Nat. Hazards Earth Syst. Sci. Discuss., 1, 2633–2665, 2013
www.nat-hazards-earth-syst-sci-discuss.net/1/2633/2013/
doi:10.5194/nhessd-1-2633-2013

Natural Hazards and Earth System Sciences
Open Access
Discussions

A simple model for the estimation of the number of fatalities due to floods in Central Europe

M. Brazdova and J. Riha

Brno University of Technology, Institute of Water Structures, Brno, Czech Republic

Received: 18 April 2013 – Accepted: 15 May 2013 – Published: 12 June 2013

Correspondence to: J. Riha (riha.j@fce.vutbr.cz)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

In this paper a model for the estimation of the number of potential fatalities is proposed based on data from 19 past floods in Central Europe. First, the factors contributing to human losses during river floods are listed and assigned to the main risk factors: hazard – exposure – vulnerability. The order of significance of individual factors has been compiled by pairwise comparison based on experience with real flood events. A comparison with factors used in existing models for the estimation of fatalities during floods shows good agreement with the significant factors identified in this study. The most significant factors affecting the number of human losses in floods have been aggregated into three groups and subjected to correlation analysis. A close-fitting regression dependence is proposed for the estimation of loss of life and calibrated using data from selected real floods in Central Europe. The application of the proposed model for the estimation of fatalities due to river floods is shown via a flood risk assessment for the locality of Krnov in the Czech Republic.

1 Introduction

The consequences of extreme flood events in Central Europe that have occurred during the last decades show the necessity for a systematic approach to flood protection. Procedures based on the theory of risk management appear to be very effective for this purpose. One of the most important issues when implementing Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Directive, 2007) is multi-criteria floodplain risk assessment.

Most of the existing flood risk studies in Central Europe still focus on material losses and economic risk (Drab and Riha, 2010). One of the important risks which should be taken into account is loss of human lives. To include this risk component in analyses it is necessary to estimate the potential loss of life (LOL) due to floods with a given return period.

NHESSD

1, 2633–2665, 2013

A model for estimating the number of flood fatalities in Europe

M. Brazdova and J. Riha

In this paper a simple model is proposed for the estimation of the number of expected fatalities during a flood. Firstly, the factors contributing to the loss of life due to river floods were listed and analysed. The most significant factors contributing to the fatalities during past floods were aggregated to three groups and were included in the model for estimating the loss of life due to river floods. The model, which takes the form of a multiple regression function, was calibrated using highly reliable and detailed data from 19 selected real floods in Central European countries like the Czech Republic, Slovakia, Poland, Austria, Germany and Switzerland. The applicability of the model is restricted to similar countries with comparable flood forecasting and warning systems, flood routing techniques and also living standards. The proposed model is demonstrated for the area of the town of Krnov in the Czech Republic, where flood protection measures have recently been proposed.

The objectives of the paper are to summarize factors contributing to the loss of life due to river floods and to propose a model for the estimation of the potential number of fatalities. The paper is structured as follows. In Sect. 2 a review and brief analysis of published models is carried out. The factors contributing to loss of human life during floods are listed and analysed in Sect. 3, which is the most comprehensive part of the text. In Sect. 4 a model for loss of life estimation is proposed based on empirical data from real floods. Section 5 is concerned with a case study. Conclusions and specifications for further research are found in Sect. 6.

2 Current methods of modelling fatality numbers

Approximately since the nineteen seventies, studies dealing with the classification of the causes and circumstances of death due to flood action have been performed worldwide. The subject is the loss of life caused by river floods, dam break floods, and flooding caused by coastal events such as hurricanes, storm surges or typhoons. A comprehensive work identifying and analysing published methods for all types of floods was produced by (Jonkman et al., 2008). The authors concluded that "...coastal flood events are even more catastrophic than inland floods in terms of loss of life."

Human losses during river and coastal floods have been studied systematically by authors in the Netherlands, Great Britain and USA (Friedman, 1975; Lee et al., 1986; Waarts, 1992; Ramsbottom et al., 2003, 2004; Surendran et al., 2006; Priest et al., 2007; Vrouwenvelder and Steenhuis, 1997; Jonkman and Kelman, 2005; Jonkman, 2007; Jonkman et al., 2008, 2009). In many cases the impacts of both river and coastal floods were studied together.

Most of the methods for loss of life estimation use empirical data from real flood events. According to the review of relevant literature, most authors use the term "flood mortality" (Jonkman, 2007) or "fatality rate" (Graham, 1999), which is defined as the number of fatalities divided by the number of people exposed, or the population at risk (PAR). Individual authors express mortality using various factors that influence the loss of life caused by a given flood type.

Waarts (1992) used data collected regarding the catastrophic coastal flood which affected the south-west of the Netherlands in February 1953. Aside from enormous economic losses the flood also brought 1835 fatalities. Waarts classified the area in which flooding resulted in fatalities into three zones, namely regions with high flow velocity, regions with rapidly rising water levels, and remaining zones. He derived an exponential function where water depth was the only factor. Formulas which were formally the same were proposed by the Japanese author Mizutani (1985) for typhoons Isewan and Jane (see Jonkman et al., 2008). Based on Waarts' formula, Vrouwenvelder and Steenhuis (1997) expressed flood mortality as a function of water depth and the rate of water level rise. The formulas proposed suffer due to not including important factors like warning, evacuation and rescue activities in their analysis.

Vrouwenvelder and Steenhuis (1997) proposed a method taking into account the effect of collapsed buildings, the effect of distance from the dam breach, evacuation and also other factors.

NHESSD
1, 2633–2665, 2013

A model for estimating the number of flood fatalities in Europe

M. Brazdova and J. Riha

In his Ph.D. thesis (Jonkman, 2007) and in the following paper (Jonkman et al., 2008), Jonkman gives a comprehensive overview of approaches to loss of life modelling. The model proposed in his study is applicable both for coastal and river floods and includes factors such as water depth and velocity, rate of water level rise and the effects of evacuation and rescue of exposed people.

A promising method was proposed by Zhai et al. (2006), who derived a functional relationship between the number of flooded houses and the number of fatalities. This approach reflects mainly the population at risk and flood characteristics (depth, velocity, rate of water level rise) but omits the influence of other factors like warning, evacuation, etc. Because of this there is considerable variation in the results obtained by the model.

In the UK at the Department for Environment, Food and Rural Affairs (DEFRA) and at the Environment Agency, Flood and Coastal Defence R&D Programme, a method for the estimation of the risk of loss of life during floods has been proposed (Ramsbottom et al., 2003, 2004). The project consisted of two phases. In phase 1 the Risks to People Methodology was developed. The procedure is based on an assessment of three factors: flood hazard, human vulnerability and area vulnerability. For the flood hazard rating the results of human instability testing were used (Abt, 1989). Three case studies for areas in the UK demonstrated good agreement between modelling results and historical data. The second phase involved the development of guidelines that explain how the method can be applied in flood risk management, urban planning and relevant flood protection activities.

