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Hydrological hazards in Russia: origin, classification, changes and risk assessment

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Abstract Hydrological extreme events pose an imminent risk to society and economics. In this paper, various aspects of hydrological hazards in Russia are analysed at different scales of risk assessment. It is shown that the number of hydrological and meteorological hazards in Russia has been growing every year. The frequency of economic losses associated with extreme low flow in this century has increased by factor five compared to the last decade of the previous century. With regard to floods, an interesting spatial patter can be observed. On the one hand, the number of floods in the Asian part of the country has increased, whereas on the other hand, the number and intensity of floods in estuarine areas in the European part of Russia have significantly reduced since the middle of the twentieth century, especially in the 2000s. This decrease can be attributed to runoff flooding in the mouths of regulated rivers, with an effective system of flood and ice jam protection. The analysis shows that there is an 8–12-year periodicity in the number of flood occurrences and that flood surges have intensified over the last 110 years, especially on the European territory of Russia. An integrated index that accounts for flood hazards and socio-economic vulnerability was calculated for each region of Russia. A classification of flood risk was also developed, taking into account more than 20 hydrological and social–economic characteristics. Based on these characteristics, hazard and vulnerability maps for entire Russia were generated which can be used for water management and the development of future water resources plans.

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1 Introduction

Studying dangerous hydrological events is of high priority, due to their strong influence on society and economics. The Second IPCC Assessment Report shows that for Europe (including European Russia) climate change affects the frequency of extreme events and precipitation (Watson et al. 1998). It is supposed that the global hydrological cycle is intensifying and that the extremes of droughts and floods become more common (Watson et al. 1998). Due to climate change and increased human water needs, drought impacts are likely to get worse in the future (IPCC 2014) and will therefore require constant monitoring and assessment.

Due to the strong impacts of hydrological hazards, they have always been a key concern to hydrologists. Topics of studies include, but are not limited to extreme hydrological events, flood or drought risk assessment and hydrological change prediction. During the last years, several studies and books focused on the complex analyses of climate variability and its impact on hydrological disasters (Demuth et al. 2006), as well as on the methodologies of risk assessment (Murphy 2010; Alberth et al. 2012).

In terms of floods, the latest papers focusing on flood analyses and flood dynamics include, for example, Lugeri et al. 2006; Vojinovic and Abbott 2012; Keskitalo and Carina 2013; Hall et al. 2014; Kapucu and Liou 2014. Additionally, various aspects of the flood terminology are discussed in detail in studies by Alexander (Natural Disasters 1993, 1997). The conception of risk, hazard and vulnerability is recommended in this paper as general approach.

Economic losses caused by water-related disasters are estimated to account for more than 100,000 million US dollars, and damages caused by floods are suggested to amount to about 50 % of disaster-related losses in the world during the second half of twentieth century (Okada et al. 2007). In Russia, hydrological hazards are also of strong concern. According to Russian Ministry of Natural Resources and Ecology, total annual economic loss (direct and indirect) from floods is estimated to be 40 billion rubles (570 million US dollars) (The State Report 2010). The total area of potentially flood-affected territory in Russia is determined to be 400,000 km^2, from which $\sim$50,000 km^2 are flooded annually. These include more than 746 settlements (including 40 big cities) with more than 4.6 million inhabitants potentially facing floods (Shiklomanov 2008). Overall, many works in Russia are devoted to the different aspects of flood generation (Avakian and Polyushkin 1991; Dobroumov and Tumanovskaya 2002; Buzin 2008; Shiklomanov 2008; Agafonova and Frolova 2009; Semenov et al. 2015). Owing to geographical features of the Russian territory, approximately half of the floods are caused by snow and ice melt, rain-induced floods and ice jam floods account for 36 and 15 %, respectively, while a few number of costal floods are triggered by wind surges (Dobrovolsky and Istomin 2006). However, often the distinction of different causes of floods is not clear cut, as floods can occur due to a combination of several factors. Such factors include rain of various duration and intensity, sometimes accompanied by snowmelt, increased discharge from reservoirs into tail water pools, damage and/or destruction of hydraulic structures, mudflows and landslides, burst of landslide lakes and surges in river mouths.

Apart from floods, hydrological droughts are the other side of the hydrological extremes, which are one of the most social-reflected events (Spinoni et al. 2016). In international hydrological practice, question of drought formation and definitions is widely discussed in (Hisdal and Tallaksen 2000; Tallaksen and Van Lanen 2004; Sheffield and Wood 2011; Mishra and Singh 2010; Van Loon and Van Lanen 2013), but there is no absolute consensus about this definition (Hayes et al. 2010). According to Van Loon and Laaha (2015) for prediction and the selection of drought sensitive regions, it is crucial to know how the streamflow drought severity relates to climate and catchment characteristics. The question of drought analyses and dynamics of drought events are widely discussed in papers of "FRIEND Low Flow Group" (Corzo Perez et al. 2011; Fleig et al. 2011; Vidal et al. 2012; Van Lanen et al. 2013). Many studies focused on drought classification (Van Loon and Van Lanen 2012, 2013). Van Loon et al. (2014) define two new hydrological drought types, spread in cold climates: snowmelt drought and glacier melt drought.

Generally speaking, most of the loss is associated with hydropower generation, river navigation and water supply, for instance (Wilhite 2000; Carroll et al. 2009), but exact determination of the impacts of droughts is a very complicated and complex aim (Wilhite 2005). For Europe, it was estimated that over the past 30 years, annual drought and water scarcity affected 11 % of the population and the total economic losses accounted for 100 billion euro (European Commission 2007b). For example, catastrophic events in 1989, 1990, 1991 and 2003 affected 800 000 km^2 and 100 million European (EU) inhabitants and the average economic "drought cost" was estimated 6.2 billion euro per year (European Commission 2007b). For the period 2006–2010, 15 % of the EU territory and 17 % of the EU population was affected by drought on an annual basis (Spinoni et al. 2016). The latest update of drought event impacts in Europe was completed in 2016 for by "FRIEND Low Flow Group" (Stahl et al. 2016). It is based on the European Drought Impact report Inventory (EDII), which includes more than 5000 impact reports from 33 EU countries.

In Russia, there is currently no official methodology available on how to calculate drought impacts (Alexeevskiy and Frolova 2011). For the 2010 drought in Russia, a first estimation approach for each water use sector was developed based on the literature review, government standards and reports. It was shown that direct losses from the 2010 drought for water supply in the agricultural sector accounted for 41.8 billion ruble (597 million US dollar) (The State Online Report of Agriculture Ministry of RF 2010). According to Russian Fleet Agency, water levels were below guarantied for shipping during 50–200 days in the European part and 0–50 days for Asian part of the country. Hydroelectric power production was 16 % lower, than the previous year (according to RusHydro Corporation online graphs www.rushydro.ru). The average deficit of water resources in Russia during drought periods can be approximated to 14.3 km^3 (Shiklomanov 2008). Additionally, detailed analyses of droughts in Russia are presents in the book "Extreme hydrological events" (Koronkevich et al. 2010) and the analysis of trends in low flow is discussed by Shiklomanov 2008; Dzhamalov et al. 2012 and Semenov and Korshunov (2007). It is shown that during the last 30 years minimum monthly discharges have doubled for winter and summer season, while seasonal flood maximum decreased by 20–60 % (Dzhamalov et al. 2012; Kireeva et al. 2015).

To complement the previous studies in hydrological hazards in Russia, this paper focuses around the idea of different scales of such hazards in Russia, ranging from effects visible at the hall country total numbers, to large basins river mouth. Additionally, it is presented how the assessment of the spatial scales of flood risk can be realized and used to identify areas of priority for decision-making and governance. This is of particular importance, as in Russia, hazard assessment is usually conducted at different spatial scales, being the federal, regional, basin or local level. The level of spatial generalization determines the data that can be used in the assessment, the choice of appropriate indicators, the analysis methods and the final display of the assessment results. Therefore, this paper is structured around the three most important spatial scales for hydrological hazards in Russia: the state level (the entire Russian Federation), the level of the "so-called" Federal Subjects (constituent entities of Russia) and the level of selected large river basins (spatially river mouth).

The paper is structured as follows: first, we present a terminology for the hydrological hazards typology that is specific to Russia; second, we describe the study area and the data used in this manuscript; third, we present methods of trend analyses and risk assessment scheme; fourth, we analyse results and discuss them in terms of international research investigations. In the conclusion, we detail that changes in water regime have different impact on hydrological hazards in different Russian regions, which due to the different genesis mechanisms of floods and droughts.

2 State of the art

Before presenting our research, it is important to give an overview about the terminology used in this study. Internationally, there is a variety of terms associated with floods, such as risk, hazard, exposure, vulnerability, coping capacity, resilience and adaptive capacity. In each country, the meaning of these terms can be interpreted differently (Gallopin 2006; Cutter et al. 2008). As this paper focuses on Russia, the characteristics and terms are being used according to Russian scientific terminology, although we attempt to streamline them to be comprehensible to the international audience. Criteria for identifying hazardous events in Russia are established based on qualitative and quantitative hydrological characteristics (GOST 1995). When hydrological events reach the established criteria, they are considered hazardous (see Table 1). Hydrological processes become hazardous if changes in hydrological conditions of water bodies caused by natural or anthropogenic factors lead to the risk of economic, ecological and social damage.

