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IMPLEMENTATION OF MATRIX METHODS IN FLOOD RISK ANALYSIS AND ASSESSMENT

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ABSTRACT: In the work the matrix methods of flood risk analysis and assessment were presented. Also the issue of flood risk in terms of its regulations was presented. The flood risk analysis and assessment were performed with the use of risk matrix for one of the Subcarpathian commune. For this purpose, flood risk maps were prepared and potential flood losses were calculated in accordance with existing legislation.

KEY WORDS: flood risk, risk matrix, flood losses

 JEL: D81, Q54

Introduction

Flood due to possible negative effects should be included in crisis situation understood in accordance with art. 3 of the Act of April 26, 2007 on Crisis Management (Journal of Laws 2007 No. 89 item 590) as "a situation affecting negatively the level of safety of people, property of considerable size or the environment, causing significant restrictions on the operation of relevant public administration bodies due to the inadequacy of the forces and possessed means" (Dz.U. 2002 nr 62 poz. 558;Dz.U. 2017 poz. 209).

The Floods Directive contains important issues related to the adopted flood risk strategies. In order to create the basis of these strategies, it is necessary to develop flood risk maps and, on their basis, to develop flood risk management plans (Ahmad et al., 2013; Blažkova, Beven, 2002; Brocca, 2013; Flores-Montoya et al., 2016; Röthlisberger et al., 2017). In the latter, Member States should refrain from taking measures and implementation of measures that could increase the risk of flooding in the other Member States. And even, in accordance with the principle of solidarity, the decision should be made jointly and act along the entire course of the river (Graniczny, Mizerski, 2007).

For each river basin district, Member States should prepare a preliminary flood risk assessment, containing at least: river basin maps, description of floods that occurred in the past if the likelihood of similar floods occurrence in future is big, description of floods from the past if similar events in the future can have negative consequences. On the basis of an initial flood risk assessment, Member States identify areas where there is a high risk of flooding or the occurrence of such a risk is likely. For each river basin district flood hazard maps and flood risk maps should be prepared. Flood hazard maps show geographic areas where the probability of flooding is low or extreme events are likely to occur. For each of the above scenarios, the following elements are depicted on the maps: flood range, water depth and, depending on the needs, the water flow rate. Flood risk maps present possible negative consequences of flooding and include: estimated number of inhabitants affected by floods, type of economic activity in the area affected by flooding and other useful information depending on the Member State. On the basis of flood risk maps Member States develop flood risk management plans and set objectives for flood risk management "with particular emphasis on reducing the potential negative consequences of flooding for human health, the environment, cultural heritage and economic activity" (Bartnik, Jokiel, 2012; Dyrektywa 2007/60/WE).

From the known methods of risk analysis and assessment to perform a flood risk analysis, the most appropriate is risk matrix that is based on a basic risk definition (Cuellar, McKinney, 2017; Haimes, 2009; Lubowiecka, Wieczysty, 2000; Rak, 2004, 2008, 2009, 2010, 2014; Rincón et al., 2018; Sieg et al., 2017; Tchórzewska-Cieślak, 2008; Zhou et al., 2018). In order to create flood risk maps, the Geographic Information Systems (GIS) should be applied to the numerical terrain model (NMT) of water table elevations during floods obtained as a result of mathematical hydrological modelling (Tokarczyk et al., 2012). To set an example to show the issue, the exemplary matrices of flood risk for the commune X located in the Subcarpathian province, were presented. As a determinant of losses during floods, the number of inhabitants residing in the area at risk of flooding according to the flood hazard map was adopted. In this way, flood risk matrices were prepared for X commune, taking into account the number of people at risk of flooding in relation to the flooding probability.

The Water Law defines the flood risk as "the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event" (Dz.U. 2017 poz. 1566).

