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WATER RESOURCES AND THE REGIME OF WATER BODIES

Identification of Significant Flood Areas in Lithuania[1]

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Abstract—During preliminary flood risk assessment in Lithuania 54 significant flood areas (SFA) were identified. The detailed flood hazard and risk maps were prepared for these areas in 2014. European Union Floods Directive does not indicate the concrete criteria for SFA delineation. The uncertainty analysis shows that the total length of SFA is not very sensitive to used methodology. In some rivers the uncertainties of 100 year flood peek discharge ($Q_{1\%}$) were large, but the variation of SFA boundary location was relatively small due to properties of hydrological network. The catchment area and $Q_{1\%}$ change rapidly near the junction with large tributaries, so the boundaries of SFA are usually attached to these junctions. The formal criteria are mostly used to evaluate the possibility of significant floods, but the delineation of SFA is usually based on subjective decision.

Keywords: EU Floods Directive, flood hazard, significant flood areas, flood management, uncertainty, Lithuania

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INTRODUCTION

Floods are one of the most common hazards. The magnitude and the frequency of floods have increased in many regions due to global environmental change [32, 33]. The same trend is observed in Europe. Large floods occurred in Danube, Elbe, Oder, Sava, Vltava and other rivers in the second half of 20th century and at the beginning of the 21st century. The increased flood hazard was one of the main reasons for commence of European Union (EU) Floods Directive 2007/60/EC [8], which should guide member states to implement flood risk management plans. The development and implementation of directive inspired many flood studies [7].

The characterization of floods is a complicated task due to different genesis and regional characteristics [3, 10, 33]. According to Floods Directive the floods can be divided into several types: river floods, flash floods, urban floods and floods from the sea in coastal areas. The separation of flood types may look useful, but in large regions or regions with high variability of conditions, the floods of the same type may be caused by different drivers and the damage caused by these flood events may also be very different [5, 12, 42]. The EU Floods Directive allows Member States to determine themselves the objectives of flood risk management based on local and regional circumstances [8]. There are a lot of definitions of flood in global practice. World Meteorological Organization (WMO) defines the flood as certain phase of hydrological regime [14]. US Water Resources Council describes floods as "a general and temporary condition of partial or complete inundation of normally dry land areas from the overflow of inland and/or tidal waters, and/or the unusual and rapid accumulation or runoff of surface waters from any source" [11]. Similar approach was applied in Directive 2007/60/EC where "flood" means temporary covering by water land that is normally not covered by water. This includes floods from rivers, mountain torrents, Mediterranean ephemeral watercourses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems [8]. In flood hazard and risk management the quantitative indicators of flood are very important, because they allow to determine the need for risk estimation [18] and management.

General definitions of flood cannot provide these quantitative indicators due to different local conditions. The Directive allows countries using previous experience to define indicators for floods according to regional conditions [1, 41], but the open treatment of flood indicators may be one of the main issues for the effective flood risk estimation and implementation of the Directive [37].

The implementation of the Directive is to be carried out in tree steps. Firstly, Member States have to perform a preliminary study of flood risk to identify the potential areas where significant flood risk exists.

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During second step the detailed flood hazard and risk maps should be prepared for the areas identified in the first step. The final step is the preparation of flood risk management plans.

Member States were at the different level of flood management before the implementation of the Directive; consequently, they faced different issues [1, 7, 9, 12, 25, 41]. The main questions, which have arisen from different countries experience, are: (1) would strict and well-defined methodology of hazard and risk estimation be more effective? and (2) what is the effect of methodological uncertainties for flood hazard assessment?

In this paper the results of identification of potential areas where significant flood risk exists in Lithuania [27] are used to address these questions.

DATA AND METHODOLOGY

River floods are most common in Lithuania. According to many researches [2, 13, 36] floods in Lithuanian rivers are caused by: (1) fast snow melt; (2) heavy rainfall; (3) ice jams; (4) faults in operation of dams or accidents. The first three causes are natural, most frequent and mostly researched [2, 16, 20, 23, 29, 34].

Usually the floods are analyzed in certain river stretches where they are most significant [4, 15, 22, 28, 31, 36, 38–40]. In majority of earlier studies the floods were described by the time of event and by magnitude expressed with qualitative information like small or large flood. Different flood indicators were used to describe the flood regime. In some studies the probabilities of discharges were analyzed, in others flood water levels were studied [17]. The hydrological regime of rivers has changed due to climate change [20] and anthropogenic impact [36]. For example, after establishment of Kaunas HPS and Vileika–Minsk water supply system the floods in Nemunas near Kaunas and Neris near Vilnius became smaller [13]. Hydrological stations with long records are near large rivers and many Lithuanian rivers are ungagged.

