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Generalized model for quantifying morbidity and mortality due to floods

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Research Paper

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Existing models for assessing the harmful consequences of floods are often limited to direct economic damage, while the health and social impacts of floods are rarely systematically quantified. This paper presents a generalized model for quantifying the social aspects of floods that integrates four key risk components: exposure, vulnerability, susceptibility, and resilience. The model was developed based on an analysis of existing approaches and enables the assessment of morbidity and mortality by defining different risk coefficients and indicators. The proposed generalized model allows for the adjustment of parameters to the available statistical data and the development of more comprehensive and effective flood risk mitigation strategies and measures.

Key words:

flood risk, damage quantification, social aspects, morbidity, mortality

Prethodno priopćenje

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Generalizirani model kvantifikacije morbiditeta i mortaliteta uslijed poplava

Postojeći modeli procjene štetnih posljedica poplava često se ograničavaju samo na izravne gospodarske štete, dok se zdravstveni i socijalni učinci poplava rijetko sustavno kvantificiraju. U ovome radu predstavljen je generalizirani model kvantifikacije društvenih posljedica poplava koji integrira četiri ključne komponente rizika: izloženost, ugroženost, ranjivost i otpornost. Model je razvijen na temelju analize postojećih pristupa i omogućuje procjenu morbiditeta i mortaliteta uz definiranje različitih koeficijenata i indikatora rizika. Predloženi generalizirani model omogućuje prilagodbu parametara prema dostupnim statističkim podacima te izradu cjelovitijih i učinkovitijih strategija i mjera ublažavanja poplavnih rizika.

Ključne riječi:

rizik od poplava, kvantifikacija šteta, društvene posljedice, morbiditet, mortalitet

1. Introduction

Floods are natural phenomena whose occurrence cannot be completely prevented. Their adverse consequences are multifaceted and include loss of human life, population displacement, environmental damage, and serious threats to economic development and the continuity of economic activities (Floods Directive [1]). In the Republic of Croatia, floods are among the most frequent and destructive natural disasters. It is estimated that approximately 15 % of the country's land area is at risk of flooding, most of which is now protected with varying levels of security [2]. Due to its geographical position, the presence of significant cultural heritage, and underdeveloped protection systems, Croatia remains highly vulnerable to flood events [2].

In recent history, two flood disasters with particularly severe consequences have been recorded. The most devastating occurred in Zagreb in 1964, when 17 people lost their lives, 65 were injured, 40,000 residents were left homeless, and 10,000 homes together with more than 3,000 commercial buildings were destroyed [3]. The damage amounted to 9.8 % of the republic's gross national income at the time, and transport, energy, and industrial infrastructure were also severely affected [4]. The second major disaster struck eastern Slavonia in May 2014, when heavy rainfall and the breach of the Sava River embankments flooded a large area. The consequences were also severe in Bosnia and Herzegovina and Serbia, with a total of 76 fatalities and more than two million people affected by the flood and its aftermath [5]. In Croatia, the flood endangered 38,000 residents, caused extensive material damage to thousands of buildings including homes, schools, kindergartens, and healthcare facilities and claimed two lives [6].

Flood events have direct impacts on human health, including injuries, acute illnesses, infections, and deaths. In addition to short-term effects, floods can also cause long-term health consequences such as permanent disabilities, the development of mental disorders, the spread of infectious diseases, respiratory and gastrointestinal illnesses, the occurrence of chronic and malignant diseases, reduced work capacity, and other health issues associated with forced displacement, family separation, and deteriorating living conditions [7]. Many of these outcomes are among the leading causes of mortality worldwide and in Croatia, even outside the context of floods. Besides diseases with high mortality rates, skin and soft tissue infections and gastrointestinal disorders are also common, significantly impairing quality of life. Therefore, flood-related diseases and disorders constitute a major public health and social concern [8].

To mitigate the adverse consequences of floods, a risk-based assessment approach is employed, enabling the optimal allocation of available resources. Flood risk is defined as the combination of the probability of a flood event and its potential harmful consequences. Risk management should aim to reduce exposure and vulnerability, ensuring that the costs of protection are proportionate to the expected benefits. The Floods Directive [1] requires determining the "*indicative number of inhabitants potentially affected*", which forms the basis for a preliminary assessment of consequences. Expanding this assessment necessitates quantifying various short- and long-term impacts on the physical and mental health of the population, thereby creating a comprehensive foundation for defining more effective flood risk management measures [2].