Flood protection is the task of government and self-government administration bodies assisted by water users. The protection against floods is performed taking into account flood hazard maps (Armenakis et al., 2017; Dawson et al., 2011; Haberlandt et al., 2008; Ouma, Tateishi, 2014; Simonovic, 2009; Zischg, 2018), flood risk maps and flood risk management plans, through e.g. multi-index evaluation for flood disaster (Dou et al., 2018), building ANN-Based Regional Multi-Step-Ahead Flood models (Chang et al., 2018), using a response curve approach (Murdock et al., 2018), sketch maps (Klonner et al., 2018), cloud-model-based method for risk assessment (Yang et al., 2018), application of a bayesian approach to dynamic assessment of flood (Wu et al., 2018), a parametric distance function approach (Zheng et al., 2018).

For their preparation, it is necessary to conduct preliminary flood risk assessment, taking into account the method of calculating the value of potential flood losses in individual classes of land use, for the purposes of developing flood risk maps (Dz.U. 2013 poz. 104). The paper proposes the use of matrix methods for the analysis and assessment of flood risk in accordance with the applicable legislation.

Research methods

Matrix methods for risk analysis

The risk matrix is a combination of a point scale probability of the undesirable event with a scale of consequences. The two-parameter risk estimation matrix is one of the simplest. Point values defining the risk categories were obtained using the dependence (Rak, 2004):

$$r = P \cdot C \tag{1}$$

where:
P – the probability of the undesirable event,
C – consequences of this event.

Considering the complexity of the systems, a three-parameter risk matrix was proposed. Additional parameters included in the matrix are: exposure to hazard – E or vulnerability – V. According to the above parameters, the numerical risk assessment is their product (Rak, 2004; Rak, Tchórzewska-Cieślak, 2005):

$$r = P \cdot C \cdot E \tag{2}$$

or

$$r = P \cdot C \cdot V \tag{3}$$

Along with the development of modern techniques, almost all the areas of life are equipped with various types of security and monitoring systems, in order to increase their safety and reliability. Therefore, it seems advisable to include in the matrix a fourth parameter defining the amount of protection.

A four-parameter matrix for risk estimation based on the formula is proposed (Rak, 2004; Rak, Tchórzewska-Cieślak, 2005):

$$r = \frac{P \cdot C \cdot V}{O} \tag{4}$$

where:
O – protection against threats.

In addition to protection in the risk matrix, the risk exposure (E) known from the three-parameter matrix can be taken into account, in that way we obtain a five-parameter risk estimation matrix along with the formula (Rak, 2004; Rak, Tchórzewska-Cieślak, 2005):

$$r = \frac{P \cdot C \cdot M \cdot E}{O} \tag{5}$$

where:
O – protection point weight.

Each time, for individual parameters, the size level is assigned according to the adopted point scale, e.g. low – N = 1, medium – S = 2, high – W = 3.

In this way, a punctual scale of risk measures is obtained in numerical form, which is the basis for risk assessment.

The acceptable level of risk is determined by introducing criterion values for each level of tolerable, controlled and unacceptable risk.

Implementation of risk matrices in the assessment of flood risk

Adaptation of a two-parameter matrix

On the basis of the number of endangered inhabitants, consequences categories (C) presented in table 1 were adopted. In table 2 the categories of probability (P) of flood occurrence are presented (Zygmunt, 2017).

Table 1. Categories of consequences – C

Number of endangered inhabitants	Point weight	Description
0	1	No danger
1–10	2	Negligible
11–100	3	Marginal
101–200	4	Significant
>200	5	Serious

Source: author's own work.

Table 2. Probability categories – P

Probability of flood occurrence	Point weight	Description
0,5%	1	Improbable
1%	2	Unlikely
5%	3	Occasional
10%	4	Possible
50%	5	Frequent

Source: author's own work.

After combining the probability and consequences categories, a risk matrix was obtained according to the dependence 1, which was presented in the form of table 3.