Differences in methodology, data length and spatial coverage of previous studies meant that for implementation of the first step of the Floods Directive the new study based on same criterions should be carried out.

For assessment of the potential flood risk Member States have to identify areas for which the potential significant flood risks exist or might be considered likely to occur [8]. The definition of significant impact is not provided in the Floods Directive. All countries have to determine their own significant flood criteria. In Lithuania the floods were considered significant if their characteristics exceed the extreme event criteria [30]. The areas where such floods have occurred in the past were identified. It was also decided that significant floods might occur in the areas where 100-year flood peek discharge ($Q_{1\%}$) is higher than 100 m^3/s.

For rivers with hydrological stations, which have long records, the $Q_{1\%}$ values were estimated according to the empirical probability curve:

$$p_m = \frac{m}{n+1} \times 100\%, \quad (1)$$

where n – number of years, m – rank of year.

In Lithuania only several hydrological stations have discharge records long enough to accurately estimate $Q_{1\%}$ with the empirical probability curve. In other stations, with shorter discharge records, the $Q_{1\%}$ was calculated using six theoretical probability curves Weibull (3P), Fatigue Life (3P), Gamma (3P), Log-Logistic (3P), Wakeby and Log-Gamma. The best-fitted theoretical curve was used. The goodness of fit was estimated with Anderson-Darling criteria, which puts more weight on the tails and allows to find theoretical probability curves which fits best in lower probability range [35].

For rivers without hydrological stations or with stations which have short records the $Q_{1\%}$ was estimated with empirical Eqs. (2) and (3) [13, 26]:

$$Q_1 = \frac{A_{1\%}A}{(A+1)^{0.20}}\delta_1\delta_2, \quad (2)$$

$$Q_{1\%} = \frac{h_{1\%}K_0\mu A}{(A+1)^{0.17}}\delta\delta_1\delta_2, \quad (3)$$

where A—catchment size, km^2; $A_{1\%}$—1% probability of elementary maximum discharge, δ—coefficients which depend on the part of catchment covered by lakes, forests and wetlands, K_0—flood intensity coefficient, $h_{1\%}$—1% probability of runoff depth; μ—coefficient which describes the relationship between runoff depth and discharge.

The Eq. (2) is based on the elementary maximum discharge and Eq. (3) is based on 1% probability of runoff depth. For certain catchment both parameters can be estimated from maps [13, 26]. These maps were created by extrapolating the data from monitoring stations with the respect to regional characteristics. The maps are not very accurate, therefore the comparison of the results of both equations allows to a certain degree estimate the uncertainty of this method. The δ coefficients which describe the land cover of the lake are known for certain catchments. For cross sections with unknown δ coefficients the coefficient values for rivers from the same region and with similar catchment properties were used.

The $Q_{1\%}$ estimated by hydrological station data or by Eqs. (2) and (3) in one cross section can be recalculated to other cross sections of the same river with Eq. [26]:

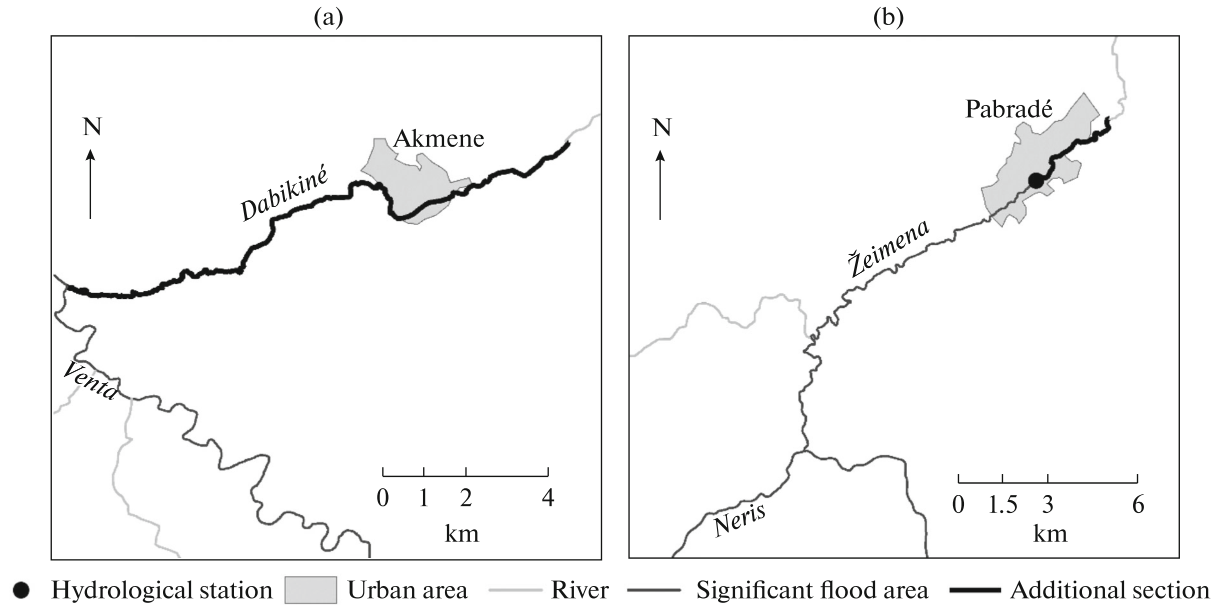

Fig. 1. Examples of the potentially SFA boundary extension upstream urban areas in the (a) Dabikinė and (b) Žeimena rivers. Red line shows added sections.

$$Q_1 = \left(\frac{A_1}{A_2}\right)^{0.8} Q_2, \quad (4)$$

where Q_1—discharge in cross section, m^3/s, Q_2—known discharge in cross section, m^3/s, A_1, A_2—the area of respective catchments, km^2.

It was assumed that $Q_{1\%}$ increases towards mouth of the river, thus the potentially significant flood areas (SFA) were delineated from the cross section where $Q_{1\%}$ exceeds 100 m^3/s to river moth. The total length of area with possible significant floods depends only on the location of the cross section with $Q_{1\%} \geq 100$ m^3/s. The beginning of SFA is usually located at the junctions with large tributaries, because the area of catchment in these places rapidly increases and it is likely that the $Q_{1\%}$ will increase in the same location as well.

The main purpose of SFA identification is flood risk management and formal criteria may not always represent the real situation. Historical significant floods in some river stretches may be not recorded because there were no hydrological stations. The calculation of $Q_{1\%}$ in rivers or river sections without gauges produces large uncertainties. Due to this, some of SFA were extended to include vulnerable territories and objects such as urban areas, significant hydro technical structures and other. For example, near the Dabikinė River mouth $Q_{1\%}$ is less than 100 m^3/s, but floods in this river can cause damages in Akmenė city, so the 15 km long SFA was delineated (Fig. 1a). There is a hydrological station on the Žeimena River near Pabradė city center. The $Q_{1\%}$ in this hydrological station is 82 m^3/s (lower than formal criteria of 100 m^3/s), but despite of this, the SFA area was extended by 3 km to include whole territory of the city (Fig. 1b).

RESULTS

In Lithuania significant flood areas were identified in 54 rivers. Total length of all SFA is 3994 km. As mentioned before two formal criteria were used as a basis for SFA identification, but the final decision was based on local conditions. Only three rivers SFA were identified because in these rivers floods exceeded extreme flood level criteria were recorded. In other 51 rivers SFA were identified due to $Q_{1\%} \geq 100$ m^3/s criteria or the subjective reasons related to vulnerability to floods. Most of SFA were delineated since they met several criteria.

Because the $Q_{1\%}$ is assumed to increase towards mouth of the river the total length of particular SFA depends only on% the location of the beginning of SFA. Only in 6 rivers the $Q_{1\%}$ exceeds 100 m^3/s in the beginning of SFA (Fig. 2). Two of these are large transboundary rivers Nemunas and Neris. The total length of these rivers in Lithuania is a SFA. One more SFA with $Q_{1\%} \geq 100$ m^3/s over all its length is Sanžilė canal. This canal connects Lėvuo and Nevėžis rivers, thus the discharge in the canal does not depend on the location. In Obelis, Jara-Šetekšna and Varduva the beginning of SFA is in the junction with large tributary. Above the junction the $Q_{1\%}$ is much smaller than 100 m^3/s and below it the $Q_{1\%}$ is a bit large than 100 m^3/s. Three rivers with $Q_{1\%} < 40$ m^3/s in the beginning of SFA are Šyša, Gėgė and Leitė. These riv-