The previously-mentioned project was the basis for research conducted by Priest (2007), who used data regarding historical flood events in Europe. The applicability of models proposed by (Ramsbottom et al., 2003, 2004) for flood management in Central Europe was assessed as part of the project. Priest (2007) proposed an improved model which should be flexible enough to be widely applied both on a regional and national level.

The impact of dam break floods was studied by Brown and Graham (1988), DeKay and McClelland (1993) and Graham (1999). Brown and Graham (1988) compiled

NHESSD
1, 2633–2665, 2013

a formula for the estimation of potential fatalities due to dam failure. The PAR and available warning/evacuation time are factors taken into account. DeKay and McClelland (1993) derived models distinguishing floods with low and high hazard potential. PAR and available evacuation time are the relevant factors used in the model. Graham (1999) expresses the loss of life (LOL) as a percentage of PAR loss depending on the flood hazard, warning time and the response to the warning. The latter factor reflects the preparedness of society against flood risk.

In the case of relatively shallow water, mortality is expressed based on tests investigating the stability of persons in flowing water. The aim of such studies is to indicate factors influencing the stability of persons in flowing water and to assign stability limits. One of the first such tests was carried out at Colorado State University (Abt et al., 1989). Tests were performed using both living bodies and rigid body monoliths similar in stature to humans. The research resulted in a critical product of velocity and water depth (sometimes called "flood intensity") related to the mass and length of persons.

The stability of persons in flowing water was also assessed within a project (RESCDAM, 2000) conducted under the supervision of the Finnish Environment Institute in Helsinki. The aim was to identify the limits of individual factors contributing to loss of stability and compile guidelines for rescue activities in the case of dam break floods. At the Czech Technical University in Prague similar research consisting of 725 tests was carried out by Salaj (2009), who studied the effect of factors like water depth and velocity, and also the weight and height of persons, their gender, skills and type of clothing. The most important factors were water depth and velocity. The comparison of the experimental results of the aforementioned research projects shows that the resulting critical flood intensity obtained by Salaj (2009) fits the (RESCDAM 2000) data quite well while the dataset published by Abt et al. (1989) is to a certain degree different, providing higher stability of individuals. The reason is probably the different conditions present during testing and the varied characteristics of individuals moving in flowing water. Jonkman and Rowsell (2008) discuss how human instability relates to moment and friction instability. Lind and Hartford (2000) and Lind et al. (2004) present mechanicaln and empirical models of the hydrodynamics of moment instability (toppling) taking into account the height and weight of the exposed persons, and the velocity and depth of the flowing water.

The review of existing models for loss of life estimation shows that they have been proposed and calibrated for conditions in different regions and for different types of floods (coastal and river floods, dam breaks, etc.). Experimental data from historical flood events are mostly used for the calibration of model parameters. Due to lack of data the existing models do not take into account all of the most relevant factors (Table 1), and in some cases factors are derived from expert judgement. The subjects of analysis are particularly large-scale flood events with extensive mortality like the coastal flood in 1953 in the Netherlands and the UK (Waarts, 1992; Kelman, 2003), Hurricane Katrina in 2005 (Jonkman et al., 2009), and other disastrous events in Asia. Experience shows that number of fatalities in Central European river floods is likely to significantly differ from the loss of life caused by other types of floods (coastal, dam break, etc.). Unfortunately, no relevant loss of life model has yet been proposed for inland river floods (similar to those in years 1997, 2002, 2006, 2008, 2010) for the conditions present in Central Europe. The objective of this paper is to propose a user-friendly model for estimating loss of life in conditions typical in the Czech Republic and surrounding Central European countries.

Table 1 shows a summary of selected models developed for the estimation of human losses due to inland flooding. In the table the area of application, factors taken into account and method of data acquisition are mentioned for each model. The most commonly used factors are water depth and velocity, the rate of water level rise, warning and evacuation. The other remaining factors like preparedness, the collapse of buildings and vulnerability of individuals (weight, height, gender, clothing etc.) are less often used.

NHESSD
1, 2633–2665, 2013

3 Factors contributing to human losses during river floods

Models for loss of life estimation should take into account as much as possible important factors contributing to fatalities during flood events. In this section the analysis of such factors is carried out in the following steps:

1. A comprehensive list of factors contributing to the loss of life due to river floods has been created (Table 2). They are referred to as "contributing factors" in the remainder of this paper. A more detailed description of contributing factors, their impact on loss of life and the availability of relevant data related to each factor has been assessed during research (Drbal et al., 2011); however, this information is not covered here due to its large extent.

2. The significance and importance of the contributing factors identified were assessed based on the analysis of fatality data from real flood events in Central Europe. The Saaty method (Saaty, 2008) was used for the semi-quantitative ranking of pairwise comparisons. The resulting "most important" contributing factors were compared with an overview of factors used by models developed for the estimation of loss of life (Table 1).

3. The most significant factors were identified and aggregated into three groups to reduce the number of parameters of the model proposed for the estimation of loss of life.

3.1 Data from existing floods

The first step was the detailed collection of data about relevant historical floods. A very important condition in the assessment of the above-mentioned contributing factors was the availability, accuracy and reliability of relevant data describing such factors and enabling their quantification in cases of both real flood situations and potential flood scenarios. The impact of each factor on loss of life has to be described and, if possible, also quantified.

NHESSD
1, 2633–2665, 2013

The comprehensive records obtained from floods all around the world that are cited in various sources encompass about 130 flood events. The data from past floods in which fatalities occurred have been used both for the identification of contributing factors and their sorting (Sect. 3.2), and also for further calibration of the proposed model for the estimation of the number of fatalities during floods (Sect. 4). For the latter purpose only floods fulfilling the following criteria have been chosen from the entire set:

– The flood data should include real loss of life, material losses and also information about the standard of living in the country and the flood routing procedures applied.

– The standard of living of affected countries should be comparable in terms of flood routing, flood mitigation and control and also land use and the amount of property. For this purpose the gross national product can be used.

– Population density in these countries should be similar and comparable with that in the Czech Republic and Central Europe.

For this reason, "non-consistent" regions like Asia, Africa and also North America have been excluded from the analysis. The required complete data have been collected for 19 European floods, these being in the Czech Republic (1997, 1998, 2000, 2002, 2006, 2009, two floods in 2010), Slovakia (1997, 1998, 1999), Austria (2002, 2005, 2009), Switzerland (2000, 2005, 2007), Germany (2002) and Poland (1997). The data from these floods are summarized in Table 5. Incomplete data from other floods that did not fulfil the above-mentioned criteria have only been used as sources of information.