Table 3. Risk matrix

POINT WEIGHT			PROBABILITY – P				
			0,5%	1%	5%	10%	50%
			Improbable	Unlikely	Occasional	Possible	Frequent
			3	4	5		
CONSEQUENCES – C	No threat	1	1	2	3	4	5
	Negligible	2	2	4	6	8	10
	Marginal	3	3	6	9	12	15
	Significant	4	4	8	12	16	20
	Serious	5	5	10	15	20	25

Source: author's own work.

Depending on the obtained results in the risk matrix theflood risk was divided into:

- weight from 1 to 4 – tolerable risk,
- weight from 6 to 10 – controlled risk,
- weight from 12 to 25 – unacceptable risk.

Adaptation of a three-parameter matrix

Considering the vulnerability (V) related to flood risk zones, the risk assessment may be determined by multiplying the probability parameter (P), the consequences (C) and the vulnerability to the risk (V), according to the equation 3.

The following scale and weight for individual parameters were proposed:

- point weights for the probability parameter – P:
  - improbable event, the probability of flood occurrence 0,5%; with a weight 1,
  - unlikely event, the probability of flood occurrence 1%; with a weight 2,
  - occasional event, the probability of flood occurrence 5%; with a weight 3,
  - possible event, the probability of flood occurrence 10%; with a weight of 4,
  - frequent event, the probability of flood occurrence 50%; with a weight of 5.
- point weights for the consequences parameter – C:
  - no threat, number of endangered inhabitants 0; with a weight of 1,
  - negligible, number of endangered inhabitants 1-10; with a weight of 2,

 – marginal, number of endangered inhabitants 11-100; with a weight of 3,
 – significant, number of endangered inhabitants 101-200; with a weight of 4,
 – serious, number of endangered inhabitants > 200; with a weight of 5.
- point weights for the vulnerability parameter – V (Nachlik et al., 2000; Ozga-Zielińska et al., 2003; Radczuk et al., 2007):
 – flood threat zone (ZS) – this area is for the most part of the year constantly flooded with water up to the average of the highest flows in multi-year (SWQ); for a water depth range of ≤ 0,5 m, with a weight of 1,
 – high flood hazard zone (ZW) – this is the area above the ZS zone and with the upper limit at the level of water from the maximum flow with the probability of exceeding 1% of the so-called hundred-year water (Qmax 1%); for a water depth range of 0,5 < h ≤ 2 m, with a weight of 2,
 – significant flood zone (ZZ) – this is the area above the ZW zone with the upper limit at the level of water caused by the flow with half the maximum reliable flood (0,5xMWW); for a water depth range 2 < h ≤ 4 m, with a weight of 3,
 – small flood hazard zone (ZM) – this is the area above the ZZ zone up to the maximum reliable flood (MWW); for a water depth range > 4 m, with a weight of 4.

In this way, we get the quantitative risk matrix presented in table 4.

Table 4. Risk matrix

POINT WEIGH			PROBABILITY – P																			
			0,5%				1%				5%				10%				50%			
			Improbable				Unlikely				Occasional				Possible				Frequent			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
CONSEQUENCES – C	No threat	1	1	2	3	4	2	4	6	8	3	6	9	12	4	8	12	16	5	10	15	20
	Negligible	2	2	4	6	8	4	8	12	16	6	12	18	24	8	16	24	32	10	20	30	40
	Marginal	3	3	6	9	12	6	12	18	24	9	18	27	36	12	24	36	48	15	30	45	60
	Significant	4	4	8	12	16	8	16	24	32	12	24	36	48	16	32	48	64	20	40	60	80
	Serious	5	5	10	15	20	10	20	30	40	15	30	45	60	20	40	60	80	25	50	75	100

Source: author's own work.

In this way, point scale measures of risk in the numerical range from 1 to 100, for the following risk scale from 1 to 4 (tolerable risk), from 5 to 10 (controlled risk), from 12 to 100 (unacceptable risk) were obtained.

Adaptation of a four-parameter matrix

In order to assess the system of protection against threats, a four-parameter risk assessment matrix, according to formula 3, was implemented.

