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ORIGINAL ARTICLE

Behaviour of the 2010 flood in Lithuania: management and socio-economic risks

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Abstract
The hydrometeorological data was analysed for the identification of the causality and behaviour of the 2010 flood in Lithuania. Moreover, 326 different articles about the selected flood were collected and reviewed to establish the extent of damage and losses. The multi-criteria analysis was used for the assessment of socio-economic risk in the area of 1% probability inundation. The applied ranking approach of the socio-economic risk was compared with the ratio-based risk of Flood Hazard and Flood Risk Maps (FHRM). The results of this paper indicated that the flood was caused by ice jams and was crucial for the areas of higher risk. The magnitude of the 2010 flood revealed many issues related to flood management. The total economic losses reached 2.8 million EUR. The effects of the flood significantly impacted socio-economic conditions and the environment of residents within the areas of inundation. The assessment of socio-economic risks indicated additional sensitive areas, which were not sufficiently taken into account in FHRM. The analysis highlighted the current issues in flood management and the consequences of not taking appropriate flood management measures.

Keywords Floods · Economic losses · Socio-economic risk · Flood management · Flood Hazard and Flood Risk Maps

1 Introduction

In Europe, river flooding is the most dangerous natural hazard in terms of economic losses. In the time period of 2003–2009, 26 major events produced direct economic losses of approximately 17 billion EUR and 320 human fatalities. The increased losses over the past decades are due to increased population and assets in the exposed areas (EEA 2010). According to recent flood experiences around the world, flood protection funds are generally allocated immediately after a flood. However, it is still impossible to eliminate floods; thus, mitigation measures and proper planning and preparedness should be proposed before they occur (Samu et al. 2018).

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The extreme hydrological events such as flooding are generally predicted to become more frequent and damaging in Europe due to changes in extreme precipitation, socio-economic development and climate change (Feyen et al. 2012; Whitfield 2012; Alfieri et al. 2015; Forzieri et al. 2016; Paprotny et al. 2017). The substantial variations among different catchments were observed, ranging from an increase in northwestern Europe to no trend or a decrease in other parts of the continent (Hall et al. 2014; Benito et al. 2015). An analysis of 46 case studies across Europe discloses that the magnitudes of a present flood are not unusual (Benito et al. 2015). Usually, flood hazards are viewed as the result of natural, physical and biological environments, which are usually heavily modified by social, economic and political environments. Di Baldassarre et al. (2018) proposed to "significantly improve our understanding of the unintended effects of flood protection" with special attention on human behaviour. This is a very important transdisciplinary approach as floods negatively affect the entire suite of unintended socio-economic and ecological environments in river systems and beyond. The artificial modifications have generally benefited urban centres, river-dependent communities and individuals who live at floodplains and had commonly experienced the loss of livelihoods and other factors contributing to their physical wellbeing (Richter et al. 2010). Climatological, geomorphological and anthropogenic factors affecting flood risk are also very important (Brakenridge et al. 2017). Part of the solution could be redirecting new housing and other economic developments onto lands that are less exposed to floods. At the best, it would be perfect if "Flood-risk management that interweaves structural with non-structural approaches can keep floods away from people and people away from floods" (Opperman et al. 2017). At the same time, flood protection requires huge financial investments (Auerswald et al. 2019). This requires an interdisciplinary approach that considers alternative solutions such as green infrastructure and emphasizes integrated flood management rather than reliance on technical protection measures.

A huge flood struck the Upper Danube basin and caused heavy damages along this river and its numerous tributaries when the total flood runoff volume (from 31 May to 17 June 2013) was 9.5 billion m^3 (Blosh et al. 2013). For example, in the UK, the annual average loss due to flooding in recent years was about \$250 million, whereas the economic costs of summer floods in 2007 alone were about \$3.2 billion, while average damages of the annual flood varied between \$500 million and \$1 billion (Penning-Rowsell, 2014). The winter floods of 2013/2014 caused approximately \$290 million of economic losses (Thorne 2014). May of 2013 was a month with abnormal temperatures and well above normal amount of precipitation in the entire territory of the Czech Republic (Daňhelka et al. 2014; Elleder 2015), contributing to a sharp rise in water levels in the Vltava River at Prague. This resulted in a very rapid filling of the Vltava River Cascade reservoirs. The mentioned rise in water level was caused by uncontrolled flow from the rivers of Sázava and Berounka. The total inundation volume was estimated at 114.5 million m^3 of retained water. For example, in 2008, the damages caused by the Siret River flooding were the greatest in that basin and Romania as a whole (Romanescu et al. 2013), when the largest maximum discharges were reached at the Dragesti station (2930 m^3/s) and Nicolae Balcescu station (2200 m^3/s).

Flood risk management practices included the early identification, analysis and mitigation of flood risks, focusing on prevention (preventing damage caused by floods), protection (taking measures to reduce the likelihood of floods or the impact of flooding in a specific location) and preparedness (informing the public about what to do in the event of flooding). To reduce the flood risk at the European scale, the Floods Directive (2007/60/EC) came into force in 2007. Flood risk management was like a three-stage process: preliminary Flood Risk Assessment (by 22 December 2011), Flood Hazard and Flood Risk Mapping (22 December 2013) and Flood Risk Management Plan (22 December 2015). The implementation of the Flood Directive started in 2010 in the EU Member States. In 2010, large parts of Europe were affected by flooding due to widespread rain that started in the middle of May (Bissolli et al. 2011). The worst affected were Poland (Southern region), the Czech Republic, Slovakia, Hungary, Croatia, Bosnia and Herzegovina, Bulgaria and Germany (Southern and Eastern regions). This flooding led to 15 fatalities. In Hungary, rescuers worked on the embankments along the rivers (more than 800 km long) and used sandbags to secure them. In Germany, severe damage was caused after an extreme flood in the Elbe and Oder River catchments (Kienzler et al. 2015). Total damage of 839 million EUR was reported to the EU Solidarity Fund in 2010 (EC, 2014). In Poland, the 2010 flood took place in May and mostly affected the right bank tributaries of the Upper and Middle Odra River (the second largest river in Poland), which caused damage and loss on land and the Gulf of Gdańsk (Szalinska et al. 2014). This flood also constituted a serious test for society, administrative structures and specialized services (Wilk et al. 2014). In the southeast region of Poland, some towns and agricultural areas were partially or even completely flooded. Many residents had to leave their homes. In 2018, the European Court of Auditors set out the results of its audits of EU policies and programmes due to the implementation of the Flood Directive in EU countries (Special report no 25/2018: Floods Directive) and gave recommendations to the European Commission. These recommendations were mainly related to (1) cross-border investment for flood control measures and development of infrastructure; (2) the better integration of the effects of climate change into flood risk protection, prevention and preparedness; (3) providing good practices and guidance for land use planning; and (4) other financial and co-finance aspects.

At the beginning of the twenty-first century, regional studies showed that the timing of flood peaks in the Nemunas River (as in most Northern European rivers) has significantly changed (Latkovska et al. 2012). Floods tend to begin earlier, and the maximal duration of the river flooding becomes shorter during the spring runoff. The flood studies of the Nemunas River included an analysis of the dynamics of the ice regime (Stonevičius et al. 2008; Dubra et al. 2013), as well as the synoptic conditions during the spring runoff (Stankunavicius et al. 2007) and the effects of climate change on the snow regime (Stonevičius et al. 2017). Both spring and flash floods were getting smaller, and the analysis of maximum discharges in 1812–2013 revealed the significant decrease of maximum discharges of spring and flash floods after 1960 (Meilutyte-Lukauskiene et al. 2017). The situation has rapidly changed over the last 30 years, and large areas of the Nemunas River Delta can be flooded, even if the snow water equivalent over the entire basin is relatively low (Valiuškevičius et al. 2018). Floods have tended to occur either due to ice jams or wind surge rather than intensive snowmelt. The frequency of such extreme events is likely to increase in the future together with an increased number of days with severe high-water levels.

In recent decades, the most damaging flood in the Lithuanian rivers occurred in 2010. To understand the physical factors and socio-economic aspects of this flood, the main tasks of this research were:

- To determine the main hydrometeorological causes of the flooding in 2010 and relevant characteristics of the river hydrological regime;
- To evaluate the magnitude and effects of the flood of 2010;
- To assess the economic losses, suffered damages and applied measures for flood risk reduction;

- To compare the socio-economic risk of the Flood Hazard and Flood Risk Maps considering the flood of 2010.

Therefore, the present research aimed to evaluate the magnitude and losses of the selected flood and to highlight the current issues of the absence of flood management to protect better floodplain residents considering the example of the flood of 2010.

2 Study area and data

The Nemunas River basin (which covers 94% of Lithuania) together with the Venta and the Lielupė river basins were selected as a study area for the analysis of the consequences of the 2010 flood (Fig. 1). The Nemunas River is a major eastern European river. This river basin formed during the Quaternary period and is located roughly along the edge of the last glacial sheet. The Nemunas River, which is 937 km long, drains an area of 97,928 km^2 (46,700 km^2 in Lithuanian territory, 45,450 km^2 in Belarus, 2520 km^2 in Poland, 3170 km^2 in Russia and 88 km^2 in Latvia). The Lielupė River basin covers the area of 8938.3 km^2. The largest part of this area falls within the Mūša River sub-basin (5296.7 km^2). The Venta River is 343.3 km long with catchment area of 11,800 km^2. The Venta River rises in Lithuania, enters Latvia in the southwest and flows northward through the Kurzeme lowland to the Baltic Sea.