Mostly hydrological hazards are related to the hydrological regime of rivers and occur due to both extremely high discharges and water levels during floods or extremely low water levels during autumn or winter low water periods resulting in the lack of water resources. The frequency of such hydrological hazards depends on both the hydrological regime of the rivers and the geographical locations. Hazardous events either may be local or occur along the whole length of the rivers. They may also occur around lakes, reservoirs and coastal areas (Frolova 2006; Alexeevskiy et al. 2007, 2010).

According to Russian Government Standards, a "*dangerous hydrological event*" is a result of hydrological processes caused by various natural and/or hydrodynamic factors that affect people, agriculture, economic infrastructure and the environment (GOST 1995). Along these lines, the term "*flood*" *is* associated with a temporary inundation of a territory inhabited by humans and economic losses in Russian (GOST 1995; Alexeevskiy et al. 2007; Shiklomanov 2008). It is considered as being one of the most serious hydrological hazards. The adverse socio-economic impacts of flood may be manifested in the form of loss of life, evacuation of population, tangible and intangible damage (e.g. Dobrovolsky and Istomin 2006; Nezhihovsky 1988).

In the international literature, the term "extreme low flow" is usually associated with a hydrological drought, being defined as a below normal water availability (Tallaksen and

Table 1 Hydrological hazards, definitions and their criteria (Guidance document. Instruction 2002; GOST 1995)

Hazard	Definition	Criteria established by
High water level	Water level caused by floods, ice gorging and ice jams resulting in inundation of low-lying areas and infrastructure. Determined for each hydrological station individually	Regional Offices for Hydrometeorology and Environmental Monitoring (ROHEMs) or by Centres for Hydrometeorology and Environmental Monitoring (CHEMs)
Low water level	Water level continuously lower than the design level of water intake facilities and irrigation systems, and the threshold level for navigable rivers and water bodies for a minimum of 10 days. Determined for each hydrological station individually	ROHEMs or CHEMs
Early ice formation	Extremely early occurrence of ice events on navigable rivers, lakes and reservoirs. Date of early ice formation, which should not occur more frequently than once in 10 years.	ROHEMs or CHEMs
Specific ice events	Ice piling on the shore near various infrastructure facilities; mass underwater ice formation near hydropower plants (HPPs) and water pipes; freezing of water bodies and water ways down to the bottom Based on the size and level of damage. Should not occur more frequently than once in 10 years	ROHEMs and CHEMs.
Ice built up	Formation of ice built up in river channels and floodplains that endanger settlements and infrastructure facilities, depending on their operating rules.	ROHEMs and CHEMs
Very high discharge	Discharge values ($\leq$10 % frequency) (natural and HPPs operational output) at which normal operation of hydraulic engineering installations and facilities is disturbed	ROHEMs and CHEMs
Very low discharge	Discharge values ($\geq$90 % frequency) (natural and HPPs operational output) at which normal operation of hydraulic engineering installations and facilities is disturbed	ROHEMs and CHEMs
Mudflow	Short-duration flooding of very high intensity containing a large amount of mineral particles and rock debris	–
Avalanche	Sudden and rapid snow movement down steep mountain slopes that poses a threat to human life and brings damage to economy	–

Van Lanen 2004; Sheffield and Wood 2011; Mishra and Singh 2010). In Russia, there is also no precise definition for "*low water*" or "*extremely low flow*" (see Table 1). The purpose of the Russian term is to describe a low flow period accompanied by various types of damage (Weather and Climate Services in Europe and Central Asia 2008), along the line of the definition of "*flood*". The term "*low water*" is rather closely associated with the concept of a hydrological drought (Hydrometeorological Risks 2008), which is different to atmospheric, soil, agricultural and water resource droughts (Bolgov et al. 2005). Generally, "*low water*" can be best described as a seasonal or long-term period of insufficient amount of water in a river resulting in social, economic and ecological damage. Under "*low water*" conditions, the operation of hydropower facilities, river transport and communal services becomes less reliable or impossible. Reduced river flow leads to deterioration of water quality, deterioration of the epidemiological situation and the decline of fish population (Fig. 1).

3 Data sources and study regions

Depending on the hydrological hazard of interest and data availability, different data sources and time periods were analysed, as shown in Table 2.

To study the patterns of hydrometeorological and hydrological hazards in Russia, time series for the period of 1991–2015 were analysed. The data archive was compiled by the Research Institute of Hydrometeorological Information—World Data Centre (RIHMI-WDC). Based on Table 1, the total number of hazardous events, the number of floods during the high water period, the number of hazardous rainfalls and the number of extreme low flow events are studied.

Changes in the number of floods in the river mouths of large river basins were analysed, based on the database "Floods in river mouths on the territory of the European Russia" developed in 2012 by the Lomonosov Moscow State University (MSU), Department of Geography, here called MSU data. This database summarizes all confirmed cases of floods and provides their occurrence, hazardous and extremely hazardous floods and water levels at the beginning of the flood inundation for selected river mouths (Table 3, Fig. 2). In addition, data of the maximum flood inundation of coastal areas (m) and the probability of threshold water levels at the beginning of inundation in coastal areas were computed for specific flood-prone areas based on the long-term time series. For the analysis, the eight-largest and most economically important river mouth areas on the territory of the European Russia were selected. The MSU data were compared with the data of maximum discharges and maximum levels from 54 stationary gauging stations for the period 1900 (1910, …, 1925) to 2013. On average, there were five to nine gauging stations in each river mouth area, which allows the assessment of the flood magnitude.

To evaluate the regions (subjects) of Russia in terms of flood risk, information summarized by Constituents of the Russian Federation was used (Fig. 3). Most of this information was taken from the previously published sources and several statistical databases of the State Inventory (e.g. National Atlas of Russia 2007; Natural hazards in Russia: hydrometeorological hazards 2001; Chalov 1979; Reimers 1990; Report on human development in the Russian Federation 2010; Gladkevich et al. 2000). For specifically flood-prone areas, the maximum flood inundation level (m) of coastal areas and the probability of high water levels at the beginning of flood inundation of coastal areas (%) were computed based on the long-term time series (more then 50-year observation period).

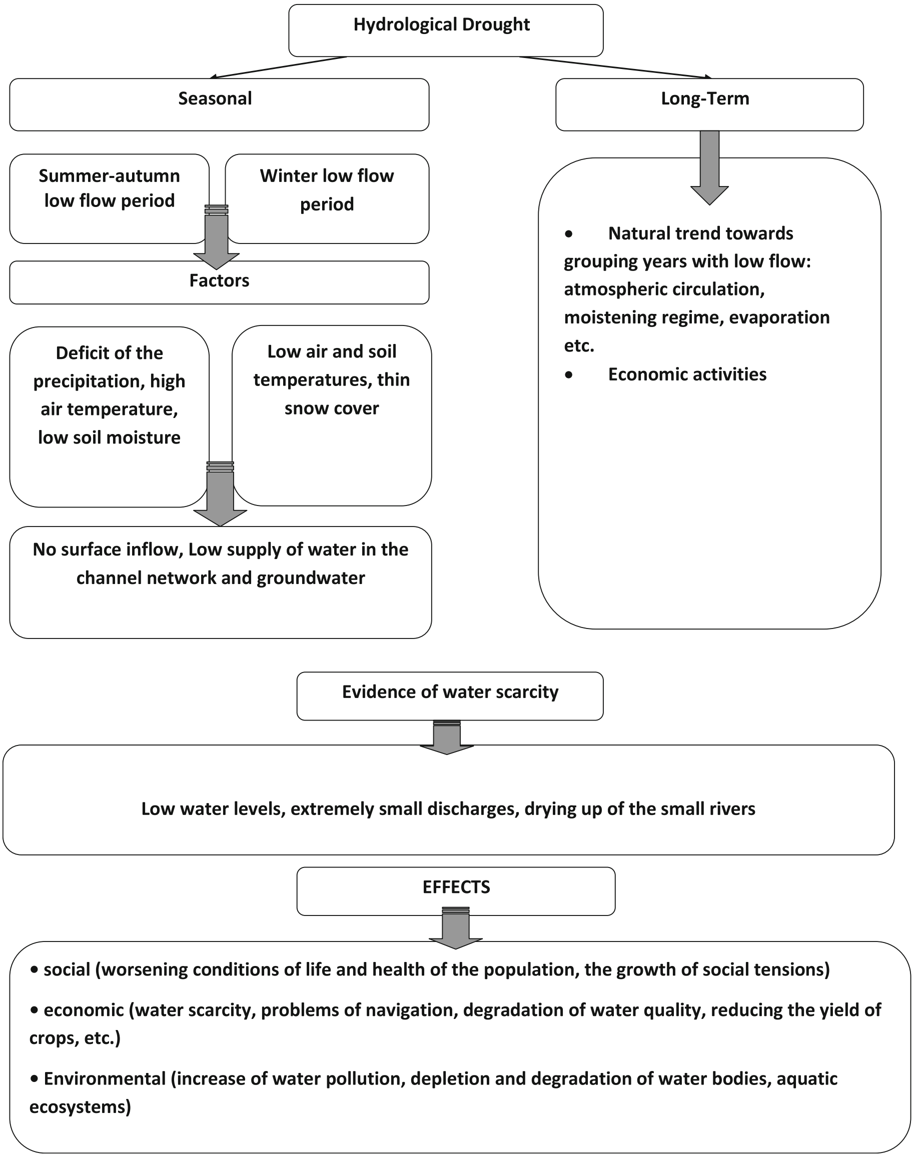

Fig. 1 Schematic structure of the factors, manifestations and consequences of low water events (updated Alexeevskiy and Frolova 2011)

