# Assessment of the community vulnerability to extreme spring floods: the case of the Amga River, central Yakutia, Siberia

N. I. Tananaev, V. A. Efremova, T. N. Gavrilyeva and O. T. Parfenova

## ABSTRACT

Spring floods in Siberia annually affect local communities. Major urban settlements in the region implemented flood control structures, so rural areas take a heavy beating. In 2018, spring floods severely hit multiple communities in central Yakutia, exposing deficient flood prevention and risk management practices. Notably, Amga village, an important local center, was severely inundated. Hydrological analysis shows that the 2018 flood had a 50-yr return period, and was caused by an ice jam in a nearby channel bend where mid-channel sand bars impede ice movement during breakup. The cold spells of late April and early May in the middle section of the river promote ice-jam development, causing extreme water stage rise. Highest water stage is unrelated to either winter snow water equivalent or early May rainfall. Estimated tangible direct damage to the Amga community equals ₽5.1B ($81.5M) in 2018 prices, but only ₽0.13B ($2.1M), or 2.5% of this total, was reclaimed. A questionnaire survey revealed that most residents report important deterioration of drinking water quality and health after flooding. Residents respond positively to risk mitigation actions, implemented by the local and regional authorities, except ice dusting and cutting, and report minor activity of official sources in spreading information on flood progress.

**Key words** | central Yakutia, hydrological hazard, ice jams, spring floods, tangible damage assessment, tangible direct damage

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## INTRODUCTION

Natural disasters are acknowledged to be both natural and social phenomena (de Goyet *et al.* 2006). On the one hand, disaster risk and associated accumulated losses are determined by event probability and exposure level, population and infrastructure assets at risk, and vulnerability to disaster (Handbook of Hazards 2012; Twigg 2015). On the other hand, the adverse effects of natural hazards evidence deficient decision-making in territorial development and socio-economic forecasting (Hewitt 1983; Oliver-Smith 1994; Heijmans *et al.* 2001). Three key components of the natural hazard risk, i.e., the occurrence probability, the exposure level, and the vulnerability of communities, are closely related to shortcomings in regional planning and management, marginalization of population, and are affected by climate change and overall environmental degradation (Wisner *et al.* 2004).

International practice, reflected in the UN recommendations, directs decision-makers towards renouncement from prioritizing spending on disaster response and recovery. The Yokohama Strategy (1994), Hyogo Framework for Action (2007), and Sendai Framework for Disaster Risk

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Reduction (2015) promote active risk management for natural hazards, implying priority action from national platforms, in wide collaboration with universities and research entities. Active risk management requires in-depth understanding of natural and social risk factors and drivers, and physical processes behind hazards. At state and regional levels, the important tasks include the unification of hazard forecasting techniques, and regional adaptation of mitigation and risk/damage reduction practices.

Floods are the most important natural hazards in terms of total damage globally. In the Russian Federation, mean annual flood damage reaches ₽124B, or $1.98B, of which around ₽3.55B ($56.4M) falls on the Sakha (Yakutia) Republic. Here and below, all values in Russian roubles (₽) are given in 2018 prices, and are converted to U.S. dollars ($) using mean annual 2018 exchange rate: $1 = ₽62.9264 (source: Central Bank of Russia). At a regional scale, cumulative flood damage for the period from 1998 to 2018 in the Sakha (Yakutia) Republic exceeds ₽40B ($638M). In years with extremely severe floods, annual damage touched a significant GRP fraction, from 2.8% in 1998 to 7% in 2001.

In the Russian Federation, owing to its large territory and the variety of physiographic settings, floods may occur in all seasons. In southern Siberia, summer floods caused by heavy rainfall are the most devastating, both in a historical perspective (Myglan & Vaganov 2011) and in the recent past. In 2013, and then again in 2019, Russian Far East regions, including Khabarovsk and Primorsky Krai, and Amur Region, were inundated because of intense monsoon precipitation (Bolgov *et al.* 2015; Semenov *et al.* 2017). Also, in 2019, Irkutsk Region in southern Siberia suffered from floods caused by heavy summer rainfall, completely submerging the city of Tulun (https://siberiantimes.com/other/others/news/flood-apocalypse-in-eastern-siberia-kills-five-and-maroons-9919-whose-homes-destroyed-or-damaged/). In Russian Arctic and Subarctic regions with harsh continental climates, receiving less summer precipitation, snowmelt runoff dominates the large river hydrology, and severe spring floods are by far the most dangerous, largely owing to ice jams (Agafonova *et al.* 2017; Magritsky *et al.* 2017).

In European Russia, the city of Velikiy Ustyug at the confluence of the Yug and Sukhona Rivers in Komi Republic suffers regularly from catastrophic ice-jam floods (Frolova *et al.* 2015), the most recent occurring in 2013 and 2016. Spring flood on the Ob' River and its major tributaries, associated in many cases with ice jams, caused an emergency situation in Yamalo-Nenets Autonomous Okrug in 2014, and in Khanty-Mansi Autonomous Okrug in 2015 (Kuznetsova 2019). In Sakha (Yakutia) Republic, three of the 27 largest Quaternary floods are associated with spring ice jams on the Lena River (O'Connor & Costa 2004). The highest flood damage is also associated with ice jams, including the 1998 and 2001 floods in Yakutsk and Lensk, widely covered by the media (Zaitsev *et al.* 2006; Whiteman 2011). In recent years, the 2013 spring flood caused by a sequence of ice jams on the middle Lena River, caused losses exceeding ₽5.6B ($89.3M), and was documented by Kontar *et al.* (2018).

In May 2018, after several years of relative tranquility, the Sakha (Yakutia) Republic was again hit by severe spring floods. In particular, central and south-eastern Yakutia suffered the worst flooding since 2008, and a federal level emergency was declared. Flood damage was recorded in 63 rural communities, affecting about 5,500 residents in more than 1,500 households. In the Amga River basin alone, 259 houses were submerged and 904 residents suffered material losses. Considerable financial losses, exceeding ₽1.5B, or $23.8M, prove that Sakha (Yakutia) Republic falls short of employing effective practices of risk reduction and mitigation. Active and informed risk management policy is highly required in the region, but is currently non-existent.

This paper discusses the physical processes behind the 2018 flood in central Yakutia. It reviews the spring hydrology of the Amga River, and evaluates tangible direct damage to Amga village, an important regional center, aiming at assessing the cumulative impact of an extreme spring flood on this small Subarctic rural community. The aims of this paper are multiple: (1) to provide a comprehensive description of the case study, including physical basis and hydrology behind recurrent floods in the Amga River basin; (2) to present and apply the most used direct damage assessment technique currently employed in the Russian Federation; and (3) to evaluate the impact of an extreme spring flood on well-being and social aspects of living in a remote rural community.

## STUDY REGION

Amga village was founded in 1652, i.e. 20 years after Yakutsk, as an agricultural community, and has since been a regional center of the Amga Ulus (district). The settlement occupies the left side of the Amga River valley, and is located on a high floodplain surface dissected by abandoned channels and oxbow lakes (Figure 1, bottom), that increases its vulnerability to flooding.

According to Soviet and Russian State Census data, the population had increased from 1,230 inhabitants in 1939 to 6,626 in 2018, owing, at least partially, to the Soviet policy of promoting large Yakutian villages in order to cut and centralize budgetary spending (Gavrilyeva & Kolomak 2017). Major economic activities are agriculture and public services. In recent years, the Amga district has also evolved as a popular weekend tourism destination for Yakutsk citizens, about 200 km to the north-west, owing to a decent connection by a local road.