Analysis of the literature, studies, and methodological approaches indicates that the quantification of adverse consequences of floods on populations has traditionally relied primarily on assessing population exposure, while the integration of all key components of risk assessment (exposure, vulnerability, and values) has been conducted in only a limited number of cases [9]. More comprehensive approaches, such as the *Flood Vulnerability Index* (FVI), aim to integrate multiple aspects of risk within a single analytical framework [10, 11]. In Croatia, the NACER methodology was developed to evaluate direct, monetizable damages to tangible assets, based on the *Corine Land Cover* database and national sources [12]. However, NACER does not account for health consequences or the social and demographic impacts of floods.

Incorporating the various health impacts of floods on populations is essential for developing more comprehensive flood protection strategies and solutions in flood-prone areas. There is a clear need to develop approaches to quantify the potential morbidity and mortality associated with floods. This study presents a generalized methodology for assessing the potential adverse impacts of floods on populations, integrating social and health aspects into the quantification of flood risks. The methodology is based on a detailed review of the available literature. Application of the proposed method in a pilot area in Croatia is presented in a separate paper currently in preparation.

2. Overview of approaches for quantifying adverse effects on the population

2.1. Overview of approaches for quantifying adverse effects

Assessing the adverse impacts of floods on population health and mortality is a complex process involving several interrelated methodological components. The number of methods developed to quantitatively evaluate loss of life and health impacts remains limited. Predominant approaches in the literature are identified, with their differences highlighted according to the degree of integration of key risk assessment components: hazard, vulnerability, susceptibility, and value.

The first group comprises models that quantify population damage primarily based on population exposure, without explicitly including other components. These include approaches for estimating mortality due to dam-failure floods, based on simple scenarios or expert judgement [13-

16]. Mortality estimates rely mainly on the exposed population and the available warning time, with additional consideration of flood severity [14, 15] and the level of knowledge about the flood hazard [15, 16]. The next group consists of models that estimate mortality based on water depth [17] and, in some cases, also include the probability of a flood event [18]. Of particular interest are integrated approaches, such as DEFRA/EA [19, 20], the Dutch Standard Method [21], SUFRI [22] and IZVRS [12], which simultaneously consider multiple risk components, including water depth, velocity, or rate of water-level rise. One of the more advanced tools is the *Flood Vulnerability Index* (FVI) [10, 11], which, although it does not explicitly incorporate the probability of a flood event, combines exposure, threat, and vulnerability. It is evident that traditional methods primarily quantify the adverse consequences of floods based on the physical characteristics of floodplains, whereas the assessment of social vulnerability provides a critical additional input. Incorporating social factors such as age, income, disability, and access to resources offers valuable insight into how a community experiences and recovers from flood damage. Integrating indicators of population vulnerability into the quantification of adverse consequences enables the development of more effective and equitable flood risk management plans and the identification of targeted measures for vulnerable populations in affected areas.

2.2. Overview of approaches to estimating loss of life due to floods

Estimating the number of flood victims remains one of the most challenging aspects of flood damage analysis. Assessing loss of life involves linking mortality in the affected area with the characteristics of the flood event, the availability of timely warnings and evacuation options, and the attributes of the exposed population. The mortality rate f is defined as the ratio of the number of deaths N_s to the number of people at risk N.
A significant proportion of global flood-related fatalities result from coastal flooding events, such as storm surges associated with tropical cyclones (hurricanes, typhoons). Empirical equations developed in Japan and the USA [23, 24] define the mortality rate f as a function of water depth h, exhibiting an *S*-shaped curve with a sharp increase at depths of 2.5–4.0 m and an asymptotic rate limit of approximately f=0.34. Analyses of Hurricane Katrina [24, 25] indicate the highest mortality rates near levee breaches and in areas of greater water depth, with particularly vulnerable groups including the elderly, 60 % of whom were over 65 years old. The US Bureau of Reclamation [13] developed methods to estimate mortality in dam-failure events based on the number of endangered people N and the warning time T. The mortality rate f ranges from 0.5 (T < 0.25 h) to 0.0002 (T > 1.5 h). Graham [15] further differentiates mortality according to flood severity (the product of depth and water velocity), warning category, and the level of risk awareness in the population. More advanced models, such as the *Life Safety Model* [26, 27] and *Lifesim* [28], integrate hydraulic parameters, human movement patterns, building stability, and evacuation efficiency. Studies following the 2004 Indian Ocean tsunami [29, 30] report mortality rates between 0.13 and 0.17, highlighting the significant influence of age and gender on the risk of death. Overall, methods for estimating mortality range from simple empirical equations based on historical data to complex simulation models incorporating hydrodynamic parameters and the effectiveness of warning systems. Analyses of recent fatal flood events underscore the importance of including socio-demographic factors in flood damage quantification. Two approaches for assessing flood damage the DEFRA/EA method and the Dutch Standard Method which account for multiple risk components, are discussed in further detail below.