4 Methods

4.1 Analyses of Hydrometeorological Hazards in Russia

The database on hydrometeorological hazards in Russia commenced in 1991, resulting in the availability of 25 years. The database offers homogenous records of good quality, which can offer valuable insights. In this study, the database was analysed for trends using

Table 2 Data involved in recent analyses

Data source	Data provider	Hydrological hazard	Variable	Time period	Study area/interest
Hydro-meteorological Data Archive focused on hazards	Research Institute of Hydro-meteorological Information—World Data Centre (RIHMI-WDC)	Hazardous events: droughts and floods	Total number No. during high water No. extreme low flow No. hazardous rainfall	1991–2015 (2012)	Patterns of hydrometeorological and hydrological hazards for entire Russia
Database on floods in river mouths on the territory of the European Russia (registration number 2013620332)	MSU Department of Geography (developed in 2012)	No and magnitude of floods in the river mouth area	Water level Duration of floods, genesis of floods, economic loss from concrete events	1900 (1910, …,1925) to 2013	Eight important river mouth of European Russia
Constituents of the Russian Federation, National Ministry reports, previous scientific investigations	Russian Government	Floods	Natural hazards characteristics and social–economic variables	1961–1991 (official WMO-period) for hazard and 1980–2010 for vulnerability	Federal regions (subjects)

Table 3 Study river mouth areas and their characteristics (area, sea basin, number of analysed gauging stations and available observation period)

No.	River	Area, ths. (km^2)	Sea	Number of station	Period
1	North Dvina	357	Barents	5	1900–2013
2	Pechora	322	Barents	6	1913–2013
3	Neva	281	Baltic	9	1900–2013
4	Pregolya	15	Baltic	5	1900–2013
5	Don	422	Azov	8	1900–2013
6	Kuban	58	Azov	8	1910–2013
7	Terek	43	Caspian	5	1925–2013
8	Volga	1360	Caspian	8	1900–2013

standard statistical criteria—Student's and Fisher's (SP 2004), together with the Spearman test and coefficient for liner trend analysis.

4.2 Dynamics of floods in Large rivers mouth

Large river mouths are one of the most dangerous territories in terms of floods all over the world as well as in Russia (Dobroumov and Tumanovskaya 2002; Dobrovolsky and Istomin 2006). As shown above, there are many different classifications of hydrological hazards and processes in Russian, including floods and low water. In this paper, a classification of hydrological hazards and processes in river mouths and coastal areas is used (based on their genesis and key factors), which was developed by the Department of Geography of the MSU (Alexeevskiy and Magritsky 2013). In this classification, best practices and existing classifications are combined, including classification of hydrological terms adopted by the National Standard of the Russian Federation (RF), classification developed by Nezhikhovski and classification of the RF Ministry of Emergency Situations (MES) and Federal Service for Hydrometeorology and Environmental Monitoring (Roshidromet).

On the basis of the MSU classification, the analysis in this paper focuses on the following hydrological hazards in river mouth:

I. Extremely high water level and discharge
   - (A) River floods (runoff floods, runoff-ice lam floods, runoff-rainfall floods and runoff-morphodynamical floods).
   - (B) Storm surges and upsurge floods, caused by wind

II. Extremely low water level and discharge
   - (C) Adverse and hazardous runoff and runoff-freeze-up low water levels
   - (D) Adverse and hazardous down fall in water level, caused by wind

In addition to the analyses performed above, the analysis also focuses on the genesis of flood and low flows. Furthermore, the statistical analysis of floods (Student's and Fisher's criteria, SP 2004) was performed based on the MSU classification for flood classes based

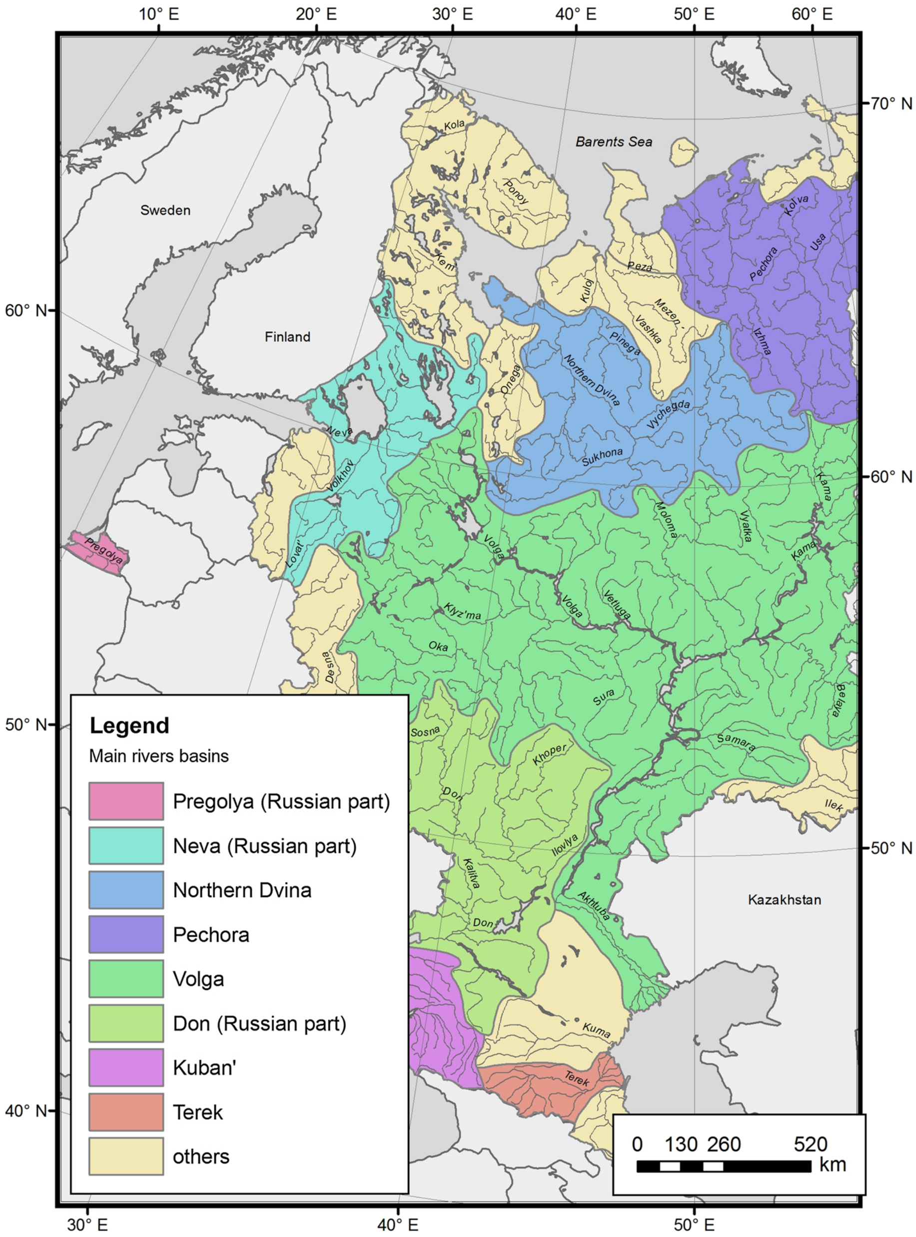

Fig. 2 Study basins and river mouth areas on the European territory of Russia

on their degree of danger (Table 4). The traditional Russian flood classification was developed by Ginkgo (1977) and Nejihovsky (1988), and later completed by Taratunin (2008), and is still widely used. The traditional classification accounts for return period, occurrence of maximum levels, percentage of the flooded area, water levels, flood's duration, width of the flooded area and property damages. Since this classification requires