Regional climate is harsh continental, with cold winters and mild summers; mean air temperature for January is −40.8 °C and for July +17.8 °C. Winter lows can descend

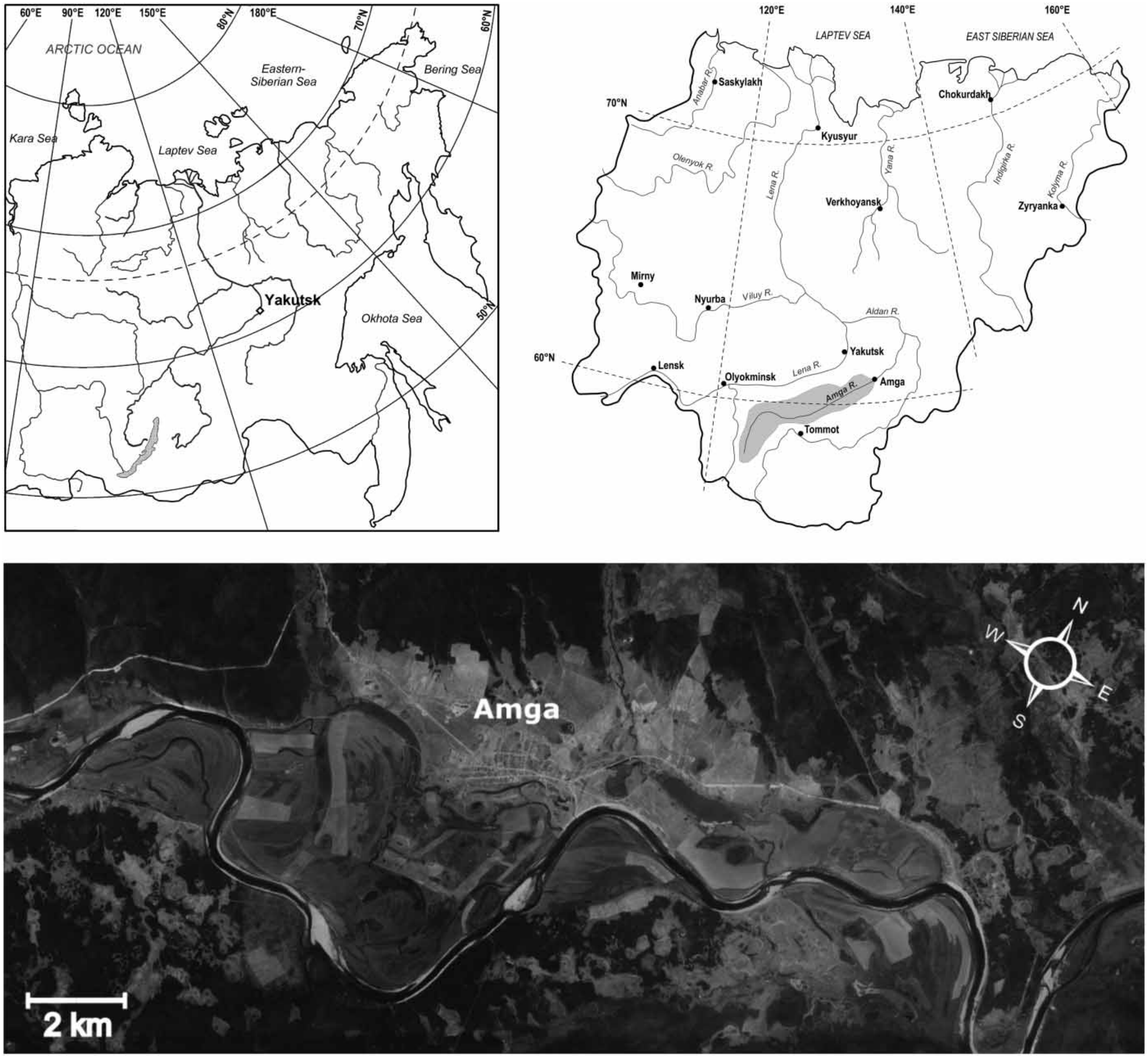

**Figure 1** | Geographical position of the Amga River and Amga village (top), and a detailed overview (bottom) (Corona KH-3 image, acquisition date: 8 August 1969).

below −60 °C, while in summer, heat waves raise the air temperature above +30 °C. Mean annual precipitation observed at the Tegyultya meteo station, about 90 km to the south-west of Amga, is 270 mm, of which 168 mm, or 62%, falls as rain; 97 mm, or 36%, as snow; 5 mm, or 2%, as mixed precipitation (1955–2015 averages).

The Amga River basin with an area of 69,300 $km^2$ occupies an interfluve surface between the Lena and the Aldan Rivers in southern and central Yakutia (Figure 1). The river headwaters drain the north-western flank of the Aldan Plateau between the Aldan and Olyokma River headwaters, with altitudes from 1,200 to 1,300 m a.s.l. In its middle section, the river is incised into the Lena Plateau with altitudes between 350 and 650 m a.s.l. Downstream of Amga, about 450 km from the river mouth, the river enters the Central Yakutian lowland, becoming a typical highly sinuous lowland river. Annual runoff volume of the Amga River in Teryut, 70 km upstream of the river mouth, is about 6.8 $km^3$, corresponding to mean annual daily flow of 216 $m^3 s^{-1}$ or annual runoff depth of 98 mm (1942–2016 averages).

The Amga River water regime is pluvio-nival, or East-Siberian in a classical Russian typology, with a pronounced spring high-flow period, numerous rain events during summer, and long winter low-flow without flow cessation (Figure 2).

Spring meltwater floods dominate the Amga River hydrology. Each year, spring flood is anticipated by the community, and preventive measures are implemented to ensure the safety of the population and livestock. To this end, our research aims at outlining the major features of spring flood hydrology of the river and its effects on the community, using both hydrological data and survey results.

## MATERIALS AND METHODS

Our hydrological analysis is based on the highest annual water stages dataset for the Amga River in Amga (see Figure 1 for spatial reference), provided by the Yakutian Hydrometeorology Agency. This dataset covers a period from 1933 to 2018. Water stage is observed at a pile gauge twice-daily at 8am and 8pm, or at increased frequency during spring freshet. Mean daily stage is derived by averaging these values, while highest annual stage is selected from the observed, and not averaged, values. The water stage data are published in centimeters above the gauge reference, and for the latter, the elevation above a Russian reference height, or Baltic 1977, datum (EPSG: 5705), is also given. For the purpose of this study, the highest annual stage, $H_{max}$, values were also referenced to the

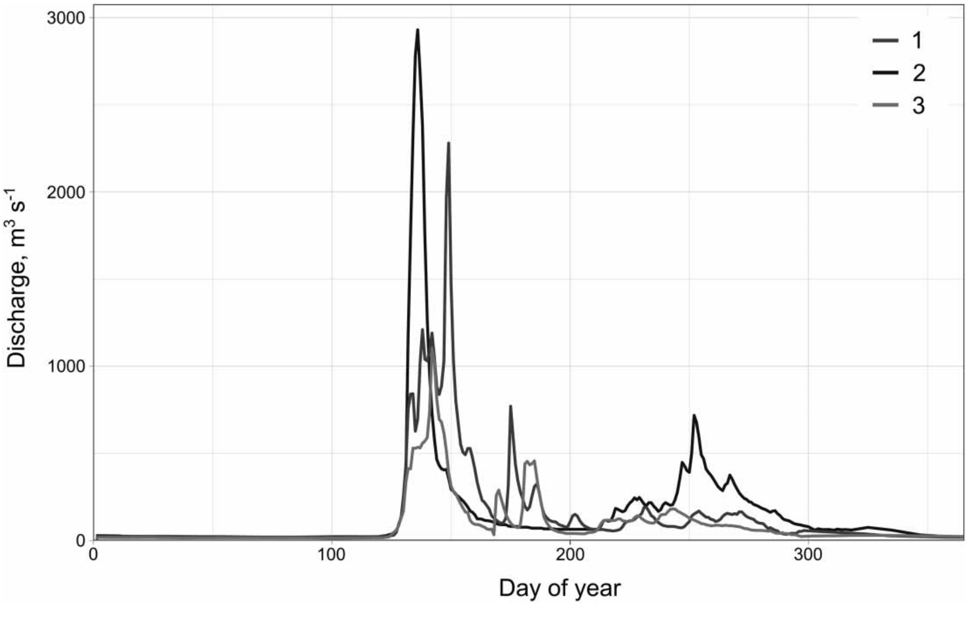

**Figure 2** | Daily flow variations of the Amga River at Teryut, around 100 km downstream of Amga, in years with annual runoff: (1) close to average, 1993; (2) high, 2008; and (3) low, 1991.

