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Flash floods on the northern coast of the Black Sea: Formation and characteristics

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Flash floods on the northern coast of the Black Sea: Formation and characteristics

Abstract: Flash floods are one of the most dangerous hydrometeorological events in the world. The current study investigates flash floods on the northern Black Sea Coast. The data about stochastic and relatively stable factors of flash flood formation (such as hydrological, meteorological, lithological, geomorphological, and anthropogenic parameters) were collected for 22 events. The main trigger of flash floods is heavy rainfall of high intensity in the region but in some cases flash flood occurrence is connected with combinations of several "non-critical" factors. The small watershed area ($\leq$ 351 km^2) of river basins experiencing flash floodspromotes very rapid flow concentration. Analysis of extreme precipitation demonstrates significant increasing trends in river basins on the Crimean Peninsula and decreasing a maximum precipitation amount in 5 days (r5d) and 1 day (r1d) in river basins in the Caucasus Black Sea Coast in the 21st century as determined by processing of Integrated Multi-satellite Retrievals for Global precipitation measurement (IMEGR) satellite data. At the same time land network data indicates increasing r5d at the Anapa and r1d at the Tuapse meteorological stations in 1961–2020. More frequent occurrence of flash floods has been suggested in the area due to statistical analysis of the longest precipitation ranges. The main reason for significant social and economic damage is uncontrolled human activity in flooded areas on the northern Black Sea Coast.

Keywords: Flash flood; Heavy rainfall; Intensity; River basin; Black Sea Coast; Caucasus; Crimea

1. Introduction

Flash floods are one of the most dangerous hydrometeorlogical events in the world. A special term for flash floods appeared in Russian hydrology after the severe flood in Krymsk in 2012 (Bolgov & Korobkina, 2013; Kotlyakov et al., 2012; Kuksina et al., 2017). No clear criteria are available to distinguish flash floods in comparison with debris flows and other events. Due to this fact and a lack of information about flash floods in the Eastern Europe, especially in English, many events did not find their place in the worldwide databases (Fig. 1) (Kuksina & Golosov, 2020; http://floodobservatory.colorado.edu). By definition a flash flood is the flood that begins within 6 h, and often within 3 h, of heavy rainfall (or other cause such as dam or levee breaks, and/or mudslides (debris flow), volcanic eruption in nival belt, etc.) (Kuksina et al., 2017; https://www.weather.gov/phi/FlashFloodingDefinition). Flash floods are a complex phenomenon, and their origin, development, and consequences are determined by interactions of hydrometeorological factors, lithologo-geomorphological factors, and anthropogenic impact (Kuksina et al., 2017).

Fig. 1. Flash floods in various climates in 1985–2018 as per Marchi et al. (2010), http://floodobservatory.colorado.edu.

Flash floods most often appear in subtropical, tropical, and equatorial climates in the northern hemisphere (Kuksina et al., 2017) but now their frequency and intensity is growing in other regions which haven't previously been substantially affected by such events (Baran-Zgłobicka et al., 2021). At the same time no systematic observations on flash floods formation are available due to hard-to-reach mountain river basins (which are regions prone of flash flood origin), difficulty of measurements during flash floods occurrence, location of the formation zones in small catchments (with area less than 1,000 km^2 (Gaume et al., 2009)), and high spatial and temporal inhomogeneity of precipitation, especially in mountains and foothills.

The most stochastic factors affecting flash floods formation and development are such meteorological parameters as quantity and intensity of heavy rainfall and its duration (Borga et al., 2014). Climate change (https://www.ipcc.ch/report/ar6/wg1/) has resulted in gradual increases in air temperature promoting snow and ice melting in the mountains, and increases in rainfall quantity and intensity since the mid 1970s (Groisman et al., 2004, 2005; Report, 2017). These hydrologic changes have influenced flash floods and debris flow occurrence (Kuksina et al., 2017; Mueller & Pfister, 2011; Poesen & Hooke, 1997). Particularly atmospheric circulation change has led to increases in the appearance of Black Sea cyclones in the Caucasus Black Sea Coast and consequently increased the frequency of extreme precipitation (Kononova, 2012; Voskresenskaya & Vyshkvarkova, 2016). Convective potential energy (CAPE) characterizes the potential intensity of convective storm movements, and it has increased threefold in summer in the Black Sea region (Aleshina et al., 2018). The current heating of the Black Sea surface (the temperature of the sea surface increased 2 °C in the period of 1982–2012 (Meredith et al., 2015)). The surface temperature activated deep convection and the formation of extreme precipitation during cyclone development on July 6-7, 2012 causing a flash flood in Krymsk (Meredith et al., 2015). Current climate change increases the risk of intensive convective precipitation on the Black Sea Coast (Chernokulsky et al., 2019) and could increase the frequency of flash floods in the region (Mal'neva&Kononova, 2012; Vishnevskaya et al., 2016).

1. According to regionalization of the Worlds' events (Kuksina et al., 2017; Kuksina & Golosov, 2020) river basins in mountains and foothills of Crimea and the Western Caucasus could be the most vulnerable region to flash floods on the Black Sea Coast and nearby areas. In addition to climatic characteristics, flash flood formation is promoted by such features of river basins as oblong configuration and significant slopes that favor rapid flow concentration in the region. Research on climate change in the Caucasus Black Sea Coast (Tashilova et al., 2019) and Crimean Peninsula (Kuksina et al., 2021; Voskresenskaya & Vyshkvarkova, 2016; Vyshkvarkova, 2021) has found increases in air temperature and growth in precipitation extreme indexes. These climate changes should result in increased flash flood occurrence in the studied area. Flash floods are a frequent cause of human fatalities in the north of the Black Sea Coast (Alexeevsky et al., 2012; https://iz.ru/1180696/2021-06-18/odin-chelovek-pogib-v-rezultate-podtoplenii-v-ialte, https://iz.ru/1200673/2021-07-30/ushcherb-ot-podtoplenii-v-krymu-otcenili-v-46-mlrd-rublei, https://ria.ru/20120723/706970587.html, https://ria.ru/20210706/podtoplenie-1740137141.html) where the latest extreme floods caused by heavy rains occurred in the summer

of 2023.

Uncontrolled economical activity is an important factor of socio-economic damage from flash floods due to unauthorized building on river floodplains, absence of drainage systems near residential houses, and vegetation overgrowth and obstruction of river channels on the northern Black Sea Coast (Alekseevskii et al., 2016; Alexeevsky et al., 2016; Bitukov et al., 2019; Kononova, 2012; https://expertsouth.ru/news/navodneniya-na-kubani-zabytye-uroki-krymskogo-pavodka/).

The main goal of the current research is collection of data and description of observed flash floods in river basins on the northern Black Sea Coast, determination of events and catchment characteristic features, and analysis of the most favorable combinations of flash floods formation factors.

2. Studied region

The studied area includes rivers flowing into the Black Sea from the Kudepsta River (19, see Fig. 2) in the east to the Durso River (11, see Fig. 2) in the west in the northern Caucasus Black Sea Coast (an exception is the Adagum River (12, see Fig. 2) in the Kuban River basin), and rivers in Kerch Peninsula and the South Coast of Crimea (Fig. 2). The territory is situated in moderate and subtropical climates, and can be divided to regions of wet (Tuapse–Sochi, Alushta –Yalta) and dry (the Ashamba River (13), Kerch Peninsula) subtropics where various moistening influences flash floods formation conditions due to antecedent soil moisture.

Fig.2. Study area of the Western Caucasus and Crimea.

Most of the rivers of the Black Sea Coast of the Caucasus flow from the southern slope of the Great Caucasus Range. The underlying rocks are represented by complexes of silt, sandstone, limestone, clay, and flees of Jurassic, Cretaceous, and Paleogene ages (Hydrogeology of the

USSR, 1968). The main ridge comes close to the Black Sea Coast, as a result of this, the size of river basins usually does not exceed 100 km^2, and the lengths of the channels are measured in the tens of kilometers. A large difference in elevation in combination with the relatively small lengths of rivers leads to the formation of high slopes of the water surface, and, as a result, leads to an intensive incision of rivers into relatively easily eroded sedimentary complexes (Voskresensky, 1968). When moving from the axial part of the Main Ridge to the Black Sea, rivers often cross a series of boundaries of uneven-aged complexes, thrust ledges, and anticlinal ridges (Khain & Lomize, 1959); as a result, the valleys acquire the character of gorges with pronounced steep (sometimes vertical and overhanging) walls (Fig. 3).

Fig.3. Ribbed slopes of the Bolshaya Khosta River (Navalishen Gorge) (No. 20 in Fig. 2).

For the steep slopes of the gorges, the processes of gravitational and block-gravitational displacement are quite typical, simultaneously supplying a large amount of material in the bottom of valleys (Fig. 4). After blockages are formed, blocking the river flow, the subsequent failure (breakage) of temporary dams may occur.

An indirect confirmation of the emergence of temporary dams in the past are the terraced surfaces. For example, one terrace was found adjacent to the confluence of the Malaya and Bolshaya Khosta Rivers (Fig. 5). These terraces are composed of loamy material with horizontal texture and rare inclusions of coarse detrital material. Such a texture is more typical for relatively calm hydrodynamic conditions and is in sharp contrast to the alluvium in the channel and on the side streams.

Fig.4.Coarse material of landslide origin, deposited on top of tree trunks in the Khosta River (No. 20 in Fig. 2). The tree trunks (crushed down by blocks from a nearby rock wall) are marked with a red rectangle.

Fig.5.The terrace in the valley of the Malaya Khosta River in the area of confluence with the Bolshaya Khosta River (No. 20 in Fig. 2).

The low resistance of the underlying sedimentary rocks to weathering, especially flysch under conditions of excessive moisture and high-temperature amplitudes, leads to the intensive formation of eluvium and its transport down the slopes to the valleys of temporary and permanent water streams. This leads to the saturation of water with the debris of various sizes. With a small valley width, the water level rise relatively quickly, which turns into instantaneous entrainment of clastic material into the flow. In the presence of high flow rates, this situation can result in the formation of debris flows (Perov, 2012), periodically arising on the territory of the Black Sea Coast of the Caucasus (Shnyparkov et al., 2013) (Fig. 6).