2.3. DEFRA/EA method

As part of the "*Flood Risks to People*" project, a DEFRA/EA methodology for assessing flood risk to populations was developed [19, 20]. The risk to people is determined by three factors: flood hazard, human vulnerability, and area vulnerability. Flood hazard assessment is based on studies of human stability in water currents and the effects of debris, while the values of other factors are determined through expert judgment. The method includes an assessment of both morbidity and mortality. Absolute morbidity refers to the total number of injuries, including fatalities, and is calculated using the following expression:

$$N_i = N \cdot X \cdot Y \tag{1}$$

where N_i is the number of injuries and deaths (absolute morbidity), N is the number of inhabitants in the area (population), X is the proportion of the population at risk within the population (for a particular flood event), and Y is the proportion of the endangered population that will suffer an injury or death.
The hazard rating HR of an area was calculated based on the depth and velocity of the water and the presence of debris. The hazard rating HR was calculated using the following equation:

$$HR = h \cdot (v + 0{,}5) + DF \tag{2}$$

where h is the water depth (m), v is the flow velocity (m/s), and DF is the debris-flow factor. The debris factor has a value of 0 for the case where the presence of debris is unlikely, 0.5 for the case where the presence of debris is possible, and 1 for the case where the presence of debris is probable.
The area vulnerability AV is defined depending on the flood warning system, speed of flood occurrence, and characteristics of the area (type of construction, presence of parks, etc.). The area vulnerability (AV) is obtained as the sum of the scores.

Table 1. DEFRA/EA model for assessing Area Vulnerability indicators (*AV*)

Vulnerability indicator	1 – low risk area	2 – medium risk area	3 – high risk area
B1: Speed of flood occurrence	Very gradual (several hours)	Gradual (about 1 hour)	Flash flooding
B2: Area characteristics	Multi-storey buildings	Typical residential area (multi-storey and single-storey buildings), commercial and industrial area	Single-family homes, caravans, roads, parks, schools, campsites, etc.
B3: Flood warning	B3 = 3 - (P1 x (P2 + P3)) where P1 = % of alert coverage target met P2 = % of warning time target met P3 = % of effective action goal fulfilled		

$$AV = B_1 + B_2 + B_3 \tag{3}$$

where B_1 represents the speed of flood occurrence, B_2 represents the characteristics of the area (type of construction, presence of parks, etc.), and B_3 represents the flood warning system. Each indicator was assigned a score of 1, 2, or 3, according to Table 1. The sum of the scores, which ranges from 3 to 9, represents the level of the vulnerability *AV*.

The share of the population at risk from the total population *X* is calculated as the product of the degree of exposure *HR* and the degree of vulnerability *AV*., considering that *X* must be less than or equal to 1:

$$X = \min\left(HR \cdot \frac{AV}{100}, 1\right) \tag{4}$$

People's vulnerability *Y* is defined based on the characteristics of the vulnerable population that can affect the likelihood of injury/death. The vulnerability level is obtained as follows:

$$Y = C_1 + C_2 \tag{5}$$

where C_1 is the proportion of the population with long-term diseases (%), and C_2 is the proportion of the population older than 75 years (%).

In addition to morbidity, the methodology provides an estimate of mortality N_s according to the following expression:

$$N_s = \min(0{,}02 \cdot HR, 1) \cdot N_i \tag{6}$$

2.4. Dutch standard method (NSM)

Several methods have been developed in the Netherlands over the past few decades to estimate the loss of life caused by coastal and river floods. These methods are mostly based on data from the 1953 flood disaster, when coastal flooding in the UK, Belgium, and Netherlands caused more than 2000 deaths [31]. Analyses have linked the loss of life to water depth *h* and water rise rate *w*, with three mortality zones identified [32, 33]. Based on previous research, the Dutch Standard Method (NSM) [21] was developed, in which the mortality rate *f* is defined as a function of the water depth *h*, flow velocity *v* and water rise rate *w*. A distinction was made between three situations (zones). Separate mortality rate functions *f* were applied to each zone as follows:

a) zone 1 – high flow velocity area:

$$f = 1: \text{if } h \cdot v \geq 7.0 \text{ m}^2\text{/s and } v \geq 2.0 \text{ m/s} \tag{7}$$

b) zone 2 – high rise rate:

$$f = \min\{1; 0.00145 \cdot e^{1.39h}\} \text{ if } h \geq 1.5 \text{ m and } w \geq 0.5 \text{ m/h} \tag{8}$$

c) zone 3 – other areas:

$$f = \min\{1; 0.00134 \cdot e^{0.59h}\} \tag{9}$$

where *f* is mortality rate (-), *h* water depth (m), v flow velocity (m/s), and *w* water level rise rate (m/h).