The flood development mechanism in the main river basins in Lithuania is very complicated and mainly depends on the amount of snow water equivalent before the beginning of the flood and precipitation amount during the flood (Akstinas et al. 2019). Additionally, other factors like soil freeze conditions in the catchment's area, potential ice jams, other meteorological conditions and regulatory influence of the Kaunas Hydropower Plant on

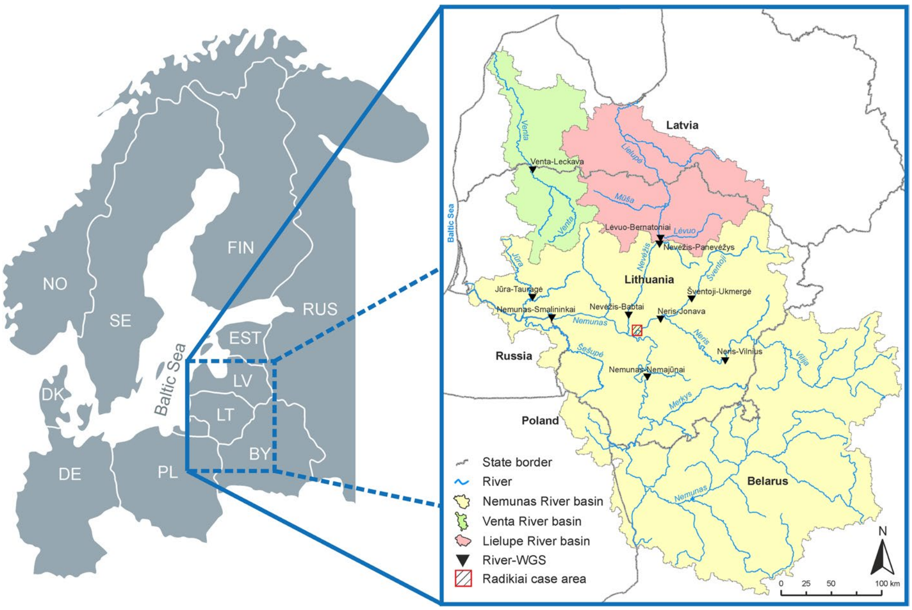

Fig. 1 The location of the Nemunas, the Lielupė and the Venta river basins in the European context

the Nemunas River may have an impact on flood formation. A sudden increase of air temperature (above zero) together with a high rate of precipitation influences a decline in the thickness of snow cover. Then, intensive snow melting causes an abrupt increase of the water level in the river and these conditions give rise to the flood in the river basin. The ice jam phenomenon is known as a powerful driving force during floods. The air temperature regime in Lithuania is determined by cold air masses from the Arctic or warm air masses from the Atlantic Ocean. Those factors are not constant in space and time, and the river regime strongly depends on their fluctuations, especially in winter.

The Nemunas River basin has approximately 180 tributaries in total, as most of them are right-side tributaries. The climatic conditions of all mentioned main river basins depend on the mid-latitude atmospheric circulation, which usually is moving eastward from the Baltic Sea. The ice events (ice formation, movements of shore ice, floating ice, etc.) in the rivers of these basins are common during the winter season and, in early spring, there usually cause ice jams. The annual amount of precipitation fluctuates from 600 mm (in the Lielupė River basin) to 750 mm (in the Venta River basin) or even 900 mm in some tributaries. Forty percent of the annual runoff of the Nemunas River is typically observed during the spring flood, whereas 44% is in the Venta River. In this study, meteorological (monthly data of 17 meteorological stations) and hydrological data (daily discharge and water level data from 10 water gauging stations (WGS)) were used. The selected WGSs are listed in Table 1.

To understand and assess the 2010 flood inundation in Lithuania, 326 articles were reviewed. They covered information concerning the damages, losses and used instruments for the reduction of this flood. Publicly available scientific articles as well as articles in media and press (printed and electronic/online version), information from the library (library achieve) and the statistical department were thoroughly investigated. Additionally, the data from insurance companies and municipalities were collected and evaluated to clarify the level of losses. To assess socio-economic risk, the gridded (250 × 250 m and 1000 × 1000 m) data of social variables as social vulnerability components (total population, percentage of female population, percentage of younger than 14-year and older than 65-year population, total houses) was taken in a shapefile format from the "Statistics Lithuania " for the year of 2011. The gridded raster data (100 × 100 m) of economic

Table 1 Characteristics of the selected WGS

River	Length, km	Length within Lithuania, km	Total basin area, km^2	WGS	WGS catchment area, km^2
Nemunas	937.4	359.0	97,863.5	Nemajūnai	42,869.0
				Smalininkai	81,129.7
Neris	509.5	234.5	24,942.3	Vilnius	15,218.8
				Jonava	24,544.9
Šventoji	246.0	246.0	6888.8	Ukmergė	5381.1
Nevėžis	208.6	208.6	6140.5	Panevėžys	1058.1
				Babtai	5784.9
Jūra	171.8	171.8	3994.4	Tauragė	1664.1
Lėvuo	145.0	145.0	1628.8	Bernatoniai	1143.9
Venta	343.3	159.1	11,800.0	Leckava	4024.2

vulnerability and the gridded raster data (1000 × 1000) of complex socio-economic risk of Flood Hazard and Flood Risk Maps (FHRM) have been provided by Environmental Protection Agency (EPA) under the Ministry of Environment of the Republic of Lithuania (Report of the Flood Hazard and Risk Assessment in the Nemunas, Venta, Lielupė and Dauguva river basins 2014).

3 Methods

The review of different types of articles and the analysis of hydrometeorological data were performed to assess the 2010 flood in Lithuania and define the causality, magnitude and damage of this flooding (Fig. 2). After the combined evaluation of the listed tasks, the comparison of Flood Hazard and Flood Risk Maps (FHRM) with the findings of this research was performed in the context of the 2010 flood together with the assessment of socio-economic risk using multi-criteria analysis and ranking approach. The comparison of determined socio-economic risk with the risk of Flood Hazards and Risk Maps (FHRM) and the consequences of the 2010 flood provided the main output of this research—the potential and underestimated "hot spots", which can be significantly affected within the area of 1% probability flooding.

The owner of FHRM is the Environmental Protection Agency under the Ministry of Environment of the Republic of Lithuania; thus, these maps are available on their official website. The maps present fluvial and coastal floods. For each type of flooding, three scenarios are mapped: high (10%), medium (1%) and low (0.1%) probability floods. The statistical probabilities were calculated based on the long-term annual maximum discharges of available observation data. FHRMs were made using 2D hydrodynamic modelling with the mentioned probabilistic discharge as the boundary conditions for the models. The models were calibrated and validated using 10-year time series. The uncertainties of water level in the maps are as follows: 35 cm for 10% probability flood, 50 cm for 1% probability flood and 60 cm for 0.1% probability flood.

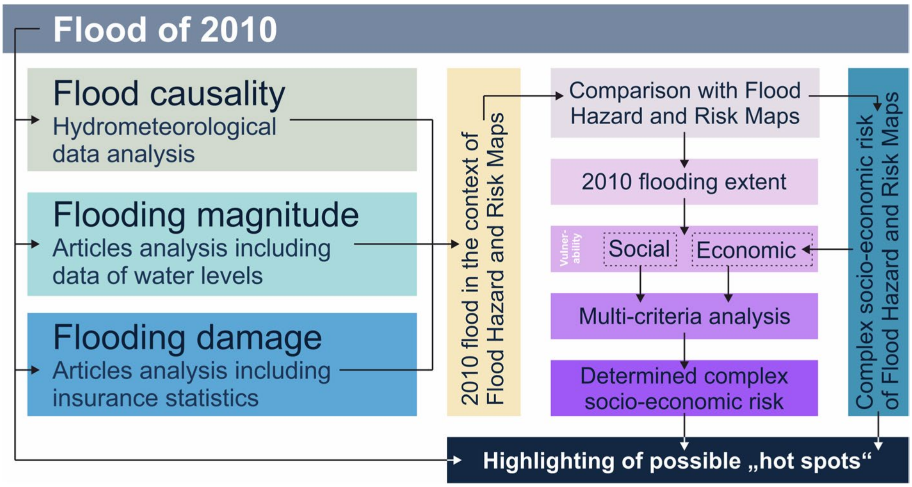

Fig. 2 The principal scheme of this research

The analysis of hydrometeorological data (air temperature, precipitation amount, river discharge and water level) was accomplished. The main factors (climatic conditions before the flood, fluctuations of water levels and river discharge during the flood) were evaluated at different water gauging stations. The probabilities of maximum water levels were determined as well.

Special attention was paid to all available information about inundated areas. Information on the damage caused and the economic losses were collected not only from the target articles but also from insurance companies. All this information was double-checked and verified in cooperation with the Lithuanian Road Administration under the Ministry of Transport and Communications, Statistics Lithuania, target municipalities and insurance companies. For the identification of the 2010 flood-related articles (published in 2010), the following search terms were applied using the search system OPAC (Online Public Access Catalog) of Kaunas County Public Library:

["Lithuania"].

AND

["2010 year"].

AND

["flood" OR "flooding"].