The description of the protection category is as follows (Ozga-Zielińska et al., 2003):

- low level of protection, basic zone – ZS and ZW hazard zones – it is a zone permanently protected against flooding, because the flow corresponding to the upper limit of the ZW threat zone is designed for technical flood protection solutions, e.g. flood banks, point weight 1,
- medium level of protection, extraordinary zone – ZZ threat zone – protection in this zone is introduced in the situation of a threat in the area where the population feels safe as it is protected by solutions applied at the border of the primary zone, point weight 2,
- high degree of protection, extreme zone – danger zone ZM – protection in this zone is usually activated after occurrence of events causing extreme high flow, point weight 3.

Other parameters are presented in point 3.2.The presented scale of point weights is a proposal for the initial risk assessment, in this way the following risk categories can be assumed:

- tolerable, point scale from 0,33 to 3,
- controlled, point scale from 3 to 20,
- unacceptable, point scale from 20 to 100.

Determination of potential flood losses

The estimated number of residents likely to be affected by the flood is assumed to be the number of people registered in the area. Residential buildings and objects of special social significance are distinguished between those "for which the water depth is less than or equal to 2 m, and objects for which the water depth is greater than 2 m" (Dz.U. 2013 poz. 104).

The values of potential flood losses for individual classes of land use are determined by the formula (Dz.U. 2013 poz. 104):

$$Sp_i = \sum_{j=1}^{4} Sp_{ij} \cdot A_i \qquad for\ i = 1...9 \tag{6}$$

where:

Sp_i – means the total values of potential unit losses for a given class of land use,

Sp_{ij} – means the value of potential unit losses for a given class of land use and the water depth range,
A_i – means the area occupied by a given land-use class.

However, the values of potential unit losses in classes are expressed as (Dz.U. 2013 poz. 104):

$$Sp_{ij} = W_i \cdot f(h_j) \tag{7}$$

where:
Sp_{ij} – means the value of potential unit losses for a given class of land use and the water depth range,
W_i – means the value of the property in a given class of land use,
$f(h_j)$ – means the value of the loss function relating to the depth of water with the loss of value of the property in a given class of land use.

The values of the loss function are selected for each class of land use according to the water depth at the limits of the intervals of these depths from the tables contained in the regulation (Dz.U. 2013 poz. 104). In turn, the value of assets in a given class of land use is selected from tables depending on the voivodship.

In table 5 the values of the loss function for residential areas which, according to the regulation, should be taken into account in order to link the water depth during floods with the loss of property value in a given class of land use, were presented.

Table 5. The value of the loss function for residential areas.

Water depth h [m]	Value of the loss function f(h) [%]
≤ 0,5	20
0,5 < h ≤ 2	35
2 < h ≤ 4	60
> 4	95

Source: author's own work based on (Dz.U. 2013 poz. 104).

Application example

The analysis was conducted on the basis of materials received from the office of the distinguished commune located in the Subcarpathian province and occupying an area of 200 km². For analysis, 12 villages of the considered commune were taken. The basic data were flood area coverage maps with a given probability of flooding. Using the ArcGIS Explorer version, a flood risk map was drawn up.