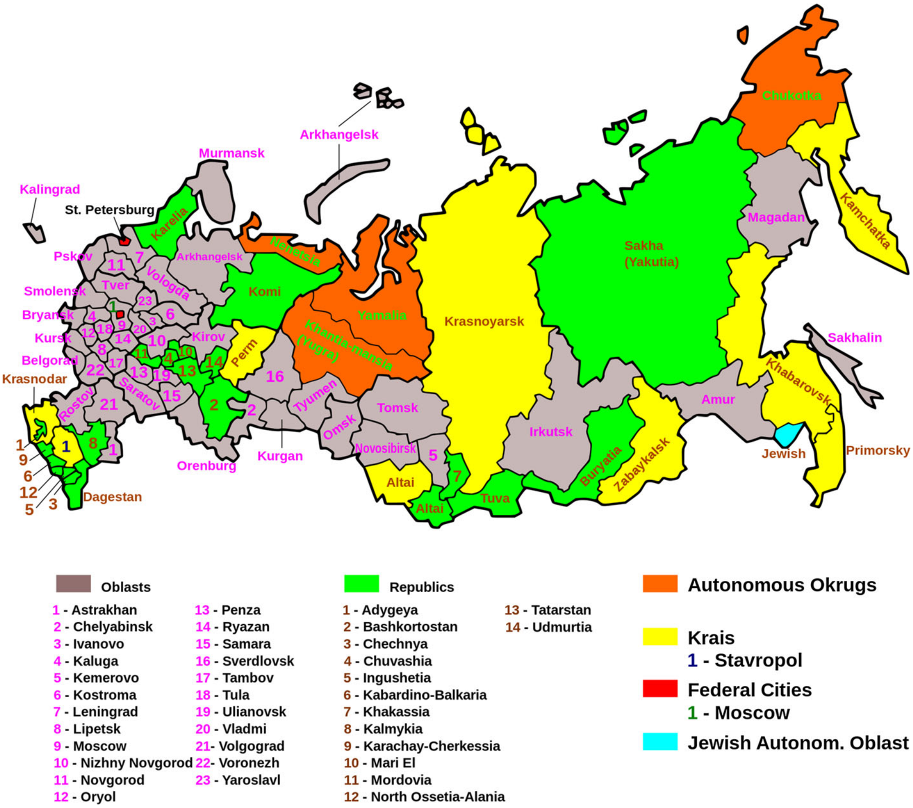

Fig. 3 Scheme of the regions (subjects) of Russia (The National Atlas 2007)

Table 4 MSU classification of the floods by the degree of danger

Risk level	Main parameter to range
Moderately dangerous	Exceeding unfavourable levels
Dangerous	Exceeding dangerous levels
Highly dangerous	Human victims, large flood depth, etc.
Catastrophic	Return period more than 50 years

many parameters, it is somewhat problematic to classify many floods, especially the historical events. Therefore, a fundamentally different approach was developed by the authors of this paper to classify these floods, accounting for the specific characteristics that are found in the river mouth areas.

The new approach first takes into account “the fact of the flooding” itself (i.e. its genesis), which was described in newspapers or historical documents. After that, the main focus is to understand the class of the flood by magnitude and the damage level. The next step is to compare known flood levels with different hydrological statistics (see Sect. 3). As a result, events can not only be classified as “floods” but also be ranked based on their risk level into four different categories (Table 4).

4.3 Flood hazard assesment

Objective risk assessment of natural hazards is not an easy task, especially if reliable data are almost impossible to obtain. Thus, the assessment of risk can only be performed subjectively based on indirect characteristics that have to be carefully chosen. In international practice (Alexander 1993, 1997; Lugeri et al. 2006; Alberth et al. 2012; Encyclopedia of Natural Hazards 2012), the general paradigm of "Risk = Hazard × Vulnerability" is the most common. According to this general concept, two main tasks have to be performed when performing risk assessments:

(1) To access the *hazard* based on hydrological parameters, characterizing floods or droughts (their probability, threshold water levels, flooded area, etc.). Such parameters have to be general enough to be applied uniformly over the study area (here all the Federal Subjects of Russia).
(2) To access the *vulnerability* stemming from complex of social and economical parameters, characterizing material resources and potential damages in the case of floods.

Two lists of the hazard and vulnerability parameters were developed in this study, to determine the hydrological risk in Russia.

The combined lists show that the risk is mainly determined by the social and economic characteristics of the affected territory.

Flood hazard parameters in Russia were determined by: *g*

- Maximum inundation depth (m);
- Probability of the water levels corresponding to the start of floodplain inundation (%);
- Average flood duration (days)
- Percentage of the potential flooded to total area (%)
- Type of the passing of the bed-forming discharge in rivers with wide floodplains, adapted and cut-in channel beds.

The degree of vulnerability for each federal subject was estimated by:

- Population density
- Percentage of the population residing in potential flooded zone
- Index of human potential development
- Cost of the main industrial and non-industrial resources
- Complex index of potential risk due to economical activities

Flooding in particular is affected by multiple factors, which determines the specific aspects to be considered in the risk assessment. As we mentioned before, the widely accepted method of treating such a system is to calculate the risks by multiplication of the hazard and the vulnerability of the territory (Alexander 1993, 1997; Lugeri et al. 2006; Alberth et al. 2012; Encyclopedia of Natural Hazards 2012). However, this model requires reliable data on potential damages that is usually not readily available. Therefore, we need to apply methods for a complex quantitative assessment to the federal regions (subjects) of Russia. Such methods have been developed at the end of 1960s in the USA and have been applied before to economic–geographical studies (Gladkevich and Mozgumov 2010; Gladkevich et al. 2012). The methods are based on a nonparametric technique of multidimensional analysis PATTERN (Planning Assistance Through Technical Relevance

Number). In its basis lies taking the values of the characteristics normalized by their maximum values:

$$t_{ij} = \frac{x_{ij}}{x_{i\max}}, \quad (1)$$

where x_{ij} are the values of a given characteristic for the federal subject, $i = 1,\ldots, n$ stands for the given characteristic and $j = 1,\ldots, k$ for the federal subjects (Fig. 4).

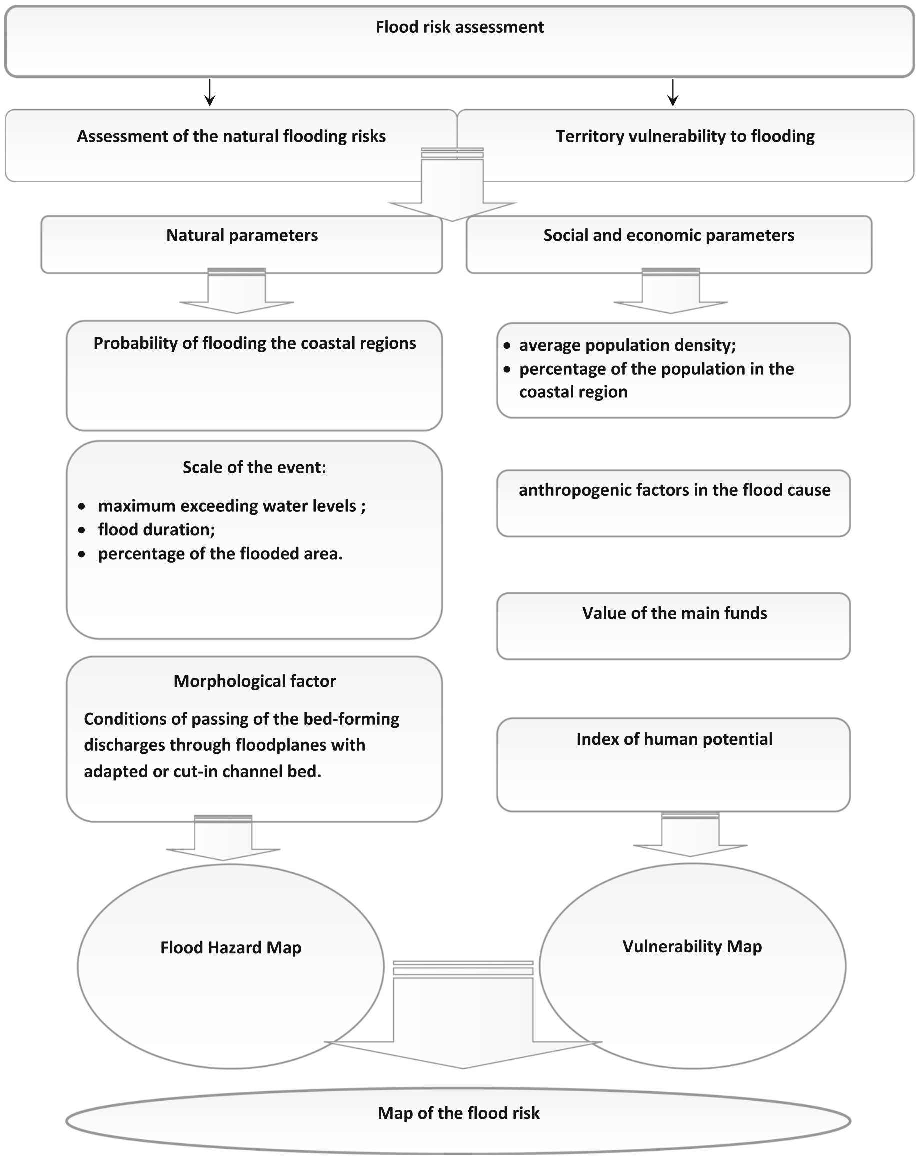

Fig. 4 Flood hazards assessment parameters

Table 5 Weight coefficients for hazard and vulnerability parameters

Natural flood hazard parameters	$K(i)$*	Socio-economic vulnerability to flooding parameters	$K(j)$*
Maximum inundation depth (m)	0.2	Population density in the regions	0.1
Probability of the water levels corresponding to the beginning of a flood (%)	0.1	Percentage of the population residing in the zone of potential flooding	0.5
Total average flood duration (days)	0.5	Index of human potential development	0.1
Percentage of the potential flooded area to total (%)	0.1	Cost of the main industrial and non-industrial resources	0.2
Type of the passing of the bed-forming discharge in rivers with wide floodplains, adapted and cut-in channel beds	0.1	Complex index of potential risk due to economical activities	0.1

*$K(i)$—weight coefficient for hazard parameters; $K(j)$—weight coefficient for vulnerability parameters

Based on the method described in Eq. 1, the resulting indexes K_1 and K_2 are calculated as the sum of different values of t_{ij} with weighted coefficients $K_h(i)$ and $K_v(i)$ (Table 5). The weighted coefficients are determined based on the quantitative contribution of every factor within the group of factors (hazard or vulnerability). They can vary considerably from region to region within Russia due to the diversity of conditions for maximum discharge formation and also due to heterogeneity in the population density and economic activity (e.g. industry, agriculture) of high-flood-risk areas. In the situation of complete lack of data and empirical evidence, the weighted coefficients are determined based on the knowledge of ten expert and additional literature (e.g. Buzin 2008). The resulting weights of the coefficients (K) for this study are presented in Table 5.