Fig.6.Modern debris sediment in the bottom of the valley of the Bolshaya Khosta River (No. 20 in Fig. 2) and a mudflow terrace cut by the river.

The development of the river valleys of the southern coast of Crimea took place in geological conditions of high complexity. The southern part of the Crimean Peninsula is occupied by mountain structures stretching in an arc about 50 km wide and 150 km long from southwest to northeast. The system of the Crimean Mountains is subdivided into three chains: the most elevated Central Ridge and, to the north of it, the Predgornaya and Outer Ridges. The

Crimean Mountains are a complexly constructed anticlinorium, the southern part of which is lowered below the level of the Black Sea. The southern coast of Crimea, allocated as a separate area, occupies the southern slope of the Central Ridge. It is deeply dissected by a network of river valleys with various morphology (Fig. 7) that began to form during the uplift of the territory in the Miocene-Pliocene time. Erosional activity is usually accompanied by rockfalls and landslides. The development of landslides is largely facilitated by the structure of the overlying flysch strata (Voskresensky, 1968).

The main ridge, also called Yaila, is subdivided into separate flat-topped massifs (Voskresensky et al., 1980). The upper part of the southern slope is composed of steep rocky limestone cliffs of erosional origin. Downslope, a complex erosional-hilly relief is developed, characterized by narrow, meandering, gently hilly watersheds, dissected by trough-like erosional valleys with thin deluvial and gravity trails. Landslides of various types are widespread within the southern coast of Crimea (Geology of the USSR, 1969).

Fig.7. River valleys on the South Coast of Crimea: a) weakly branched (almost rectilinear) basin of the Voron River (No. 0 in Fig. 2); the bottom of the valley is mostly occupied by vineyards; and b) a branched basin of the Demerdzhi River (No. 1 in Fig. 2) in the area of the Kutuzov Reservoir; the bottom and slopes of the valley are mostly forested.

The northeastern part of the Kerch peninsula is characterized by peculiar forms of denudation relief caused by the erosion of the widely developed brachyanticline dome-shaped structures. The hydrographic network of the Kerch Peninsula cuts through anticlinal valleys and monoclinal ridges in all directions. The southwestern part of the peninsula is a completely flattened plain, developed on easily eroded clayey sediment. Domed folding is not reflected here at all. The surface of the plain is dissected by numerous ravines with wide and flat bottoms (Geology of the USSR, 1969).

Mean annual precipitation in the South Coast of Crimea varies between 600 (Yalta) and more than 1000 (Ai-Petri) mm, and it is about 450 mm (Kerch’) for the Kerch Peninsula. Maximum daily precipitation promoting flash flood formation is observed in the highest mountain in Crimea and can exceed 200 mm/d; this value decreases to 100–120 mm/d in foothills (Kuksina et al., 2021), and reaches 100–160 mm/d in the Kerch Peninsula.

Some increasing of mean number of extreme precipitation events has been observed in the territory (Table 1). However, there are no stable trends for most stations in the north of the Black Sea Coast according to Aleshina et al. (2018), Bulygina et al. (2007), Vyshkareva (2021), and Zolina et al. (2009).

Distribution of river runoff corresponds to the distribution of precipitation within the year according to observations at the hydrological gages. Increased water discharges are observed during the cold period (from December to April), while the warm period (from May to November) is characterized by a low water period (up to the total runoff extinction) interrupted by short flash floods produced by heavy rains (Fig. 8). The same distribution describes the number of cases with maximum water discharges within the year (see Fig. 8).

Table 1. Mean annual number of extreme precipitation events in the Black Sea Coast and Crimea in June–October.

Meteorological station	1961–1990		1991–2020	
	1% probability*	30 mm	1% probability	30 mm
Ai-Petri 1,180 m above sea level	2.00	2.26	2.40	2.53
Kerch 49 m above sea level	4.86	1.39	4.00	2.07
Feodosiya 22 m above sea level	2.81	1.67	3.07	1.80

Anapa 32 m above sea level	1.95	1.70	2.27	2.24
Sochi 132 m above sea level	2.00	6.00	2.23	6.72
Krasnaya Polyana 567 m above sea level	2.17	6.23	1.91	6.38
Tuapse 62 m above sea level	2.06	4.93	2.17	5.43

*Recurrence is less than once in 100 years

Fig. 8. Mean monthly precipitation, water discharge, and total number of events with annual maximum water discharge in the Uchan-Su Riverat Yalta in 1946–2016. 1–precipitation, mm, 2 –water discharge, m^3/s, and 3–number of events with maximum water discharge within the year.

In spite of the characteristic distribution of water discharges within the year according to observations at the hydrological gages, maximum water discharges and the most severe flash floods occur during the summer–autumn period due to the increase of occurrence of extreme rainfall in the summer period (Alekseevskii et al., 2016; Kononova, 2012). In addition, precipitation has a lower intensity and longer duration in the winter period, significantly decreasing the probability of severe flash flood occurrence. These flash floods events often are not measured due to complexities in the measurements on location during flash floods. Waterspouts which could be specific factors of flash flood formation in the small river basins in the north Black Sea Coast also form in summer and autumn (Barinov, 2010; Tkachenko, 2012). Maximum water discharges can exceed mean annual water discharges by 200–400 times during flash floods (Ovcharuk & Todorova, 2014). As a rule, maximum sediment yield is observed at the same time.

Soils and vegetation influence surface runoff, and consequently flash flood formation. In addition grass cover density determines the intensity of the surface erosion (Wischmeier et al., 1958). Soils influence runoff in different ways in dry and wet climates. Cambisols are the most widespread soils in the Caucasus Black Sea Coast and the South Coast of Crimea (Nachtergaele et al., 2008) (they cover more than 70% of 16 among the 21 studied river basins), and they have a good water holding capacity and good internal drainage (https://www.isric.org). Luvisols are on the 2nd place by distribution in the studied region, and their area characterized by the highest "avaliable" moisture storage capacity in the agric horizon (https://www.isric.org). Chernozems also are spread throughout the Crimean Peninsula (they absolutely dominate the Melek-Chesme River basin) and have high moisture storage capacity (https://www.isric.org). Flash flood formation depends on antecedent soil moisture in wet climates when even relatively frequent precipitation can lead to hydrological event of rare recurrence (Tsyplenkov et al., 2021). Such a flood was observed in the Tsanyk River basin when precipitation of 99.9% probability (recurrence is very often) fell on wet soil and caused a significant level rise and immediate surface flow formation. The falling of intense rain on dry consolidated soil leads to immediate runoff without infiltration in dry climates. Probably such a situation occured in the Ashamba River basin in July 2012 and in the Melek-Chesme River basin in June 2021.

Vegetation is significantly transformed by human activity on the northern Black Sea Coast, and desert and steppe vegetation has spread in many regions, where these vegetation types are not native to these zones. Deciduous aestisilvae forest with various subtropical trees and bushes grow on the Black Sea Coast under natural conditions (Panagos et al., 2015). Trees and evergreen bushes grow in the South Coast of Crimea under natural conditions. Vegetation of steppe grows in the Kerch Peninsula under natural conditions (Panagos et al., 2015).

Flash flood formation depends on vegetation through reduction of surface runoff coefficients (Bitukov, 2018). Vegetation could be one of the key flash flood formation factors in some river basins (Liu et al., 2021).

3. Materials and methods

The main goal of the current study is collection and analysis of flash flood characteristics on the northern Black Sea Coast, and determination of their place in a range of the worldwide events. Key features and criteria of flash flood origin were revealed on the basis of a descriptive analysis of flash floods in Europe and all over the world.

Statistical analysis of data on floods in the world between 1985 and 2018 demonstrates the principal reason (in 95% of cases) of flash flood origin is intensive rainfall of short duration (Kuksina et al., 2017). The conclusion coincides with the same estimates for river basins in Europe (Marchi et al., 2010). According to Gaume et al. (2009), catchment area must be less than 1000 km^2, and rainfall duration before the flash flood must be less than 12 h, but some assumptions and exceptions can be accepted sometimes (Marchi et al., 2010).

The main conditions for flash flood formation are related to climate and relief. Additional criteria for flash flood determination could be significant social and economical damage according to analysis of events in the flood record (http://floodobservatory.colorado.edu). Thereby the approximate range of such flood characteristics as flash flood can be summarized as follows: 1) small basin area promotes rapid flow concentration; 2) occurrence of intense rainfall of short duration; and 3) location of the river basin in mountains and foothills in subtropical and moderate climates. River basins in the northern Black Sea Coast and the Western Caucasus region conform to these criteria to the best advantage. An algorithm for data collection for events corresponding to the described features consists of the following steps for the studied area:

Primary selection of the flash floods often has been based on analysis of information from mass media, which give the first determination of flash flood occurrence, and its scale, socioeconomical impact, and damage. For deeper analysis of selected events other publications, including scientific papers, were processed. In addition, mass media data were used during later analysis of long-term precipitation ranges, when rare heavy rainfall caused severe flash floods but these floods were just mentioned in local news without description of the main flash flood characteristics.

Scientific papers on the floods were collected after preliminary analysis of mass media information. Data containing information about floods in Krasnodar Krai were included in the list of events and short, complex descriptions of some factors (precipitation amount, water level rise, event genesis (Vishnevskaya et al., 2016), and maximum water discharges of various occurrence probabilities (Alekseevskii et al., 2016) also were listed. Publications on separate events include Alexeevsky et al. (2012), Belyakova et al. (2020), Georgievsky and Tkachenko (2012), Korshenko et al. (2020), Panov et al. (2012), and Tsyplenkov et al. (2021). There is some limited generalized data about debris flows and floods in Crimea (Klukin, 2005, 2007; Ovcharuk & Todorova, 2014).