In the next step of the 2010 flood assessment, the comparison of Flood Hazards and Risk Maps (FHRM) was made, considering inundated areas, social vulnerability and economic losses. Radikiai Village (Kaunas County) was selected for the case study since this populated area suffered the largest losses. The 1% probability inundation area defined by FHRM was compared with the extent of the 2010 flood. The comparison included the rise of water level and flood extent in Radikiai Village. The number of flooded houses was estimated and compared with the actual numbers determined by reviewing the articles/media information. The defined complex socio-economic risk in FHRM was compared with the results of this research. In FHRM, the MOORA (Multi-Objective Optimization based on Ratio Analysis) method (Brauers and Zavadskas, 2006) was applied for the assessment of the social vulnerability of the flooding. Meanwhile, the ranking technique (Wu et al. 2002; Shivaprasad Sharma et al. 2018) was used to evaluate the social and economic vulnerability in this research. Moreover, the ranking method was applied also for the evaluation of complex socio-economic risk in the study area for highlighting the higher risk areas comparing with the results of FHRM (ratio-based) within the area 1% probability flooding. The ranking was performed for the different social (total population, percentage of female population, percentage of younger than 14-year and older than 65-year population, total houses) and economic (economic losses in EUR according to FHRM of EPA) parameters according to the data within the 1% flooding area. The data of social variables was provided in two different spatial resolutions (250 × 250 and 1000 × 1000-m grid cells). The size of these cells depended on the location area because, in urban areas, there were available data of the finer scale (250 × 250), whereas, in the other areas, the social data were available only in 1000 × 1000-m grid cells. Therefore, as detailed information as possible is used. The same situation was with the economic losses; only the available data were in 100 × 100-m grid cells (Report of the Flood Hazard and Risk Assessment in the Nemunas, Venta, Lielupė and Dauguva river basins 2014). All mentioned social and economic data were divided into five ranks (classes) according to the statistics of data of the selected cells. The first rank (1) indicated the lowest vulnerability, while the fifth rank (5) the highest. The ranking was based on the applied data amplitude and distribution. For the parameters of the total population and houses, the intervals of exponential growth were chosen to highlight the vulnerability in cells where a higher number of residents lived. For the other social parameters, the equal intervals of 15% were defined. For the economic losses, the intervals of ranks were divided 25 thous. EUR categories, and less than 10 thous. EUR. According to assigned ranks, the social and economic data were recalculated into rasters for further multi-criteria analysis.

For the complex evaluation of socio-economic risk, the GIS-based multi-criteria analysis was applied (Malczewski 2006). This analysis included ranks of four main social criteria (total population, percentage of female population, and percentage of younger than 14-year and older than 65-year population, total number of houses) as social vulnerability components and ranks of economic vulnerability. The multi-criteria analysis was performed in ArcGIS 10.5 via Raster Calculator because all social and economic parameters in gridded raster files were prepared. For the calculation of socio-economic risk, the same weights (as in FHRM) for the selected social and economic factors were assigned:

$$Rank_{socio-economicrisk} = 0.125(Rank_{\text{total population}} + Rank_{\%offemalepopulation}$$
$$+Rank_{\%of<14yrand>65yr} + Rank_{\text{total houses}}) + 0.5Rank_{\text{economic losses}}$$

In this research, the ranking of the complex socio-economic risk of FHRM was made as well for the appropriate comparison with the results of socio-economic risk assessment based on the ranking method used in this research. The socio-economic risk of FHRM (ratio-based) consisted of an aggregated index that fluctuated from 0 (no risk) to 1 (maximum risk). The aggregated index was divided into five equal categories—ranks (first rank, 0.0–0.200; second rank, 0.201–0.400; third rank, 0.401–0.600; fourth rank, 0.601–0.800; fifth rank, 0.801–1.0), where rank 1 indicated the lowest risk and rank 5 the maximum risk. The differences in a socio-economic risk between those assessed by FHRM (ratio-based) and those determined in this research (ranking approach) were estimated.

4 Results

4.1 Hydrometeorological aspects of the 2010 flood

In Lithuania, the flood was observed in the season of 2009/2010. This flood was caused by the formation of ice jams together with low temperatures, heavy rain, large snow cover and other ice phenomena. In December 2009, the average air temperatures were very close to the average annual values and the amount of precipitation was near the norm (Fig. 3). Therefore, permanent snow cover began to form in the second decade of December. The coldest period started at the end of January (negative anomaly of − 8– − 9.5 °C). The soil freezing reached a depth of 40–50 cm. During the last days of February 2010, the soil freezing started to decrease. The snow cover began to melt by the end of this month, and there was no continuous snow cover in the southwestern region. The first ice phenomenon was recorded on 16–18 December of 2009 (almost 2 weeks later than usual), and some segments of the Nemunas River were ice-covered. However, the ice cover quickly disappeared. At the end of February, ice floes moved in the rivers of the Nemunas and Neris (Fig. 3). Accordingly, the ice jams events began to form and resulted in water level increase in these rivers. In March, the average air temperature was higher than the long-term average. On 21 March 2010, the water level began to rise very rapidly due to the sudden increase in air temperature and a high amount of precipitation in the Neris River basin. These meteorological conditions caused the movement of the river ice and the formation of jams in hot spots

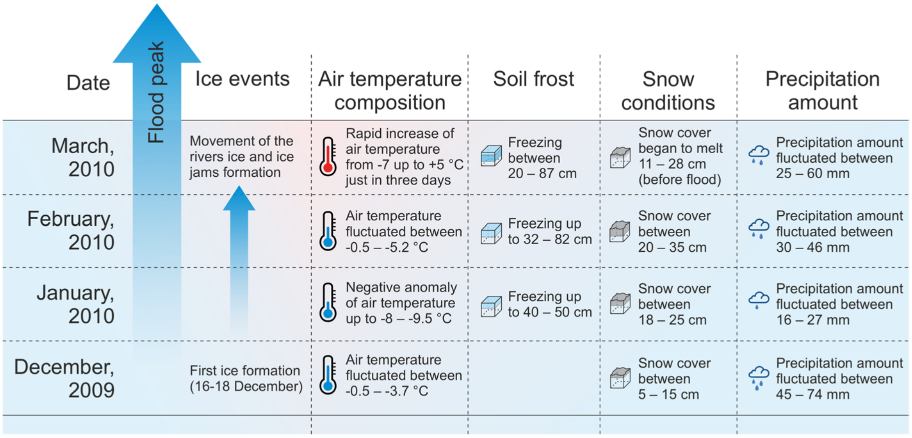

Fig. 3 Main drivers of the 2010 flood

(islands, meanders, confluences etc.). The maximum water level (366 cm) was reached on 23 March 366 m in the Neris at Jonava WGS and the maximum values last 2 days.

For the spatial analysis of flood magnitude in 2010, the data of 11 WGSs were used. Analysis of maximum water levels showed their different characters of the fluctuation in 2010, which mainly depended on ice events, snow cover, soil freezing and river tributaries etc. At two WGSs (Nemunas at Smalininkai and Nevėžis at Panevėžys), the water level was much higher than the multi-annual maximum value. Consequently, ice floes started to flow in certain rivers of the Nemunas River basin in March, and this phenomenon caused a large ice jam flood in some areas of the basin. In 2010, the highest maximum water levels were observed in the following WGSs: Nemunas at Smalininkai (832 cm), Šventoji at Ukmergė (390 cm) and Nevėžis at Panevėžys (503 cm). During the flood of 2010, the highest maximum water levels were in the Nemunas at Smalininkai WGS and the lowest in the Lėvuo at Bernatoniai WGS (286 cm). In the Venta at Leckava WGS, the maximum water level was 11.87 times greater in comparison with the multi-annual water level, while in the Lėvuo at Bernatoniai WGS, 9.23 times bigger. The highest maximum water levels were observed in the confluences of the rivers with their tributaries (due to additional inflow of ice floes to the main river) as well as in the presence of islands (barrier to ice floes). All these processes created favourable conditions for the formation of ice jams.

The probability distribution of maximum water levels in 4 WGSs of the Nemunas River basin in 1958–2017 is shown in Fig. 4. During the 2010 flood, the highest water level of 1% probability flooding was observed in the Nemunas at Smalininkai WGS (832 cm), 10% in the Neris at Jonava WGS (373 cm), 15% in the Neris at Vilnius WGS (519 cm) and 40% in Nemunas at Nemajūnai WGS (470 cm).

The analysis of the river discharges during the flood of 2010 showed that the high-water level of 1% probability flooding was at Nemunas-Smalininkai WGS (832 cm). However, the discharge was only 2300 m^3 (like the mean annual maximum discharge). According to long-term observations, at this station, the discharge of 1% probability flooding was about 6580 m^3/s (three times bigger than the flood of 2010) almost at the same water level (884 cm) in 1958. The case of the 2010 flood and its specific nature confirm the importance of investigating the impact of the ice jam phenomenon on water

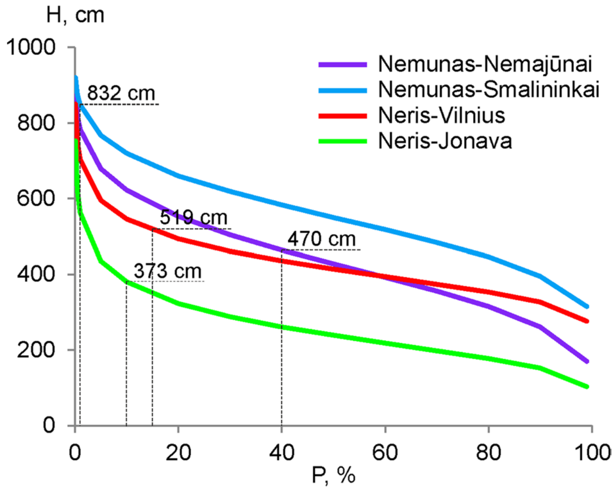

Fig. 4 The probability of maximum water levels of the 2010 flood in four WGSs of the two largest Lithuanian rivers in the context of 1958–2017

level rise. Therefore, it is very important to assess several characteristics of floods and reasons to carry out a comprehensive flood analysis.