Table 6. Flood risk in the distinguished commune

Location	Number of residents	Flood threat			
		The probability of flood	The number of vulnerable households	Percentage ratio	Number of endangered people
A	3563	due to the lack of a large watercourse flowing through the distinguished location, there are no people at risk of being exposed to a flood			
B	1399	despite the flow of the stream through the settlement, there are no people at risk of flooding			
C	896	no watercourse threatening the inhabitants, so there are no people at risk of flooding			
D	1415	due to the location of the buildings directly on the banks of the river and near the estuary, the number of people at risk of flooding was determined depending on the flood probability			
		50%	1	0,3%	4
		10%	3	1%	13
		5%	10	3%	45
		1%	42	13%	188
		0,5%	57	18%	255
E	4191	the stream flowing through the village is a threat to the inhabitants only in the case of extremely high flood			
		0,5%	3	0%	14
F	788	due to the lack of a large watercourse flowing through the village, there are no people at risk of a flood			
G	318	no watercourse and endangered inhabitants			
H	1355	the location of the village on the banks of the river poses a great threat to the residents, therefore the number of people at risk was determined			
		50%	2	1%	10
		10%	20	7%	98
		5%	32	12%	157
		1%	61	22%	298
		0,5%	91	33%	445
		50%	2	1%	10
I	972	due to the lack of a watercourse in the village, there are no people exposed to the flood			
J	293	due to the proximity of the river, the number of endangered inhabitants is presented in the next lines			
		10%	5	8%	22
		5%	13	20%	58
		1%	30	45%	133
		0,5%	32	48%	142
K	1749	there is a threat due to the proximity of the river			
		10%	5	1,3%	23
		5%	6	2%	27
		1%	60	16%	273
		0,5%	70	18%	318
L	3483	as in the case of the village of E, despite the flow of the stream, the flood risk is not too high and the number of endangered inhabitants is presented in the following lines			
		5%	1	0,1%	5
		1%	4	1%	19
		0,5%	8	1%	39

Source: author's own work.

On the basis of the flood hazard maps, the flood hazard number obtained in each location and the number of households, the percentage of all households in a given location in danger of flooding, was calculated (table 6) (Zygmunt, 2017).

For particular location of the commune scales of the probability (P) and the consequences (C) were assumed and the value of flood risk (r) was calculated, according to the formula 1, using the guidelines of the two-parameter matrix. Summary of the results together with the division of flood risk is presented in table 7.

Table 7. Flood risk in the concerned commune

Location	P	C	r	Description
A	1	1	1	Tolerable risk
B	1	1	1	Tolerable risk
C	1	1	1	Tolerable risk
D	2	4	8	Controlled risk
E	2	1	2	Tolerable risk
F	1	1	1	Tolerable risk
G	1	1	1	Tolerable risk
H	2	5	10	Controlled risk
I	1	1	1	Tolerable risk
J	2	4	8	Controlled risk
K	2	5	10	Controlled risk
L	2	3	6	Controlled risk

Source: author's own work.

On the basis of the obtained results for the flood risk in particular localities of the analysed commune, the estimated flood losses in the housing areas of the commune were calculated.

The formula presented in the Regulation of the Minister of Environment, Minister of Transport, Construction and Maritime Economy, Minister of Administration and Digitization and Minister of the Interior of 21 December 2012 on the development of flood hazard maps and flood risk maps was used for this purpose (Dz.U. 2017 poz. 1566).

According to formula 5, the values of potential flood losses for residential areas and water depth ranges were calculated using formula 6.

The value of assets for residential housing areas, which according to the regulation is adopted for the calculation of flood losses depending on the province, for the Subcarpathian province is 201,25 PLN/m^2 (Dz.U. 2017 poz. 1566). The obtained values of potential unit losses for residential areas and water depth ranges are presented in table 8.

Table 8. Values of potential flood losses

Water depth h [m]	The value of the loss function f(h) [%]	Sp_{ij}
≤ 0,5	20	40,25
0,5 < h ≤ 2	35	70,44
2 < h ≤ 4	60	120,75
> 4	95	191,19

Source: author's own work based on (Dz.U. 2017 poz. 1566).

In order to estimate the area occupied by residential buildings in individual location of the considered commune flooded with water during the flood, with the probability assumed in the flood risk matrix with the division into water depth ranges, according to table 7, flood hazard maps were used. Analogously to the earlier proceedings, the map was enlarged to a size that makes it possible to distinguish individual households and the number of flooded householdsin the given depth ranges was calculated. Places in which tolerable flood risk occurred have not been taken into account in further calculations. Therefore flood losses were calculated for five locations in the analysed commune, in which the controlled flood risk was found (table 9).