The key stochastic factors of flash flood formation such as intense rainfall of short duration and antecedent soil moisture were investigated for individual cases. The frequency of precipitation causing flash floods and antecedent soil moisture (for 5, 10, 20, and 30 d) was examined on the basis of open access data (www.meteo.ru). Variability in precipitation total amount, and maximum and extremeness indexes (Li & Hu, 2019) were assessed on the basis of daily data at the meteorological stations (Kerch, Sochi, Tuapse, and Anapa, data is available at www.meteo.ru). Estimation of trend significance was determined using the Mann-Kendall test.

Estimation of maximum water discharges for various crosssections is an important task during flash floods description on the Black Sea Coast. These evaluations allowed flash floods on the northern Black Sea Coast to be compared with the similar events in Europe.

Maximum water discharges during flash floods are indirectly estimated by high water marks (Dobroumov & Lubimov, 1979). Direct measurements often are impossible during flash floods due to the hydrological equipment being submerged and damaged by water (e.g., the hydrological gage was partly broken in Krymsk in 2012, and hydrological equipment is taken away during each severe flood in Tuapse), and measurements using contact methods become dangerous for the observers. Non-contact level gages have started to be used in study region (www.emercit.com), but the data often are not reliable yet. Estimation of maximum water discharges was implemented using the slope-area method by means of the one-dimensional Manning's equation (Jarett, 1987). Hydrographical surveys of the crosssections, high water level signs, local water slope, and roughness has been implemented after flash floods (Lumbroso & Gaume, 2012; Soto & Madrid-Aris, 1994). Maximum water discharges are estimated using this method at hydrological gages cross sections and in ungauged crosssections too. Detailed hydrographical studies also are implemented on the main tributaries and upstream regions of rivers after historical floods. Estimates of maximum water discharges in various cross sections inside the river basin are published for floods in the Tuapse River in 1991 and 2010 (Panov et al., 2012) and the Adagum River in 2012 (Georgievsky & Tkachenko, 2012).

The key relatively stable characteristics of flash flood formation are morphometric parameters of the river basin such as catchment area, mean elevation, elevation amplitude, and basin configuration; bedrock, soil, and vegetation, urban land in the basin, and presence of hydraulic regulation structures such as dams, reservoirs, lakes, etc. Probable sediment yield during flash floods can be estimated on the basis of potential erosion assessment in the river basin (Wischmeier et al., 1958).

Morphometric analysis was implemented using MERIT DEM (Yamazaki et al., 2017) prepared for hydrological purposes on the basis of Shuttle Radar Topography Mission (SRTM) with a resolution of 3 arcseconds. Basin area for various crosssections, mean elevation and average basin slope were estimated by Spatial Analyst (hydrology, surface andzonal statistics). Model river network was built with a threshold basin area of 0.5 km^2. River length was estimated from the vector layer of the hydrological network.

Information about bedrock, soil, and vegetation, and forest-covered areas in the basin was obtained from a database on river basins in the European part of Russia (Ermolaev et al., 2017). The data base doesn't contain data about river basins in Crimea, and the necessary parameters for those basins were obtained from publications and maps (Benavidez et al., 2018; Nachtergaele et al., 2008; Panagos et al., 2015).

The lag time in the basin is an important characteristic affecting the flash floods due to the socio-ecomonical consequences of the event. It may be estimated as the follows (Marchi et al., 2010):

$$T_{\mathrm{L}} = 0.08A^{0.55} \text{ for } A \leq 350 \text{ km}^2$$
$$T_{\mathrm{L}} = 0.003A^{1.10} \text{ for } A > 350 \text{ km}^2 \quad (1)$$

where A is the basin area, km^2.

Processing of the data collected for river basins in the north of the Black Sea Coast was implemented in the following steps:

1) The table of stochastic (changing from one event to another in the river basin) and relatively stable (see Table 2) parameters was prepared for flash floods in river basins in the north of the Black Sea Coast and the Western Caucasus since 1990 following the method of Gaume et al. (2009). Completion of the table was done using 1) published data; 2) GIS analysis for estimation of morphometric characteristics in the basin; 3) application of soil, vegetation, and geological maps of the study area; 4) data on precipitation causing flash floods; 5) antecedent moisture in the basin; 6) estimation of the maximum water discharges in the crosssections; and 7) application of the geographic database of Ermolaev et al. (2017);

2) Analysis of the dynamic characteristics (including estimation of precipitation probability, duration, and maximum intensity during the flash flood; analysis of flash flood seasonal repetition; estimation of antecedent precipitation (e.g., antecedent soil moisture in wet and dry climates); estimation of water level rise intensity and the total water level rise; flash flood duration; assessment of maximum water discharges for various cross sections; sediment yield; socio-economical indicators such as the total damage, number of casualties and victims, and specific factors reflecting anthropogenic impacts in the river basin);

3) Analysis of relatively stable characteristics (including basin area, river length, and slope steepness which influence the flow concentration rate; elevation amplitude, and mean elevation; lag time estimation; bedrock, soil type, forest-covered land in the basin; presence of hydraulic regulation structures in the basin; and urban land);

4) Analysis of the interactions between some relatively stable and stochastic parameters, particularly, intercorrelation between maximum water discharge and basin area. Studied flash floods are compared with similar river basins with flash floods in Europe (http://www.hydrate.tesaf.unipd.it).

4. Results and discussion

Specificity of flash flood formation was studied on the basis of data prepared for 22 flash floods since 1990 in the north of the Black Sea Coast considering stochastic and relatively stable parameters with various degrees of details. Table 2 lists the main parameters of those flash floods. Groups of factors influencing the extreme water level rise during flash flood formation were determined. Stochastic factors and their combinations (see Fig. 9) play the key role in flash flood formation due to relative stability of relatively stable parameters of river basins. The prevailing factor in flash flood formation is rainfall of rare frequency (Kuksina & Golosov, 2020). Other factors can influence flash flood severity but don't play an important role in their formation. Waterspouts approaching river valleys could be a specific factor of flash flood formation in the north of the Black Sea Coast (Barinov, 2010). Sometimes flash floods can originate during precipitation of relatively common frequency, when its formation depends on previous conditions of the underlying surface and soil type is important due to antecedent soil moisture (Tsyplenkov et al., 2021).

The presence of natural or anthropogenic hydraulic regulation structures (such as dams, reservoirs, lakes, ponds, etc.) in the river basin can also significantly influence water level rise during a flash flood. Even low precipitation can result in water evacuation from reservoirs to prevent overflow and dam destruction in some cases (e.g., in Yalta in 2021, and in Alushta in

2017), and also can cause outburst floods, overflow and consequent discharge of caverns which are characteristic features of the studied area (Gergedava, 1988; Klimchouk et al., 2013; Vakhrushev, 2009). Precipitation can also cause destruction of temporary dams formed by blockage of rivers (Alekseevskii et al., 2016). Unfortunately, the available data doesn't allow all flash floods to be delineated into the various groups, but there are several examples in Table 2 which could be grouped. Using the scheme in Fig. 9, all events are denoted as flash floods because flash floods and debris flows have the similar origination conditions. But it's necessary to remember the division of these very similar events is a very urgent task because one event can transform to the other (Alexeevsky et al., 2012), and there often is no clear opinion on what type of event took place. Flash floods are sometimes studied as debris flows (Chernyavsky, 2010; Shnyparkov et al., 2013) or are considered as the flow of mixed type during inundations research (Alexeevsky et al., 2016).

Table 2**.** The most significant flash floods in the north of the Black Sea Coast and theirmain influencing factors in 1990–2021

Date	Region	Rainfall, Mm	River/ site	Watershed area, km^2	Qmax, m^3/s ($m^3/s/km^2$)	Rising time, h	Average intensity of water level rise, m/h	Other rivers affected	Economic losses, mln USD	Casualties, N of people
1 Aug 1991	Caucasus	68.6–151.2	Tuapse	351	2,300* (6.6*)	5	1.3	Pshish, Makopse, Ashe, Psezuapse, Shakhe, Loo, and Buu	230–345	27
2 Sept 1991	Crimea	167	Voron	10.3	6 (0.6)	—	—	—	—	—
11 Aug 1997	Crimea	93.1	Demerdzhi (*debris flow*)	53.0	146** (2.8**)	—	—	—	—	—
22 Aug 1997	Caucasus	15.1	Sochi	296	990* (3.4*)	—	—	—	—	—
			Z. Dagomys	49.0	511* (10.4*)	—		—	—	—
9 June 1998	Crimea	80.2	Voron	10.3	—	—	—	—	—	—
7–9 Aug 2002	Caucasus		Shirokaya Balka (*debris flow*)	32	1,120** (35**)	20 min		Tsemes, and Durso	60	59
15–16 Oct 2010	Caucasus	53–101	Tuapse	351	1,630* (4.6*)	—	0.32	Vulan, Dzhubga, Psebe, Nechepsukho, and Makopse	82	17
6 July 2012	Caucasus	156–311	Ashamba	44.3	200** (4.6**)	—	—	Tsemes, and Mezyb’	620	16 (1 death)
6–7 July 2012	Caucasus	156–311	Adagum in Krymsk	328	1,350–1,500 (4.1–4.6)	4–5	—	—		155 (2 deaths)
22 Aug 2012	Caucasus	??	Nechepsukho	—	—	—		Shapsukho	32	4
25 June 2015	Caucasus	95.5	Z. Dagomys	49.0	366 (7.5)	3	1.2	Sochi, and Kherota	14	1
		108.6	Khosta	98.5	386 (3.9)	3	1.3			
19 Aug 2017	Crimea		Demerdzhi	53.0	—	—	—	—	—	—
24–25 Oct 2018	Caucasus	208.9	Z. Dagomys	49.0	325 (6.6)	0.3–2	—	Sochi, and Kudepsta, Mzymta	53	—
		77	Khosta	98.5	400 (4.1)	3.5	1.2			—
		253–362	Tuapse	351	1,400 (4.0)	6	—	Makopse		3 (1 death)
25–27 Oct 2018	Caucasus	218–362	Pshish	710	1,860 (2.6)	> 10	—			4
17–18 June 2021	Crimea	133.1	Uchan—Su	16.8	43 (2.6)	—	—	Melek-Chesme, Belbek, and Dederkoika	—	2 (1 death)
4 July 2021	Crimea	84.8–113.5	Kokkozka	83.6	219 (2.6)	—	—	Belbek	—	1
5–6 July 2021	Caucasus	91.4–246.6 142–319 (559)	—	—	Not yet	—	—	Psekups, Afips, Vulan, Dzhubga, Shapsukho, and Tuapse,…	Sochi 0.245	2 5
22–23 July 2021	Caucasus	36–145	—	—	Not yet	—	—	Dagomys, Sochi, Matsesta, Khosta, Kudepsta, and Kherota	—	4

* Peak discharge and unit peak discharge probably are overestimated

**Precipitation and water discharge probably are underestimated.

Fig.9. The most frequent triggers of flash floods in the north of the Black Sea Coast.