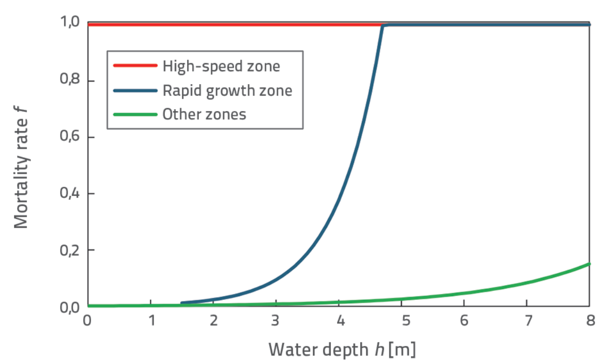

Figure 1. Mortality rate functions for the Dutch Standard Method [20]

When estimating the number of victims, building height and the possibility of evacuation are taken into account. It is assumed that people in high-rise apartments (more than three floors above ground) are safe and can be treated as effectively evacuated. The method allows for the inclusion of partially evacuated populations through the factor f_E. This factor is set to 0 in areas without warning or evacuation and can rise to 1 in areas with effective warning systems and organised evacuation. The total number of fatalities is multiplied by $1-f_E$ to account for the impact of possible evacuation. In the subsequent step, new mortality functions were developed based on an analysis of empirical data from historical floods [34].

3. A new model for quantifying the harmful consequences of floods for the population

3.1. Theoretical model

A theoretical quantitative model for assessing adverse consequences can be formulated using indicators in the following general form:

$$P = r(Q) \tag{10}$$

where gdje je $P = (p_1, p_2, ..., p_j)$ is the set of output indicators (the most significant consequences), $Q = (q_1, q_2, ..., q_j)$ is the set of input indicators, and $r(Q)$ is the functional relationship (transformer) formulated by the model. The quantification of consequences can be determined for any number of input indicators, such that when estimating the number of injuries ($N_{p,j}$) for a particular consequence, any number of state coefficients and indicators are used by the expression

$$N_{p,j} = k_{p,j} \cdot N \tag{11}$$

where $N_{p,j}$ is the number of consequences, $k_{p,j}$ is the coefficient of consequence, j is the index of the individual type of consequence $(p_1, p_2, ..., p_j)$ and N is the number of people at risk.
The consequence coefficient $k_{p,j}$ is calculated separately for each consequence $(p_1, p_2, ..., p_j)$, and is obtained by considering the four state coefficients as follows:

$$k_{p,j} = \min\left(\frac{k_{a,j} \cdot k_{b,j} \cdot k_{c,j}}{k_{d,j}}, 1\right) \tag{12}$$

where $k_{a,j}$ is the hazard coefficient, $k_{b,j}$ is the susceptibility coefficient, $k_{c,j}$ is the vulnerability coefficient, $k_{d,j}$ is the resilience coefficient, and j is the index of the individual type of consequence $(p_1, p_2, ..., p_j)$.
The hazard coefficient $k_{a,j}$ is defined through the hazard indicator qa_i, which represents the hydraulic conditions (water depth, water velocity, etc.) in the area.

$$k_{a,j} = f(qa_1, qa_2, ..., qa_i) \tag{13}$$

The susceptibility coefficient $k_{b,j}$ is defined by normalised susceptibility indicators qb_i, which represent the susceptibility of the area in question (height of buildings, presence of mobile homes, etc.) and associated weighting coefficients β_i:

$$k_{b,j} = \sum_{i=1}^{n_b} \beta_i \cdot qb_i \tag{14}$$

The vulnerability coefficient $k_{c,j}$ is defined by normalised vulnerability indicators qc_i, which represent the presence of vulnerable population (population with difficulties, very old population, etc.) and associated weighting coefficients γ_i:

$$k_{c,j} = \sum_{i=1}^{n_c} \gamma_i \cdot qc_i \tag{15}$$

The resilience coefficient $k_{d,j}$ is defined by normalised resilience indicators qd_i, which represent the possibility of risk reduction (presence of early flood warning, internet access, etc.) and associated weighting coefficients δ_i:

$$k_{d,j} = \sum_{i=1}^{n_d} \delta_i \cdot qd_i \tag{16}$$

All risk indicators, hazard qa_i, susceptibility qb_i, vulnerability qc_i and resilience qd_i were defined according to the desired and available risk indicators for the population in the national databases.