The material losses for the analysed floods have been converted to USD using current exchange rates and converted to the 2010 currency level. Euros have not been used as some floods preceded the adoption of the Euro in 2002.

Individual flood events have been described in more detail. The description includes the climatic and hydrological circumstances of the flood, the characteristics of the flooded area, a description of the course of the flood, material losses, the number

NHESSD
1, 2633–2665, 2013

of fatalities and their causes, and other information. Attention has been paid to the quantification of individual factors affecting the number of casualties, and also the aggregated factors (Sect. 3.3).

Finally, the classification of flood deaths proposed by Jonkman and Kelman (2005) has been adopted and completed by so-called “flood tourism”, which occurs during practically every regional flood. The floods in the Czech Republic (1997, 2000, 2002, 2006, 2009, 2010) have been classified according to the proposed distribution of causes of deaths and surrounding circumstances (Table 3). It must be noted that some data in Table 3 overlap, namely those from the flood in August 2002 in the Czech Republic mentioned both by Jonkman and Kelman (2005) (columns 3 and 4) and those discussed within this study (columns 5 and 6).

3.2 List of contributing factors and their significance

The list of factors influencing flood-induced fatalities was compiled based on experience from past floods in the Czech Republic and also in neighbouring countries like Slovakia, Poland, Austria, Germany and also Switzerland. The literature sources discussed in Sect. 2 were also taken into account. Identified contributing factors are listed in Table 2.

When employing the concepts of hazard, exposure and vulnerability as components of flood risk (Gouldby and Samuels, 2005; Drab and Riha, 2010), the contributing factors influencing the amount of loss of life during floods can be related to these components.

Factors expressing hazard (potential for injury, loss) like the extent of the flood, water depth, water velocity, rate of water level rise and speed of flood arrival can be determined using hydrological and hydraulic modelling. Increasing water depth, velocity, rate of water level rise and speed of flood arrival results in higher risk to the exposed population. Floating debris and ice can also be taken into account when modelling obstructive hydraulic structures like bridges, culverts or weirs. Floating debris is a source of hazard and can be assessed from the nature of the catchment (forestation, deposits

NHESSD
1, 2633–2665, 2013

on the floodplain). Unfavourable climate conditions and low water temperature during the flood complicate the mobility of persons in water and also rescue activities. Flooding and the washing out of pollutants from industrial facilities or waste water treatment plants located in the flooded area can cause a worsening in water quality. Experience shows that in the case of extreme floods pollution concentrations are not usually high and have almost no influence on the number of lost lives.

Exposure as an act of being subjected to the influence of flooding is linked to contributing factors expressing contact between persons and water, and its hazardous impact. Contributing factors like the general preparedness of inhabitants, timeliness and reliability of hydrological forecasting, warning and the response to warning can reduce the size of the exposed population. The duration of the flood usually does not directly influence loss of life; however, it may increase the stress on evacuated persons. Well organized evacuation and rescue activities can significantly reduce the number of lives lost, though on the other hand single fatalities have been reported during rescue attempts. A certain proportion of loss of life stems from unnecessary risk-taking behaviour, also including so-called “flood tourism” (Jonkman and Kelman, 2005). The percentage of flood-related deaths increases at twilight or during darkness, especially in the case of flash floods.

Vulnerability (susceptibility to injury, loss of life) is related to the characteristics and capabilities of individuals. The influence of factors like the weight, height, age, gender, physical conditions and experience with mobility in water of individuals, and also the clothing and footwear worn, was studied via numerous stability tests (Abt et al., 1989; RESCDAM, 2000; Salaj, 2009). The vulnerability of individuals is also influenced by contributing factors like the carrying of loads and use of support when walking in flowing water. The trapping of persons in vehicles was reported namely in the case of floods in the USA. Buildings can provide shelter to persons against floating debris and the effect of moving water and as such decrease the vulnerability of individuals, although in the event of destruction of the building by the flood the hazard to the occupants will rise dramatically.

NHESSD
1, 2633–2665, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Some of the contributing factors, namely those related to vulnerability, are important when assessing fatality at the individual level. In further considerations these factors are averaged over the affected flooded area and the corresponding population at risk. Factors expressing local hazard (water depth, flow velocity, etc.) are projected into the aggregated parameters (e.g. parameter D – see below) by integration over the flooded area.

It is evident that it is not practicable and feasible to take all contributing factors into account when proposing a model for the estimation of loss of life. Therefore, the aim of this study has been to find the factors with the most significant impact on the number of fatalities during flood events. The importance of the contributing factors identified was assessed using pairwise comparison based on the analysis of data and experience from past flood events. The pairwise comparison was carried out in two steps. First, qualitative analysis was applied to determine which criteria are more important. This was done by mutual comparison of the criteria via a "binary" rating in which the more important criteria were assigned the number "1" and the less important "0". After that, each criterion was assigned a more apposite quantitative weight following a ranking scheme ranging from 1 to 5:

1. – equal preference,

2. – low preference,

3. – medium preference,

4. – high preference,

5. – dominant preference.

The definite assignment of weights was accomplished by the analysis of 35 questionnaires completed by professionals from the academic sphere (4), research institutes (3), engineering consultancies (5), river board agencies (7), administrative bodies (4), evacuation and rescue services and fire brigades (4) and other populations affected by

NHESSD
1, 2633–2665, 2013

floods (8). All respondents were provided with the classification of flood deaths summarized in Table 4 and with the detailed description of contributing factors contributing to flood fatalities. This enabled the assignment of factors listed in Table 2 to individual fatalities during floods and their causes and circumstances. The respondents filled in their own binary and also "Saaty" (Saaty, 2008) scoring into the decision matrices which were afterwards subjected to final analysis and compiled in an ordered list of contributing factors according to the significance of their impact on loss of life.

The most important factors were compared with the factors used in existing models for loss of life estimation summarised in Table 1.

The resulting ranking of parameters based on the procedure mentioned above is shown in Table 4, where the contributing factors are ordered according to their final ranking. In this table the comparison with existing models for loss of life estimation is shown as well. Quite good agreement can be noted between the currently used factors and those identified by the formalised procedure in this study.

From the order of the factors shown in Table 4 it can be seen that the most important of them are the preparedness of the municipality, warning time, rescue activities, water depth, flood extent, water velocity, the speed of the flood's arrival, the response to the warning, evacuation and the rate of water level rise. Most of these factors are used in existing "loss of life" models.