4.1. Analysis of stochastic factors influencing flash floods in the north of the Black Sea Coast

Analysis of the seasonal distribution of flash floods in 1990–2021 demonstrates that the events occur in the summer–autumn period with the maximum occurrence in August (Fig. 10). The distribution coincides with the common tendency for rivers in the Northern Hemisphere (Kuksina et al., 2017) and occurrence of the most catastrophic inundations in the North Caucasus (Alekseevskii et al., 2016). Seasonal distribution of flash floods doesn’t correspond to the distribution of precipitation within the year while reflects the features of extreme precipitation in warm period of the year in the studied region (Alekseevskii et al., 2016).

Fig. 10.Seasonal distribution of flash floods in river basins in the north of the Black Sea Coast in 1990–2021.

The precipitation amount during flash floods varies between 65.6 (Khosta, August 17, 2019) and 429 mm (Gelendzhik, July 6-7, 2012). In most cases the precipitation amount corresponds to very low frequency (recurrence is less than once in 100 years), except the event in the Tsanyk River basin in September, 2018, when relatively small precipitation caused significant rapid water level rise due to high antecedent soil moisture (Tsyplenkov et al., 2021). The possibility of such situations also is mentioned by other authors (Archer & Fowler, 2015; Tripoli et al., 2005). It should be noted precipitation data are given for meteorological stations which often are situated in downstream locations. Probably these data don’t represent objective data for the spatial distribution of precipitation in the river basin and in upstream areas (zones of flash flood origin) due to spatial irregularity of precipitation especially in mountains and foothills (Sungmin & Ulrich, 2019). Blockage of cyclones in the European part of Russia is the main reason of extreme precipitation and flash floods. This blockage provokes intensification of cyclonic activity in the periphery due to the changes of atmospheric circulation in the Northern

Hemisphere (Kononova, 2012). For instance, record rainfall was measured in the region on August 13–16, 2021 (https://vk.com/wall-42886009_1149515). Precipitation exceeded or was close to historical maximum on June 17–18, 2021 in some regions of the Crimean Peninsula due to anonmobile cyclone in the east of the Black Sea (when four monthly rations fell at Ai-Petri, and 133 mm fell at Yalta (with the historical maximum of 135 mm)). Heavy rainfall at Kerch was measured twice in the summer of 2021, and precipitation on August 12–13 (87 mm) exceeded rainfall on June 17–18 (82 mm) but the damage was significantly lower due to the channel clearance.

The frequency of “flash flood forming” precipitation was estimated by statistical analysis of the daily data from the meteorological stations in the river basins in the Western Caucasus and Crimea (see Table 3) for the period since 1990. Because extreme precipitation is observed more often than flash floods in the studied area, 44 cases of extreme precipitation (see Table 3) were observed at Tuapse between 1991 and 2020 while 3 flash floods were observed in the Tuapse River. For example, there were 33 cases of heavy rainfall in Kerchbasin between 1991 and 2020 and there weren’t any flash floods in the Melek-Chesme River basin during the same period. These results demonstrate the low level of knowledge about flash floods in the study area. As an example, very heavy rainfall was registered at Kerch on September 16, 2002 (it exceeded precipitation on June17–18, 2021), while a resulting flash flood wasn’t mentioned in any databases and scientific papers. One more example is the flash flood on the 25th of June, 2015, in Kerch which was only mentioned in local mass media news. The same situation can characterize the Tuapse River basin where heavy rainfall of 118 mm (probability is 0.1%) was registered on the 8th of July, 2014, but the event was only described in local news and social networks. A greater number of extreme precipitation events in comparison with described flash floods can also suggest significant spatial inhomogeneity of rainfall when precipitation at a meteorological station (typically situated in the downstream area of the river basin) doesn’t prove the precipitation of similar intensity occurred in other parts of the river basin. The precipitation features analysis indicate the necessity of a denser hydrometeorological observation network in the studied region to estimate intensity and spatial inhomogeneity of rainfall in small river basins and foreshadow rapid water level rise connected with it.

Table 3.Frequency of extreme precipitation in the north of the Black Sea Coast.

Meteorological station	Observation period	Number of cases with daily precipitation periodicity 1 time in 100 years		
		Total	1961–1990	1991–2020
Tuapse	1936–2020	100	34	44
Sochi	1874–2020	195	32	36
Krasnaya Polyana	1936–2020	146	56	48
Kerch	1936–2020	83	26	33
Yalta	1961–1990	25	25	—
Ai-Petri	1961–2019	85	45	40
Simferopol	1886–2020	145	43	34

Some features of precipitation were revealed on the basis of the analysis of the longest station data ranges. The EPI index (mean annual extreme precipitation intensity) has increased in Feodosiya and the CWD (number of consecutive days with precipitation greater than 1 mm) and the CDD (duration of dry periods) indexes vary at Ai-Petri in 1961–2019 in Crimea (Kuksina et al., 2021). Positive trends were revealed for stations in the Caucasus Black Sea Coast – maximum precipitation amount for 5 days (r5d) in Anapa and for 1 day (r1d) in Tuapse during 1961–2020. However, stable trends haven’t been found in extreme precipitation in the North Caucasus and the Crimean Peninsula in total (Aleshina et al., 2018; Vyshkareva, 2021; Zolina et al., 2009).

Flash flood formation depends on antecedent soil moisture through soil type. In all cases rainfall of small intensity preceded extreme precipitation in wet climates (the Tuapse, and

Uchan-Su rivers, see Fig. 11(a) and 11(b)), and rainfall was absent in moderate climates (the Afagum River, see Fig. 11(c)) and dry subtropics (the Melek-Chesme River, see Fig. 11(d)).

Fig. 11.Precipitation 3, 5, 10, 15, and 30 d before the flash flood (a) in the Tuapse River – Tuapse gauge on October 28, 2018, (b) the Uchan-Su River–Yalta gauge on June 17, 2021, (c) the Adagum River–Novorossiisk gauge on July 6, 2012, and (d) the Melek-Chesme River – Kerch on June 25, 2015. 1–precipitation 3, 5, 10, 15, and 30 d before flash flood, 2 – precipitation initiating the flash flood.

Maximum precipitation intensity varies within relatively small limits in comparison with river basins in Europe. The most severe events (the Adagum River (No. 12 in Fig. 2) in 2012, the Tuapse River (No. 15 in Fig. 2) in 1991, 2010, and 2018) were characterized by lower maximum rainfall intensity, while the amount of precipitation corresponds to probability less than 1% (recurrence is less than once in 100 years).

Past events are characterized by very rapid water level rise of about 1.2–1.3 m/h, and the maximum intensity of water level rise was 1.7 m for 10 min (the Zapadny Dagomys River (No. 18 in Fig. 2), on October 24–25, 2018) (Korshenko et al., 2020). Water level rose only during 5–6 h (Panov et al., 2012), and in some cases during 20–40 min (Klukin, 2005; Korshenko et al., 2020). Water level rose in 3–5 h during the most severe flash floods (Alexeevsky et al., 2012; Panov et al., 2012), and the maximum water level rise reached 7 m in the Adagum River basin (Georgievsky & Tkachenko, 2012).

There is a lack of data about sediment yield during flash floods. Information for the Khosta, Mezyb, and Tsanyk rivers demonstrates the sediment yield during one flash flood is comparable with the mean annual sediment yield (Fig. 12) (Arkhipkin et al., 2013; Jaoshvili, 2002;

Korshenko et al., 2020; Tsyplenkov et al., 2021), and the data corresponds to the estimations for other regions in the world (Cohen & Laronne, 2005; Cohen et al., 2010).

River channel and valley transformations can be indirect sign of significant sediment yield during flash floods. Flash floods have caused catastrophic relief changes due to erosion, landslides, and other exogenous processes in most cases on the Black Sea Coast. Flash floods originate in rivers' upstream areas (Kuksina et al., 2017) under the influence of natural factors without significant anthropogenic activity impact. However, the most severe flash flood consequences usually are observed in foothills and lowlands, which are characterized by human activity. Anthropogenic impacts can lead to significant flash flood development (through the high runoff rate increase for asphalt-paved territories, artificial runoff concentration, and increasesin erosion downstream (Shvarev et al., 2020)). The territory of the Caucasus Black Sea Coast and mountains of Crimea are no exception.

Fig. 12.Mean annual suspended sediment yield (SSY) (1) and SSY during the flash flood in 2010 (2) in the Vulan River (No. 14 in Fig.2).

Human activity can impact flash flood formation and development directly and indirectly. The most significant influence results from deforestation, fires, destruction of vegetation, tillage, hydrotechnical construction, and urbanization. Emergency water evacuation often occurs during extreme rainfall events and rapid water level rise to avoid reservoir overflow and possible dam failure. Such evacuations lead to catastrophic floods downstream. The examples of such flash floods are the Demerdzhi River (No. 1 in Fig. 2) in 1997, and August 19, 2017 (Klukin, 2005; Kuksina et al., 2021). A similar situation was observed in Kerch in June 2021 when ponds were eroded in the Melek-Chesme River (No. 2 in Fig. 2) and emergency water evacuation from the ponds was done in Bakhchisaray region. Uncontrolled building in river valleys and obstruction of river channels also lead to significant socio-economical damage (Alekseevskii et al., 2016; Alexeevsky et al., 2016; Kononova, 2012).