Baltic 1977 datum and are presented as elevations, in meters above sea level, to be used in flooded area mapping.

The $H_{\max}$ exceedance probability was estimated using: (1) manual fitting; (2) a Kritsky–Menkel distribution, widely used in Russia for engineering purposes (Rozhdestvensky & Zvereva 1975); and (3) a family of extreme value distributions, including Gumbel, Weibull, generalized extreme value (GEV), and generalized Pareto (GPD) distributions, based on the Fisher–Tippett theorem (Hosking *et al.* 1985). The Kritsky–Menkel distribution belongs to a gamma distribution family, and has three parameters, related to its first three moments: mean, coefficient of variation $C_v$, and $C_s/C_v$ ratio, where $C_s$ is Pearson's moment coefficient of skewness. These parameters were calculated in compliance with the Russian Building Code 33-101-2003 by maximum likelihood estimation, using StokStat (2008) software. The extreme value distribution parameters, and corresponding return periods, were calculated using RStudio (2019), a GUI envelope for R language, and a *distLextreme()* function, based on L-moments, from package 'extremeStat' (Boessenkool 2017).

Flooding area was mapped in ArcGIS v. 10.2 using ArcticDEM Release 7 data with 2 m resolution (Porter *et al.* 2018), provided by the University of Minnesota Polar Geospatial Center from their website at https://www.pgc.umn.edu/data/arcticdem/. This pan-Arctic elevation coverage is referenced to the WGS-84 ellipsoid surface (EPSG: 6893), currently aligned with EGM2008 geoid reference. A positive offset between the EGM2008 and Baltic 1977 systems for the region of interest is unknown, but is expected to not exceed +0.49 m, a value reported for the Baltic countries by Ellmann *et al.* (2009).

Weather pattern analysis for years with extreme floods was performed descriptively, using NCEP/NCAR Reanalysis daily composite plots for 10-day intervals from 11 April to 20 May. Data and images were provided by the NOAA ESRL Physical Sciences Division, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd.

Tangible direct damage was estimated using a technique developed by Russian Institute of the Economics of Mineral Commodities and Mining, Russian Academy of Sciences (VIEMS), which is officially published as a calculation guideline (Technique 2006). This guideline provides, in tabular form, the unit costs of flood damage per 1 ha, by region of the Russian Federation, or by river basin, in 2006 prices. Official deflator index values, published annually by the Russian Ministry of Economical Development, are used as multipliers to recalculate 2006 prices to actual values. Separate tables are provided for floods falling within the exceedance probability ranges from 1 to 5%, 5 to 10%, 10 to 25%, 25 to 50%, and 50 to 75%. Total flood damage is calculated separately for residential areas, industrial grounds, and communications/engineering facilities. The VIEMS technique has been recommended by the Federal Agency of Water Resources for use in flood damage forecasting; otherwise, no unified methodology of tangible direct damage estimation exists in Russia, which has been officially approved at state level.

A survey was administered on-site during the 2018 flood to assess its impact on local ecology and social security expectations. Paper questionnaires were distributed among the general population through a network of relatives and acquaintances of one of the authors, aiming to equally cover households affected and unaffected by flooding. This questionnaire was successfully tested earlier in Namsky district, central Yakutia, in the aftermath of the heavy 2013 flood, by the researchers from North-Eastern Federal University, based in Yakutsk. This questionnaire comprised 38 questions, both closed and open-ended, split into nine groups; the design and structure of the questionnaire are thoroughly discussed by Kontar *et al.* (2018). Most questions aimed to assess the efficacy of the authorities in damage prevention, informing the general population about flooding, and post-flood mitigation measures, but also concerned the influence of floods on sanitary and epidemiological situation, health, and migration.

## FINDINGS

### Spring flood hydrology, the Amga River

In southern and central Yakutia, the spring season starts around mid-April, but can shift to as late as mid-May because of frequent cold returns. Snowmelt runoff contributing to spring freshet mostly originates from the mountainous headwaters of the Amga River on the Aldan Plateau, South Yakutia. At the onset of melting, snow water equivalent in central Yakutia period is negligible because of marked climate continentality and an important role of snow sublimation in the transition months (Pomeroy *et al.* 1999).

Spring freshet on the Amga River in Amga peaks in May; in a single case, in 1943, a late April peak was observed. Only in four cases the highest annual water stage was observed during summer rain events: in 1956 and 1987, in early June, and in 2006 and 2016, in August. Water stage during these rain events was 1.5 to 2.6 m below the bankfull levels, hence none of them caused any damage to the community. Highest spring flood stage is most frequently observed between 11 and 20 May, in 49% of years, and less frequently between 21 and 31 May (28%), or between 1 and 10 May (23%). In the last decade, the timing of the spring freshet peak has shifted toward earlier dates, and in six years out of ten, it was observed in the first ten days of May.

During spring freshet, the water stage in Amga can rise as fast as several meters per day, which is most frequently caused by ice-jam development. Spring floods, i.e., annual events with floodplain inundation and officially recorded damage to the community, were observed in 16 out of 85 years of record, or 20%. Extremely severe floods were observed in 1957, 1980, 2008, and 2018 (Figure 3). These record floods were preceded by prolonged periods of relatively low freshet peaks, which could lead to ‘false safety’ expectations in the community, as was observed previously in both central Yakutia and Interior Alaska in a recent comparative study (Kontar *et al.* 2018).

Highest annual water stage time series appear to share cyclic behavior with snow water equivalent and spring rainfall, with about 40-yr cycles (Figure 3), but no significant linear correlation was found between these variables: Pearson $r$ is between 0.02 and 0.05. Therefore, although both winter snow and spring rainfall contribute to a total spring freshet volume, there are other local factors at play, supposedly related to ice-jam formation, that trigger catastrophic flooding in the studied area.