From the hazard factors list (see above), the predominant influence on the damages is determined by the duration of a given flood and the maximum water depth in the affected area. Amongst the factors of socio-economic vulnerability, the most important ones are the percentage of the population residing in the high-flood-risk zone and the parameter of anthropogenic development.

According to the PATTERN method, flood hazard and vulnerability coefficients are calculated as sum of the partial ones (Eq. 2):

$$\begin{aligned} K_h &= \sum K(i) \cdot t_{ij} \\ K_v &= \sum K(j) \cdot t_{ij} \end{aligned}, \qquad (2)$$

According to the expert judgement, the integral risk index (K_{int}) in Eq. 3 is the sum of natural risk (K_{h}) and socio-economic vulnerability (K_{v}), indices with weighted coefficients $\alpha_{\mathrm{h}} = 0.2$ and $\alpha_{\mathrm{v}} = 0.8$, respectively.

$$K_{\mathrm{int}} = \alpha_{\mathrm{h}} \cdot K_{\mathrm{h}} + \alpha_{\mathrm{v}} \cdot K_{\mathrm{v}}, \qquad (3)$$

The method described above is used to create maps of flood hazard and vulnerability for region (subject) scale, and they are combined to create a complex map of integral flood risk to allow for a qualitative classification of flood risks spatially. The obtained flood risk index is divided into six intervals, ranking from "very low" to "extremely high" risk (Table 6).

Table 6 Classification of the flood risk level

	Risk level					
	1 Very low	2 Low	3 Medium	4 High	5 Very high	6 Extremely high
Integral flood risk index, K_{int}	<0.2	0.2–0.25	0.26–0.3	0.31–0.35	0.36–0.4	>0.4

5 Results

5.1 Hydrometeorological hazards in Russia for the past 25 years

Due to its large territory and unevenly distributed resources, the socio-economic domain of Russia is nearly constantly exposed to severe weather and hydrometeorological hazards. The results of our analysis for the period 1991–2015 show that there is a statistically significant trend ($p < 0.05$, Student's test). On average, the number of hydrometeorological hazards increases by 13 events per year. The total number of hydrological hazards has therefore more than doubled, ranging from 142 to 252 events in the 1990s to 322–469 by the early 2010s (Fig. 5). Using the methodology of RosHydromet as described above, all hydrometeorological hazards can be divided into nine groups (Fig. 6). The mostly common events are dangerous winds (24 %), followed by heavy rain and hail (23 %). Flood events account for only 10 % and droughts for 4 %. However, these two hazards amount for more than 40 % of economic loss in total (The State Report 2010).

Therefore, we now present in a more detailed analysis on floods and droughts. Figure 7 shows that although the number of hydrometeorological hazards and floods has an increasing tendency, the share of floods to the total number has an overall decreasing tendency. At the same time, the share of droughts to total number rises from 1 to 3 %.

Additionally, in Fig. 8, we investigate the number of heavy rain, which lead to flooding (1991–2012), hazardous seasonal floods (defined as snowmelt) and occasional floods (defined as rain-derived) (1991–2013) for which any socio-economic damage has been documented by ROHEM. It can be seen that there is a general increase in heavy rain over

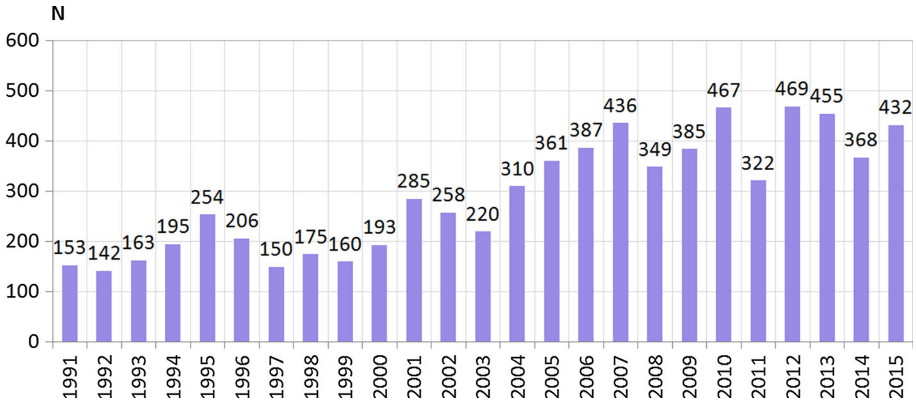

Fig. 5 Number (N) of hydrometeorological hazards per year in Russia for the period 1991–2015

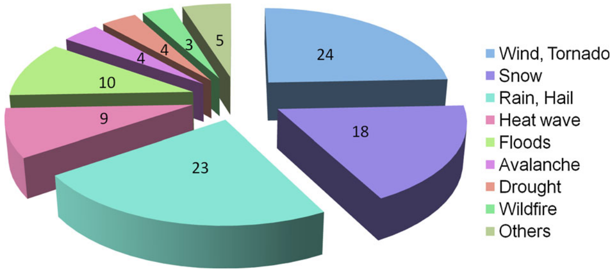

Fig. 6 Distribution of hydrometeorological hazards in Russia over the following types (1991–2015)

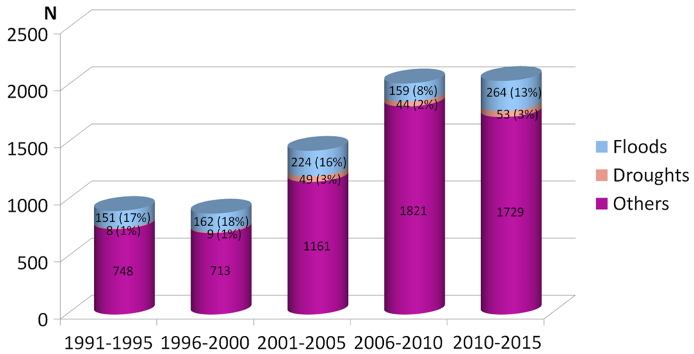

Fig. 7 Number of floods, droughts and total number of hydrometeorological hazards

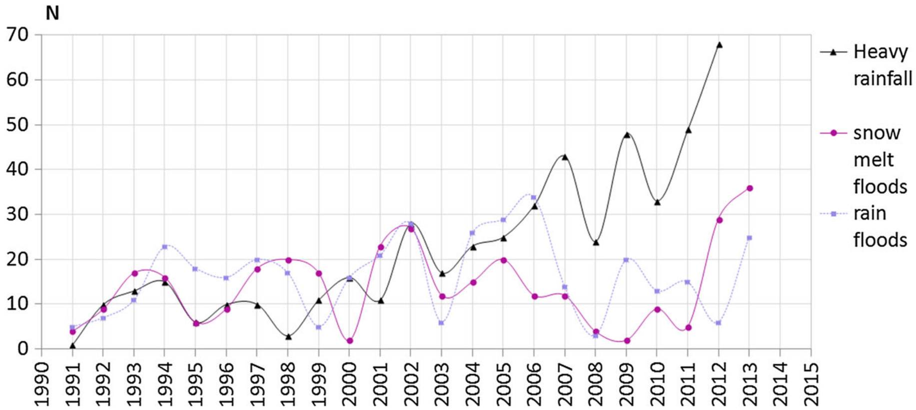

Fig. 8 Annual number (*N*) of heavy rain, hazardous seasonal and occasional floods

the analysis period. During 2001–2005, there has been a pronounced increase in the number of hazardous floods, with a decreasing (2006–2010) and an increasing fluctuation (2011–2015) afterwards.