4.2. Analysis of relatively stable factors affecting flash floods in the north of the Black Sea Coast

The most important relatively stable factors affecting flash flood formation are catchment area, river length and slope steepness which influence the flow concentration rate; basin elevation which affects precipitation distribution; bedrock presence which affects sediment yield; and soil and vegetation which regulate surface runoff. The main morphometric parameters of river basins experiencing flash floods are listed in Table 4.

Topographic relief influence flash flood formation resulting from precipitation collecting in the river basin and rapid flow concentration is promoted by morphometric parameters of the basin. Mean basin elevation and elevation amplitude determine precipitation variation with elevation. Severe mountain topography leads to precipitation retention and as a consequence increases the mean annual water discharges (Fig. 13(a)) and precipitation (Fig. 13(b)) with the increase in basin elevation.

Fig. 13.Variability of (a) water discharge and (b) mean annual precipitation with the increase in river basin elevation.

Table 4. The main morphometric parameters of river basins with flash floods (note: LS is the product of the slope length factor and slope gradient factor of the Universal Soil Loss Equation, T_L is the basin lag time).

River	Name	Area, km²	River length, km	Minimum elevation, m	Maximum elevation, m	Range, m	Mean elevation, m	Mean slope, %	Mean slope of stream network, %	LS_mean	T_L, h
Voron	Voron	10	8	207	851	645	467	28.7	14	5.62	0.29
Demerdzhi	Alushta	53	13	14	1355	1341	476	21.3	13	3.96	0.71
Melek-Chesme	Kerch’	84	16	5	186	181	87	3.5	2	0.72	0.92
Bel’bek	Kuibyshevo	270	28	139	1420	1281	574	21.3	12	4.19	1.74
Uchan-Su	Yalta	17	4	143	1365	1223	920	26.8	20	4.86	0.38
Derekoika	Yalta	50	9	14	1512	1498	747	34.4	25	6.40	0.69
Kokkozka	Aromat	84	18	217	1362	1145	789	26.8	16	5.14	0.91
Ulu-Uzen’	Solnechnogorskoe	33	11	20	1277	1257	582	28.7	18	5.42	0.54
Baga	Bakhchisaray region	21		287	839	551	580	19.4	11	3.81	0.43
Durso	Abrau-Durso	54	14	4	529	524	191	21.3	9	4.28	0.72
Tsemes	Novorossisk	83	14	5	520	515	156	14.1	6	8.76	0.91
Ashamba	Golubaya Gukhta	44.6	15	5	758	754	233	19.4	9	6.14	0.65
Vulan	Arkhipovo-Osipovka	265	27	6	739	734	225	24.9	9	4.19	1.72
Nechepsukh	Novomikhailovsky	225	26	−1	890	891	271	28.7	10	5.57	1.57

o											
Tuapse	Tuapse	351	29	24	1399	1375	384	26.8	14	7.61	1.89
Kuapse	MamedovaShel’	14	6	39	908	869	381	38.4	20	8.56	0.34
Psezuapse	Tkhagapsh	238.0	24	127	1831	1704	801	40.4	23	11.27	1.62
Zapadny Dagomys	Dagomys	47	38	5	916	911	393	34.4	15	12.24	0.67
Khosta	Khosta	99	18	12	1100	1088	421	26.8	15	10.70	1.00
Kudepsta	Kudepsta	86	21	3	1065	1066	362	24.9	12	7.61	0.93
Adagum	Krymsk	328	39	24	632	609	224	15.8	7	7.92	1.94

Slope length and steepness are the most important topographic relief characteristic influencing flash flood formation, resulting in rapid flow concentration and minimum lag time (Gaume et al., 2009), and slopes can have moderate steepness for flash flood formation (Marchi et al., 2010). The LS factor, or relief erosive potential (Wischmeier et al., 1958), can describe total effect of slope and steepness. The product of the slope length factor and the slope gradient factor (LS) of the Universal Soil Loss Equation reaches its maximum in small river basins, and it varies between 3.8 and 6.4 in Crimea (the plain Melek-Chesme River basin is an exception with LS0.7) and changes in larger limits in the Western Caucasus, i.e. 4.2–12.2.

Smaller basin areas (≤ 350 km^2) characterize rivers impacted by flash floods in the north of the Black Sea Coast in comparison with river basins in Europe, and this fact indicates more rapid flow concentration in river channels of the study area. According to Eq. (1) (Marchi et al., 2010), the lag time doesn't exceed 2 h and in most cases doesn't exceed 1 h (only 29% of the lag timesare more than 1 h) in river basins of the Western Caucasus, while the lag time exceeds 2 h in many cases in Europe (Marchi et al., 2010). About 70% (15 river basins) have area less than 100 km^2 among the 21 river basins with flash flood cases (Table 2). Theminimum lag time is only 17 min in the Voron River basin. Shorter rainfall durations (4–6 h) in comparison with European river basins also confirm more rapid flow concentration. Thereby it can be suggested flash floods form and develop in a very short time in the north of the Black Sea Coast, and their forecast is a very complicated task due to the basin parameters.

Average basin slope varies in small limits, and it reaches its minimum in the western direction (see Table 4). Elevation amplitude and average basin elevation reach large values, and in addition to small catchment areas and river length causes very rapid flow concentration. Significant elevation difference in one river basin indirectly indicates vast spatial inhomogeneity of precipitation.

Easily erodible slates and limestone, and occasional sandstone and clay rock are the prevalent bedrock in studied river basins. Soils are not very diverse in the river basins experiencing flash floods. The most widely spread are brown forest and sod-podzol soils with high water permeability and low moisture content.

Antecedent soil moisture has to be considered due to climate conditions (shorter and less intense precipitation preceded flash floods in almost all cases except the Melek-Chaesme and Adagumrivers).

Forest-covered land varies from 34% (in the Tsemes, Horota River basin, no. 9 in Fig. 2) to 96% (in the Khosta, Makopse River basin, no. 20 in Fig. 2), and in most cases the value exceeds 70% in the studied river basins. However, this factor has secondary meaning in comparison with other factors during severe flash flood formation in the Black Sea Coast.

A lot of human settlements in downstream and middle course locations demonstrate the high level of urbanization in lower parts of the river valleys which are the most vulnerable to flash flood influence. Population density can exceed 2,000 people per 1 km^2 (Novorossisk).

Most rivers of the Caucasus Black Sea Coast are not regulated (except for Durso Lake) while Crimean rivers are characterized by varied regulation by ponds and reservoirs and channeling. This regulation often can intensify flash flood consequences (as examples flash floods in Krymsk in 2012, in Alushta in 1997, and 2017, in Yalta in 2021, in the Bakhchisaray region in 2021, and in Kerch in 2021).

The Melek-Chesme River (No. 2 in Fig. 2) is an exception from the range of river basins for relatively stable geomorphologic factors. Its basin has no significant slopes and mean basin elevation is the lowest one. But rare precipitation falling in the small river basin, absence of vegetation (minimum forest-covered land among river basins of 2%), and soils with low water permeability promote rapid surface runoff concentration. Erosion of ponds in upstream areas was a factor in flash flood intensification.

4.3. Comparison with flash floods in Europe

The main factors for flash flood formation and their variability were analyzed on the basis of information in Table 4 with stochastic and relatively stable parameters for river basins in the north of the Black Sea Coast. Those characteristics were compared with the features of flash floods in Europe. In European countries (Italy, Spain, Greece, Austria, France, Romania, and Slovakia) flash floods are characterized by a greater range in parameters (see Table 5). According to Gaume et al. (2009), basin area is limited to 1,000 km^2, and rainfall duration has not exceeded 34 h, but sometimes it's possible to accept some exceptions (Marchi et al., 2010). All events in the north of the Black Sea Coast fit in the range of flash floods in Europe and don't exceed the boundary values of the parameter ranges.

Table 5.Flash floods characteristics in Europe and in the north of the Black Sea Coast.

Characteristic	Europe	Western Caucasus	Crimean Peninsula
Watershed area, km^2	0.26–3,701	14.0–351	10.3–270
Average basin slope, %	0.5–68.3	15–42	4–36
Average elevation, m	70–1,966	156–801	90–730
Elevation amplitude, m	50–2,998	520–1,704	181–1,498
Peak discharge, m^3/s, probable	1.7–4,000	200–2,300	6–146
Unit peak discharge, $m^3/s/km^2$, probable	0.33–40.7	2.34–35	0.6–8.1
Average annual precipitation, mm	419–2,024	623– 1,718	448–1,013
Total rainfall duration, h	1–72	4–6	
Maximum total accumulated point rainfall, mm	2–547	65.6–429	80.2–167
Maximum intensity over time of concentration, mm/h	7.56–600	24.7–75	50–60

Comparison of the flash floods events was implemented on the basis of

$$Q_{\mathrm{U}} = f(A) \qquad 2)$$

where Q_{U} is unit peak discharge, $m^3/s/km^2$, A is basin area, km^2, for flash floods in the north of the Black Sea Coast and described at http://www.hydrate.tesaf.unipd.it and situated in similar climatic conditions. Table 5 and Fig. 14 demonstrate correspondence of the European and Black Sea Coast events.

Fig. 14. Unit peak discharge and watershed area ratio for river basins in Europe (data from the http://www.hydrate.tesaf.unipd.it) and in the north of the Black Sea Coast.

Runoff coefficients during flash floods in the northern Black Sea Coast vary between 0.40 and 0.95 (mean value is 0.70), and exceed values for the European river basins by two times (Marchi et al., 2010). Such values of runoff coefficients indicate the specificity of flash floods in the Black Sea region. The majority of precipitation becomes surface runoff during intense rainfall due to the features of the underlying watershed surface.