## Weather patterns in extreme flood years (1980, 2008, 2018)

The Amga River flows from SW to NE, and the spring freshet wave moves northward from headwaters toward downstream river sections with intact and stable ice cover, promoting ice-jam formation (Lindenschmidt *et al.* 2018). With this, high spring freshet wave is expected to rapidly reach the middle section of the river, and push the moving ice from the south towards stable ice cover farther northward. Therefore, early and warm spring, producing rapid snowmelt in the headwaters, along with late spring or cold

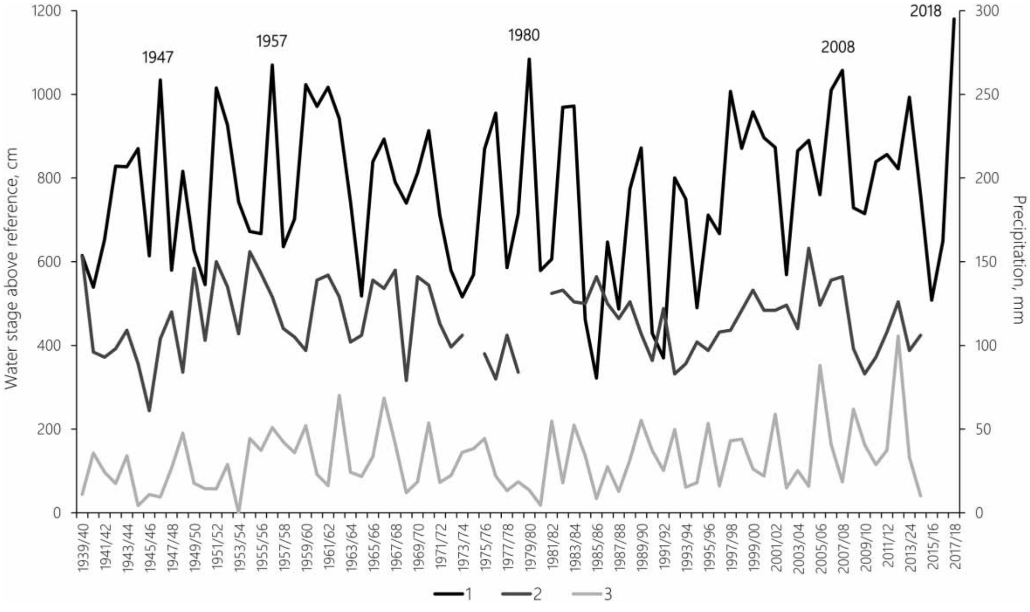

**Figure 3** | Highest annual water stage, Amga River at Amga (1), winter snow water equivalent (2), and May rainfall (3) at Dikimdya meteo station close to the Amga River headwaters.

blasts in central Yakutia should, other factors being equal, favor ice-jam development. Spring weather patterns during years with major flooding – 1980, 2008, and 2018 – were qualitatively compared to assess the potential role of weather in flood progression.

In 1980, the spring in the Amga River catchment was by 1 to 3 °C colder than average until early May, when a rapid warming occurred in central Yakutia (Figure 4). Snowmelt and flood wave buildup were in their midst, when air temperatures dropped in mid-May after a cold spell from the Okhota Sea reached Transbaikalia. This cold blast could provoke ice cover refreezing during breakup and subsequent ice jamming. The highest water stage was observed on two consequent days, 13 and 14 May, evidencing

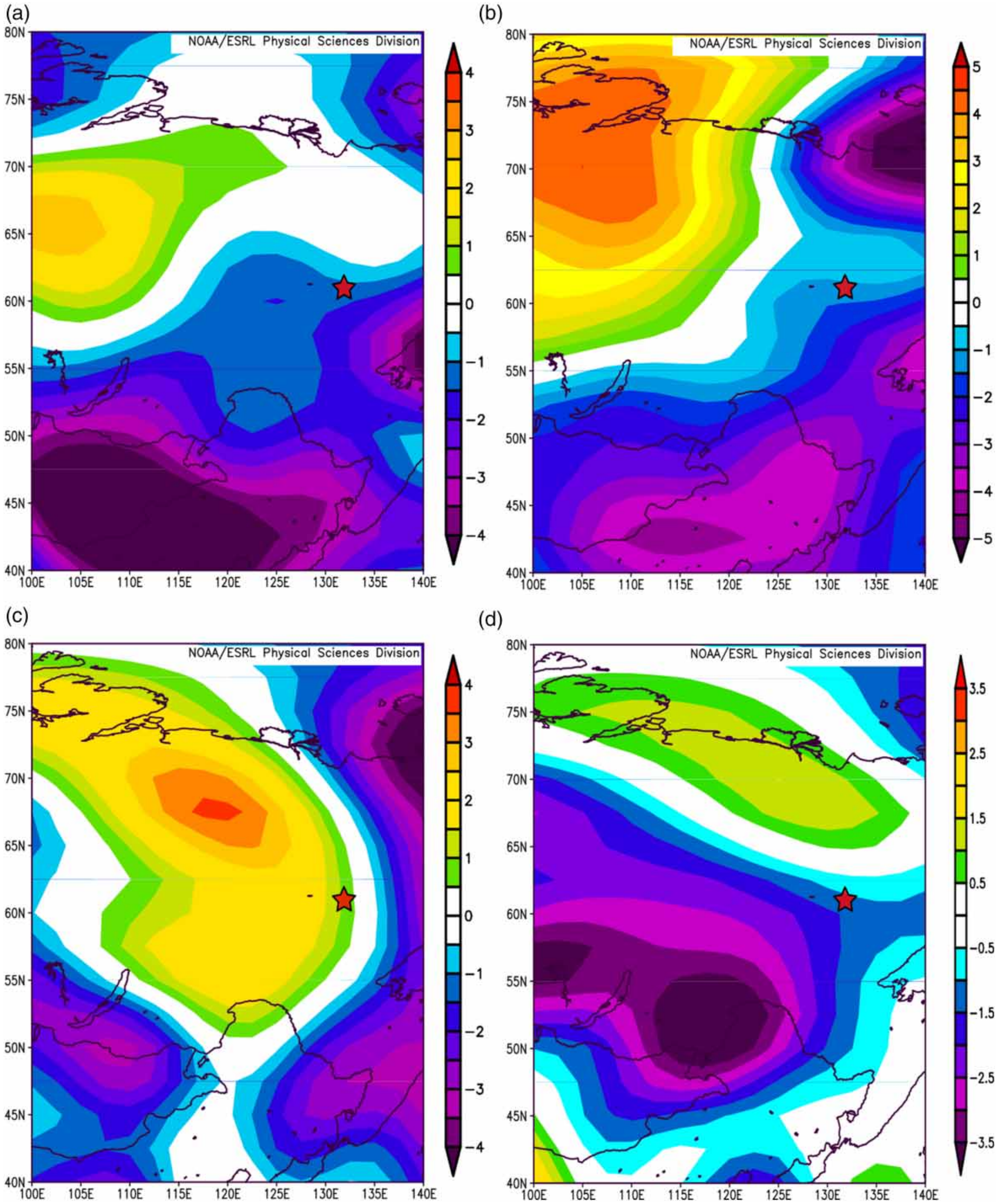

**Figure 4** | NCEP/NCAR Reanalysis averaged daily composite air temperature fields in spring 1980: (a) 11 to 20 April; (b) 21 to 30 April; (c) 1 to 10 May; (d) 11 to 20 May. Here and below, the Amga village location is shown with a star.

equilibrium ice-jam conditions (Beltaos 1995). The water stage observed in 1980 set a new record high, which was exceeded in 2018.

In 2008, a negative temperature anomaly persisted over central Yakutia and Amga village until early May, and spring began later than on average (Figure 5). Low temperatures over the Amga River catchment and, in particular, in its middle section, maintained stable ice cover and limited its thermal deterioration at the onset of spring freshet, which peaked on 16 May 2008.