3.2. Generalized damage assessment model

Based on the theoretical model Eqs. (10) to (16) and the DEFRA/EA methodology presented, a generalized model for quantifying the number of injuries (morbidity) and fatalities (mortality) from floods can be defined by further specifying the model parameters. Absolute morbidity (the total number of injuries and deaths) is calculated as

$$N_i = k_i \cdot N \tag{17}$$

where k_i is the morbidity coefficient (injuries and deaths), and N is the number of people at risk.

Mortality (number of deaths) is expressed as

$$N_s = k_s \cdot N \tag{18}$$

where k_s is the mortality coefficient (deaths).

Morbidity coefficient k_i is obtained as the product of the individual state coefficients as follows:

$$k_{p,j} = \min\left(\frac{k_{a,j} \cdot k_{b,j} \cdot k_{c,j}}{k_{d,j}}, 1\right) \tag{19}$$

where $k_{a,j}$, $k_{b,j}$, $k_{c,j}$ and $k_{d,j}$ are the coefficients of hazard, susceptibility, vulnerability, and resilience, respectively, and j is the index of a particular type of consequence $(p_1, p_2, ..., p_j)$.

The mortality coefficient k_s is calculated from the morbidity rate as

$$k_s = k_{as} \cdot k_i \quad (20)$$

where k_{as} is the mortality risk coefficient.

3.2.1. Hazard coefficient

The hazard coefficient was calculated from the general form of the flood hazard factor separately for morbidity k_{ai} and mortality k_{as}, according to the following expressions:

a) hazard coefficient for morbidity (k_{ai})

$$k_{ai} = \min\{0.045[qa_1 \cdot (qa_2 \cdot qa_4 + 0.5) + qa_3]\} \quad (21)$$

b) hazard coefficient for mortality (k_{as})

$$k_{as} = \min\{0.020[qa_1 \cdot (qa_2 \cdot qa_4 + 0.5) + qa_3]\} \quad (22)$$

where qa_1 is the representative water depth (m), qa_2 is the representative flow velocity (m/s), qa_3 is the debris potential indicator, and qa_4 is the flow velocity coefficient. The debris potential qa_3 was calculated according to Table 2, and takes into account the prevailing surface type and hydraulic conditions (water depth and flow velocity) were considered.
In defended areas situated behind protective dikes or walls, locally higher water velocities can occur due to flooding or breaches of the defence lines during high flows. To account for scenarios involving local increases in water velocity, an additional water velocity coefficient qa_4 has been introduced in the exposure assessment. This coefficient is determined by dividing the area into three zones (A, B, C) based on the shortest distance from the defence line (see Table 3). The hazard coefficients for morbidity k_{ai} and mortality k_{as} are calculated for each zone, incorporating the flow velocity coefficient qa_4.

3.2.2. Susceptibility coefficient

The susceptibility coefficient k_b is determined from the normalised susceptibility indicators qb_i and their associated weighting coefficients β_i. These susceptibility indicators are derived from statistical reports, GIS analysis of the area, and available databases. All indicators are normalised relative to the average condition in the area, with a value of 1 representing the mean condition.

The indicator "*qb_1-% of single-storey houses in the total number of residential buildings*" is calculated from the relationship:

$$qb_1 = \frac{\textit{Residential buildings with 1 apartment}}{\textit{Total apartments in residential buildings}} \cdot 100\% \quad (23)$$

The indicator "*qb_2-% of apartments for temporary housing in the total number of apartments*" is calculated from the relationship:

$$qb_2 = \frac{\textit{Apartments for temporary residence}}{\textit{Total apartments}} \cdot 100\% \quad (24)$$

The weighting coefficients for the susceptibility indicators are $\beta_1 = 0.80$, $\beta_2 = 0.20$.

3.2.3. Vulnerability coefficient

The vulnerability coefficient k_c is determined from normalised vulnerability indicators qc_i and associated weighting coefficients γ_i. The vulnerability indicators were obtained from statistical reports. All indicators were normalised to the average condition in the area where the indicator had a value of 1.