The significance of the contributing factors shown in Table 4 closely fits findings reported in the literature, e.g. (Jonkman and Kelman, 2005; Jonkman et al., 2008). Flood extent, water depth and velocity, rate of water level rise and speed of flood arrival are the most cited factors related to flood hazard. Preparedness of the population at risk, warning, evacuation and rescue activities rank among the most important "exposure" related factors. On the other hand, the relationship between factors related to the vulnerability of individuals (age, gender, height of individuals, etc.) and the number of fatalities cannot be reliably confirmed, which is partly due to the inadequacy of the records available.

NHESSD
1, 2633–2665, 2013

A model for estimating the number of flood fatalities in Europe

M. Brazdova and J. Riha

3.3 The aggregation of factors

Due to the extent of the list of identified factors it is advisable to choose only the most important ones and aggregate them into a limited number of groups. The main intention was:

- to take into account the most important factors influencing the number of fatalities (Table 4),
- to enable the evaluation of aggregated factors for past and also potential future floods at locations subjected to flood risk analysis.

In our study three groups (D, P, W) were proposed for further processing.

These groups do not include some contributing factors connected with vulnerability, floating debris, climatic conditions, water temperature and quality, and time of day. The reason for excluding these factors from further analysis is the lack of data concerning such circumstances gathered during flood events, and in some cases their minor influence on loss of life.

Group D is represented by material losses *D*. This group involves hazard factors contributing to material losses like the extent of the flood, water depth, water velocity and also the duration of the flood and the number of people at risk (PAR). Extensive research carried out within project No. 129120 "Maintenance of flood prevention I" (MACR, 2006) based on census and GIS data (COSMC, 2009; CSO, 2009) demonstrated close correlation between the PAR, property and property loss in the endangered area. The functional relationship between the number of flooded buildings and the number of fatalities was also confirmed by Zhai et al. (2006). Material losses *D* were therefore used as an appropriate aggregated parameter containing all contributing factors mentioned above.

Group P (general preparedness) expresses the general preparedness of society for flood management and control. It reflects flood awareness, the understanding of activities and behaviour during floods, etc. This is also related to the initiatives of flood

NHESSD
1, 2633–2665, 2013

committees, their response to hydrological forecasts and flood warnings and subsequent evacuation and rescue activities. Its value is determined by assessing the following items P_i closely corresponding with general preparedness and the aforementioned contributing factors:

- P_1 – flood awareness and general knowledge about flood hazards,
- P_2 – flood memory, frequency of flooding in the area of interest,
- P_3 – existing flood documentation (flood extent maps, flood management plans),
- P_4 – understanding of activities and behaviour during floods,
- P_5 – initiatives and activities of flood committees,
- P_6 – response to hydrological forecast,
- P_7 – response to flood warning,
- P_8 – evacuation and rescue activities, level of training of personnel.

The items P_i mentioned above are semi-quantitatively scored in the range $\langle -1, 1\rangle$. General "aggregated" preparedness P (also in the range $\langle -1, 1\rangle$) is determined using the formula:

$$P = \frac{1}{4} \cdot \sum_{i=1}^{8} P_i, \tag{1}$$

where P_i represents the scores of items mentioned above. Here -1 denotes a completely unsatisfactory state, $+1$ represents an excellent state.

Group W (warning) includes factors influencing the warning of the population. The assessment is analogous to the case of group P. The contributing factors like the hydrological forecast, speed of the flood's arrival, warning and the rate of water level rise were included in the analysis. The following items W_i have to be assessed:

NHESSD
1, 2633–2665, 2013

- W_1 – hydrological forecast, its reliability, meteorological models used, etc.,
- W_2 – speed of the flood's arrival, which significantly differs for upper and lower sub-catchments, for flash and regional floods,
- W_3 – warning system, existence of digital warning systems,
- W_4 – expected rate of water level rise.

These items are semi-quantitatively scored in the range $\langle -1, 1 \rangle$ in a manner analogous to the case of group P. The general "aggregated" effect of warning W (in the range $\langle -1, 1 \rangle$) is determined using the formula:

$$W = \frac{1}{2} \cdot \sum_{i=1}^{4} W_i, \tag{2}$$

where W_i represents the scores of items mentioned above.

4 Fatality estimation model

4.1 General assumptions

In order to calibrate the model an extensive search was carried out for data regarding historical floods. As mentioned above, the first step involved the collection of data for floods occurring all over the world. The study showed that flood hazards and the preparedness of societies and their inhabitants vary extremely widely across the various continents and also between individual countries, due to their different cultures, economies and living standards. Also, the required detailed data for evaluation were not available for the majority of floods. As a result, only 19 floods which took place in Central European countries over the last approximately 15 yr were chosen and used in the analysis. A list of these floods is shown in Table 5. The location and nature of the analysed floods limit the use of the proposed model to countries with similar climate, living standards and economies to Austria, the Czech Republic, Germany, Poland, Switzerland, the Slovak Republic, and other similar European countries.

As was mentioned above, the basic strategy was to deal exclusively with material losses, D. It was assumed that material losses reflect both the flood hazard (the destructive ability of the flood) and the number of endangered inhabitants (the amount of property in flooded areas corresponds to the size of the population at risk). In order to have practical applications this approach requires the use of techniques for loss estimation in selected flood scenarios. These methods are available in practically all countries in Central Europe.

It is expected that the most important contributing factors (Table 4) are sufficient to express the number of fatalities during floods acceptably. They are aggregated into three groups, D, P and W, and expressed numerically by parameters (quantifiers) D, P and W. Based on the available information and data the material losses D and number of fatalities LOL were assigned to 19 selected historical floods. The above-mentioned scoring for parameters P and W was carried out for these floods (see Table 5).

4.2 Functional dependence

The functional dependence between "dependent" variable LOL and "independent" variables D, P and W was determined using correlation analysis. This dependence between LOL and D, P and W was searched for in such varied functional relationships as linear, exponential, logarithmic and power functions. It was discovered that the best fit approximation of loss of life is provided by the power function of variables D, P, W. This can be proposed in a form which guarantees zero LOL for zero material losses and positive LOL for P and W within the range $\langle -1, 1 \rangle$. The correlation coefficients expressed for individual pairs LOL–D, LOL–P, LOL–W after their linearization by logarithmisation are as follows: $R_{\mathrm{LOL,D}} = 0.544$, $R_{\mathrm{LOL,P}} = -0.595$, $R_{\mathrm{LOL,W}} = -0.372$.

NHESSD
1, 2633–2665, 2013

Other dependencies gave much smaller correlation coefficients and in some cases did not satisfy logics requiring a positive number of fatalities for $D > 0$.