4.4. Prospects in the flash flood study in the north of the Black Sea Coast

Flash floods are one of most dangerous natural hazard events due to socio-economical consequences (Kuksina & Golosov 2020). Flash floods are the reason for deaths (in all cases in the Tuapse River basin (No. 15 in Fig. 2)). The maximum number of victims was in 2012 in the Adagum River (No. 12. In Fig. 2) when 153 persons were dead and three people were missing. Probably, such a high number of victims was connected with the rapid water level rise (less than 3 h) and flash flood peak overnight. Five dead persons were registered during the most recent severe flash floods in the north of the Black Sea Coast in the summer of 2021. Flash floods also are a reason for significant economic damage. Economic losses were estimated as more than 600 million of dollars (Georgievsky & Tkachenko, 2012). The approximate damage was estimated in 65 million of dollars in Crimea in the summer of 2021 (https://iz.ru/1180696/2021-06-18/odin-chelovek-pogib-v-rezultate-podtoplenii-v-ialte; https://iz.ru/1200673/2021-07-30/ushcherb-ot-podtoplenii-v-krymu-otcenili-v-46-mlrd-rublei).

Analysis of flash floods in the north of the Black Sea Coast demonstrates the necessity of certain flash flood formation factors and especially their interactions, which lead to the most severe consequences in some cases. There are no reliable flash flood forecasts due to the absence of data about rainfall intensity and its spatio-temporal variability within the river basins in the northern Black Sea Coast.

Reliable precipitation forecasts are the key task in flash flood forecasting with the current description of conditions in a potential hazard prone river basin. Unfortunately, precipitation analysis is very complicated due to the spatial and temporal variability of precipitation in mountain areas. Asolution could be connected with application of radar data (Borga et al., 2014) and improvement of satellite data analysis. More hydrological stations will provide better description of the current events, and enhance quality forecast subsequent. The Black Sea Coast territory is characterized by a divided network of water level loggers (www.emercit.com) but there is no unified algorithm of data proceeding and for detection of measurement errors.

The definition of watershed lag time is based on estimation of the distance between the flow formation center and the point of concentration in the river basin, and flow velocity depending on hydraulic conditions such as river slope and channel geometry and roughness.

The urgent task is still clear definition of flash floods and division of flash floods from other events (e.g., debris flows) due to their interconnections (Alexeevsky et al., 2012). Analysis of achieve data (http://floodobservatory.colorado.edu;http://www.hydrate.tesaf.unipd.it; Hooke & Mant, 2000; Llasat et al., 2010) demonstrated the absence of many events in databases because they weren't considered as flash floods. Clear factors and their quantitative assessment are necessary for each extreme erosive event.

The estimation of anthropogenic impact threshold value leading to rapid increases in flash flood formation probability must be improved. It should be noted most flash floods have occurred in river basins with developed human activity, and as a result economic losses have reached significant values.

At the current stage of the research it is supposed that the most adverse consequences of flash floods are connected with anthropogenic impact more than natural factors. Analysis of precipitation frequency in the region allows us to conclude intensive rainfall is regularly observed in the north of the Black Sea Coast. But there is less data about flash floods. Probably the data couldn't be obtained because of the following reasons: 1) flash floods didn't greatly affect the area in the past due to lower infrastructure development; 2) less data availability could make many events hidden to the public; and 3) rainfall of high intensity doesn't always form flash flood. Flash floods are natural events in the north of the Black Sea Coast, and the determination of issues connected with their occurrence could be based on: 1) detailed study of flash flood formation and development with the aim of future forecasting, including modeling of previous events; 2) careful planning of human activity in the region due to analysis of flash floods and their consequences (e.g., asphaltic surface and absence of drainage systems result in very rapid flow concentration); 3) preventive actions in zones of flash flood formation (upstream areas), i.e., obstruction clearing in the channel, and protection of dams stopped in early 1990 (Alexeevsky et al., 2016), construction of drainage systems; 4) development of a hydrometeorological stations network will allow advancement in the quality and quantity of flash flood forecasts; and 5) development of a warning system and public education will allow reduction or avoidance of injured and dead persons.

5. Conclusions

The main groups of dynamic and relatively stable factors of flash flood formation were divided on the basis of event analysis in the north of the Black Sea Coast. These groups include hydrological, meteorological, morphometric, lithological, geomorphological, and anthropogenic factors. As a rule intense rainfall is the "motive force" of flash flood origin. However, flash flood origin and especially the most catastrophic consequences appear during combinations of several factors such as if previous conditions in the basin reached some "critical point" with enough collected deposits ready for movement by runoff. Even relatively slight precipitation (amount and intensity) can cause flash floods in such case. Anthropogenic factors can very seldom initiate flash floods, but they can significantly intensify the severity and lead to socio-economic losses.

Statistical analysis of precipitation over long data ranges allows the suggestion that flash floods are formed more frequently than they are observed and described in the north of the Black Sea Coast. Data from meteorological gauges don't reflect the precipitation distribution in the whole river basin due to significant spatial inhomogeneity of rainfall especially in mountain regions.

In the XXIst century significant increasing trends in mean annual intensity of extreme precipitation have been observed for some river basins in the Crimean Peninsula due to processing of Integrated Multi-satellite Retrievals for Global precipitation measurements (IMEGR) satellite data (https://gpm.nasa.gov/data/imerg). Decreasing indexes (r1d and r5d) are observed in the river basins in the Caucasus Black Sea Coast. According to the land network data maximum precipitation amount has increased at the Anapa (r5d) and Tuapse (r1d) stations in 1961–2020 time period.

River basins experiencing flash floods have smaller watershed areas in the north of the Black Sea Coast in comparison with river catchments in Europe, and indicate more rapid flow concentration in the river network, and, as a consequence, less advance flash flood forecast time.

The main reason for increasing socio-economic damage is uncontrolled human activity in flooded areas, absence or reduction of channel protection, and lack of preventative protective measures in upstream areas where the majority of the flash floods originate.