Table 2. Determination of debris potential (qa_3) considering the prevailing surface type and hydraulic conditions in the area

Debris class	Water depth and flow velocity	Water depth class	Flow velocity class	qa_3		
				Agricultural areas	Forests and semi-natural areas	Artificial surfaces
1	$h \leq 0.5$ m and $v \leq 0.5$ m/s	1	1.2	0	0	0
2	$0.5 < h \leq 1.5$ m and $v \leq 0.5$ m/s	2	1	0	0	0.5
3	$0.5 < h \leq 1.5$ m and $0.5 < v \leq 2.0$ m/s	2	2	0	0.5	1.0
4	$h > 1.5$ m and/or $v > 2.0$ m/s	3.4	3	0.5	1.0	1.0

Table 3. Determination of the flow velocity coefficient (qa_4) according to distance from the reference line

Distance zone from the reference line	Distance from reference line [m]	Flow velocity coefficient (qa_4)
Zone A	0 – 50 m	2.0
Zone B	50 – 100 m	1.5
Zone C	>100 m	1.0

The indicator "qc_1*-% of the population with disabilities in the total population*" is calculated from the relationship:

$$qc_1 = \frac{Population\ with\ difficulties}{Total\ population} \cdot 100\% \qquad (25)$$

The indicator "qc_2*-% of children under 10 years of age in the total population*" is calculated from the relationship:

$$qc_2 = \frac{Under\ 10\ years\ old}{Total\ population} \cdot 100\% \qquad (26)$$

The indicator qc_3*-% of people over 75 years of age in the total population*" is calculated from the relationship:

$$qc_3 = \frac{Older\ than\ 75\ years}{Total\ population} \cdot 100\% \qquad (27)$$

The weighting coefficients for the vulnerability indicators are equal and amount to $\gamma_1 = \gamma_2 = \gamma_3 = 0.333$.

3.2.4. Resilience coefficient

The resilience coefficient k_d is determined from normalised resilience indicators qd_i and associated weighting coefficients δ_i. The resilience indicators were obtained from statistical reports and available databases. All indicators were normalised to the average state in the area where the indicator had a value of 1.

The indicator qd_1 *% of households using the Internet out of the total number of households*" is calculated from the relationship:

$$qd_1 = \frac{Households\ using\ the\ internet}{Number\ of\ private\ households} \cdot 100\% \qquad (28)$$

The indicator "qd_2 *Presence of floods in the past of the system*" is determined according to the Table 4. If at least one flood has been recorded in the area in the last 5 years, then the indicator is "YES". The register of flood events is available on the Croatian Waters website. The indicator "qd_3*: Presence of a flood early warning system*" is determined according to the Table 5.

Table 4. Determination of the presence of floods in the system's past (qd_2)

Existence of floods in the system's past	qd_2: Floods in the past
NO	0.80
YES	1.20
unknown	0

Table 5. Determination of the presence of a flood early warning system (qd_3)

Existence of a warning system	qd_3: Warning system
NO	0.80
YES	1.20

The weighting coefficients for the resilience indicators are equal, with values of $\delta_1 = \delta_2 = \delta_3 = 0.333$.