4.2 The magnitude and effects of the flood

During the flood of 2010, the municipalities of Šilutė, Pagėgiai, Kaunas, Panevėžys, Jonava and Joniškis were flooded (40 thous. ha in total). In the mouth of the Nemunas River (Nemunas Delta), this flood inundated 35 thous. ha territory, where more than 400 residents live (The water level is rising 2010). Already in the morning of 26 of March of 2010, more than 37 km of Lithuanian roads were flooded (The water level is rising 2010). The section of 100 km of the national road Kaunas-Jurbarkas-Šilutė-Klaipėda was underwater (11–12 cm deep). Some roads of Šilutė and Pagėgiai municipalities were also flooded. The total length of such road sections is about 81.3 km. The water depth varied from 0.25 to 1.70 m. As a result, traffic on these road sections was closed (Water depth 87 cm on the road Šilutė-Rusnė 2010).

The largest areas were flooded in two municipalities—Šilutė (up to 24 thous. ha) and Pagėgiai (16 thous. ha) (Life after the flood: the victims are afraid of the Neris River 2010). The rising water level in the Akmena River (Western Lithuania) flooded the central part (around 29.5 ha) of Pagramantis town (About the flood in Pagramantis village 2010). According to media, some populated areas in Lithuania looked like "Venice" (The water level is rising 2010). Only in Kaunas District Municipality, 32 villages, over 300 houses and homesteads, as well as 27,000 garden houses, were damaged (Stankevičiūtė 2010).

In 1 day (22–23 of March 2010) in Jonava, the water level of the Neris River raised to 1.46 m, and already on 24 of March, the water level reached 3.73 m (Žirlienė 2010). A similar situation was observed in the Nevėžis River (at Babtai village), where the water level raised from 0.96 to 7.89 m in 1 day (03/24/2010). The water level in Panevėžys municipality exceeded the norm of multi-annual maximum water level: in the Nevėžis River, it was 4.79 m (critical value 4 m), in the Lėvuo River, 2.69 m (critical value 2.5 m) and in the Sanžilė canal (connection of the rivers of the Nevėžis and the Lėvuo), 2.24 m (critical value 1.9 m) (Rinkūnienė 2010). Due to the ice drift and the ice jam in the Akmena River, the Pagramantis village was flooded, and 28 houses were damaged as well as outbuildings, school stadium and the main street of the village were affected (About the flood in Pagramantis village 2010).

During this flood, even small rivers (the Audruvė River (catchment area 148.2 km^2) and its tributary the Purvė (catchment area 14.9 km^2)) in Joniškis City inundated 56 houses. Due to this situation, the systems of heating and hot water supply were interrupted in some village streets (Kybartienė et al. 2010).

In the Neris River, a large flood arose after ice floats jammed at the island downstream villages of Kleboniškis and Radikiai (Fig. 5). This flood was very sudden (the water level rose to 3 m in 1 h), and this increase in water level occurred overnight (03/22/2010). Everything was underwater—homes, cars, tethered dogs and sleeping residents. It was impossible to open the house doors because of the strong river flow. Therefore, residents waited for help on the 2nd floor of their houses (Žirlienė and Širvinskas, 2010). In the morning of the same day when the ice jam moved downstream, the confluence of the rivers of Nemunas and Neris with surrounding areas in the old town of the Kaunas city was flooded, and all newly constructed quays were underwater (Fig. 5).

In many ways and a long time afterwards, it was discussed: "*Was it possible to avoid and to control this flood or not?*" However, all residents from flooded territories did not hide the fact that responsible authorities are just "paper strategists" and cannot make quick and proper decisions in extreme situations (Kybartienė 2010).

4.3 Evaluation of the economic and social losses, and applied measures for flood risk management

With the first flood wave, the insurance companies began to estimate possible financial losses due to applications of flood-affected residents (Rivers reminded about themselves 2010). A representative person of the largest insurance company (Lietuvos draudimas) informed that within 1 day over 200 clients applied for insurance. However, this number of clients could then have reached up to 500 (Rinkūnienė 2010). Also, 77 clients applied to the insurance company "ERGO Lietuva" (Razmaitė 2010). Due to this natural disaster, the total amount of the payments made by "ERGO Lietuva" was almost 1.15 million EUR (The nature – biggest challenge for insurers 2010).

After this disaster, the municipalities of Joniškis, Jurbarkas, Kaunas, Panevėžys, Šilutė and Tauragė have submitted applications for compensation of flood-related losses to the government as well (Fig. 6). Out of requested 608.2 thous. EUR, 521.3 thous. EUR were requested only for Kaunas District Municipality (No one is in a hurry to

Fig. 5 **a** A house in Radikiai village (01:05 p.m. 22/03/2010), **b** the quay of the Nemunas River in the Old town of Kaunas city (Lithuania) during the flood of 2010 (01.22 p.m. 22/03/2010) and **c** now (29/01/2020). Photos by D. Meilutyte-Lukauskiene

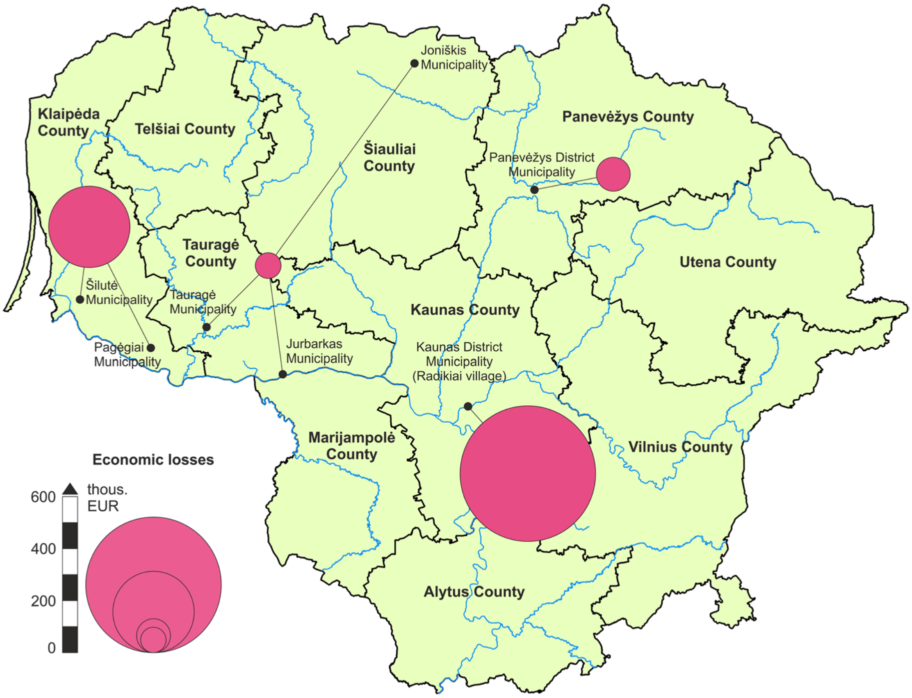

Fig. 6 Distribution of the economic losses in municipalities during the 2010 flood

pay the loss 2010). According to the data of the Administration of Panevėžys District Municipality, 121 individual claims for compensation were received after flooding. The estimated losses of residents from the mentioned municipality were 129.6 thous. EUR (Adomaitis 2010). However, not all applications for the compensation were approved. For example, only 39% of the damages caused by the flood in Joniškis town were compensated (No one is in a hurry to pay the loss 2010). Therefore, the affected (by the flood disaster) representatives of the Lithuanian municipalities rebelled against the Government of the Republic of Lithuania because it did not go with them into discussions for the compensation of damages. After this extreme situation, the mayor of Šilutė District Municipality said about the current situation: “For the politicians, it is important to look good in front of the cameras in disaster areas and to promise the support, and after that, all the promises are placed in a drawer” (No one is in a hurry to pay the loss 2010). In addition, during this flood in Radikiai village, many cars got underwater (in the floodplain of the Neris River). Compensation amounted to 28.9 thous. EUR for the cars that were fully insured (Between the floods damage are cars 2010). However, many residents had not insured their properties, and they were waiting for compensation from the government. After justification of a total declared amount (521.3 thous. EUR) in Radikiai village, the Lithuanian government provided only 161.6 thous. EUR to the residents as compensation after the 2010 flooding (The flood is over, but grievances remained 2010).

The total losses of the flood of 2010 amounted to 2.8 million EUR. 744.3 thous. EUR of that amount was related to private properties. State and municipal institutions and enterprises, as well as other economic subjects, have suffered losses of 2.1 million EUR (Stankevičiūtė 2010). Finally, on 29 of September 2010, after summarizing the national-wide losses, the Government of the Republic of Lithuania decided to allocate 1.0 million EUR to compensate the losses of this flooding (Adomaitis 2010; Resolution of Government of the Republic of Lithuania about the fund allocation 2010).