4.3 Model calibration and verification

Based on the above-mentioned functional dependence analysis the following general form was proposed for the model for the estimation of the number of human losses:

$$y = k \cdot x_1^b \cdot x_2^c \cdot x_3^d, \tag{3}$$

where k ,b, c, d are model parameters, y is a "dependent" variable characterizing loss of life, and x_1, x_2, x_3 are "independent" variables corresponding to material losses, preparedness and warning.

After substituting LOL for y, 10^a for k, D for x_1, $(P+2)$ for x_2 and $(W+2)$ for x_3, Eq. (3) becomes:

$$\mathrm{LOL} = 10^a \cdot D^b \cdot (P+2)^c \cdot (W+2)^d. \tag{4}$$

For the optimization using the least square procedure the values of LOL, D, P and W were taken from Table 5 for the 19 selected floods. To determine parameters a, b, c, d using the least square method it is advantageous to logarithmise and so linearise the Eq. (4). Therefore, in Eq. (4) the numeral "2" was added to parameters P and W to avoid logarithmisation of negative values (parameters P and W vary within the interval $\langle -1, 1 \rangle$).

When substituting the obtained parameters a, b, c, d into Eq. (4), after some manipulation the resulting formula for the estimation of loss of life was obtained:

$$\mathrm{LOL} = 0.075 \cdot D^{0.384} \cdot (P+2)^{-3.207} \cdot (W+2)^{-1.017}. \tag{5}$$

The verification of the proposed model Eq. (5) was carried out by backward substitution of D, P and W values from Table 5. The results of model verification using the line

NHESSD
1, 2633–2665, 2013

of agreement are shown in Fig. 1; a comparison of actual fatalities with the calculated ones can also be seen in Table 6. The graph shows acceptable accuracy when taking into account the uncertainties in the estimation of material losses during a flood and also in the evaluation of preparedness and warning factors. The agreement of results is also influenced when other contributing factors affecting the number of fatalities are neglected (see Table 4).

5 The application of the model

A locality was chosen for the demonstration and application of the loss of life model: the town of Krnov, which lies on the Opava River in the north of the Czech Republic. The theoretical analysis was carried out for floods corresponding to the return periods $N = 2, 5, 10, 20, 50, 100$ and 500 yr. For these floods the exceedance probability p was evaluated using the formula:

$$p = 1 - e^{-\frac{1}{N}}. \tag{6}$$

For the studied floods, flooded areas and material losses D were evaluated using the official Czech methodology (Guideline, 2008) employing damage functions and asset values for structures located in the flooded area (CSO, 2009). Then, quantifier P was evaluated according to Eq. (1) and W according to Eq. (2) using the method described in Sect. 3.3. Finally, the loss of life LOL was estimated for each flood scenario using Eq. (5). The results are shown in Table 7.

The dependence $p = G(\mathrm{LOL})$ was plotted on a logarithmic scale in a so-called F–N diagram and compared with acceptable and tolerable risk margins (Fig. 2).

These margins were recommended for the Czech Republic within past research (Drbal et al., 2011). The relations for the acceptable risk $\mathrm{RI_P}$ and tolerable risk $\mathrm{RI_T}$ are expressed via the corresponding constants C_P and C_T using so-called "aversion factors", k_P and k_T:

$$\mathrm{RI_P} = G_\mathrm{P}(\mathrm{LOL}) \cdot \mathrm{LOL}^{k_\mathrm{P}} = C_\mathrm{P}; \quad \mathrm{RI_T} = G_\mathrm{T}(\mathrm{LOL}) \cdot \mathrm{LOL}^{k_\mathrm{T}} = C_\mathrm{T} \tag{7}$$

NHESSD
1, 2633–2665, 2013

where G_P(LOL) and G_T(LOL) are the exceedance probabilities for acceptable and tolerable risk, respectively. Based on experience from other fields and countries the constants proposed for the Czech Republic are as follows (Drbal et al., 2011):

$$C_P = 10^{-3}, \quad \text{for LOL} = 1; \quad C_P = 10^{-5}, \quad \text{for LOL} = 10; \quad k_P = 2$$
$$C_T = 10^{-1}, \quad \text{for LOL} = 1; \quad C_T = 10^{-4}, \quad \text{for LOL} = 100; \quad k_T = 1.5$$

Figure 2 shows that floods with return periods of 5 to 100 yr do not agree with the acceptable risk requirements.

A more detailed description of the designation of acceptable and tolerable risk margins such as the ALARP concept and methodology is outside the scope of this paper. More detailed information can be found e.g. in HSE (2001), Jonkman et al. (2002), Trbojevic (2004), Drbal et al. (2011), and others.

6 Conclusions

In this paper a simple model for the prediction of the number of human losses during river floods is proposed. Firstly, all relevant contributing factors affecting the number of fatalities during floods were listed and ordered according their significance. It was shown that the most important factors are related to the flood hazard, the preparedness of inhabitants and activities related to warning. These significant factors include water depth and velocity, evacuation and rescue activities, hydrological forecasting, the flood warning time and the response to it, the speed of the flood's arrival and the rate of water level rise. These factors were aggregated into three groups, D, P and W. Group D expresses material losses (in our case in USD) and includes factors related to the flood hazard and also the number of inhabitants in the exposed area (PAR). Factors related to groups P and W were subjected to semi-quantitative scoring. The values of corresponding parameters D, P, W were calculated for 19 selected floods and related to real numbers of human losses during these floods (Table 5).

The parameters LOL and D, P, W were subjected to dependence analysis, which outlined the form of the resulting formula as a power function. The exponents in the proposed Eq. (4) were determined by the least square method using data from 19 selected past floods. The resulting Eq. (5) was verified by backward substitution of values D, P, W for individual floods when calculated LOL values were compared with real fatalities identified during real floods. Even though there is a relative difference between modelled and real values of more than 300 % in cases when single fatalities occurred (an absolute difference of 2 or 3 fatalities), in the case of the more catastrophic floods the relative error does not exceed 50 %. This agreement can be regarded as acceptable when considering uncertainties in the calculations of material losses, the certain subjectivity and lack of accurate data in the scoring of preparedness and warning factors, and also when neglecting the remaining, less important contributing factors. Similar differences between reported mortality figures and calculated results are shown by Jonkman et al. (2008).

The proposed model can be applied in flood protection studies when assessing the acceptability of the number of human lives lost during floods (F–N diagrams). The number of expected fatalities during floods is a necessary input in multi-criteria risk analysis. To quantify parameter D the results of hydraulic modelling of individual flood scenarios and the estimation of corresponding flood losses are necessary. For the determination of P and W it is crucial to have detailed information about the area and river basin, and also regarding individual items giving an idea of the preparedness and warning procedures in the country and area, and their reliability.

The location of data sources (Table 5) used during the construction of model Eq. (5) limit the applicability of the proposed model to inland floods in countries and areas of Central Europe with similar terrain morphology, land cover, climate conditions, population density and living standards. The method is not suitable for estimating loss of life in coastal floods, hurricanes, etc.