For individual towns where flood losses occurred, the weights were calculated for the flood risk value (r), according to the formula 4, using a four-parameter matrix. The summary of the results together with the division of flood risk is presented in table 10.

Table 9. Number of households in water depth ranges

Location ≤ 0,5		Ranges of water depth [m] 0,5 < h ≤ 2	 2 < h ≤ 4	 > 4	
D	Number of households in water depth ranges	21	21	0	0
	Percentage of the water depth ranges [%]	6,65	6,65	0,00	0,00
	The value of flood losses in thousand [PLN]	1 540	2 695	0,00	0,00
H	Number of households in water depth ranges	35	22	4	0
	Percentage of the water depth ranges [%]	12,64	7,94	1,44	0,00
	The value of flood losses in thousand [PLN]	3 472	3 819	1 190	0,00
J	Number of households in water depth ranges	21	9	0	0
	Percentage of the water depth ranges [%]	31,82	13,64	0,00	0,00
	The value of flood losses in thousand [PLN]	194	2 494	1 871	0,00
K	Number of households in water depth ranges	25	32	3	0
	Percentage of the water depth ranges [%]	6,49	8,31	0,78	0,00
	The value of flood losses in thousand [PLN]	2 328	5 215	838	0,00
L	Number of households in water depth ranges	4	0	0	0
	Percentage of the water depth ranges [%]	0,56	0,00	0,00	0,00
	The value of flood losses in thousand [PLN]	274	0,00	0,00	0,00

Source: author's own work based on (Dz.U. 2017 poz. 1566)

Table 10. Flood risk in the concerned commune

Location	P	C	V	O	r	Description
D	2	4	1	1	8	Controlled risk
	2	4	2	1	16	Controlled risk
H	2	5	1	1	10	Controlled risk
	2	4	2	2	8	Controlled risk
	2	4	3	2	12	Controlled risk
J	2	4	1	1	8	Controlled risk
	2	3	2	1	12	Controlled risk
K	2	5	1	1	10	Controlled risk
	2	5	2	1	20	Controlled risk
	2	3	3	1	18	Controlled risk
L	2	3	1	1	6	Controlled risk

Source: author's own work.

The estimated potential flood losses for residential areas in the concerned municipality at the occurrence of a flood with a probability of 1%, i.e. the floods of the century, are over PLN 25 million. Places in the order of the highest losses are: H, K, J, D and L.

Conclusions

Flood risk analysis and assessment aims to protect people, property and the environment from the effects of flood, it is developed in the form of flood hazard maps, flood risk and flood risk management plans.

The following conclusions were proposed after performed flood risk analysis:

- on the basis of the analysis of table 9, it was found that the flood risk in the considered commune depends on the distance of individual towns from the largest river flowing through the commune,
- the unacceptable risk does not occur in any location in the concerned commune,
- the controlled risk occurs in five locations of the commune: D, H, J, K and L. All these towns are in the vicinity of the river,
- the tolerable risk occurs in the other seven locations of the commune: A, B, C, E, F, G and I. None of these locations are adjacent to the river,
- the concerned commune is a relatively safe place in terms of flood risk when taking into account inhabited areas. For areas used for agriculture, flooding is likely to be more severe, because in these areas water depth will be larger,
- the largest flood hazard in the concerned commune is found in the location near the only bridge in the commune. In case of "the flood of the century" nearly half of the households in the J location will be flooded and almost 1/3 of the households in the neighbouring location H will be flooded,
- a slightly smaller threat is found in the village of K, also located near the bridge and in the village of D in the vicinity of the estuary, because less than 1/5 of the farms will be flooded with hundred-year-old wate,
- flood losses occur adequately to the flood risk: the higher the risk, the greater the losses.

For the location, where the controlled flood risk was found, exemplary flood losses for residential areas were calculated in accordance with the guidelines included in the regulation on the preparation of flood risk maps and flood risk maps. The flood losses expressed in monetary values in the event of "the flood of the century" will amount to approx. 25 740 thousand PLN.