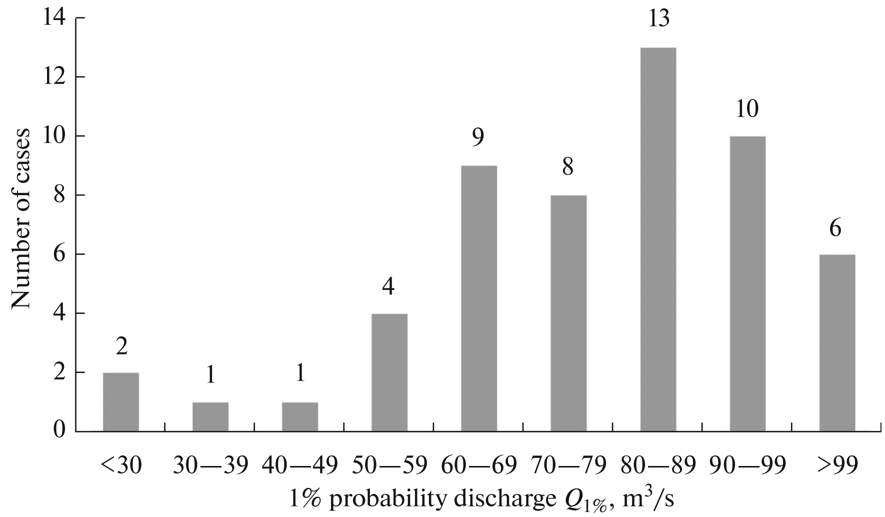

Fig. 2. The distribution of $Q_{1\%}$ in the highest cross section of SFA.

ers are small tributaries of Nemunas in its flat lower reaches and during floods their water level is affected by water level in the Nemunas River. The extreme water levels have been recorded in all three rivers. The extension of SFA towards reaches due to area vulnerability to floods is the main reason why the $Q_{1\%}$ in the highest cross section of SFA is smaller than 99 m^3/s in the rest 45 rivers.

Total length of SFA indicated in Lithuania is 3994 km. The values of $Q_{1\%}$ estimated by theoretical probability curves and by empirical Eqs. (2) and (3) have large uncertainties. Only in five rivers Mūša, Tatula, Nevėžis, Minija and Nemunėlis location of SFA highest cross section was estimated employing theoretical probability curves. In Šaltuona, Pyvesa, Vokė and Siesartis the results of Eqs. (2) and (3) were used. In remaining 42 rivers the final decision on location of SFA highest cross section was made according to local conditions and based on subjective estimate.

The $Q_{1\%}$ calculated by using theoretical probability curve depends on type of selected curve and its parameters. There are many empirical and theoretical curve-fitting techniques, but the results cannot be perfect and some degree of uncertainty remains. To estimate uncertainties of $Q_{1\%}$ in rivers where SFA boundaries were evaluated using hydrological station data and theoretical probability curves the set of Weibull (3P), Fatigue Life (3P), Gamma (3P), Log-Logistic (3P), Wakeby and Log-Gamma curves were used. These curves showed the best fit for all rivers. The $Q_{1\%}$ values in cross section of hydrological station were calculated using all six theoretical curves. Later the maximum and minimum $Q_{1\%}$ values were identified (Table 1). The catchment area and distance from river mouth of

Table 1. Difference in the location of the highest SFA cross section estimated using different theoretical probability curves

River	Hydrological station	Catchment area of hydrological station, km^2	Minimum $Q_{1\%}$ in hydrological station, m^3/s	Maximum $Q_{1\%}$ in hydrological station, m^3/s	The ratio between minimum and maximum $Q_{1\%}$ in hydrological station	The catchment area and distance from river mouth of highest significant flood area cross section estimated by minimum and maximum $Q_{1\%}$				Difference in the highest significant flood area cross section location, km
						minimum		maximum		
						area, km^2	distance, km	area, km^2	distance, km	
Mūša	Miciūnai	792	131	257	1.96	374	130	221	144	14.4
Tatula	Trečionys	404	63	144	2.31	453	0	260	18	18.1
Nevėžis	Panevėžys	1058.1	151	227	1.50	425	155	305	156	0.7
Minija	Kartena	1220.1	186	307	1.65	542	130	306	160	29.9
Nemunėlis	Rimšiai	877.2	126	268	2.13	362	149	172	165	16.4

the highest SFA cross section were estimated using Eq. (4) with minimum and maximum $Q_{1\%}$ in hydrological station.