In mid-April 2018, Siberian Asia was 2 to 5 °C warmer than average (Figure 6), contributing to earlier snowmelt and ice breakup on most Yakutian rivers south of the Arctic Circle. Late April was, however, 1 to 2 °C colder than average in central Yakutia, and the lower Amga River was in the epicenter of this anomaly (Figure 6(b)). Again,

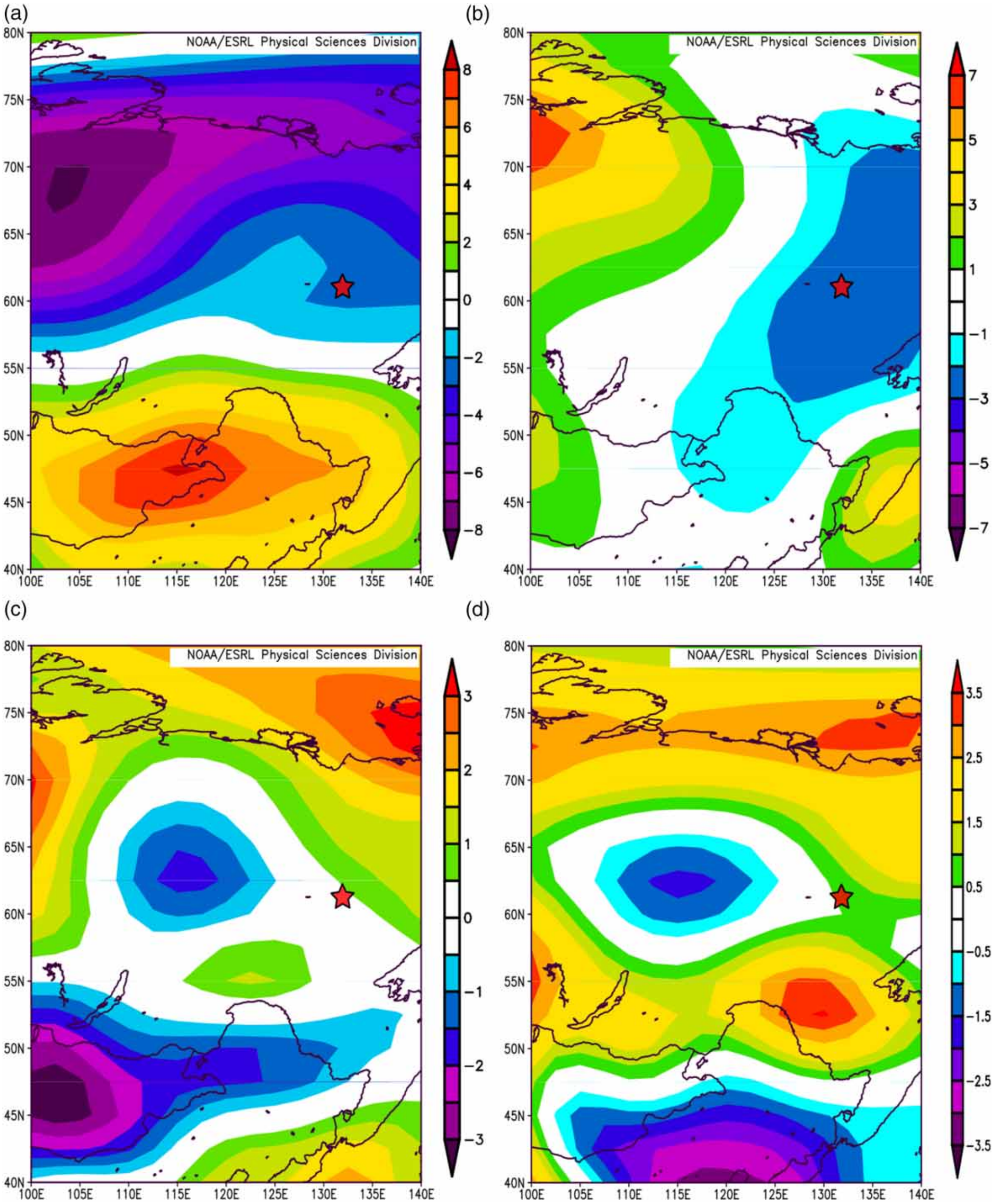

**Figure 5** | NCEP/NCAR Reanalysis averaged daily composite air temperature fields in spring 2008: (a) 11 to 20 April; (b) 21 to 30 April; (c) 1 to 10 May; (d) 11 to 20 May.

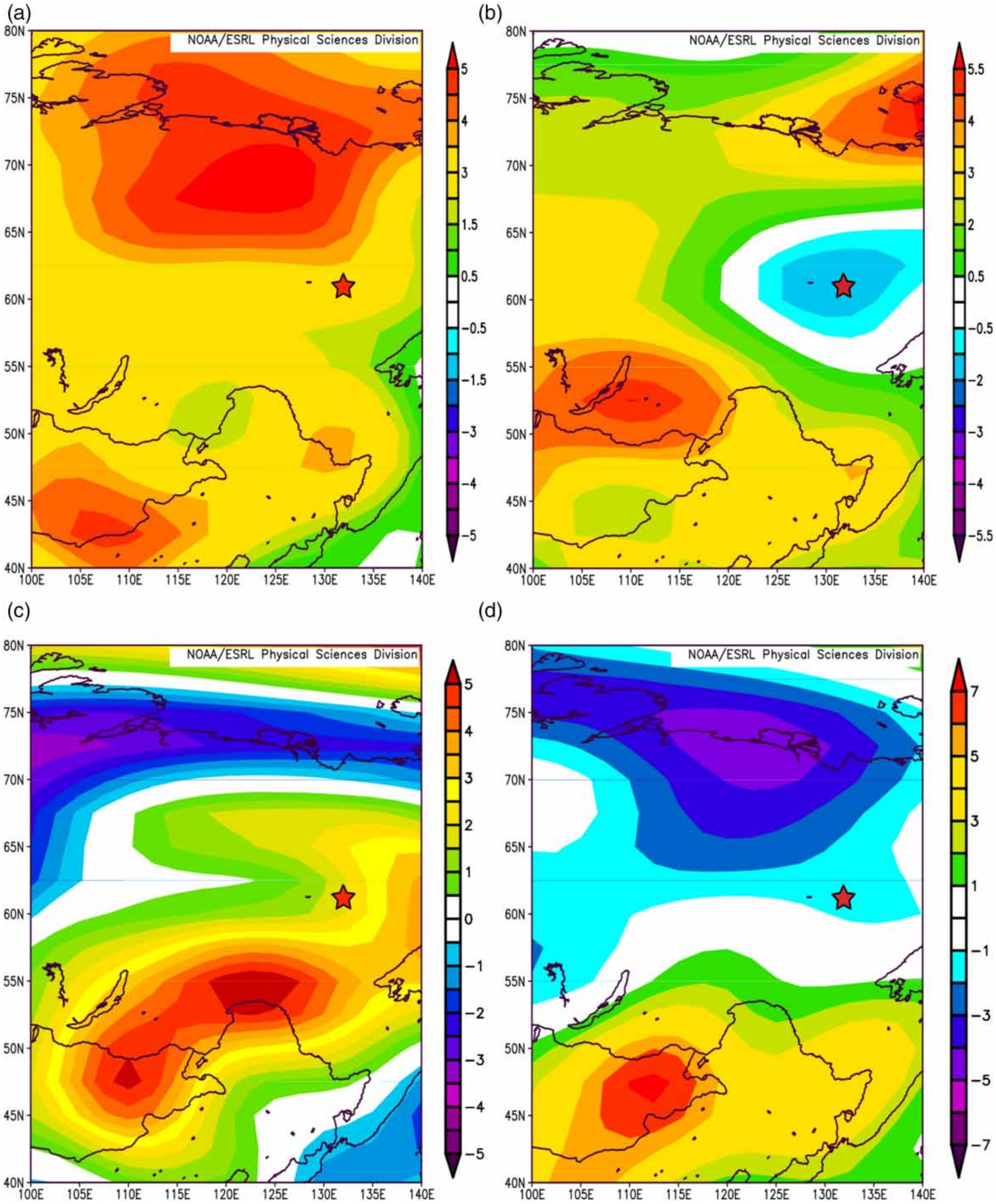

**Figure 6** | NCEP/NCAR Reanalysis averaged daily composite air temperature fields in spring 2018: (a) 11 to 20 April; (b) 21 to 30 April; (c) 1 to 10 May; (d) 11 to 20 May.

thermal deterioration of the ice cover could be significantly retarded during this cold spell. Early May, in its turn, was up to 5 °C warmer than average in the Amga River headwater area, promoting intense snowmelt. By this time, starting from 7 May, ice jams were forming several kilometers downstream from Amga village. Numerous ice blasts gave only temporary relief, and an emergency was finally declared on 11 May; water stage started to decline slowly after 14 May.