Apart from the analysis of floods above, the analysis of droughts is shown in Fig. 9. For the period 1993–2015, a total of 163 cases of socio-economic damage due to water scarcity were documented, most of which 146 (89 %) occurred after 2000. Thus, the frequency of

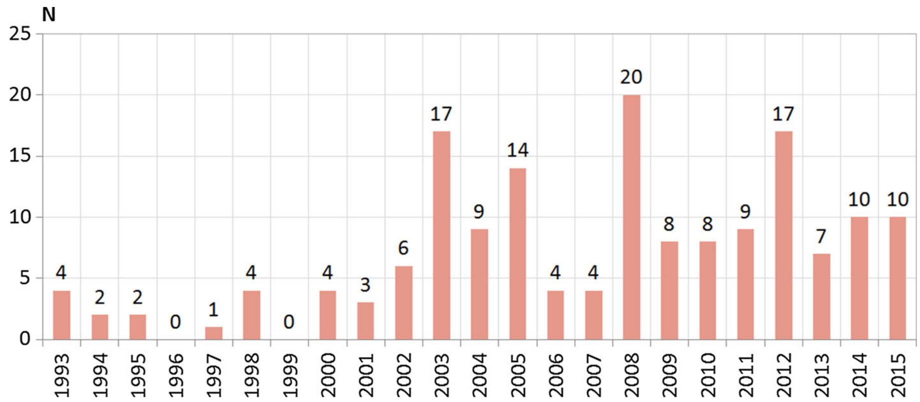

Fig. 9 Annual total (*N*) of extremely low flow periods with documented damage

economic losses associated with extreme low flow increased by almost five times in this century, compared to the last decade of the previous century.

5.2 Temporal variability of flooding in estuarine areas of the major rivers of European Russia

The results from the analysis of the MSU database of estuarine floods (Fig. 10) show that the total number of river floods in river mouth regions during the period 1900–2013 (2015)

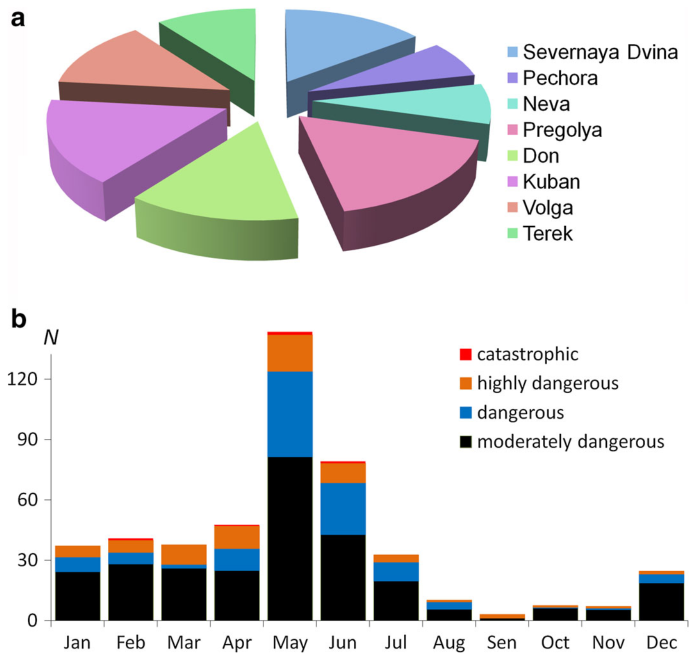

Fig. 10 Distribution of the number of the flooding events amongst the rivers of the European region of Russia (**a**) and in a year for the period between 1900 and 2013 (**b**)

accounts for 480 occurrences (omitting small rivers on the coast). This includes 146 jam floods (ice jams at both fall freeze-up and spring break-up) and 334 runoff floods. River floods occurred in all regions but with some spatiotemporal variability. Break-up jam floods are dominant in the mouth of the Northern Dvina River (62 occurrences), and they happened often at the mouth of the Pechora, Pregolya and in the delta of the Kuban. Freeze-up jams are characteristic for the pre-delta region of the Neva River. Runoff floods are almost exclusive to the mouth of Don (67 occurrences), Volga (63) and Terek (50).

In total percentage, the most dangerous river mouths on the European part of Russia (except small rivers) are Pregolya (17 %), Kuban (16 %) North Dvina (15 %) and Don (14 %). They are responsible for 60 % of floods in river mouth area (Fig. 10a).

The timing of flooding at river mouths is highly variable. The most “fruitful” months for flooding are May and June, with 47 % of all floods occurring during these two months, whereas between August and November floods are rare (6 %) (Fig. 10b). In the Winter and Spring months, jam floods (freeze-up and break-up) are most common (more then 70 %).

Despite the increase in the number of all hydrometeorological hazards in the last 30 years (as shown in Fig. 6), frequency and intensity (according to the MSU classification) of runoff-derived floods in the European Russia’s river mouths have shown a substantial decrease since the mid-twentieth century and especially during the 2000s (Fig. 11a). Prior to 1950, there are on average 4.8 floods observed, whereas after 1950 the number is reduced to 3.8 floods. The downward is statistically significant ($\alpha = 0.05$) (Spearman rank correlation ($R = -0.27$). Additionally, a $\sim$8–12-year cycle in number of flood events can be seen with in the moving averages.

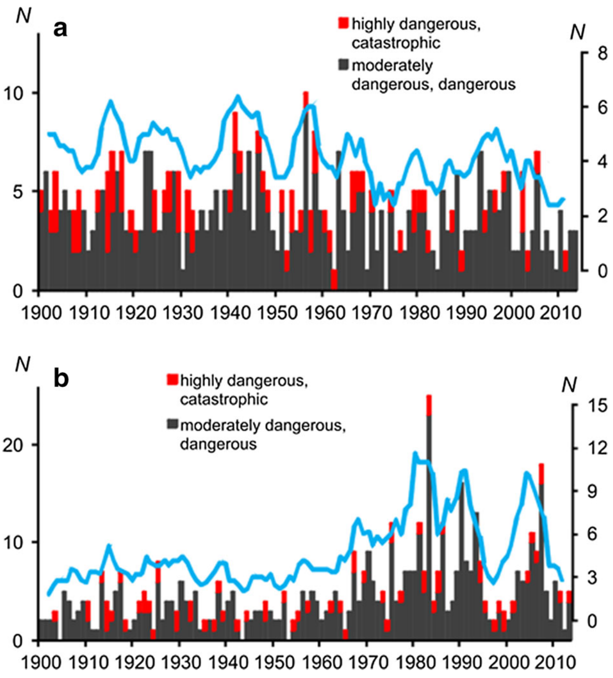

Fig. 11 Long-term fluctuation of number (*N*) of runoff-derived (**a**) and surge (**b**) floods in estuaries of rivers of European Russia (classes corresponds to MSU classification, Table 4). *Blue line* shows the 5-year moving average

Surge floods (defined as costal floods, driven by high wind of certain direction) in the estuaries of the Azov, Baltic and White Sea show the opposite dynamics compared to the runoff-derived floods. The number and intensity of flood surges as well as the water levels during surges (not shown here) have increased, particularly since the 1970s (with a drop during 1995–2005). There is a statistically significant trend (Spearman, $R = 0.42$) observable, with pronounced increases during the 1970–1990s and in the 2000s. The frequency of runoff flood events in the river mouth area is decrease (Fig. 12). This process is more evident for North Dvina and Terek.

5.3 Spatial distribution of the flood risk on the territory of Russia

To analyse the spatial distribution of flood risk, maps of the flood hazard and vulnerability are created focusing on the regional scale (based on subject division). Northern Caucasus, Southern Ural and Western Siberia are amongst the regions that were classified as being in the high hazard group due to natural conditions (K_h) are the (Fig. 13). Almost all regions with an index K_h of >0.75 (Sverdlovskaya region, Kemerovskaya region, Zabaykalsky Krai, Stavropolsky Krai, Dagestan, Adygeya, Krasnoyarsky Krai, Northern Osetiya, Tomskaya Oblast, Sakhalinskaya Oblast) have a maximum flood durations of 120–150 days (1991–2005) and a probability of flooding of up to 45 %. However, the flooded area is usually small (<3 %) except in Adygeya, where it reaches 16.7 % of the territory. The north-western part of the European Territory of Russia and Chukotka are at low risk of flooding.

The maximum socio-economic vulnerability (K_v) is observed in the regions where most of the population resides at zones of high flooding potential (Kabardino-Balkarskaya Republic, Astrahanskaya Oblast, Northern Osetiya, Zabaykalsky Krai, Tyva Republic). The least vulnerable areas are the Central Regions of the European Territory of Russia, the Ural region, the southern part of Western Siberia, Irkutskaya Oblast, Khabarovsky Krai

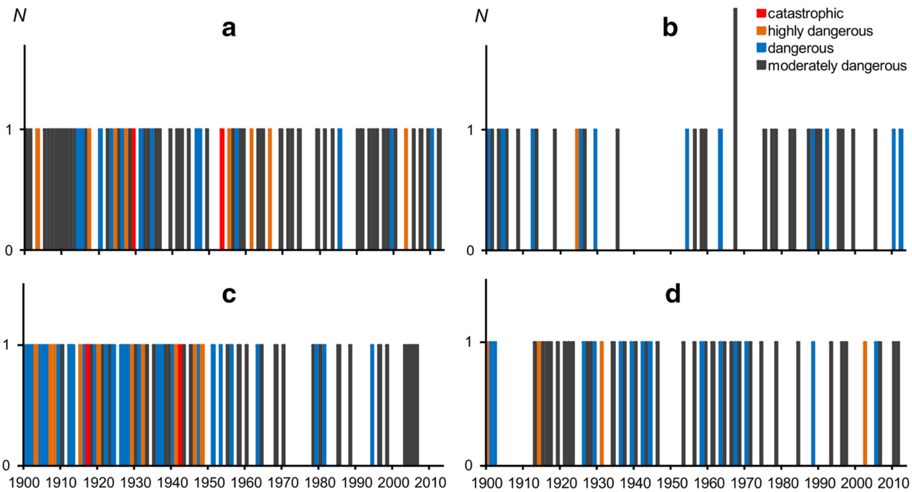

Fig. 12 Long-term dynamics of repeatability of runoff-derived floods for the 1900–2013 biennium at the mouths of rivers Northern Dvina (**a**); Neva (**b**); Don (**c**); Terek (**d**). The *red line* is a difference integral curve (right axis)