The study of flash flood forming factors and their combinations is the key objective in flash flood investigation. Implementation of this task is possible on the basis of observations in representative small basins in various orographic and climate zones.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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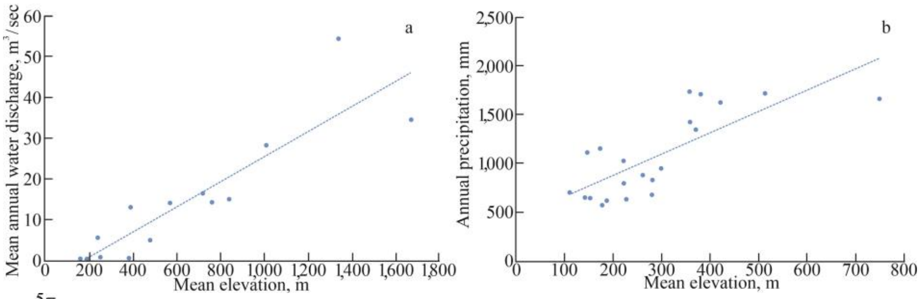
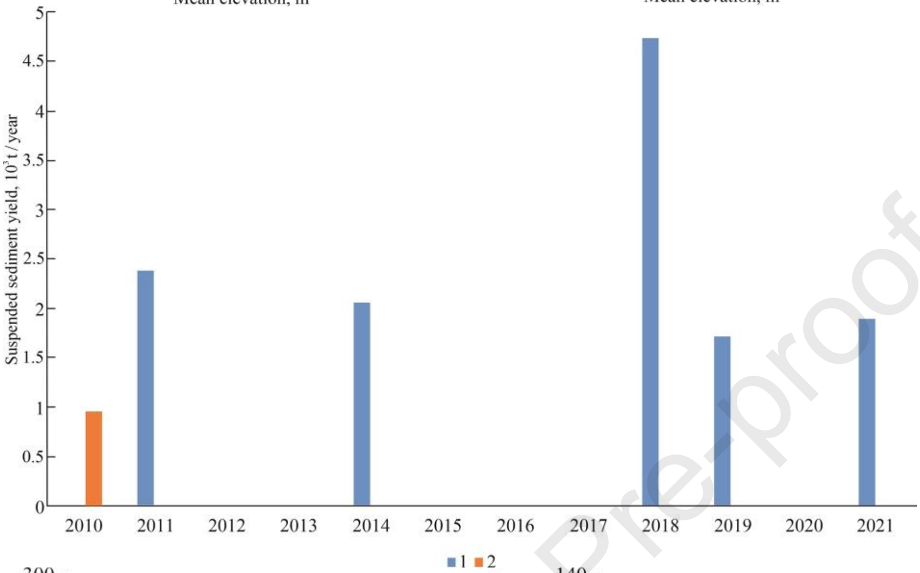
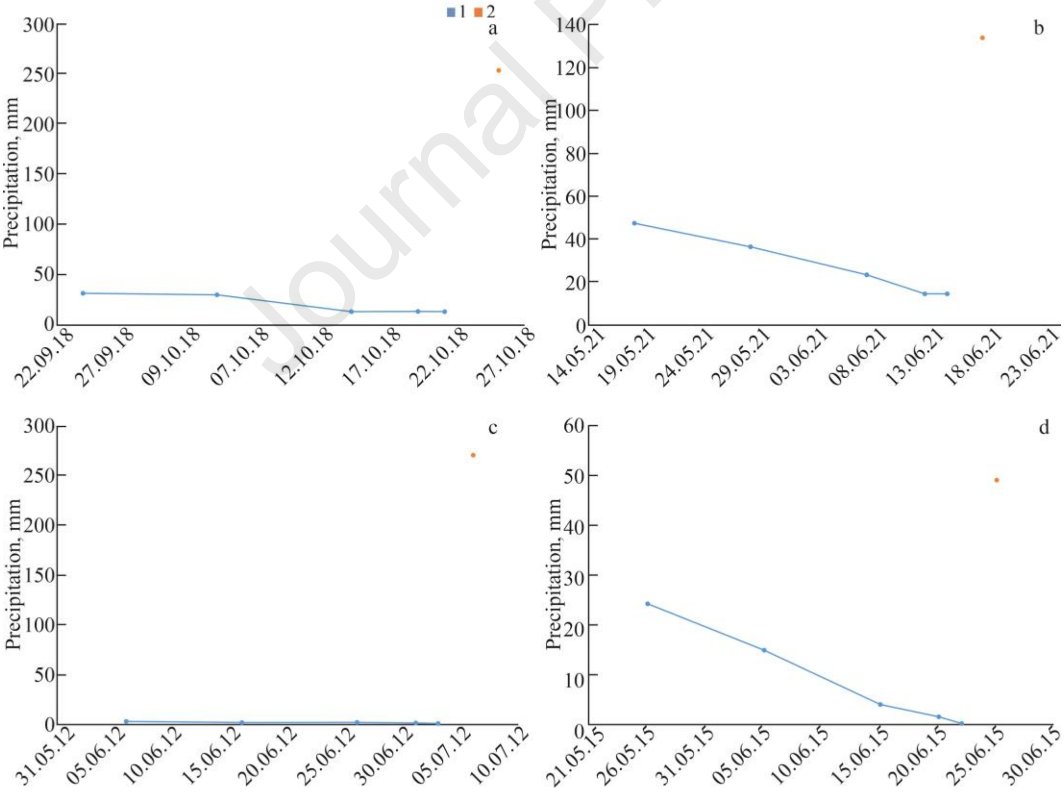
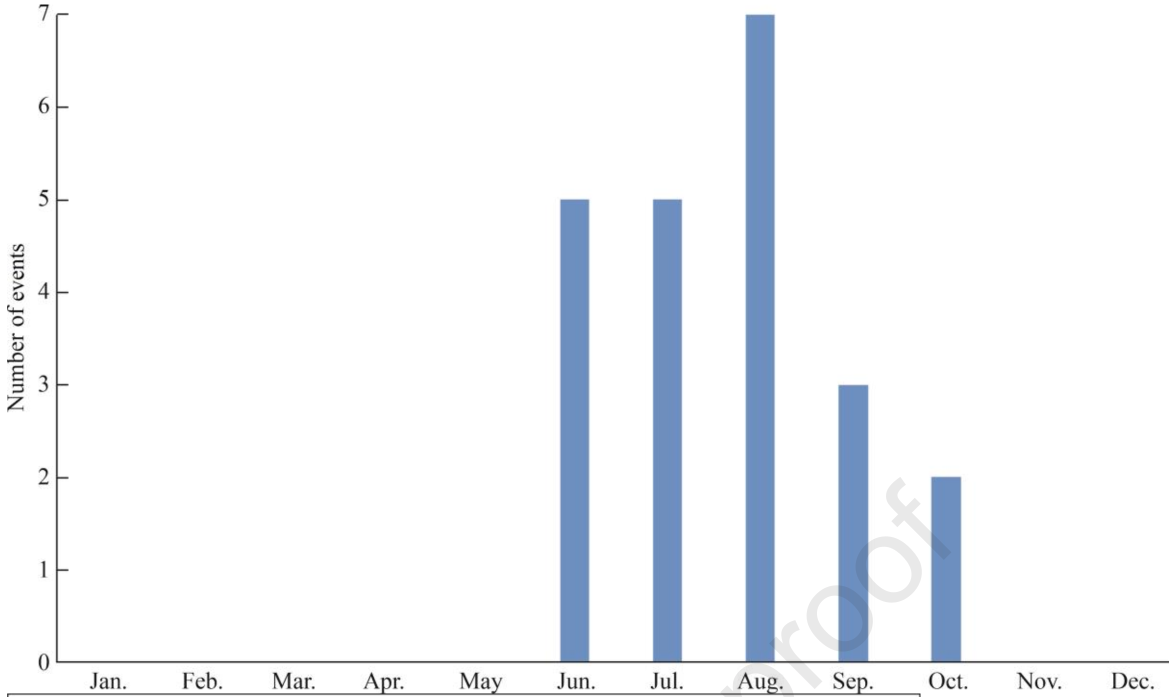
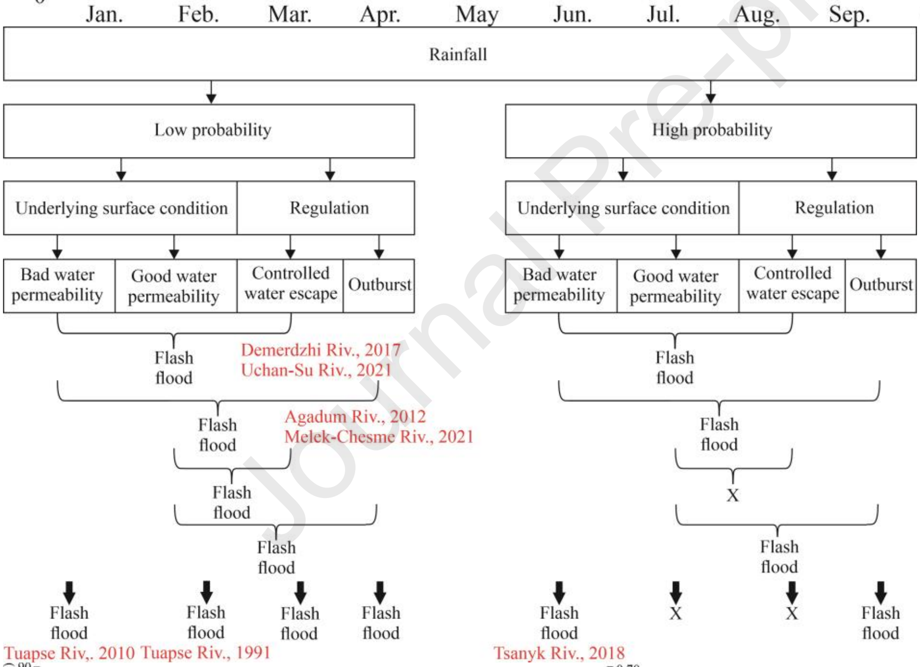
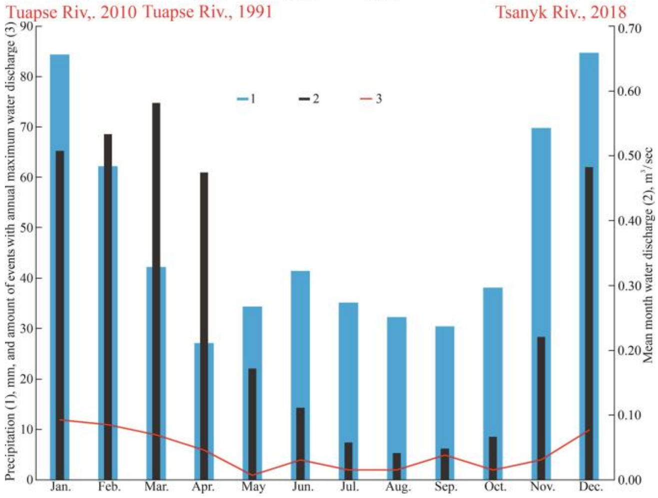

a
b
Mean annual water discharge, m³/sec
Annual precipitation, mm
Mean elevation, m
Mean elevation, m

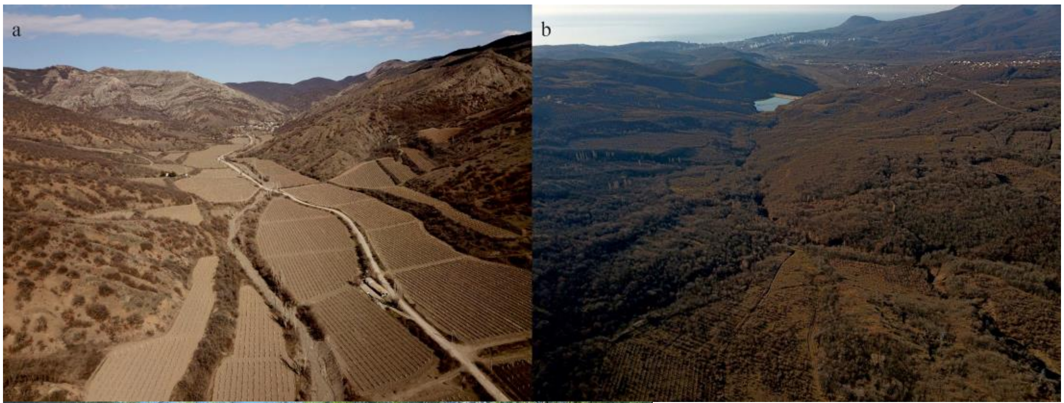

Suspended sediment yield, 10³ t / year
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
1
2