NHESSD
1, 2633–2665, 2013

Acknowledgements. The paper contains results from Ministry of the Environment of the Czech Republic research project No. SP/1c2/121/07, Risk maps resulting from flood danger in the Czech Republic.

References

Abt, S. R., Wittler, R. J., Taylor, A., and Love, D. J.: Human stability in a high flood hazard zone, Water Resour. Bull., 25, 881–890, 1989.

Brown, C. A. and Graham, W. J.: Assessing the threat to life from dam failure, Water Resour. Bull., 24, 1303–1309, 1988.

Brown, A. J. and Gosden, J. D.: Interim Guide to Quantitative Risk Assessment for UK Reservoirs, Thomas Telford, London, 2002.

COSMC: Fundamental basis of geographical data (ZABAGED), Czech office for surveying, mapping and cadastre, Prague, available at: http://www.cuzk.cz, last access: 15 January 2013, 2009.

CSO: Census District and Building Register, Czech statistical office, Prague, available at: http://www.czso.cz/csu/rso.nsf/i/registr_scitacich_obvodu, last access: 15 January 2013, 2009.

DeKay, M. L. and McClelland, G. H.: Predicting loss of life in cases of dam failure and flash flood, Risk Anal., 13, 193–205, 1993.

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks, Official Journal of the European Union, Brussels, 2007.

Drab, A. and Riha, J.: An approach to the implementation of European Directive 2007/60/EC on flood risk management in the Czech Republic, Nat. Hazards Earth Syst. Sci., 10, 1977–1987, doi:10.5194/nhess-10-1977-2010, 2010.

Drbal, K., Rektorik, J., Riha, J., Satrapa, L., Slavikova, L., and Stepankova, P.: Risk maps resulting from flood danger in the Czech Republic, Final report, Brno, 1–84, available at: http://www.vuv.cz/index.php?id=290, last access: 20 November 2012, 2011 (in Czech).

Friedman, D. G.: Computer simulation in natural hazard assessment, Institute of Behavioral Science, University of Colorado, Boulder, Colorado, 194 pp., 1975.

Gouldby, B. and Samuels, P.: Language of Risk, Report T32-04-01, FLOODsite Consortium, available at: http://www.floodsite.net/, last access: 15 January 2013, 2005.

Graham, W. J.: Floods caused by dam failure, Dam Safety Office report DSO-99-6, 1999, U.S. Department of Interior, Bureau of Reclamation, Dam Safety Office, Denver, Colorado.
Guideline for the assessment of flood risk and losses in floodplains, The Ministry of Environment of the Czech Republic, Water Research Institute, available at: http://www.vuv.cz/index.php?id=290, last access: 15 January 2013, 2008 (in Czech).
HSE – Health and Safety Executive: Reducing risks, protecting people, HSE's decision-making process, London, 88 pp., 2001.
Jonkman, S. N.: Loss of life estimation in flood risk assessment, theory and applications, Dissertation, Delft University of Technology, 360 pp., 2007, Delft, the Netherlands.
Jonkman, S. N. and Kelman, I.: An Analysis of the Causes and Circumstances of Flood Disaster Deaths, Overseas Dev. Institute, Oxford, UK, 75–97, 2005.
Jonkman, S. N. and Rowsell, E. P.: Human Instability in Flood Flows, J. Am. Water Resour. As., 44, 1–10, 2008.
Jonkman, S. N., Gelder, P. H. A. J. M., and Vrijling, J. K.: Loss of Life Models for Sea and River Floods, Flood Defense 2002, vol. I, Science Press, New York, 2002.
Jonkman, S. N., Vrijling, J. K., and Vrouwenvelder, A. C. W. M.: Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method, Nat. Hazards, 46, 353–389, 2008.
Jonkman, S. N., Maaskant, B., Boyd, E., and Levitan, M. L.: Loss of life caused by the flooding of New Orleans after hurricane katrina: analysis of the relationship between flood characteristics and mortality, Risk Anal., 29, 676–698, 2009.
Kelman, I.: CURBE fact sheet 3: UK Deaths from the 1953 Storm Surge, Version 3, July 2003, University of Cambridge, Cambridge, UK.
Lee, R., Hu, P. S., Neal, D. M., Ogles, M. R., Sorensen, J. H., and Trumble, D. A.: Predicting loss of life from floods, Oak Ridge National Laboratory Draft Report, prepared for the Institute for Water Resources, US Army Corps of Engineers, 131 pp., 1986, Oak Ridge, TN.
Lind, N. and Hartford, D.: Probability of human instability in a flooding: a hydrodynamic model, in: Proceedings of the International Congress on Applications of Statistics and Probability, Sydney, NSW, Australia, Balkema, Rotterdam, 12–15 December 1999, 1151–1156, 2000.
Lind, N., Hartford, D., and Assaf, H.: Hydrodynamic models of human stability in a flood, J. Am. Water Resour. Assoc., 40, 89–96, 2004.
MACR: Maintenance of flood prevention I, Program documentation No. 129120, Ministry of Agriculture of the Czech Republic, Prague, 2006.

NHESSD
1, 2633–2665, 2013

A model for estimating the number of flood fatalities in Europe

M. Brazdova and J. Riha

Priest, S., Wilson, T., Tapsell, S., Penning-Rowsell, E., Viavattene, Ch., Fernandez-Bilbao, A. Building a Model to Estimate Risk to Life for European Flood Events – Final Report, Report number T10-07-10, Floodsite, UK, 174 pp., 2007, HR Wallingford, UK.
Ramsbottom, D., Floyd, P., and Rowsell, E.: Penning – Flood Risks to People, Phase 1, R&D Technical Report FD 2317, Defra – Flood Management Division, London, 109 pp., 2003.
Ramsbottom, D., Wade, S., Bain, V., Hassan, M., Penning-Rowsell, E., Wilson, T., Fernandez, A., House, M., and Floyd, P.: Flood Risks to People, Phase 2, R&D FD 2321/IR2, Food and Rural Affairs/Environmental Agency, 2004, Agency, London, UK.
RESCDAM: The Use of Physical Models in Dam-break Flood Analysis, Final Report, Helsinki University of Technology, 57 pp., 2000, Helsinki University of Technology, Finland.
Saaty, T. L.: Relative measurement and its generalization in decision making: why pairwise comparisons are central in mathematics for the measurement of intangible factors - the analytic hierarchy/network process, RACSAM, Real Academia de Ciencias de Madrid. Serie A. Mat., 102, 251–318, 2008.
Salaj, M.: Flood Risks Analysis for Humans, Ph.D. thesis, Czech Technical University, Prague, 85 pp., 2009.
Surendran, S., Ramsbottom, D., Wade, S., Bain, V., Floyd, P., Penning-Rowsell, E., Wilson, T., Fernandez, A., House, M.: Flood Risks to People, Phase 2, FD 2321/TR1 The Flood Risk to People Methodology, DEFRA - Department for Environment, Food and Rural Affairs, Flood Management Division, London, 92 pp., 2006.
Trbojevic, V. M.: Risk criteria in EU, Presentation at SAFERELNET workshop, Paris, France, 2004, 10–12 May 2004.
Vrouwenvelder, A. C. W. M. and Steenhuis, C. M.: Secondary flood defences in the Hoeksche Waard, calculation of the number of fatalities for various flood scenarios, Report TNO 97-CON-R0332, 1997, Dutch Organization for Applied Scientific Research (TNO), Delft, the Netherlands.
Waarts, P. H.: Method for determining loss of life caused by inundation, Report TNO B-91-1099, Delft, 1992, Dutch Organization for Applied Scientific Research (TNO), Delft, the Netherlands.
Zhai, G., Fukuzono, T., and Ikeda, S.: An empirical model of fatalities and injuries due to floods in Japan, J. Am. Water Resour. As., 42, 863–875, 2006.