3.3. Brief comparison of model results

The following presents a summary of the mortality rate estimation (the ratio of the number of deaths to the number of people at risk) for the generalized model (GM), the Dutch Standard Method (NSM), and the DEFRA and SUFRI models, in relation to changes in the flood early warning system indicator. The flood early warning indicator directly influences the mortality rate in the DEFRA, SUFRI, and generalized models, whereas in the NSM method it is incorporated through additional equations [21]. In the DEFRA model, the indicator B_3 is included in the area vulnerability level *AV* (Table 1), which appears in the numerator of Eqs. (1) and (4); thus, the mortality rate is directly proportional to this input indicator. In the generalized model (GM), the indicator qd_3 (Table 5) is included in the calculation of the resilience coefficient k_d, which appears in the denominator of Eq. (19); therefore, the mortality rate is inversely proportional to the indicator.
The mortality rate results are presented for three input indicator values: (a) lower bound (minimum), (b) average value (mean), and (c) upper bound (maximum). The DEFRA and SUFRI models correspond to cases with an effective warning system ($B_3 = 1$ za DEFRA, *Cp3* za SUFRI), limited warning system ($B_3 = 2$ za DEFRA, *Cp2* za SUFRI) and no warning system ($B_3 = 3$ za DEFRA, *Cp1* za SUFRI). For the generalized model (GM), the results are presented for two groups (two ranges) of indicators, qd_3. Group 1 (GM1) refers to the smaller range of indicators $qd_3 = 0.8$ and 1.2, while group 2 (GM2) refers to the larger range $qd_3 = 0.4$ and 1.6. For the two groups mentioned, the resilience coefficients $k_b = 0.87$ and 1.13 for group 1 (GM1) and $k_d = 0.73$ and 1.27 for group 2 (GM2) are obtained. All other input indicators retain their average values in the models: $w \geq 0.5$ m/h for the NSM model, $B_2 = B_3 = 2$; $PV = 20$ % for the DEFRA/SUFRI models and $DF = 0{,}50$; $k_b = 1.0$; $k_c = 1.0$ for the generalized model.
Adjusting the flood warning indicator to its lower and upper limits results in the DEFRA and SUFRI methods producing the same mortality rate ratios relative to the central value (0.83 for the lower limit and 1.17 for the upper limit of the indicator). In the generalized model for group 1 (GM1), slightly narrower ranges (0.88 and 1.15) are observed, whereas for group 2 (GM2), slightly wider ranges (0.79 and 1.36) are observed compared with the DEFRA method. It is also shown that a 33 % change in the input indicator ($qd_3 = 1.2$ for GM1, $qd_3 = 1.6$ for

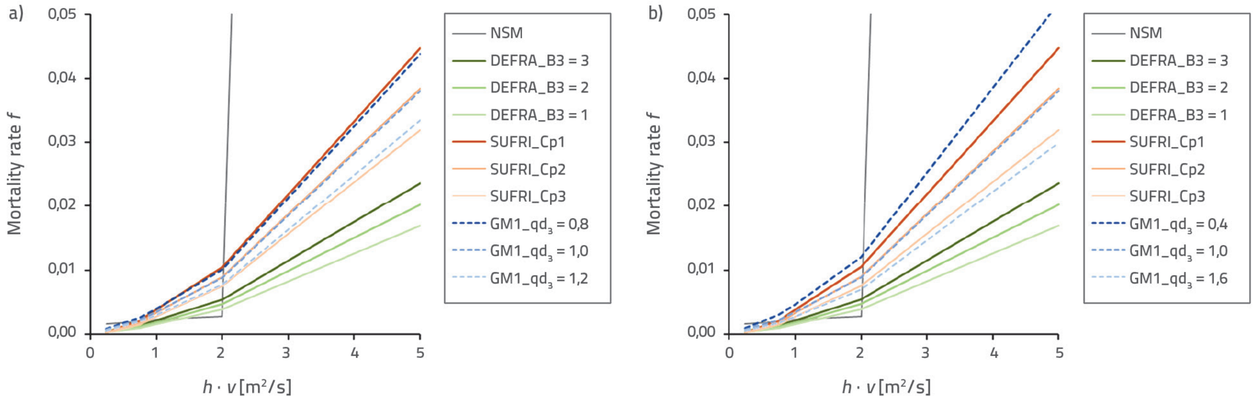

Figure 2. Sensitivity of mortality rates to changes in flood early warning system indicators for the NSM, DEFRA, SUFRI, and generalized model methods. For the generalized model (GM), results are shown for two groups of indicators: a) GM1 for qd_3 = 0.8, 1.0, 1.2; b) GM2 for qd_3 = 0.4, 1.0, 1.6

Table 6. Mortality rate for the NSM method for a water level rise rate of $w \geq 0.5$ m/h

f (-)	*h* [m]										
v [m/s]	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	5.25
0.0	0.0016	0.0021	0.0028	0.0165	0.0331	0.0663	0.133	0.266	0.533	1	1
0.5	0.0016	0.0021	0.0028	0.0165	0.0331	0.0663	0.133	0.266	0.533	1	1
1.0	0.0016	0.0021	0.0028	0.0165	0.0331	0.0663	0.133	0.266	0.533	1	1
1.5	0.0016	0.0021	0.0028	0.0165	0.0331	0.0663	0.133	0.266	0.533	1	1
2.0	1	1	1	1	1	1	1	1	1	1	1
2.5	1	1	1	1	1	1	1	1	1	1	1

GM2) results in an approximate 10 % reduction in mortality rate (GM2 versus GM1). These results for the two groups of input indicators demonstrate the elasticity of the generalized model and its capacity to adapt readily to changes in input values.