According to the Lithuanian Road Administration, the damage caused to the roads of state significance in the territories of the municipalities of Šilutė and Pagėgiai (the Nemunas River delta) amounted to approximately 314.2 thous. EUR (Certificate concerning the spring flood 2010). This amount was distributed among different enterprises that operated different road segments. 104.3 thous. EUR were dedicated to the state enterprises of "Tauragės regiono keliai" and 159.3 thous. EUR to "Klaipėdos regiono keliai". The remaining amount of 50.7 thous. EUR was used to cover damage on the flooded road section of Šilutė-Rusnė.

During the 2010 flood, a lot of the dykes built to protect villages from flooding were particularly ravaged. The total length of damaged dykes consisted of 2 km. The greatest damages were caused by an ice jam in Pakalnė polders (Rusnė Island) and Alka polders (in the lower reaches of the Minija River). The strengthening of damaged dykes cost at least 290 thous. EUR. The same amount was paid for electricity because a lot of water was pumped out from the polders and agricultural lands (Between the floods damage are cars 2010).

During the flood of 2010, some measures to reduce inundation were applied. On the morning of 4 March 2010, the State Border Guard Service informed that it was prepared for the flood in the Nemunas River basin. They were ready to evacuate residents and additionally prepared two helicopters, motor launches, amphibians, boats and a ship on the airbag to control the flood (The flood will be even if will be not 2010). On the 23rd of March 2010, Lithuanian soldiers started to clear clogged culverts, strengthen and rebuild dykes and evacuated residents. For example, the flow of the Lėvuo River destroyed the dyke on the 24th of March and flooded Pakuodžiupiai village. The affected dyke was quickly rebuilt with the help of the rescue service and soldiers with more than 500 sandbags. The works lasted for several hours, and the water level in Pakuodžiupiai village decreased significantly. In Daukniškiai village (the Lėvuo River), soldiers together with officers from the fire and rescue department built up the powerful water pumping stations, laid their main hoses, while others began to manage clogged culvert, strengthen and rebuild dykes (The Lithuanian Army immediately provided assistance to the flood zone 2010).

To reduce the magnitude of the 2010 flood, plastic explosives were widely used for ice blasting. On the 25th of March, 60 kg of explosive material was used in the mouth of the Atmata River. During the explosion, the ice was broken, and the river part of 300 m width and 100 m long was unclogged. Explosive material was also used in the Sanžilė canal (Panevėžys municipality). In the two blasting days, a total amount of 80 kg of the material of plastic explosive was used, and 12 blasts were made (The Lithuanian Army immediately provided assistance to the flood zone 2010). Two explosive warheads of 1.5 kg each were used for the ice breaking in the Lėvuo River (from the bank of the river). The explosions were successful—the ice collapsed, and part of it started to move. However, the entire ice jam was longer than 300 m. More powerful devices could not be used due to the nearby bridge and village.

4.4 The timeline and role of national flood management and its practical application

After analysing and evaluating the extent of economic and social losses of the 2010 flood, it is important to underline the status of the flood management stage of those days when the 2010 flood suddenly hit Lithuania and was not sufficiently managed. Several measures, approaches and design criteria have been developed over time. Understanding their role, significance and correlation towards risk-based flood management is crucial. The direct impacts of a flood are caused by direct contact with the flood, while indirect impacts occur as a result of the interruptions and disruptions in socio-economic aspects. The flood management in Lithuania had to go a very long way until it got a current appearance (Fig. 7). The development of flood management in the rivers can be described by the main breaking points during the last four periods of Lithuania. These breaking points were divided into the different relations between society and floods, i.e. living with flood, flood control and flood management. The first official observations of water level and other hydrological measurements were started at the beginning of the nineteenth century. The oldest water gauging station (WGS), which exists today, was established in 1811 on the Nemunas River at Smalininkai village. During the next hundred years, the interest in understanding hydrological processes and especially hydrological extremes increased; in 1910, river runoff was monitored already in 40 WGSs.

The sufficient primary database of hydrological observations provided an opportunity to plan new hydrotechnical projects for the redistribution of river runoff in temporal and spatial scales as well as to control floods. In 1932, the first canal between the Merkys and the

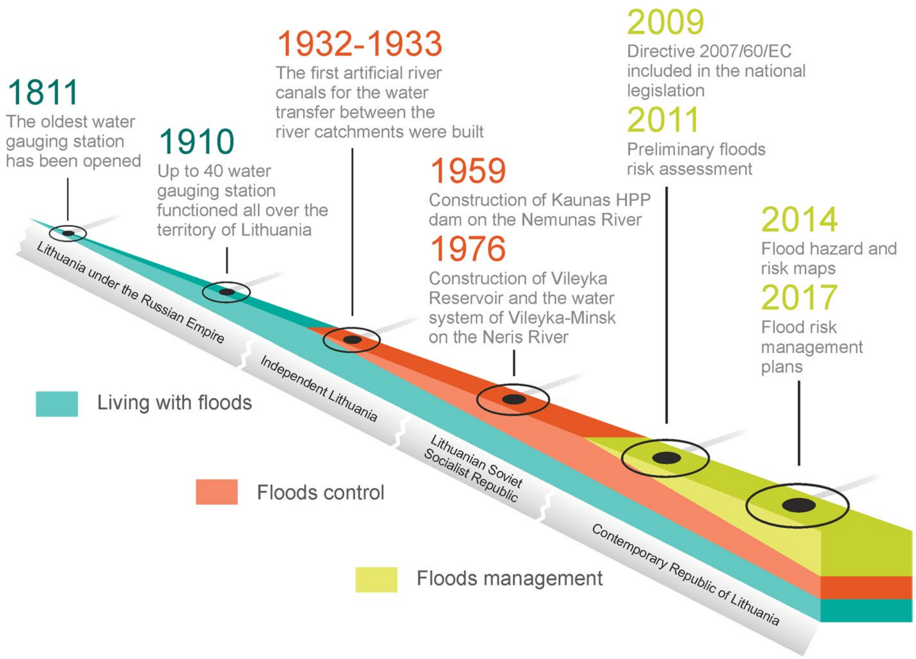

Fig. 7 The roadmap of the development of flood management in Lithuania

Vokė rivers was built to supply the cardboard factory (located near the Vokė River) by sufficient water discharge. Due to this canal system, 83% of the Merkys River discharge was transferred to the Vokė River (Gailiušis et al. 2017). The second step was done the following year (1933) when the canal was constructed between the Lėvuo and the Nevėžis rivers. The mentioned artificial canal allowed to control the floods in the Lėvuo River catchment because the canal was able to transfer a discharge of 30–40 m^3/s from the Lėvuo River to the Nevėžis River. In the middle of the twentieth century, the most ambitious hydrotechnical project throughout the history of Lithuania was launched. That was the construction of the Kaunas Hydropower Plant (HPP) on the largest Lithuanian river—Nemunas in 1959. The dam of this hydrotechnical structure created a reservoir with a surface area of 63.5 km^2 and a volume of 462 million m^3. The reservoir has 222 million m^3 useful volume, which can considerably control the volume of flood downstream of the Kaunas HPP. The accumulative effect of the Kaunas reservoir can reduce floods by 10% probability and higher in their average magnitude (Šikšnys and Jarmakaitė, 2012). According to Gailiušis et al. (2017), the volume of floods at Smalininkai WGS decreased on average by 8.7% under the influence of Kaunas HPP. However, the most significant effect of mentioned HPP was evidenced in the tailwater section where discharged water from the reservoir prevents the formation of river ice and ice jam floods at the confluence of the rivers of Nemunas and Neris (Kaunas City).

The second largest hydrotechnical structure (Vileyka Reservoir and water system of Vileyka-Minsk) was built on the Neris River upstream of the border of Lithuania and Belarus. This system ensures the water supply for Minsk (the capital and the largest city of Belarus). Since the Vileyka Reservoir has 235 million m^3 of usable volume, it significantly controls the river runoff during the year. An example of 1980 disclosed that the Vileyka-Minsk water system reduced the spring flood of the Neris River at Vilnius WGS by 24% (Gailiušis et al. 2017). Notwithstanding previously mentioned hydrotechnical structures, there are up to 100 small HPP and 450 reservoirs (larger than 5 ha) in Lithuania. All these artificial constructions and water bodies play a significant role in attempting to control floods. However, it was not enough for the complex attention of society on the flood risk. In the first small steps of flood management in Lithuania, the most important breaking point was the adoption of Directive 2007/60/EC (on the assessment and management of flood risks) in national legislation. This action created a basis for the following flood management stages including Assessment of Flood Risk, preparation of Flood Hazard and Risk Maps and preparation of Flood Risk Management Plans. Long way in the flood management can finally propose appropriate legal engineering and informing the public measures for the prevention, protection and preparedness for the floods.