The contribution of the authors

All authors contributed equally to the manuscript.

Literature

Ahmad S. et al. (2013), *Spatial and temporal analysis of urban flood risk assessment*, "Journal of Urban Water" No. 10, pp. 26-49

Cuellar A.D., McKinney D.C. (2017), *Decision-Making Methodology for Risk Management Applied to Imja Lake in Nepal*, "Water" No. 9(8)

Armenakis C. et al. (2017), *Flood risk assessment in urban areas based on spatial analytics and social factors*, "Geosciences" No. 7(4)

Bartnik A., Jokiel P. (2012), *Geografia wezbrań i powodzi rzecznych*, Łódź

Blažkova S., Beven, K. (2002), *Flood frequency estimation by continuous simulation for a catchment treated as ungauged (with uncertainty)*, "Water Resources" No. 38, pp. 1-14

Brocca L. et al. (2013), *Application of a model-based rainfall-runoff database as efficient tool for flood risk management*, "Hydrology and Earth System Science" No. 17, pp. 3159-3169

Chang L.C. et al. (2018), *Building ANN-Based Regional Multi-Step-Ahead Flood Inundation Forecast Models*, "Water" No. 10(9)

Dawson R.J. et al. (2011), *An agent-based model for risk-based flood incident management*, "*NaturalHazards*"No. 59, pp. 167-189

Dou Y. et al. (2018), *Multi-index evaluation for flood disaster from sustainable perspective: A case study of Xinjiang in China*,"International Journal of Environmental Research and Public" No. 15(9)

Dyrektywa 2007/60/WE Parlamentu Europejskiego i Rady z dnia 23 października 2007 r. w sprawie oceny ryzyka powodziowego i zarządzania nim, Dz.U.UE L 288/27 z dnia 6.11.2007

Flores-Montoya I. et al. (2016), *Fully Stochastic Distributed Methodology for Multivariate Flood Frequency Analysis*, "Water" No. 8(6)

Graniczny M., Mizerski W. (2007), *Katastrofy Przyrodnicze*, Warszawa

Haimes Y.Y. (2009), *On the complex definition of risk: A systems-based approach*, "Risk Analysis" No. 29, pp. 1647-1654

Haberlandt U. et al. (2008), *A space-time hybrid hourly rainfall model for derived flood frequency analysis*, "Hydrology and Earth System Science" No. 12, pp. 1353-1367

Klonner C. et al. (2018), *Capturing Flood Risk Perception via Sketch Maps*, "ISPRS Int. J. Geo-Inf." No. 7

Lubowiecka T., Wieczysty A. (2000), *Ryzyko w systemach zaopatrzenia w wodę*, in: M. Maciejewski (ed.), *Ryzyko w gospodarce wodnej*, Monografia Komitetu Gospodarki Wodnej PAN, z. 17, Warszawa, pp. 113-143

Murdock H.J. et al. (2018), *Assessment of Critical Infrastructure Resilience to Flooding Using a Response Curve Approach, "*Sustainability" No. 10(10)

Nachlik E. et al. (2000), *Strefy zagrożenia powodziowego*, Wrocław

Ouma Y.O., Tateishi R. (2014), *Urban Flood Vulnerability and Risk Mapping Using Integrated Multi-Parametric AHP and GIS: Methodological Overview and Case Study Assessment*, "Water" No. 6, pp. 1515-1545

Ozga-Zielińska M. et al. (2003), *Powodziogenność rzek pod kątem bezpieczeństwa budowli hydrotechnicznych i zagrożenia powodziowego*, materiały badawcze, Warszawa

Radczuk L. et al. (2001), *Wyznaczanie stref zagrożenia powodziowego*, Wrocław

Rak J.R. (2004), *Istota ryzyka w funkcjonowaniu systemu zaopatrzenia w wodę*, Rzeszów

Rak J.R. (2008), *Wybrane zagadnienia niezawodności i bezpieczeństwa w zaopatrzeniu w wodę*, Rzeszów

