from research and numerous practical applications have recently been integrated into the Guidelines [Drbal et al., 2008] of the Directive [ES, 2007]. Further research into flood risk analysis needs to be focused on the following topics related to the implementation of the Directive:

- multicriterial floodplain risk assessment,
- inclusion of risks from the exposure of inhabitants to flood danger, assessment of individual and societal risk,
- assessment of environmental risks and risks to sensitive structures,
- estimation of indirect losses,
- more comprehensive uncertainty analysis in risk management,
- the influence of climate changes.

The most important issue when implementing the Directive [ES, 2007] seems to be multicriterial floodplain risk assessment. In the initial chapter of this paper the floodplain risk management process was mentioned. From the point of view of technical structural
arrangements the process culminates with the design and construction of risk attenuation measures, or alternatively measures for the maintenance of risk at an acceptable level. The proposals are assessed based on the comparison of the present risk level with the acceptable level. At present the quantitative risk analysis methods are dominantly based on the assessment of direct economic losses; the other aspects, such as human, social and environmental losses, are taken into account only marginally. Therefore, the future intention will be to search for methods for multicriterial floodplain risk analysis. In compliance with the Directive [ES, 2007] the following risks should be assessed within comprehensive floodplain risk analysis:

- economic risk,
- risk of injuries and loss of human life,
- risks from the flooding of pollution sources and extensive water contamination during the floods,
- risks due to the flooding of sensitive facilities (historical monuments, social care institutions, hospitals, rescue services, police, etc.).

5. References


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