4.5 Comparison of Flood Hazard and Flood Risk Maps (Radikiai village case)

In this paper, the evaluation of the 2010 flood at Radikiai village in the context of Flood Hazard and Risk Maps (FHRM) was done. The residents are living near the Neris River (Radikiai village) and were hit by the ice jam flood because their homes are in the floodplain areas. In the national legislation, it is stated that land uses in the floodplain cannot be changed for living purposes. However, permits for these homes were obtained (Garnienė 2010). During this ice jam flood below this village, residents of this area were hit the most. The comparative analysis between the 2010 flood and FHRM showed an inundated area of flood probability of 1% for this village (Fig. 8). It is important to emphasize that the origin of the 2010 flood differed comparing with the FHRM evaluation. Since the 2010 flood was

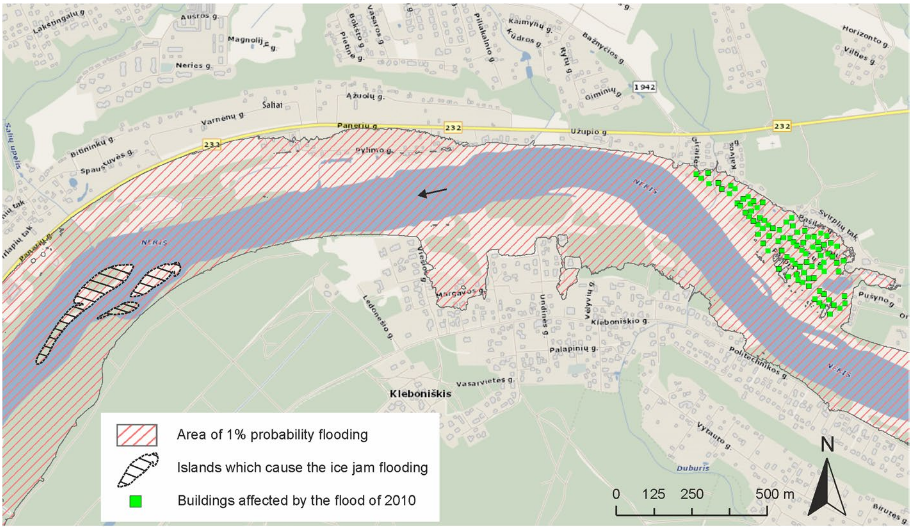

Fig. 8 The area of inundation of 1% probability flood according to Flood Hazard and Risk Maps (according to Environmental Protection Agency) in comparison with inundated buildings in 2010

driven by the ice jam event, the flood probability in FHRM was estimated using peak flood discharge. Despite these differences, an inundated area during the 2010 flood coincided with the area of 1% probability flooding. Therefore, this situation in Radikiai village illustrated the importance of these risk maps for assessing flood risk in other river valleys areas, which are densely populated. Only in 2010, the first step of preparation of the flood directive was started by the Environmental Protection Agency of Lithuania.

During the flood of 2010, 91 houses (this village has 150 houses in total) and 30 cars were flooded in Radikiai village (Čiučiulkaitė 2010). Flood Hazard and Risk Maps (according to Environmental Protection Agency) were used for assessing the extent of the flood inundation in this village (Fig. 9). This analysis disclosed the real extent of the flood inundation. It was determined that those 91 buildings in Radikiai village were built in the risk zone based on the 1% probability of flood with possible inundation area. Once again, this situation highlighted the importance of Flood Hazard and Risk Maps in flood management and future actions related to floods management as well.

According to the Flood Hazard and Risk Maps, legal measures for the reduction of the flood risk within the areas of inundation are proposed. In this study, Radikiai village (Kaunas County) was one of the most affected territories during the flood of 2010. This area is included in FHRM as a vulnerable territory. The following additional legal measures for flood prevention are proposed there:

1. **Preventative measures**: the establishment of a floodplain in the zoning system, improvement of the construction activities in the floodplain, ensuring the safety of hydrotechnical structures, provision of essential services during the flood, the establishment of a compensation system for flood losses.
2. **Non-structural measures for the protection from the flood**: forestation, wetland restoration, agro-environmental measures, water retention in urban areas.

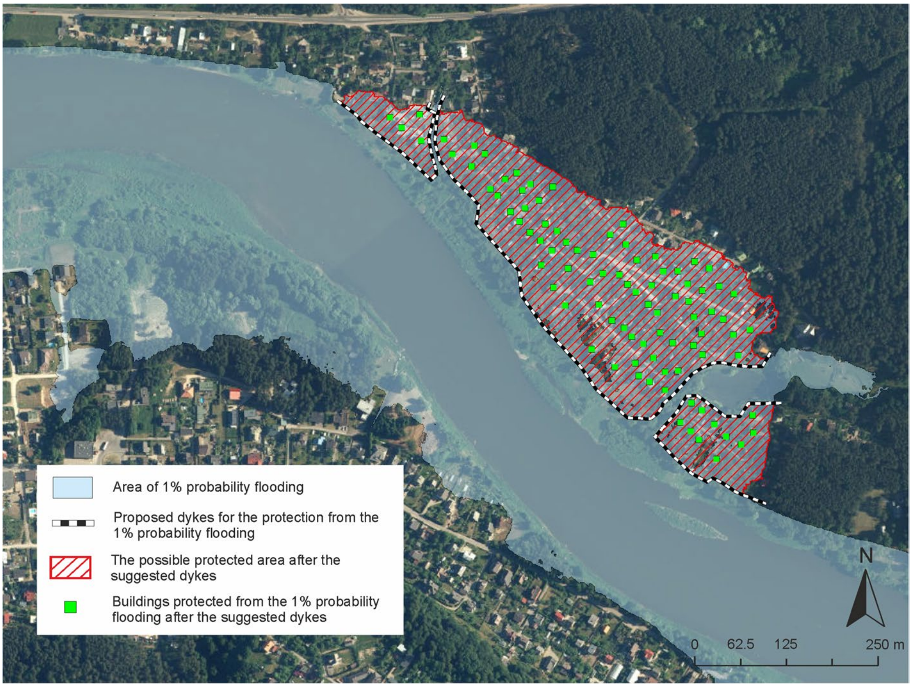

Fig. 9 Proposed measures for the protection of Radikiai village from the 1% probability flooding

3. Pre-flood measures: improvement of flood forecasting system, modernization of existing electric sirens, dissemination of Flood Hazard and Risk Maps, recommendations for residents about the protection of property during the flooding, plans of road traffic diversion, collection of ice jam data and recommendations for the removal of an ice jam.

4. Recovery measures: residents evacuation, strengthening of rescue systems, improvement of the insurance system for the flood damages.

Additionally, the FHRM proposed the engineering measures (dykes), which require investments for the protection from 1% and higher probability floods at Radikiai village. The territory of the village covers 10 ha and consists of 115 residents. The preliminary amount/number of investments for the construction of new dykes is about 757 thous. EUR. After the flood of 2010, the economic losses of the residents of Radikiai village reached 492 thous. EUR. However, the potential economic losses in 100 years period according to the FHRM would be 2.6 million EUR in this area. This comparison of numbers highlights the importance of investments. These investments would help to decrease the flood risk on the social environment for 100 years and to save money for regional and national authorities in the long-term period.

After the flood of 2010, many significant additions and changes were done to the flood management plan. Specifically, for reducing the flooding risk in the area of Radikiai village, additional legal instruments are applied now: warning and information system for residents, flood forecasting system (currently under development), instruments to ensure the safety of hydrotechnical structures, resolution of the Government of the Republic of Lithuania on Special Conditions for Land and Forest Use, territorial planning system and Directives (85/337/EEB, 92/82/EB, 2001/42/EB).

During the flood of 2010, obtained damages and losses motivated us to compare the socio-economic risk defined by FHRM. In the face of a natural disaster, the risk in Radikiai village was not sufficiently evaluated and managed. According to the FHRM, the complex socio-economic risk (based on the ratio methodology) fluctuated from 0.186 to 0.279, and over 100 residents are at risk of flooding in the Radikiai area. All these numbers justify the importance of a more detailed analysis of socio-economic issues applying the other methods in order to estimate the wider potential flooding risk.

4.6 Assessment of socio-economic risk and its comparison with FHRM

The case of Radikiai village disclosed additional natural hazards (ice jam flood) that can cause huge economic losses in terms of the analysed region. The analogy of the ice jam flood of 2010 with the 1% probability flooding of FHRM induced a concern to the other areas within the 1% probability inundation. Therefore, a what-if scenario was tested in terms of another approach for the evaluation of complex socio-economic risk in the mentioned area. The social and economic parameters were evaluated according to their values and range in certain grid cells (Table 2). It provided a basis for the evaluation of criteria and assignation of the rank. In total, 5 ranks were attributed for each variable considering the impact range from very low to very high vulnerability. The grid cells were selected only for the territory within the 1% flooding area. For the evaluation of social variables, the 2192 grid cells of 250×250-m resolution and 3020 grid cells of 1000×1000-m resolution in urbanised and rural territories were selected respectively. The total number of 179,727 grid cells of 100×100-m resolution was selected for the evaluation of economic losses. According to these data, the complex socio-economic risk was evaluated for the 1% flooding area. The determined complex socio-economic risk was compared with the risk of FHRM (based on the ratio method). Such a comparison figured out the main differences in the performance of the individual approach since FHRM did not include the evaluation with the other possible methodology. The application of one approach creates some limitations and uncertainties that not all possible risks are evaluated properly.