NHESSD
1, 2633–2665, 2013

A model for estimating the number of flood fatalities in Europe

M. Brazdova and J. Riha

Table 1. Overview of the selected models developed for the estimation of loss of life due to different kinds of floods.

Model	Area of application	Water depth	Water velocity	Rate of water level rise	Warning and evacuation	Preparedness	Collapse of buildings	Vulnerability of individuals (weight, height, gender, clothing)	Data obtained from HP – real floods; L – laboratory research
Waarts (1992) – detailed	River and coastal floods	•	•	•	•				HP
Vrouwenvelder and Steenhuis (1997)		•		•	•		•		HP
Jonkman (2007, 2008)		•	•	•	•	•			HP/L
Ramsbottom et al. (2003, 2004)		•	•	•	•		•	•	HP
Priest (2007)		•	•	•	•		•		HP
Brown and Graham (1988)	Dam break floods				•				HP
DeKay and McClelland (1993)					•				HP
Graham (1999)		•	•		•	•			HP
Lind and Hartford (2000)	Stability of persons in flowing water	•	•						HP
Abt et al. (1989)		•	•					•	L
Rescdam (2000)		•	•					•	L
Salaj (2009)		•	•					•	L

Table 2. Summary of contributing factors influencing loss of life during floods.

Risk component	Number of the contributing factor	Contributing factors
Hazard	1	Flood extent
	2	Speed of flood arrival
	3	Rate of water level rise
	4	Water depth
	5	Water velocity
	6	Water temperature
	7	Water quality
	8	Climate conditions
	9	Floating debris
Exposure	10	Preparedness of municipality
	11	Hydrological forecast
	12	Warning
	13	Duration of flood
	14	Response to warning
	15	Time of day
	16	Evacuation
	17	Rescue activities
Vulnerability	18	Weight of individuals
	19	Height of individuals
	20	Age of individuals
	21	Gender
	22	Physical condition of individuals
	23	Experience with mobility in water
	24	Clothing and footwear
	25	Carrying of load
	26	Use of support
	27	Trapped in vehicle
	28	Trapped in building

NHESSD
1, 2633–2665, 2013

Table 3. Causes and numbers of fatalities during selected floods.

Cause of death	Circumstances of death	Europe, USA (Jonkman and Kelman, 2005) Fatalities	Fatalities in %	Czech Republic, floods in 1997, 2000, 2002, 2006, 2009, 2010 Fatalities	Fatalities in %
Drowning	As a pedestrian	62	25.1	30	28.3
	Trapped in a vehicle	81	32.8	5	4.7
	Falling from a boat	7	2.8	3	2.8
	During a rescue attempt	2	0.8	2	1.9
	In a building	15	6.1	5	4.7
	Flood tourism	0	0	4	3.8
Physical trauma	As a pedestrian	4	1.6	1	0.9
	Trapped in a vehicle	14	5.7	1	0.9
	On a boat	2	0.8	0	0.0
	During a rescue attempt	1	0.4	2	1.9
	In a building	8	3.2	7	6.6
	Flood tourism	0	0	1	0.9
Heart attack		14	5.7	8	7.5
Electrocution		7	2.8	0	0
CO poisoning		2	0,8	1	0.9
Fire		9	3.6	0	0
Other, or not known		19	7.7	36	35.8
Total		247	100.0	106	100.0

NHESSD
1, 2633–2665, 2013

Table 4. Overall assessment of contributing factor significance.

Contributing factors	Final order of factors	Factors taken into account in existing models
Preparedness of municipality	1	River floods
Warning	2	River floods
Rescue activities	3	
Water depth	4	River floods, stability tests
Flood extent	5	River floods
Water velocity	6	River floods, stability tests
Speed of flood arrival	7	
Response to warning	8	
Evacuation	9	River floods
Rate of water level rise	10	River floods
Physical condition of individuals	11	
Floating debris	12	
Time of day	13	
Experience with mobility in water	14	
Age of individuals	15	
Duration of flood	16	
Hydrological forecast	17	
Climate conditions	18	
Trapped in building	19	River floods
Water temperature	20	
Trapped in vehicle	21	
Gender	22	Stability tests
Weight of individuals	23	Stability tests
Clothing and footwear	24	Stability tests
Height of individuals	25	Stability tests
Water quality	26	
Carrying of load	27	
Use of support	28	

NHESSD

1, 2633–2665, 2013

Table 5. Data related to real flood events used for the calibration of the loss of life model.