Rak J.R. (2009), *Bezpieczeństwo systemów zaopatrzenia w wodę*, Warszawa

Rak J.R. (2014), *Problematyka ryzyka w wodociągach*, Rzeszów

Rak J.R., Kwietniewski M. (2010), *Niezawodność infrastruktury wodociągowej i kanalizacyjnej w Polsce*, Warszawa

Rak J.R., Tchórzewska-Cieślak B. (2005), *Metody analiza i oceny ryzyka w systemie zaopatrzenia w wodę*, Rzeszów

Rincón D. et al. (2018), *Flood Risk Mapping Using GIS and Multi-Criteria Analysis: A Greater Toronto Area Case Study*, "Geosciences" No. 8(8)

Röthlisberger V. et al. (2017), *Identifying spatial clusters of flood exposure to support decision making in risk management*, "Science of the Total Environment" No. 598, pp. 593-603

Rozporządzenie Ministra Środowiska, Ministra Transportu, Budownictwa i Gospodarki Morskiej, Ministra Administracji i Cyfryzacji oraz Ministra Spraw Wewnętrznych z dnia 21 grudnia 2012 r. w sprawie opracowywania map zagrożenia powodziowego oraz map ryzyka powodziowego, Dz.U. 2013 poz. 104

Sieg T. et al. (2017), *Tree-based flood damage modeling of companies: Damage processes and model performance*, "Water Resources Research" No. 53, pp. 6050-6068

Simonovic S.P. (2009), *Managing flood risk, reliability and vulnerability* "Journal of Flood Risk Management" No. 2, pp. 230-231

Tchórzewska-Cieślak B. (2008), *Niezawodność i bezpieczeństwo systemów komunalnych na przykładzie systemu zaopatrzenia w wodę*, Rzeszów

Tokarczyk T. et al. (2012), *Wstępna Ocena Ryzyka Powodziowego jak element wdrażania Dyrektywy Powodziowej*, "Infrastruktura i Ekologia Terenów Wiejskich" No. 3, pp. 67-78

Ustawa z dnia 18 kwietnia 2002 r. o stanie klęski żywiołowej, Dz.U. 2002 nr 62 poz. 558 z późn. zm.

Ustawa z dnia 18 lipca 2001 r. Prawo wodne, Dz.U. 2017 poz. 1121 z późn. zm.

Ustawa z dnia 20 lipca 2017 r. Prawo wodne, Dz.U. 201poz. 1566

Ustawa z dnia 26 kwietnia 2007 r. o zarządzaniu kryzysowym, Dz.U. 2017 poz. 209 z późn. zm.

Wu J. et al. (2018), *Application of Bayesian Approach to Dynamic Assessment of Flood in Urban Underground Spaces*, "Water" No. 10(9)

Yang S. et al. (2018), *Cloud-Model-Based Method for Risk Assessment of Mountain Torrent Disasters*, "Water" No. 10(7)

Zheng J. et al. (2018), *Re-examining regional total-factor water efficiency and its determinants in China: A parametric distance function approach*,"Water" No. 10(10)

Zhou Q. et al. (2018), *Recent Changes in the Occurrences and Damages of Floods and Droughts in the United States*, "Water" No. 10

Zischg A.P. (2018), *Floodplains and Complex Adaptive Systems-Perspectives on Connecting the Dots in Flood Risk Assessment with Coupled Component Models*, "Systems" No. 6(2)

Zygmunt A. (2017), *Zasady analizy ryzyka powodziowego*, praca dyplomowa magisterska, Rzeszów

Żelaziński J. (2007), *Rola map terenów zalewowych w planowaniu ochrony przeciwpowodziowej, Bezpieczna gmina nad Odrą*, Kampania informacyjno-promocyjna na rzecz ochrony i zachowania nadodrzańskich terenów zalewowych dla ochrony przyrody i poprawy bezpieczeństwa powodziowego, materiały informacyjne, Wrocław