Descriptive analysis of spring weather patterns over Siberian Asia shows no marked similarities between the three years in question, but one major point should be made. The alteration of warm and cold spells during snowmelt season and breakup appears to be common in years with severe ice-jam floods. Air temperature field in late April and early May shows a dipole pattern with warm air in the headwaters and cold air in the middle reach.

Warm spells in the headwater area intensify snowmelt while cold blasts in the middle part of the catchment enhance ice cover stability and provoke ice jamming. Otherwise, this pattern may well have occurred in years with no significant flooding, in which case it may serve as a prerequisite for major flooding but not its major cause. An ensemble of local conditions then comes into play, ultimately transforming this weather pattern into an emergency situation, when water stage increases above the critical point.

## Highest annual water stage statistics

In the Russian Federation, as in many Nordic countries, flood-prone areas are defined as areas inundated at least once in 100 years, or during a 1% exceedance probability flood. Delineation of potentially flooded areas is based on the statistical analysis of highest water stage data, and can vary depending on the probability distribution function used in this analysis (Majumdar & Sawhney 1965).

Manual fitting of the distribution curve gives $H_{1\%} = 145.35$ m a.s.l. Russian federal regulations, e.g., Building Code 33-101-2003 (2004), require that Kritsky–Menkel distribution be used in hydrological statistic analysis. The probability distribution function of highest annual water stage at Amga village has negative asymmetry, with $C_v = 0.246$, $C_s/C_v = -1$, and a 100-yr flood stage $H_{1\%}$ is 145.82 m a.s.l. Fifteen distributions were fitted to the Amga River at Amga highest stage dataset to test their performance against the Kritsky–Menkel distribution (Table 1). Group V average yields exactly the same mean value as presented above, with $H_{1\%} = 145.82$ m a.s.l. Therefore, this value can be reliably used in flood-prone area mapping, at least at this probability level.

In 2018, the water stage at Amga reached 145.38 m a.s.l., which is close to a 50-yr flood, and in 1980 it was some 0.2 m less, 145.18 m a.s.l., roughly corresponding to a 33-yr return period. We can conclude that what is an extreme flood and a severe blow for the community in terms of damage and recovery costs, is, from a statistical viewpoint, a routine event well below the catastrophic limits. A catastrophic 1,000-yr flood will exceed this 100-yr level by about 1 m, equaling 146.66 m a.s.l., based mean $H_{0.1\%}$ value from Group V distributions.

**Table 1** | Water stage at 100-yr flood from selected extreme value distributions

| Group | Distribution | $H_{1\%}$, m a.s.l. | Group mean |
|---|---|---|---|
| I | Exponential | 149.69 | 149.69 |
| II | Gumbel | 148.18 | 148.14 |
| | Laplace | 148.10 | |
| III | Rayleigh | 147.15 | 147.13 |
| | Gamma | 147.10 | |
| IV | Normal | 146.36 | 146.34 |
| | Generalized logistic | 146.32 | |
| V | Generalized Pareto[a] | 145.95 | 145.82 |
| | Generalized normal | 145.87 | |
| | Pearson type III | 145.85 | |
| | Weibull | 145.82 | |
| | Fisher–Tippett (GEV) | 145.59 | |
| VI | Modified Gumbel | 145.19 | 145.16 |
| | Kappa | 145.18 | |
| | Wakeby | 145.09 | |

[a] Generalized Pareto distribution tends to underestimate $H_{max}$ for return periods less than 100 yr, and to significantly overestimate it for 1,000 yr return period.

## Flood area mapping

The highest water stage at Amga, observed on 11 May 2018, 145.38 m a.s.l., was used in mapping the flooded area and evaluating the tangible direct damage to the community (Figure 7). Flood extent is generally mapped using an elevation model; in Russia, the official topographic data scaled below 1:100,000 are classified, so the researchers are limited to open data with significantly lower quality (Hawker *et al.* 2018).

In the present study, ArcticDEM mosaic was used in flood extent mapping as a base elevation layer (Figure 7, top), but in test mode only, as it is known to be: (a) a digital surface model (DSM), uncorrected for vegetation and urban features, e.g., housing and (b) referenced to WGS-84 ellipsoid, which is known to be offset related to Baltic 1977 datum. Rather unexpectedly, however, the use of ArcticDEM yielded reasonable results concerning flood water extent and submergence depth. Flooding extent matches local topography and corresponds well with helicopter imagery acquired around the flood peak dates (Figure 7, bottom). Total flooded area within the community limits equals 3.74 km$^2$, predominantly of unoccupied floodplain surfaces.

The drawbacks of an ArcticDEM DSM become clearly visible in densely built-up areas, where elevation is 3 to