After the comparison of the actual flooded area of 2010 with FHRM, the approach of the ranking of the socio-economic risk disclosed more “hot spots”. There the risk is much more expressed than in the FHRM (Fig. 10). According to the ranking-based risk, the obtained results showed how many ranks of the risk are higher than in FHRM. Even at Radikiai village, the risk of FHRM was lower in two ranks comparing with the results of this research (Table 2). Moreover, an additional 152 grids were identified all over Lithuania, where the difference in socio-economic risk was by two ranks higher than in FHRM. The higher determined values of risk were defined at 105 grids for differences in 3 ranks and 22 grids—in 4 ranks. A major part of the country is covered by low differences in risk. But still, in more populated areas where 1% of flooding can pose a threat to the residents, there are some points of higher risk. For the identified grids where differences in socio-economic risk were so high, it requires deeper analysis (especially for those 22 grids with differences in risk of 4 ranks). Most risk zones and areas were assessed. The measures for the risk reduction were proposed in FHRM. However, the case of Radikiai village and the comparison of complex risk (according to another approach) showed that socio-economic risk may still be underestimated nationwide. Consequently, the scale and distribution of

Table 2 Socio-economic parameters

Variable	Unit, per cell	Evaluation criteria	Vulnerability	Rank	Count of cells		
					100 × 100	250 × 250	1000 × 1000
Total population[a]	Number	> 500	Very high	5	-	43	23
		101–500	High	4	-	262	271
		51–100	Moderate	3	-	264	209
		11–50	Low	2	-	744	998
		≤ 10	Very low	1	-	879	1519
Population, female[a]	% of total population	> 60	Very high	5	-	250	194
		46–60	High	4	-	691	676
		31–45	Moderate	3	-	120	174
		16–30	Low	2	-	-	1
		≤ 15	Very low	1	-	1131	1975
Population under 14 and over 65[a]	% of total population	> 60	Very high	5	-	5	13
		46–60	High	4	-	53	53
		31–45	Moderate	3	-	350	343
		16–30	Low	2	-	309	357
		≤ 15	Very low	1	-	1475	2254
Total houses[a]	Number	> 250	Very high	5	-	46	14
		101–250	High	4	-	92	91
		51–100	Moderate	3	-	134	143
		11–50	Low	2	-	624	692
		≤ 10	Very low	1	-	1296	2080
Economic loss[b]	EUR (€)	> 75,000	Very high	5	23	-	-
		50,001–75,000	High	4	57	-	-
		25,001–50,000	Moderate	3	174	-	-
		10,001–25,000	Low	2	496	-	-
		≤ 10,000	Very low	1	178,977	-	-

[a]Statistics Lithuania

[b]FHRM (Environmental Protection Agency)

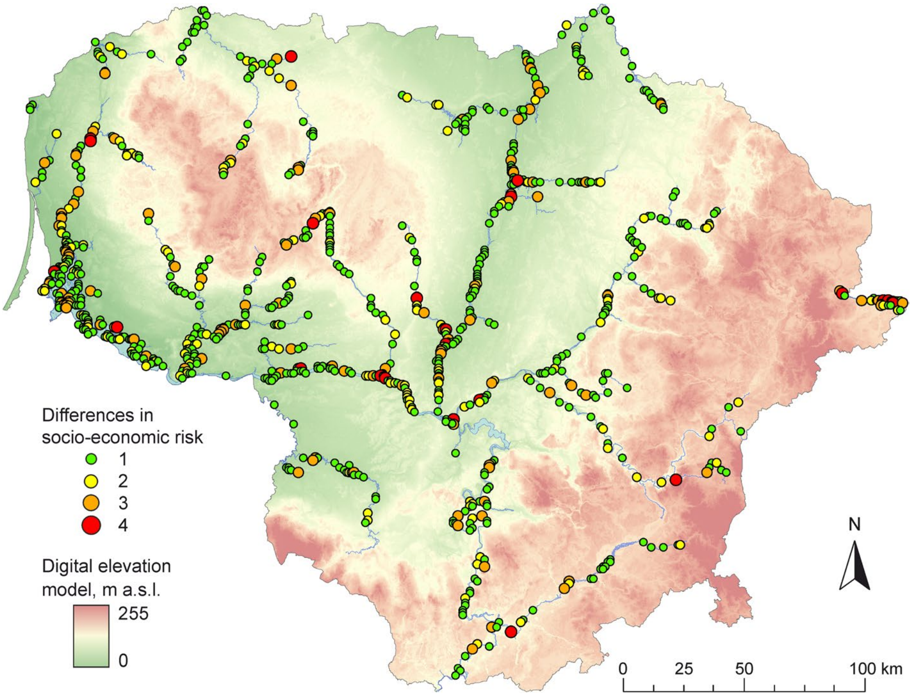

Fig. 10 Differences in socio-economic risk of FHRM and determined risk according to the ranking

the analysed risk can be influenced by the selected methodology because the methodological aspects of the used approaches differed from each other. The ratio-based approach had its limitation due to one or several high values that reduced the overall magnitude of the assessed impact. The ranking-based approach equalized the results, especially for the places where one of the joint risk variables had a really high value of risk. The main advantage of the ranking-based approach consisted of the integrity of output results because it evaluated overall risk proportionally by eliminating statistical outliers. During the 2010 flood, the proper measures were not applied for the comprehensive risk reduction with a special focus on vulnerable areas. Even 1% of flooding at the studied site can be caused by two different sources of origin, i.e. discharge and ice jam. Therefore, it is important to notice that the ice jam floods increase the annual exceedance probability of floods compared to the calculations based only on the river discharge. All these factors of causality require additional analysis and raise new issues, i.e. how the different origins of floods formation interact with each other and how they affect the recurrence period. The mentioned aspects are relevant to the areas where two types of flood formation are common and should be considered in the implementation of the new updates in the FHRM as well as in the development of the modern flood risk management.

5 Discussion

Ice jam floods are important hydrological and hydraulic events in Europe, which are of major concern for citizens, authorities, insurance companies and government agencies. These floods are particularly dangerous because they come together with ice on the shore that breaks different structures located within the flood zone. In recent years, there were advances in assessing climate change impacts on river ice processes; however, an understanding of regulation impacts on the timing and magnitude of ice jam floods is still limited. Some of the rivers in European Russia freeze for 4 months or more each year and these ice jam floods often had higher maximum water levels (Agafonova et al. 2017). In many northern countries, rivers are prone to ice-related flooding with high water levels and more extensive damages (Lindenschmidt et al. 2018). In Iceland, the perception of ice jam floods and risks is in its early stages (Pagneux et al. 2011) and showed three significant patterns: (1) there is poor awareness and little worry about historical inundations in the area; (2) experience of the past flooding events in town is the most effective source of knowledge; (3) awareness, risk estimation and worry are not correlated. In Western Finland, ice breakup jam floods negatively impacted livelihood and destroyed houses and a locally essential highway between the cities (Aaltonen and Huokuna, 2017). In Sweden, ice jam floods along the Torne River made huge damages because this river had unregulated flowing (Lindenschmidt et al. 2018). In Norway, ice jam floods in the Tana River and its tributaries damaged 13 estates. These damages were caused by a 4-km-long ice jam that formed downstream of Utsjoki village. Analysis of the flood 2010 in the Tornionjoki-Muonionjoki River (Finland) assessed the significant flood risk areas and took into account possible consequences caused by this flood (Centre for Economic Development, 2010): (1) negative impact to human health and security; (2) long-term interruption in many important services (water or energy distribution, telecommunications, road traffic etc.); (3) negative and long-term impact to the environment; and (4) irreparable negative impact to cultural heritage.

For the understanding of the behaviour of the 2010 flood in Lithuania, the 326 different types of articles were revised and analysed as well as data from the insurance companies and municipalities were also collected and assessed. This analysis revealed that this flood made huge damages to the floodplain residents, farmlands, roads, enterprises etc. Insurance companies and private properties had a lot of legal discussions and proceedings related to suffered losses of residents and who should cover it. Additionally, the comparison of socio-economic risk during this flood disclosed the importance of the application of different methodologies for the assessment of possible risks. Summarizing, the authors of this paper figured out the following relevant issues, which caused the assessed damage during the 2010 ice jam flood in Lithuania:

1. Till 2010, the legal framework for economic activities in flooding areas (except for some provisions in the Law on Protected Areas) was not regulated in the country. Consequently, it has allowed intensive struggle over construction activities in the river floodplains.
2. Up to 2010, architects have not designed any projects of residential houses, which could safely withstand the impact of flood waves.
3. There was no coordination system of actions during the flood of 2010 in the country. Only an FRT (Fire Rescue Service) was prepared for such a disaster, but it could only evacuate and rescue residents.

4. There were no information flyers or websites for the citizens, where during the flood period, the rules of behaviour of the residents were described in a clear and simple manner.
5. There were no official warning information or written instructions from the responsible services about the possible extent and character of the 2010 flood (except several interviews with representative persons in media).
6. Till now, the discussion continues about the possibility to remove river islands in complicated areas (if those islands are not in protected areas).

The losses would be significantly less, if the listed issues were considered before the flood of 2010. It would help to prepare an appropriate strategy for future flood management. After 1 year, the flood again came to the studied area and showed how the lessons were learned from the 2010 flood as well as the preparedness to control the magnitude of flood. A very good practice was shown by using peats during the flood of 2011 in the Kaunas District. The peats were spread on the potentially emerging ice jam area in the lower reaches of the Neris River (below Radikiai village). They were scattered by the plane, and as the result, the melting of ice jams was accelerated with the relatively small expenses (9210 EUR) (The peat sprinkling will cost over 30 thous. Litas in the Neris River 2011). But still, the situation in the act communication has not changed very significantly. There was a lot of discussion among the residents (especially from the Radikiai village), municipalities and politicians on how to manage the flood. However, the suggestions for the flood prevention were divergent. The residents proposed for official authorities to construct new or reconstruct current dykes and to remove the islands in the Neris River, which cause the ice jams. The government, instead of focusing on the development of local mitigation plans and providing technical assistance to local authorities, emphasized that the safety of residents' houses is only their own business since these buildings were constructed in the floodplain (even though they received permits for these constructions). For example, in the northern European Russia, the sequence analysis of the ice jam flood in the Northern Dvina enabled formulating recommendations for preventing the inundation of populated localities (Frolova et al. 2015). As well in our case, the recommendations and proposals for the protection and investments in the hydrotechnical structures (dykes) and their constructions in any way will be lower than economic losses after a flood without these investments.