The uncertainties of the highest SFA cross section location related to theoretical probability curve selection are relatively small (Table 1). The accumulated uncertainty in SFA length in all five rivers is 79.5 km or 2% of total identified SFA length (3994 km). The ratio between minimum and maximum $Q_{1\%}$ in hydrological station varies from 1.50 to 2.31. The relationship between minimum and maximum $Q_{1\%}$ ratio and difference in SFA boundary location is poor. The main reason to this is the effect of hydrological network. The $Q_{1\%}$ changes rapidly near junctions with large tributaries so relatively large difference in $Q_{1\%}$ may result in relatively small changes of SFA boundary location if there is the junction with large tributary.

The $Q_{1\%}$ value calculated using 1% probability elementary maximum discharge (Eq. (2)) and 1% probability runoff depth (Eq. (3)) depends on the method used and how well the coefficients which describe catchment properties are selected. To estimate uncertainties in $Q_{1\%}$ estimation the calculations for Šaltuona, Pyvesa, Vokė and Siesartis were made according to both equations and using different land use parameters. The maximum and minimum $Q_{1\%}$ values were estimated and the lowest and highest locations of the first SFA cross section were estimated in all four rivers. The small range of possible location was found only in Šaltuona River (2.3 km). In the rest three rivers the $Q_{1\%}$ uncertainties were outweighed by hydrological network and did not have an effect to the location of SFA boundary.

The maximum $Q_{1\%}$ calculated using equation 3 exceeds 100 m^3/s in the mouth of Kiršinas River, but in this river the SFA was not originally delineated. In short distance (3.2 km) from Kiršinas mouth there is the junction with large tributary Šuoja-Kurys, which catchment area accounts for 60% of total Kiršinas catchment area. The $Q_{1\%}$ changes rapidly near junction and if the SFA would be identified in Kiršinas it would be only 3.2 km long. The accumulated uncertainty in five rivers in which the $Q_{1\%}$ value was calculated using 1% probability elementary maximum discharge (Eq. (2)) and 1% probability runoff depth (Eq. (3)) is only 5.5 km. The total uncertainty of all qualitative methods is 85 km (2.1% of all delineated SFA).

DISCUSSION

During preliminary flood risk assessment 54 SFA (3994 km) were identified. The detailed flood hazard and risk maps were prepared for these areas in 2014. Flood Directive does not indicate the concrete criteria for SFA delineation. In Lithuania two main criteria were used: the exceedance of the extreme event criteria and higher than 100 m^3/s 100 year flood peek discharge. The SFA are identified for flood risk estimation, so the information on vulnerability to floods was also included in SFA delineation. The formal criteria were usually used to identify the rivers with possible SFA but the locations of SFA boundaries in particular rivers were estimated considering the vulnerability.

The boundaries of 42 (83.3%) from 54 identified SFA were estimated according to subjective evaluation. In these rivers the highest cross sections of SFA were extended towards reaches of rivers to include possibly vulnerable to floods urbanized areas and hydrological objects. Only the locations of 9 SFA (16.7%) highest cross sections were based entirely on formal criteria.

The uncertainty analysis shows that the total length of SFA is not very sensitive to used methodology. In some rivers the uncertainties of $Q_{1\%}$ were large, but the variation of SFA boundary location was relatively small due to properties of hydrological network. The catchment area and $Q_{1\%}$ changes rapidly near the junction with large tributaries, so the boundaries of SFA are usually attached to these junctions.

It seems that the fact that the preliminary flood risk estimation is related to risk management reduces the importance of strict criteria. The formal criteria are mostly used to evaluate of possibility of significant floods, but the delineation of significant flood areas is usually based on subjective decision.

CONCLUSIONS

Based on historical events and the extreme event criteria 54 significant flood areas with 3994 km total length were identified in Lithuania. The location of boundaries of most significant flood areas (83.3%) were identified due to subjective decision based on vulnerability to floods. The total uncertainty of all significant flood areas due to different methodology applied is only 85 km (2.1%). The methodological uncertainties of significant flood area boundary location are small because they are overweighed by the hydrography of the river. The runoff increases rapidly after the junction with large tributaries, therefore the boundaries of significant flood areas in most cases coincide with the junction. The strict methodology in the identification of potentially flooded areas is not necessary because these areas are usually defined accordingly to the local conditions. In Lithuania the major factor for subjective delineation of potentially flooded areas was the vulnerability of the area to floods. The boundaries of most significant flood areas were extended to include the urban areas and reservoirs, since the losses caused by flood event may be much large in urban areas or caused by the damages of reservoir dams.

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