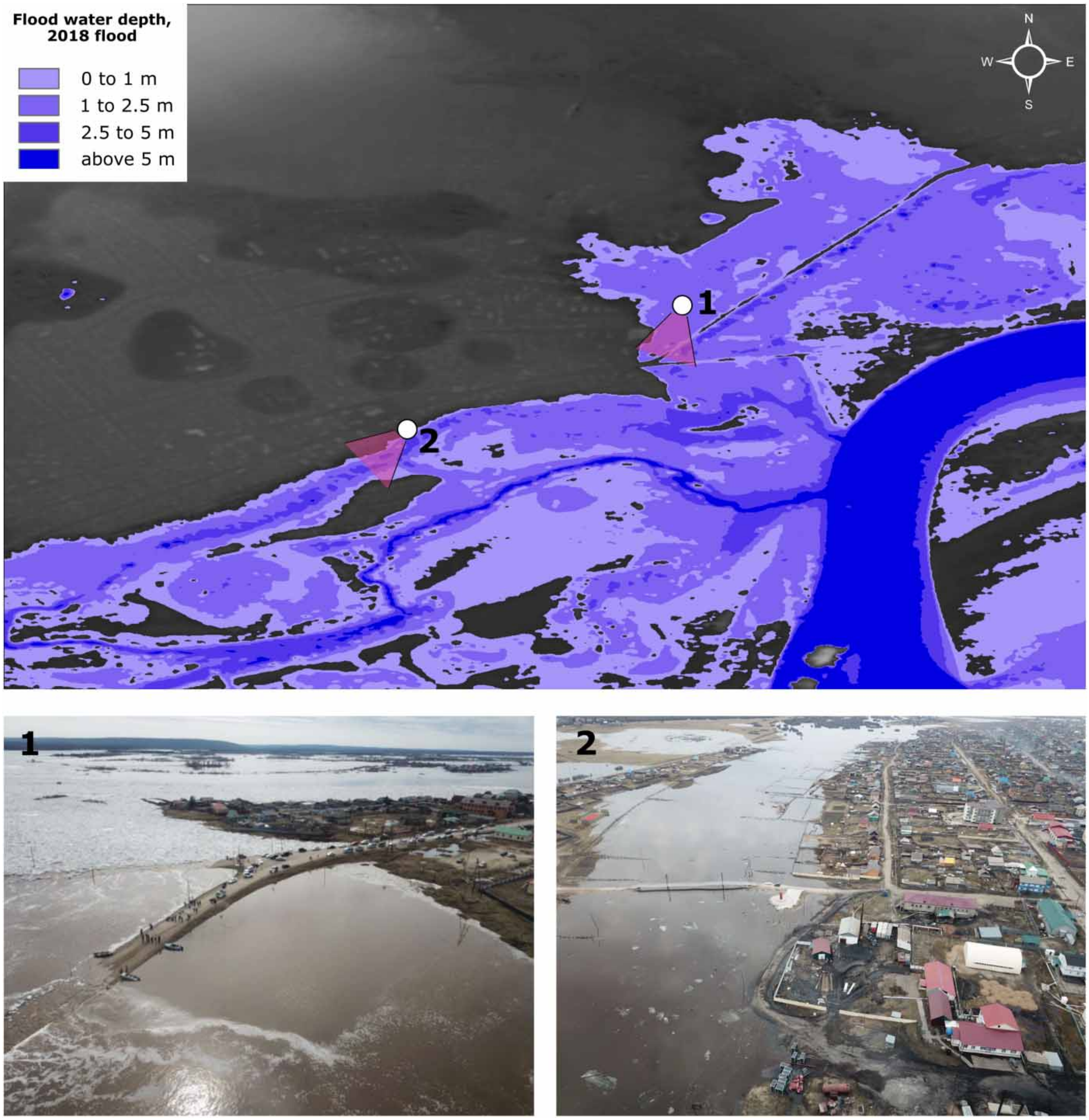

**Figure 7** | Flood water extent and depth during 2018 flood (top); numbered points and shaded areas show point-of-view and shooting angle of corresponding photographs (bottom).

5 m higher than expected, which corresponds to an average rural house height. Even a single building can affect DSM elevation value in a spot at least three times its size. In densely built-up areas, where the ground elevation is virtually undetectable, these areas may be erroneously marked as non-inundated. Besides, evident artefacts, e.g., non-inundated patches in the river channel, at the lower right corner of Figure 7, are present in the DSM data.

## Tangible direct damage

Tangible direct damage was estimated using flood extent derived from the ArcticDEM DSM. This estimate is expected to be slightly undervalued because of the potential offset between the elevation reference datums. The VIEMS technique (Technique 2006) requires data on the surface of submerged residential and industrial areas, and communications/engineering facilities. These values, presented in Table 2, were calculated in ArcGIS from an overlay of flooding area limits and a Federal Cadastre Map, openly available as a standard WMS Server layer. De facto, only 29.4 ha, or less than 10% of total flooded area, were subject to direct damage. A deflator multiplier 2.538 is used to switch to 2018 prices. Estimated total tangible direct damage exceeds ₽5.1B ($81.5M), or 0.55% of the gross regional product, split equally between general population and industry (Table 2).

Official post-flood reports present significantly lower damage to the community. As a general practice, governmental sources refer to mitigation and recovery costs, and not tangible direct damage, in their publications. The annual report of the Sakha (Yakutia) Republic government, available online at https://prav.sakha.gov.ru/ot-31-yanvarya-2019-g—-74-r (in Russian), claims total mitigation and recovery spending reaching ₽1.5B ($23.8M) throughout the Republic, of which, ₽0.3B ($4.77M), or ₽65,000 ($1,033) per household, were spent as household recovery assistance, in the form of both direct and indirect money transfers, and building materials' supply. The Amga village community only reclaimed about ₽0.13B ($2.1M) as response and recovery funding, and neither direct nor indirect damage was assessed to be put on the table as an argument in future discussions on flood prevention strategies and risk reduction planning.

Current Russian practice in flood damage estimation is highly ambiguous. The presented VIEMS technique is widely used to evaluate the probable tangible direct damage from floods, but only before the flooding has occurred in reality. In post factum calculations, this approach is completely discarded and only documented damage to property and loss of assets is used in official reports. Household recovery assistance is covered by regional and/or federal budgets, and the amount paid to households is detached from real-life damage.

## Survey data analysis

The questionnaire survey involved 45 households, or about 17% of the total affected population, with an average of four family members per household. Among the respondents were 11 men (24%) and 34 women (76%), with an average age of 45 years. The aggregate income level of five households (11%) did not exceed ₽30,000 ($477), in 19 households (42%) it was from ₽30,000 to ₽50,000 ($477 to $795), in 18 households (40%) – from ₽50,000 to ₽100,000 ($795 to $1,590), and in one household it exceeded ₽100,000 ($1,590).

The general population (80% of the respondents) is aware of the preparative measures taken by the local administration in the face of flood, including forming operational headquarters, which organize and supervise alerting and evacuating the residents from flood-affected areas. The majority (27 respondents, 60%) evaluated the effectiveness of local government actions positively, 18% (8 households) negatively, and 22% found it difficult to answer.

Among the preparations for the spring flood, the evacuation of the population received most positive assessment among the population; 21 respondents (47%) rated it positively. However, the effectiveness of other preventive and preparatory measures, such as channel dredging, ice blackening and sawing, ice-jam blasting, was questioned – 33% of respondents (15 people) rated them negatively, and 62% (28 people) found it difficult to answer.

At the same time, only 35% of respondents reported that they had received an alert more than 5 days ahead of flood,

**Table 2** | Tangible direct damage to Amga village during the 2018 flood, estimated by the VIEMS technique (Technique 2006)

| | | Tangible direct damage, $\times 10^6$ rubles (in parentheses, values $\times 10^6$ US dollars) | | |
|---|---|---|---|---|
| | **Flooded area, ha** | **Unit value, per ha (Technique 2006)** | **2006 prices** | **2018 prices** |
| Residential areas | 17.4 | 59.7 (2.41) | 1,041 | 2,642 (42.0) |
| Industrial areas | 11.8 | 82.1 (3.31) | 971 | 2,465 (39.2) |
| Communication lines | 0.2 | 37.3 (1.50) | 8.0 | 20 (0.32) |
| Total | 29.4 | – | 2,020 | 5,127 (81.5) |

while one-third of respondents were alerted only 1 day or less before the flood peaked. In addition, more than half of the respondents (23 households, 51%) received information about emergency evacuation not from the local administration representatives, but from their relatives or neighbors.

Eighty-seven percent of respondents, or 39 households, kept track of the spring flood progress. When asked about the sources of information about the flood wave advance, respondents could choose several answers. Among the most popular sources, the respondents named mobile social network applications (29%, or 21 of 72 answers), television (21%, 15 of 72), and phone calls to/from relatives living upstream (14%, 10 of 72).

When asked about preparatory measures undertaken by their households, 16 respondents, or 36%, named the transfer of their belongings to the upper floors of their houses as a priority measure. Eleven households, or 24%, prepared documents and valuables for the emergency evacuation, five households, or 11%, relocated children and elderly family members to relatives living in safe areas. In addition, 29% of respondents (13 households) answered that they do not prepare for floods, since their house is not included in the potentially flooded zone defined by local administration.

Fifty-three percent of respondents (24 households) suffered direct damage from floods, of which in ten households (22%), the amount of damage amounted to more than ₽500,000 ($7,950), or close to a household annual income. As well, all respondents indicated a deterioration of drinking water quality and overall sanitary and epidemiological situation in the village; 29% of respondents (13 people) reported health deterioration due to flooding.

Permanent relocation of the household from the flood-prone area to higher terrain or other settlement is envisaged by eight respondents, or 18%. At the same time, 20 respondents (44%) support the idea of complete relocation of the village.