A flood hazard map delineated the flood extent areas and gave information on flood characteristics (for example, depth and velocity) (Aaltonen and Huokuna 2017). Additionally, a flood risk map provides information about the potential consequences of a flood event, including the number of inhabitants or infrastructures vulnerable to flooding, and the potential economic damage for that specific event. In this research, the comparison of Flood Hazard and Risk Maps (FHRM) with the findings of this study revealed underestimated flood risk areas using the multi-criteria analysis of the socio-economic risk. The ranking technique was applied for the comparison of the complex socio-economic risk of FHRM instead of the ratio-based method. The ranking technique tends to be a more generalised approach and disclosed a whole risk, which covered an adequate range of target groups in comparison with the ratio-based method. The main limitation of the ratio-based methodology consisted of the one or several high values (in some cases it could be a statistical outlier), which could distort the objective evaluation of the potential risk because of the reduced risk of the analysed variables in general due to high values (near the 1 (highest risk)). Consequently, the ratio of the other values was much lower; however, the significance of their risk still remained very important. Whereas, the ranking approach was based on the range of the potential risk of the target group, which eliminated the effect of separate high values. On the other hand, the ranking-based method could generalise the risk strongly and eliminate very important points when the analysed criteria showed crucial risk. The comparison of these methodologies highlighted insufficiently evaluated areas under a flood risk. It can be the first step for the improvement of FHRM in order to assess all possible areas under higher risk adequately. In addition, it provides an opportunity to develop an appropriate flood risk management strategy and to propose effective flood risk reduction measures.

Sustainable flood management is a strategic approach that provides guidelines for the flood protection of socio-economic systems. In recent decades, flood risk management experts adopted new methods, tools and technologies for the better management and mitigation of flood damage. Geographical information systems and numerical modelling techniques were widely introduced to map floodplains, quantify potential damages and analyse flood risks. Many countries started to shift from flood damage and risk reduction strategies to damage and risk management strategies. In the USA, the community has an important role in the decision-making process to control land use modification (Samuels et al. 2006). Considering a central part of the risk mitigation strategy, the government of the USA took various initiatives to increase awareness of flood threat and flood plain management. In Europe, the Flood Directive was proposed by the European Commission on 18/01/2006 and was finally published in the Official Journal on 6 November 2007. It aims to reduce and manage the risks that floods pose to human health, the environment, cultural heritage and economic activity. For example, the 2007 Floods Directive had limited impact in France, because a national strategy (not required by the directive) was a good implementation and success (Larrue et al. 2016). On the one hand, the new planning tools established by the European Directive do have limited legal force, and on the other hand, the Directive does not change the balance of power among public authorities. In Poland, two shock events (floods of 1997 and 2010) with losses of 3 billion EUR each had a significant impact on Flood Risk Management (Matczak et al. 2016). After the flood of 1997, there was a plan to establish a universal flood insurance system, but the attempt was failed. Since the 2000s, the dominant hydrotechnical approach towards flood risk management was criticised more and more vividly. Finally in Poland, the newly built flood management system concerted with the EU Flood directive was successfully implemented. The governments of Germany and UK had prepared a special act “room for rivers” and “making space for water”, in the 1990s, focusing on land use regulation as a central part of the flood management approach (Krieger 2013). In Germany, different restrictiveness on land use modifications was incorporated in flood management plans based on the return period of floods. Before adopting a new catchment flood management plan in England and Wales, a pilot study was conducted for various catchments incorporating hydrodynamic modelling and other scientific analysis to identify the effectiveness in the proposed plan (Evans et al. 2002). After 2010, the development of flood management in Lithuania had significantly changed in a better way as well. However, the state government should take more effective steps in flood management. The analysis of the flood that occurred in 2010 is completed by identifying the causes of the damage. However, simply mentioning what should have been done but what was not done is not enough to mitigate the damage from the floods. Good practice and early actions of both local authorities and residents (use of peat to melt ice jam and small reinforcement of dykes) significantly decreased losses during the flood of 2011 (The peat sprinkling will cost over 30 thous. Litas in the Neris River 2011). Therefore, a more in-depth analysis of current Lithuanian flood risk governance in terms of its ability to apply diversified flood risk management is needed. Overall, the multiple, interconnected and often unintended socio-economic consequences of flood damage must be better considered before any planning, construction and restoration of protection measures in Lithuania. In contrast, traditional flood protection requires huge financial investments and results in major, and persistent changes in the landscape.

The current flood management can finally propose appropriate legal engineering structures as well as measures for public information for the prevention, protection and preparedness for floods. The first significant step of flood management in Lithuania was the adoption of Directive 2007/60/EC in national legislation (2009). This action created a basis for the following flood management stages: (a) assessment of Flood Risk (2012), which described the river basins, characterized previous floods, and their negative effects, indicated the territories which have high risks of floods and also described the possible negative effects of future floods; (b) preparation of Flood Hazard and Risk Maps (2014); (c) preparation of Flood Risk Management Plan (2017). Despite the advancements in scientific technologies of all aspects of ice jam flood management strategies, national and international collaboration in this field is still very limited. Accordingly, it should be done in an open discussion with stakeholders, policymakers and the community. This discussion must include the full suite of arguments, community proposals and future costs. The state government should also take effective steps in multi-institutional communication and coordination of flood risk identification, assessments and management with a special focus on the local problems during the floods and to provide technical assistance to local authorities. The same confirms the European Court of Auditor (Special report no 25, 2018: Floods Directive: progress in assessing risks, while planning and implementation need to improve", 2018), which established that the Floods Directive had positive effects overall, i.e. Member States began implementation of Flood Risk Management Plans, but improvements are still needed. Two main problems in current flood management strategies remained: first, national and regional flood management agencies do not collaborate as much as they could especially in communication with stakeholders, and second, environmental factors are not well-integrated into flood risk management approaches. These statements were also partially mentioned in the report from the European Commission to the European Parliament and the Council on the implementation of the Water Framework Directive (2000/60/EC) and the Floods Directive (Commission staff working document: first flood risk management plans - Member State: Lithuania., 2019). Based on the report's comments for Lithuania, the key areas for further development were related to the lack of efforts for public participation and stakeholder engagement. Therefore, the main recommendation was to strengthen the public consultation process and to ensure the greater involvement of stakeholders. The environmental factors were highlighted in the European Commission Staff Working Document where country-specific assessment for Second River Basin Management Plans was done (Europe Commission 2021). According to the comments which were provided in this document, the Second River Basin Management Plans contained no information concerning the prioritisation of green infrastructure. Based on the Commission recommendations, Lithuania should consider and prioritise the use of green infrastructure and natural water retention measures that provide a range of environmental, social and economic benefits which can be in many cases more cost-effective than grey infrastructure. Under the environmental benefits, flood protection was highlighted. To address these challenges and achieve sustainable flood management approaches, new strategies need to be adopted. These should include the following: the agreement of all levels of stakeholders, communities and institutions; non-structural measures and adaptation strategies; and flood management systems (based on socio-economic factors). The development of such integrated strategies will require a transdisciplinary approach that combines the perspectives and individuals (e.g. scientists and stakeholders) from different disciplines related to water management (e.g. hydrology).

6 Conclusions

During the flood of 2010 (ice jam flood of 1% probability), the total area of 40 thous. ha was flooded. This flood inundated 35 thous. ha of territory in the mouth of the Nemunas River (Nemunas Delta) with more than 400 residents. The total economic losses reached 2.8 million EUR. The analysis of hydrometeorological factors confirmed the favourable conditions for the formation of ice jams in high-risk areas. Due to the low temperatures, a huge amount of ice floes began to form and got stuck at the natural barriers. This situation led to a rapid rise in water levels in residential areas. Although the maximum spring flood discharge did not reach the multi-annual average maximum discharge, the water levels in some parts of the Nemunas River basin were close to critical.

The case study of the 2010 flood in Radikiai village confirmed the high accuracy of Flood Hazard and Risk Maps (FHRM), as they corresponded exactly to the inundated area of 1% probability flood and the actual number of flooded houses. According to FHRM, the complex socio-economic risk (based on the ratio methodology) fluctuated from 0.186 to 0.279. These numbers were relatively small compared to the actual situation in the area. During the 2010 flood alone, Radikiai suffered 492 thous. EUR economic losses, while the investment for the dykes would be 757 thous. EUR. For the evaluation of complex socio-economic risk, the ranking method was applied, which disclosed 105 and 22 grids where differences were by 3 and 4 ranks higher than in the FHRM (based on the ratio method). Therefore, it confirmed additional “hot spots” where the risk was not sufficiently investigated and which required more in-depth analysis.

Overall, flood management in Lithuania had come a very long way before it took on its current shape. During the last hundred years, the understanding of hydrological extremes increased considerably. All modern tools (Flood Risk Assessment, Flood Hazard Risk Maps and Flood Risk Management Plan) for the implementation of the Flood Directive can propose reasonable measures for floods management in order to reduce flood risk in the sensitive areas. During the 2010 flood, Lithuania was on the first steps of the Flood Directive implementation therefore occurred flood was not sufficiently managed and caused the estimated damages.

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