Flood event Date	Locality	Number of fatalities LOL	Material loss D [USD]	P	W
1997 – July	Czech Republic	49	1.91E+09	−0.55	−0.19
1998 – July	Czech Republic	10	6.18E+07	−0.43	−0.53
2000 – March	Czech Republic	2	1.03E+08	0.24	0.44
2002 – August	Czech Republic	17	2.32E+09	0.14	0.11
2006 – spring	Czech Republic	11	2.74E+08	0.27	0.30
2009 – June	Czech Republic	18	3.21E+08	0.30	−0.58
2010 – May, June	Czech Republic	3	2.45E+08	0.36	0.47
2010 – August	Czech Republic	5	5.23E+08	0.37	−0.30
1997 – July	Slovakia	1	6.71E+07	−0.23	0.43
1998 – July	Slovakia	47	3.04E+07	−0.82	−0.81
1999 – July	Slovakia	1	5.43E+07	0.10	−0.34
2002 – August	Austria	9	2.27E+09	0.30	0.23
2005 – August	Austria	3	1.40E+07	0.53	0.48
2009 – July	Austria	1	7.34E+06	0.58	−0.05
2000 – October	Switzerland	16	3.82E+08	−0.03	0.27
2005 – August	Switzerland	6	2.33E+09	0.38	−0.26
2007 – August	Switzerland	1	3.15E+08	0.49	−0.10
1997 – July	Poland	54	2.80E+09	−0.49	−0.13
2002 – August	Germany	21	8.75E+09	0.26	0.05

Table 6. Comparison of real casualties with those estimated using Eq. (5)

Flood event Date	Locality	Number of casualties LOL	Estimated number of casualties LOL using Eq. (5)	Relative difference [%]	Absolute difference
1997 – July	Czech Republic	49	45.6	−7	−3.4
1998 – July	Czech Republic	10	11.7	17	1.7
2000 – March	Czech Republic	2	2.7	36	0.7
2002 – August	Czech Republic	17	12.1	−29	−4.9
2006 – spring	Czech Republic	11	4.0	−63	−7.0
2009 – June	Czech Republic	18	6.7	−63	−11.3
2010 – May, June	Czech Republic	3	3.2	6	0.2
2010 – August	Czech Republic	5	6.1	22	1.1
1997 – July	Slovakia	1	4.9	393	3.9
1998 – July	Slovakia	47	27.6	−41	−19.4
1999 – July	Slovakia	1	3.9	287	2.9
2002 – August	Austria	9	9.0	0	0.0
2005 – August	Austria	3	0.8	−72	−2.2
2009 – July	Austria	1	0.8	−21	−0.2
2000 – October	Switzerland	16	7.3	−54	−8.7
2005 – August	Switzerland	6	10.5	74	4.5
2007 – August	Switzerland	1	3.8	284	2.8
1997 – July	Poland	54	44.8	−17	−9.2
2002 – August	Germany	21	17.4	−17	−3.6

NHESSD
1, 2633–2665, 2013

Table 7. Loss of life estimated for the Krnov locality.

Return period N	G(LOL)	D [mil. USD]	P	W	LOL estimate
500	0.0020	3.709	0.55	0.52	0.48
100	0.0100	2.659	0.61	0.52	0.40
50	0.0198	1.426	0.63	0.52	0.31
20	0.0488	0.536	0.63	0.52	0.21
10	0.0952	0.314	0.73	0.52	0.15
5	0.1813	0.105	0.73	0.52	0.10
2	0.3935	0	0.73	0.52	0.00

NHESSD
1, 2633–2665, 2013

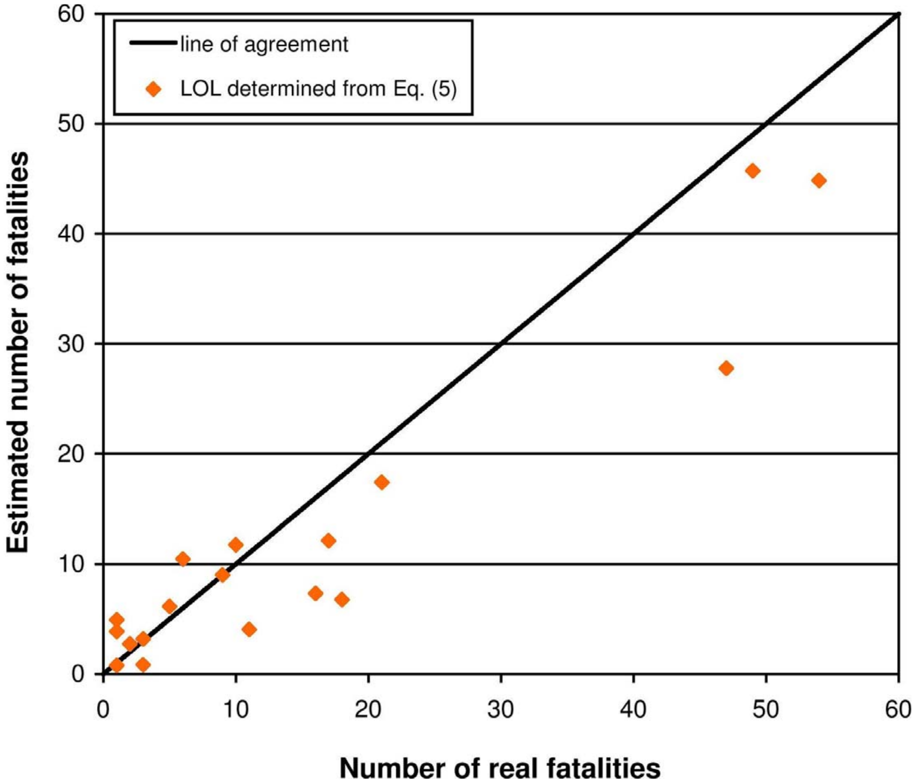

Fig. 1. The degree of agreement between the real and calculated number of fatalities.

NHESSD
1, 2633–2665, 2013

A model for estimating the number of flood fatalities in Europe

M. Brazdova and J. Riha

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

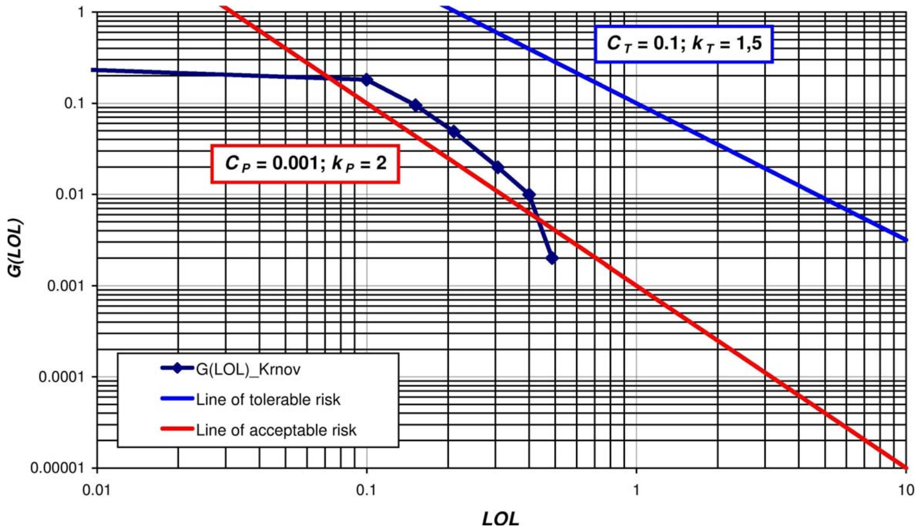

Fig. 2. *F–N* curve for the Krnov locality.