## Flooding as a social phenomenon: the Amga case

Flooding, besides natural reasons, has a distinct social dimension. The level of community vulnerability to flooding can be defined as the capacity to adapt the settlement structure and prevention/recovery measures to probable flooding scenarios, in other words, certain strategical flexibility. The Amga village flooding in 2018 showcases a lack of flexibility at all decision-making levels, from local to federal, in dealing with flood hazards.

After a row of devastating floods in Siberia, Russian Far East, and Southern Russia in the 2000s and 2010s, multiple federal laws have imposed restricted land use within the flood-prone areas, including bans on housing construction. Flooding zone limits corresponding to floods with 1% recurrence probabilities were to be delineated on the master plans of the settlements. For Amga village, this work was planned for late 2018, and there is no openly accessible information on whether this work has ever been accomplished. Local administrations have no control on this process, as this work is contracted by the regional government, i.e., Ministry of Ecology, Sakha (Yakutia) Republic, and supervised by numerous federal stakeholders, including Lena River Basin Water Management Agency, Yakutian Hydrometeorology Agency, and Far Eastern Department of Russian Hydrometeorological Agency. Moreover, land use restrictions are not applied to settlements subject to flood protection measures, i.e., ice cutting and dusting, so local inhabitants have no objections to occupy the flooded lands.

From the local perspective, Amga administration is in constant need of additional space to accommodate the increasing population. Safer areas at higher terrain, outside the potentially flooded area, generally belong to Federal Forest Reserves, and are, as such, unavailable for private housing construction. Hence, the cheapest lands available are allocated to local residents by the administration, including areas vulnerable to flooding; these lands are allocated on-demand to young families, which is a common practice in the Sakha (Yakutia) Republic. According to previous studies (Kontar *et al.* 2018), the communities, in their decision-making, tend to rely on the 'false safety' feeling in the absence of major floods, and intensely develop terrains adjacent to riverbanks and oxbow lakes.

Centralized water supply is absent in Amga, and blocks of river ice are used as drinking water supply, a common practice in rural Yakutia (Takakura 2018). For this purpose, also, people tend to settle as close as possible to freezing water bodies, increasing vulnerability to flooding.

### Flood management practices in Sakha (Yakutia) Republic

Flood management practices are based, as we put it, on five major elements: (1) forecasting, (2) prevention, (3) preparative measures, (4) direct response, and (5) recovery actions.

Flood forecasts are issued on a regular basis by the federal state-funded Yakutian Hydrometeorology Agency, and are updated with the progression of spring freshet. These forecasts are communicated to a general audience and major stakeholders; however, official flood warnings are only issued when the water stage exceeds the critical threshold. In Amga, this threshold is exceeded, on average, once in four years, and is not necessarily related to heavy loss to property or livestock.

Preventive measures include ice dusting and cutting, and ice-jam blasting as a last resort option. Their efficiency is questionable, but they remain in place, yielding a certain ‘placebo effect’ on the local community and stakeholders. Ice cutting and dusting have been implemented at the same spots each year since 2009, regardless of changing ice conditions, giving yet another example of the lack of flexibility. Unsurprisingly, these measures receive little support from local residents. In contrast, preparative measures and response actions, mostly taken by local administration under supervision from numerous stakeholders’ representatives, are deemed rather effective. Households respond positively to flooding announcements, react individually, and implement measures that they judge relevant. Residents are not forced to move out to safer terrain; they either relocate in advance of flooding, or are rescued as an emergency during direct response phase at peak flood.

In the recovery phase, the community residents declare their losses and claim financial compensation from regional and federal budgets. The amount of this compensation is variable and depends largely on federal media coverage, the number of residents affected, and available funds. As well, both regional and federal funding is used to recover roads, communications, and other key infrastructure elements. Tangible direct damage is further calculated based on total spending in the recovery phase, and does not include flood prevention and preparatory measures. Insurance, as a risk management practice and a source of financial support to affected residents, is relatively unpopular. Large insurance agents constrain their activity in this field, lacking evidence-based knowledge on the structure of hydrological risks and potential damage. In the Sakha (Yakutia) Republic, insurance covers only 1% to 7% of total damage reclamation. Rural communities are particularly unattractive for insurance companies because of the housing age and low solvency of rural residents (Parfenova 2017).

## CONCLUSIONS

Ice jams are commonly observed during breakup on Russian Arctic rivers, and may result in heavy flooding affecting the well-being of riverine communities. The studied case of Amga village shows that both natural and social drivers act jointly in increasing its exposure and vulnerability to flooding. Weather pattern analysis reveals that although no particular similarities exist between years with major floods, a ‘dipole pattern’ of high air temperature in headwater areas and cold blasts around breakup dates in the middle section of the river could promote ice cover stability and induce ice jams. Local channel morphology with abundant shallow sandbars retards ice movement and increases the probability of ice-jam development. Prolonged cold spells play an important role in limiting ice thermal deterioration, or promoting ice-jam buildups upon refreezing.

From the statistical viewpoint, the 2018 flood on the Amga River had a 50-yr return period, which is a rare but not a catastrophic event. Even at this exceedance probability level, about 23% of the total settlement area was flooded, or 374 out of 1,633 ha, resulting in an estimated tangible direct damage around ₽5.1B ($81.5M). A 1,000-yr flood will exceed the observed highest water stage by more than 1.0 m, and the consequences of such flood to the community are still poorly understood.

Amga village appeared to anticipate the 2018 flood, but with numerous reserves. Significant space within flood-prone areas was allocated to families for housing construction, as it was the cheapest option with no official restrictions on land use. Younger generations were unaware of the heavy flooding consequences, since the 1980 flood was too long ago to be remembered, and readily occupied the floodplain surface adjacent to the village core. The general population was informed of the coming disaster, but almost one-third of respondents received the flood announcement less than one day in advance. Social networks and 'word of mouth' were among the most referred information sources, and official broadcasting network was not active enough.

Tangible direct damage to the community is estimated around ₽5.1B ($81.5M), but the community reclaimed only a minor fraction of this total as recovery costs for residents and industry. This fact adds to the controversy between two divergent understandings of tangible direct damage, either as a potential flood damage (VIEMS approach) or a reclaimed financial support, regardless of real damage to the community (state Emergency Ministry approach).

Finally, the Amga village authorities were lacking resources and political influence to force discussions on the lack of long-term preventive measures to reduce the flood risks. The settlement remains vulnerable to ice-jam flooding, but the 2018 agenda is no longer an actuality in 2020, replaced by forest fires in Central and Northern Siberia. Another decade might pass until the next flood, which may well exceed the 1% probability and turn into a catastrophe, but its potential consequences are put aside.

Ice jams are extremely unpredictable and difficult to anticipate (Rokaya *et al.* 2018), which complicates the implementation of adequate mitigation techniques. The 'last resort'' techniques, such as ice blasting, proved their inefficiency during the 2018 flood, and on multiple previous occasions. Current preventive measures are centered around the community response, i.e., population and livestock relocation, and not the prevention of ice jams, the main reason of flooding. In the local context, the removal of sandbars by dredging, and channel transformation to equilibrium conditions may serve as an effective mitigation strategy. Active ice-jam prevention by forcing ice cover decay, both mechanical and thermal, through insulative snow accumulation, ice removal with bulldozers and diggers, or ice cover weakening with air-cushioned vehicles, may be efficient at given conditions. As well, a series of small in-channel submerged dikes may be implemented to control the equilibrium channel geometry and prevent ice-jam buildup; a system of flood control levees and retention ponds may be effective in decreasing the maximum flood level; raising houses on piles may prevent them from being submerged. Non-structural measures, i.e., flood insurance, can decrease financial pressure on local authorities, by putting extra financial pressure on the local population, which makes this measure difficult to implement.

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