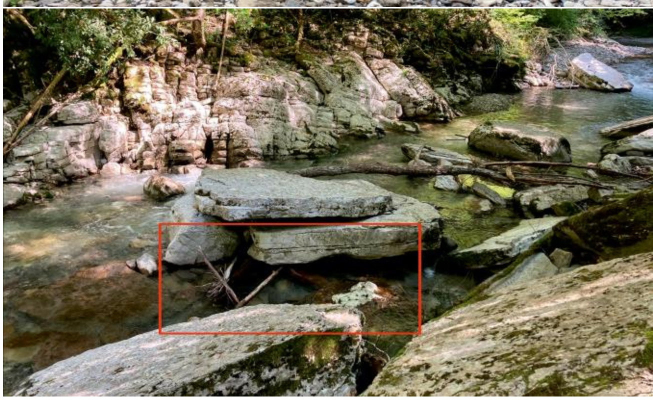

a
b
c
d
Precipitation, mm
Precipitation, mm
Precipitation, mm
Precipitation, mm

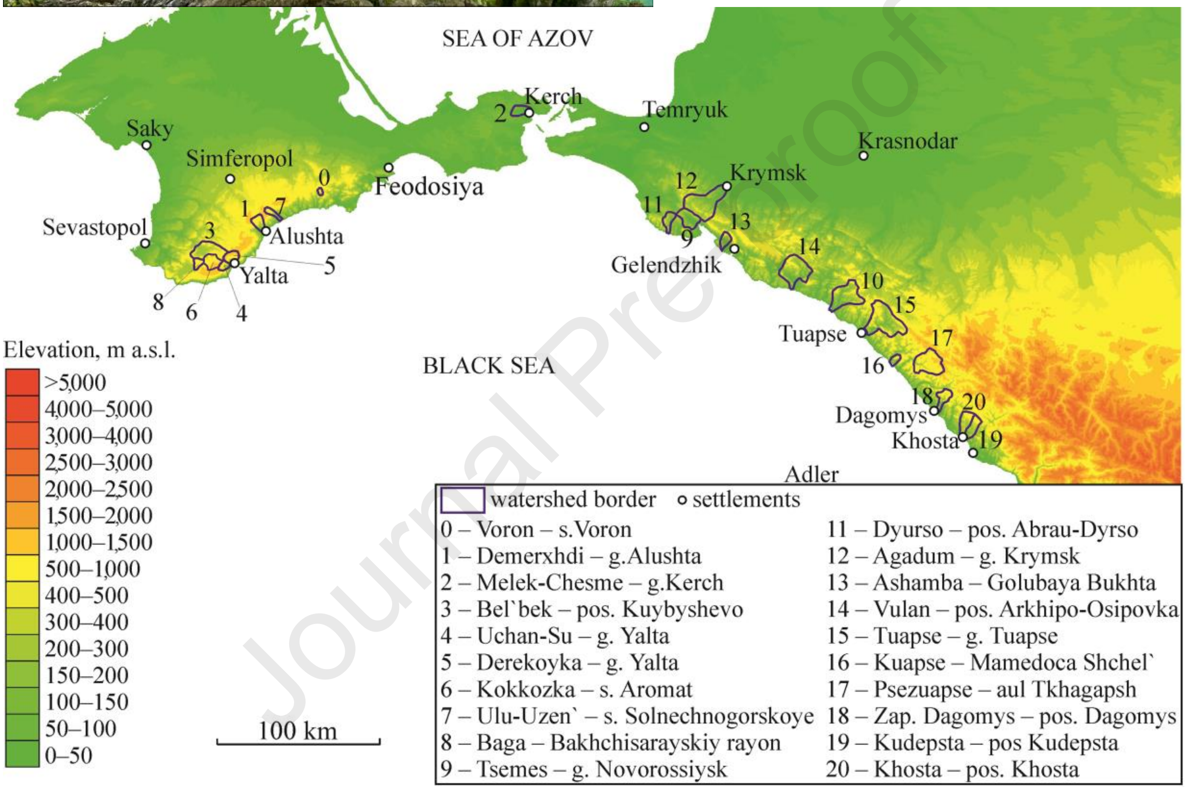

Number of events
0
1
2
3
4
5
6
7
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.

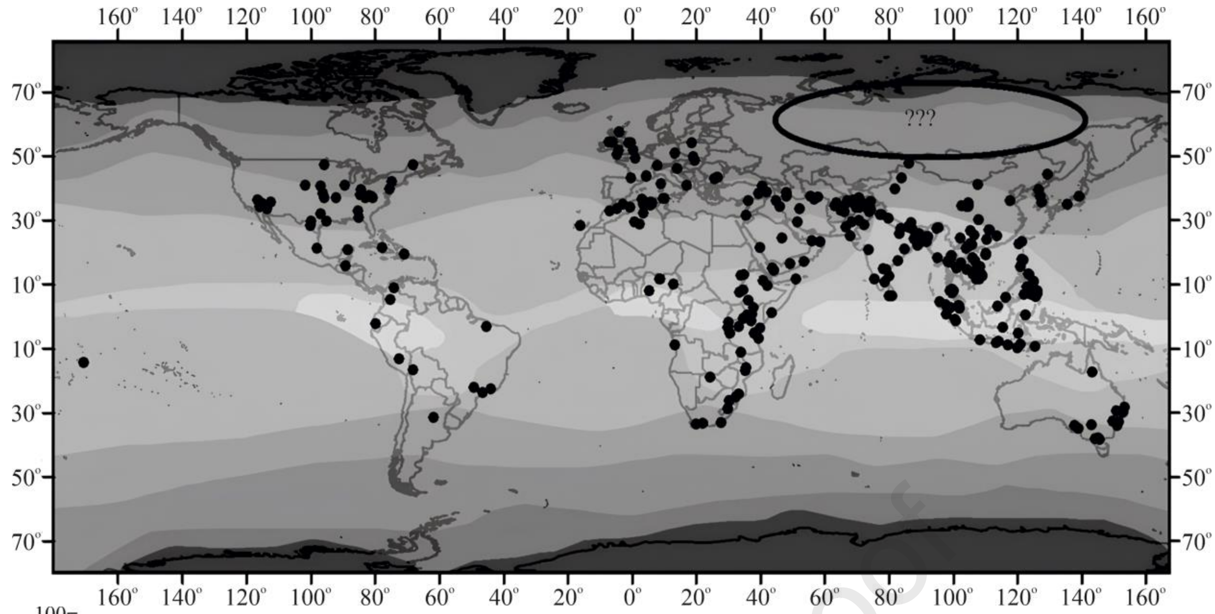

Rainfall
Low probability
High probability
Underlying surface condition
Regulation
Bad water permeability
Good water permeability
Controlled water escape
Outburst
Flash flood
Demerdzhi Riv., 2017
Uchan-Su Riv., 2021
Agadum Riv., 2012
Melek-Chesme Riv., 2021
X
Tuapse Riv,. 2010
Tuapse Riv., 1991
Tsanyk Riv., 2018


Precipitation (1), mm, and amount of events with annual maximum water discharge (3)
Mean month water discharge (2), m³/sec
1
2
3
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.


a
b




SEA OF AZOV
Kerch
Temryuk
Krasnodar
Saky
Simferopol
Feodosiya
Sevastopol
Alushta
Yalta
Krymsk
Gelendzhik
Tuapse
Dagomys
Khosta
Adler
BLACK SEA
Elevation, m a.s.l.
>5,000
4,000–5,000
3,000–4,000
2,500–3,000
2,000–2,500
1,500–2,000
1,000–1,500
500–1,000
400–500
300–400
200–300
150–200
100–150
50–100
0–50
100 km
watershed border
settlements
0 – Voron – s.Voron
1 – Demerxhdi – g.Alushta
2 – Melek-Chesme – g.Kerch
3 – Bel`bek – pos. Kuybyshevo
4 – Uchan-Su – g. Yalta
5 – Derekoyka – g. Yalta
6 – Kokkozka – s. Aromat
7 – Ulu-Uzen` – s. Solnechnogorskoye
8 – Baga – Bakhchisarayskiy rayon
9 – Tsemes – g. Novorossiysk
11 – Dyurso – pos. Abrau-Dyrso
12 – Agadum – g. Krymsk
13 – Ashamba – Golubaya Bukhta
14 – Vulan – pos. Arkhipo-Osipovka
15 – Tuapse – g. Tuapse
16 – Kuapse – Mamedoca Shchel`
17 – Psezuapse – aul Tkhagapsh
18 – Zap. Dagomys – pos. Dagomys
19 – Kudepsta – pos Kudepsta
20 – Khosta – pos. Khosta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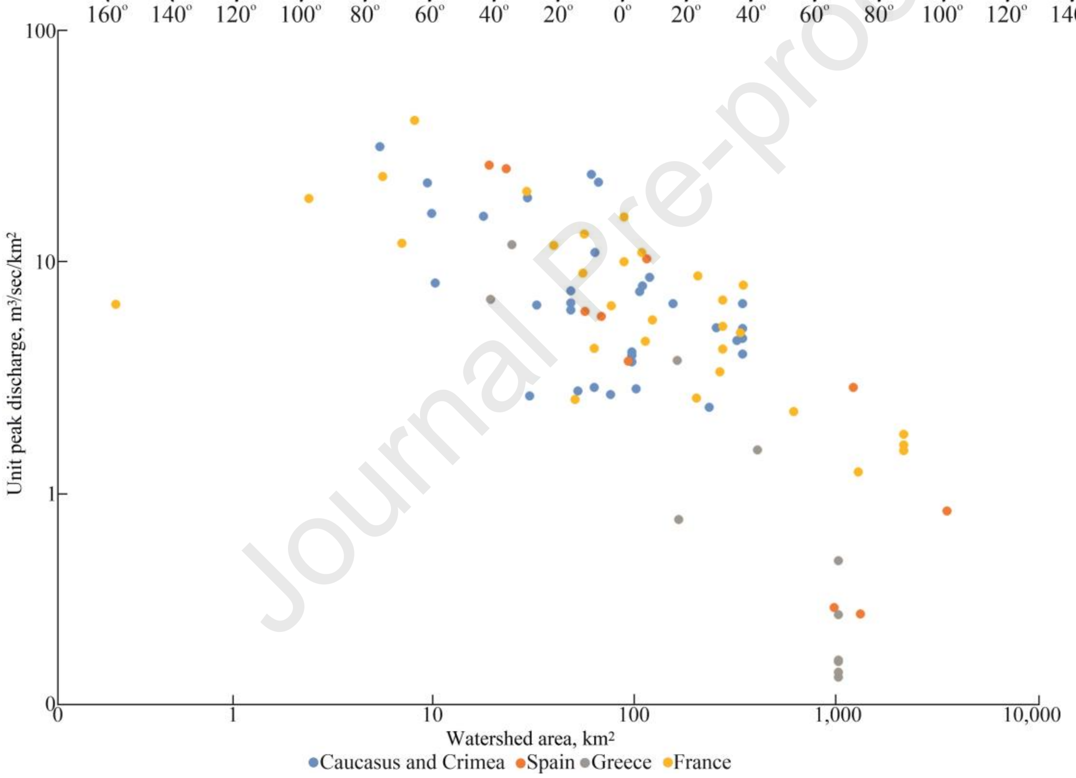
Unit peak discharge, m³/sec/km²
Watershed area, km²
Caucasus and Crimea
Spain
Greece
France