A comparison of model results (Figure 2) further indicates that mortality rates from the generalized model (GM) are approximately equal to those from the SUFRI method and about 85 % higher than those from the DEFRA method. Mortality rates from the NSM method are similar to those from the DEFRA and GM methods for lower hazard coefficient values $h \cdot v \leq 2.0$ m²/s, whereas for higher hazard values $h \cdot v > 2.0$ m²/s, the mortality rate rises sharply to $f = 1.0$.

A comparison of mortality rate results shows that, in the DEFRA/EA approach, mortality and morbidity are continuous functions of water depth and velocity. In the Dutch Standard Method (NSM), the mortality function is continuous with respect to depth but discontinuous with respect to velocity, exhibiting a sharp transition to a value of 1.0 (Table 6). Moreover, in the NSM method, for water velocities less than $v < 2.0$ m/s, the mortality rate remains constant for all velocities. Studies of individual stability in floodwaters indicate that adults become unstable at water depths above $h \geq 0.27$ m and water velocities greater than $v \geq 1.0$ m/s [34], suggesting that the NSM method requires additional verification for water velocities above $v \geq 1.0$ m/s, particularly at greater water depths $h \geq 1.25$ m. Considering these functional characteristics and the types of floods for which it was developed, the DEFRA/EA method is considered more appropriate than the NSM method for assessing the consequences of river floods.

4. Discussion

The proposed approach is designed to estimate adverse consequences (morbidity and mortality) using the fundamental risk components exposure, hazard, vulnerability, and resilience for the average conditions in the observed area. For the development of the generalized approach, the DEFRA/EA and NSM methods were selected. These methods were developed for river floods (with the NSM method applicable to both coastal and river floods) based on recorded historical events and have been further refined and validated since their initial development. The DEFRA/EA method served as the basis for defining the number of consequences, as it explicitly accounts for exposure based on both water depth and velocity, whereas most other methods consider only water depth. Furthermore, the DEFRA/EA method is the only one that allows for the assessment of both morbidity and mortality. The principal advantage of the proposed approach is its ability to estimate various potential adverse consequences of river floods at multiple levels of detail. The approach can be applied at macro, meso, and micro scales (state, city, settlement), with the level of detail in the assessment of consequences (physical, psychological) determined by the availability and granularity of input variables. Polygons of water depth classes are used as the basic spatial units. For strategic or planning purposes, further spatial subdivision is unnecessary, whereas for detailed study-level analyses, depth polygons are subdivided according to water velocity classes. A key feature of the approach is its robustness. The model is developed for the average conditions in the area, allowing the inclusion or exclusion of one or more input risk indicators without making the results highly sensitive to changes in a single indicator. The following paper will present the process of defining the most important flood consequences and associated indicators, as well as a comparison of the assessment of consequences according to the proposed approach with other methods for a pilot area in Croatia.

5. Conclusion

Based on a review of existing approaches, this paper presents the development of a generalized model for quantifying the social consequences of floods, offering a deterministic framework that incorporates population hazard, susceptibility, vulnerability, and resilience. Unlike existing methods that focus primarily on material damage or a limited range of health impacts, this model includes an assessment of both morbidity and mortality, enabling a more comprehensive evaluation of the societal impact of flood events. The use of a system of indicators, derived from nationally available databases and statistical reports, allows the quantification of different risk scenarios and their adaptation to specific spatial and demographic conditions. The effectiveness of the generalized model is demonstrated through several key features:

- The model permits the application of different functional relationships, or consequence coefficients, for each type of outcome, allowing more reliable quantification of flood impacts depending on the nature of the consequence.
- Any number of input indicators can be used for each consequence, with one or more indicators describing the same type of outcome. This adaptability allows the model to be updated by modifying the number or type of input indicators, ensuring continuous alignment with new findings and available datasets.
- The consequence coefficient is calculated by multiplying the weighted, normalised state indicators. Individual indicators are evaluated through normalisation, ensuring consistency and comparability of results across different model components.
- Each normalised indicator transforms the possible outcomes of its corresponding input into a standardised range from 0 to 1, allowing heterogeneous data to be combined within a single analytical framework.

The generalized model provides a foundation for informed decision-making on investment priorities in flood protection systems, optimising early warning strategies, and developing targeted protection measures for the most vulnerable populations. In the long term, its application can contribute not only to reducing loss of life and injury but also to strengthening community resilience, improving public health outcomes, and promoting more efficient use of financial resources allocated for flood protection.

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