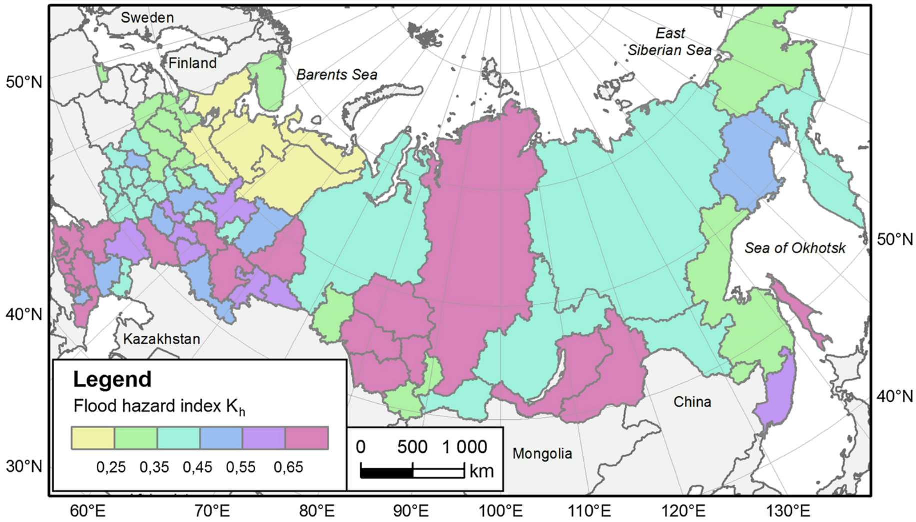

Fig. 13 Flood hazard map

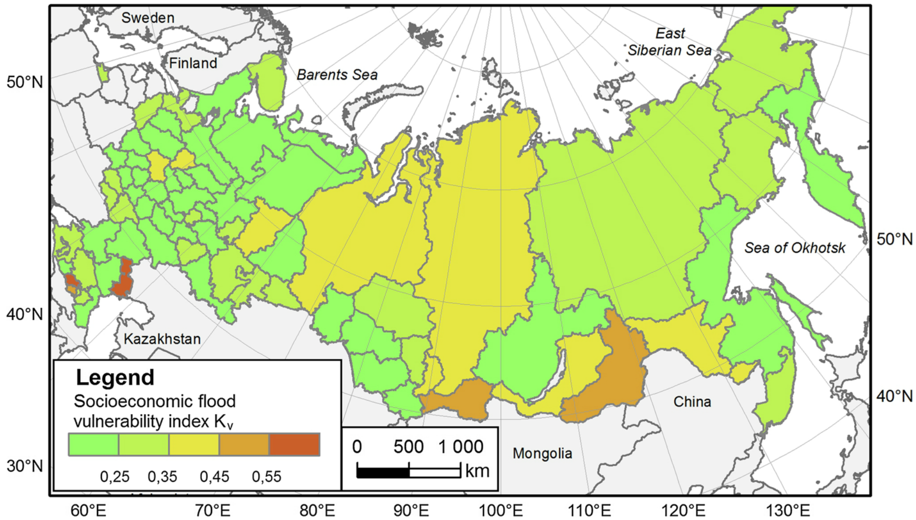

Fig. 14 Vulnerability map

and Kamchatka (Fig. 14). In these regions, only a very small population lives in zones of high flood risk.

To assess the spatial distribution of integrated flood risk in Russia, a qualitative classification was developed to assess the flood risk, as described in Sect. 4 (see Table 6). The results of this analysis are shown in Fig. 15.

The highest class in terms of integrated flood risk is typical for the Transbaikal and the Astrakhan region, the Republic of North Osetia and Kabardino-Balkaria ($K_{int} > 0.5$). High levels of flood risk are observed in the first one due to a large part of the population and the economy being located on floodplains, together with the duration of the flood being the

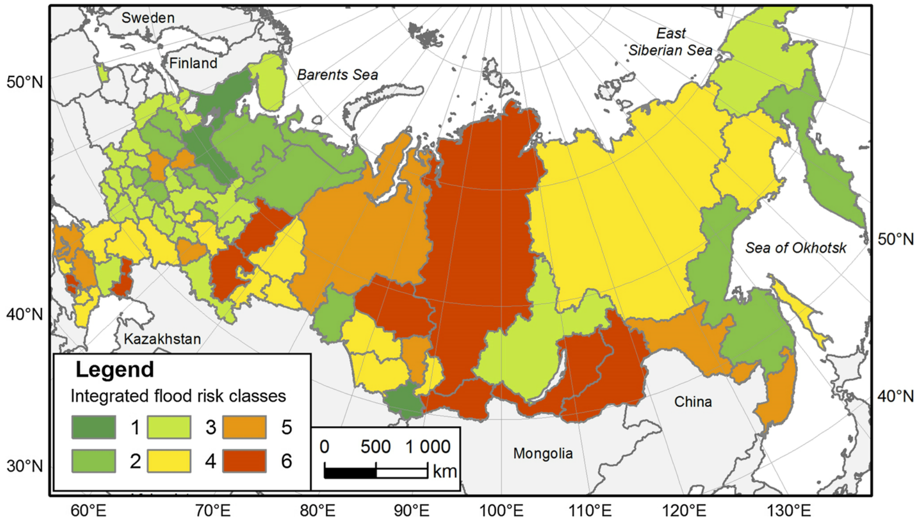

Fig. 15 Map of the integrated flood risk in the Federal Subjects of Russia

highest (up to 150 days in total). A large part of the Astrakhan region is occupied by the river system of the Lower Volga; therefore, a large proportion of the population (up to 48 %) is forced to live and farm within the floodplain area. A similar situation is observed in the above-mentioned republics of the North Caucasus, located in the mountainous part of the Terek basin. The proportion of the population living in the potentially flooded area accounts to 29 and 53.3 %, respectively. Also in the North Caucasus, there is very high probability of flooding (up to 45 %), with floods also playing an important role in negative dynamic processes, i.e. channel erosion.

The regions with the lowest risk of flooding are located in the northern and north-western part of European Russia, to a large extent in the central–south region, together with Chukotka, Kamchatka and Khabarovsk Territory, the Orenburg region, the Republic of Kalmykia and Altai. For these subjects, the vulnerability coefficient is very low ($K_h < 0.25$) due to the low population density, very rare industrial activities and a rural lifestyle.

6 Discussion

6.1 Floods

Generally speaking, the number of hazardous events very often depends on trends in seasonal runoff. It is expected that the effects of climate change will have an ambiguous effect on flood runoff, maximum water discharge and the frequency of hazardous floods in different climate belts and regions.

The rising number of hydrometeorological hazards as shown above can not only be observed in Russia. For instance, in Poland the number of floods was also observed to increase. For example, in 1950 and 1960 there were approximately 1.6 events per year on average, while in 1980 and 1990 the floods increased to about 8.4 and 7.6, respectively (Dobrowolski et al. 2004), where the dominant type of flood generating processes is rainfall. In Russia, heavy rain events are also playing more important role in flood hazards generation (Dobrovolsky and Istomin 2006; Bolgov and Korobkina 2013; Semenov 2011). These tendencies can be explained by changes in the water regime of Russian rivers in which the cold-period discharge characteristics are being transformed (Kireeva et al. 2015; Dzhamalov et al. 2012). The rising number of extreme heavy rainfall events is a sign of such a transformation, and it can be shown that rain-driven floods events will become more common, whereas snowmelt-driven floods are decreasing especially in small- and mid-sized rivers with a drainage area <50,000 km^2.

In Hall et al. (2014) it is hypnotized that there might be flood-rich and flood-poor periods during the time period analysed. Also it is widely known that extreme values of runoff (floods or droughts) can cluster in time. This process is called "Hurst phenomenon" (Hurst 1951). There are hypotheses related to climate–ocean fluctuations or long-term memory of hydrological processes (Hall et al. 2014; Markonis and Koutsoyiannis 2012; Montanari et al. 1997).

Maybe some of these tendencies can be seen in the total number of hydrometeorological hazards identified in this research, but the return period of rich or poor period is short with about 11–12 years. Additionally, according to Fig. 2 the trend is linear and vary stable, and therefore, we assume that this does not apply to our data

Apart from the changes found in flood frequency, the flood runoff and maximum water of the rivers in northern European Russia and some parts of central European Russia did either not change significantly (rivers of Karelia and the Kolskiy Peninsula, individual tributaries of the upper Oka, some parts of the Kama basin) or decreased (rivers in northern European Russia, except for the Pechora tributaries; tributaries of the Volga, Kama, Don, Dnieper, Oka) (Dzhamalov et al. 2012; Semenov 2011). The decrease in spring floods and maximum discharges were also observed in the Baltic region. The same results were found in Sarauskiene et al. 2014 for Lithuania's, Latvia's and Estonia's rivers. The most evident changes found in this study were decreases in the spring maximum discharge, which were observed across the southern extents of Central Siberia. Such decreases in flood magnitude in Eastern European countries for the last 50 years were also found in a review on European floods by Hall et al. 2014. However, in other regions, for example the Caucasus and on the rivers draining into the Black Sea, an increase in the maximum water discharge was prevailing during spring and summer floods (Vishnevskaya et al. 2016). In Asian Russia, there was also a dominant increase in runoff and maximum water discharge during floods (Semenov 2011). However, this observed increase, highly variable depending on the latitudinal and/or orographic location of the basin. In the subarctic and subpolar regions of Siberia and in the mid-latitudes of the temperate Siberian zone, positive trends were prevailing in the period 1985–2010 (Rawlins et al. 2009), whereas in the southern plain regions, negative trends were dominant, particularly on the Transbaikalian rivers (Shiklomanov et al. 2007). In the mountain regions of the upper Yenisei, no changes in the flood runoff were recorded, while in the mountain regions of Western Siberia (the upper Ob' basin), positive trends were prevailing (Semenov 2011). However, the patterns of changes were different for the rain and the mixed snow–rain flood runoffs in the Amur River basin and on the Pacific Coast rivers (1951–1985). Positive changes were observed for rivers, whose basins were located on the eastern slopes of the range Sikhote-Alin which are subjected to monsoon rains. Starting in the 1980s, this trend became more evident, which gave rise to the catastrophic flood on the lower Amur River in 2013 (Semenov 2011; Bolgov et al. 2015). In 2014, in the Altai Mountains, Western Sayan mountains and in the Lena and Kolyma river basins, intensive and hard-to-predict floods took place as a result of the combination of positive temperature anomalies, which had produced snow and ice melting in the mountains, with the abnormal area and duration of rains that exceeded the monthly norm by a factor of 2–2.5 (Semenov 2011). In European Russia, flood-producing rains in the mountain and foothill zones of Northern Caucasus and the Black Sea region pose the highest danger (Bolgov and Korobkina 2013).

Having shown how our findings relate to other research, it is important to note that the impact of hazardous events as well as number of them is not only related to natural factors. The same input is derived by shelter, industry and agriculture organization (El-Masri and Tipple 2002). So, when the process of development has an extensive model and involves more and more territories into its activities, it is evident that it triggers more spatial-scaled floods or droughts.

Another factor that may affect the numbers of hazardous events is the higher level of information technology. For example, in Russia during the Soviet period or in the early 1990 it was necessary collect information about hazardous events form newspapers (sometime—locals) or inform local reports of the Hydrometeorological Service. Nowadays, information about flood events is publicly available in the social media and it takes a few hours (sometimes only minutes) to know that a flood took place.

6.2 Droughts

In Russia, extreme low flow events have been traditionally been observed in the southern Asian part, in the basins of Western Siberia and in Baikal region (Semenov 2011). However, during the last decade dry periods also started occurring further north: not only at the upstream regions but also in the middle course of the rivers. This may be attributed to an increase in the seasonal climate contrast, which is reflected in the redistribution of rainfall throughout the year (Bolgov et al. 2015; Dzhamalov et al. 2012). This effect leads to an increase in the duration of dry periods, which now does occur not only in the summer but also in the spring period. Moreover, in the twenty-first-century water scarcity is connected to the appearance of extreme low flow on the rivers of European Russia. These trends are particularly noticeable in the south of the region: in the basin of the Don, Volga and the Ural. For instance, a 8-year-long drought event was observed in Don River basin (during …), which severely affected agriculture, industry and society. It is interesting to note that the total number of drought events as shown here does not seem to reflect the most severe events or the most severe years for some regions. While in 2010 European Russia was suffering from extreme low flow and drought, Siberia had very wet weather conditions and the total number of droughts was high but not the highest on record. According to research by Spinoni et al. (2015), in the European territory of Russia there were only six cases of water shortages during 1950–2010. The longest duration of extreme water shortage (using the Russian terminology) occurred in 1950–1971 and lasted 44 days, the last one occurring in 2010. The frequency of extreme low flow periods with economic loss increased from 1991 to 2015, with 80 % of the occurrences being observed after 2003.

6.3 Mouth of rivers

The observed decrease in runoff floods can be related to major rivers runoff regulations (Don, Kuban, Volga and Terek) and the construction of flood protection measure (Severnaya Dvina). Additionally, an extensive programme to ensure water supply safety was started in the 1950s with a large number of reservoirs being constructed in European Russia.

The increase in the number of tidal/storm surge floods as found in this research is very likely due to the lack of the possibility “to regulate” surging process, but also due to the rise in the average sea level and the changes in the synoptic situation, in particular the increased storm activity (Valchev et al. 2012; Kislov et al. 2016). For example, a rise in the runoff flood can be observed in the years with the most powerful tidal/storm surges occurring at the Black Sea coast. The temporal coincidence of these two events may be triggered by an increase in duration of the southern meridional atmospheric circulation and the occurrence of the southern cyclones (Gulev et al. 2001). The same results were found for Russian Arctic.

In our research, the hypothesis put forward by Shiklomanov et al. (2007) of “an increased flood risk due to high discharge magnitude events” for Russian arctic river mouths was not confirmed. However, this paper does not assess the risk of floods originating from backwater conditions, such as ice jams and wind tides (surges). An additional factor that indirectly reduces the risk of river flooding is the river channel erosion downstream of Krasnodar and Tsimlyansk reservoirs (up to 1–2 m and 0.5–0.8 m, respectively) (Alexeevsky et al. 2016). Another factor is the removal of warmer water from the reservoirs, which leads to a reduction in the ice regime of the river and hence reduces the possibility of ice jams occurring. Human-induced decrease in the total runoff of the Kuban, Terek and especially Don River (due to water abstraction for drinking water supply, industry and agriculture) may also be a factor reducing the flood occurrences. For instance, after the construction of the Tsimlyansk reservoir in 1952, the annual runoff of the Don has decreased from 26.3 to 21.2 km^3 in 1952–2013 (Fig. 11). Maximum water discharge at the river mouth decreased from 5230 to 1570 m^3/s due to redistribution of flow within the year, in favour of the months with low flows.

On the other hand, several factors can also increase the risk of flooding. For example, in the delta of the Terek natural factors dominate the flood hazard in this estuary area. Large amounts of the river sediment load (20.8 million t/year) and intensive accumulation in the river bed (resulting in an increase in the bottom elevation of 0.5–1.5 m) caused in the water levels to rise and their excess over terrain elevation behind the levied banks (Alexeevsky et al. 2016). This very fast sedimentary process coincided with the impact of rapid and large-scale fluctuations of the level of the Caspian Sea. As a result, the natural factors influencing floods was dominant over the anthropogenic runoff regulation (Karagalinsk reservoir), causing increased flood risk.

6.4 Risk assessment

The map of risk map illustrates the complex assessment of flood in terms of loss. It correlates with same maps presented in The National Atlas… (2007) and The State Report… (2010).

Overall, there seems to be a paradox in the results of this research. On the one hand, spring discharges in the European part of Russia tend to decrease due to milder winter conditions, thaws and transfer of precipitation from snow to rain events during winter (Kireeva et al. 2015; Dzhamalov et al. 2012), but on the other hand the number of hydrological droughts increased and extreme floods occur once again.

Based on the discussion of the results, the hypotheses of this paper is that the runoff flood (mostly snowmelt in the Russian territory) tends to decrease, but that the rain-driven, surge and ice jam flood may tend to increase. In terms of droughts, this means that due to an earlier spring-flood wave the dry period starts already in spring, resulting in a longer and more sever low flow period.

7 Conclusions

This paper aimed to provide an overview of the various aspects of hydrological hazards in Russia. The hydrological hazards were analysed at different scales, ranging from individual hydrological stations to large river basins and regional (subject) scale. The analysis has shown that the number of hydrological and meteorological hazards in Russia is growing every year. This is largely due to changing climate stability, namely the increase in seasonal variation in different regions of the country. Therefore, one should expect an increasing area of land being subjected to floods and extreme low flow. Additionally, in regions with humid climate intensive rain events and flash floods are observed more often. On the other hand, the frequency of water scarcity connected with hydrological droughts has increased significantly since the beginning of twenty-first century. This happened dominantly in the southern regions, but in recent years such events have also been observed even in the middle latitudes of Russia.

Therefore, the most urgent need is to adapt to the hydrological hazards observed in the south of Russia. The most critical areas have been identified in this research as, on the one hand, the mountainous and foothill regions where the dry and warm winters reduce water resources in dry years and on the other hand the coastal regions and deltas increase the risk of surge flooding.

To support such adaptation, the authors will focus on the analysis of recent tendencies in seasonal flow and try to find the connection between seasonal flow dynamics and hydrological hazards (floods and droughts).

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