Spatial-temporal trends analysis of flood events in the Republic of Armenia in the context of climate change
Hrachuhi Galstyan, Shamshad Khan, Hovik Sayadyan, Artur Sargsyan and Tatevik Safaryan

ABSTRACT
The primary goal of the study is to analyze the spatial-temporal trends and distribution of flood events in the context of climate change in Armenia. For that purpose, some meteorological parameters, physical-geographical factors and the flood events data were studied for the 1994–2019 period. The linear trends demonstrate an increasing tendency of air temperature and precipitation. Those trends expressed increased flood occurrences, especially for the 2000s, whereas the Mann–Kendall (MK) trend test reveals no significant change. The number of flood events reaches its maximum in 2011 with its peak in May. Out of 191 flood events, half of the occurrences are recorded in the flat areas and southern aspects of the mountains (22% of the country's territory). There is a certain clustering of flood events in the areas with up to 5° slopes (66% of flood events). The most flood vulnerable areas were analyzed and mapped via Geographical Information System (GIS). The GIS-based mapping shows the location of flood vulnerable areas in the central, northern parts of the country, and the coastal areas of Lake Sevan. Our methodological approach elaborates the localization of flood-prone sites. It can be used for the flood hazard assessment mapping and risk management.

Key words | climate change, flood vulnerable areas, GIS, Republic of Armenia (RA), slopes and aspects, spatial-temporal distribution of floods

HIGHLIGHTS
- The negative impact of global climate change is studied rather comprehensively in the Republic of Armenia (RA).
- The damage caused by floods calls for immediate attention due to its increasing trend in the RA.
- The used approach successfully determined the high-risk flood zones. This implies that this methodology can be scaled-up for flood analysis or flood mapping in similar mountainous regions.

INTRODUCTION
Natural hazards are physical events that can cause significant damage to the natural and human environment. Endogenic or exogenic processes such as active tectonics and climate changes are capable of changing landforms and triggering natural hazards, which in some cases, control human activities (Bathrellos et al. 2018). One issue worth considering is the fact that climate change is likely to alter the frequency and severity of extreme events. Changes in extreme events could cause more significant consequences in terms of short-term impacts on the ecosystems and
human livelihoods than changes do in average values (Vastila et al. 2010). Flooding is considered one of the extreme events and it occurs frequently in some parts of the world. A great percentage of the global population lives in the floodplain. This clarifies why millions of people are affected by floods (Kaya et al. 2017). Especially in urban or rural areas, floods are considered among the most dangerous natural hazards due to their increasing recurrence. Their consequences are not only environmental but social and economic as well since they may damage urban areas, agricultural lands and even result in fatal accidents (Merz et al. 2010).

During the last decades, flood events have increased the mortality rate and caused damage all over the world (Transboundary Floods 2005). Among different kinds of floods, the ones formed in the river basins are very common. They are extremely dangerous, particularly for mountainous regions, because most of the river basins are located in residential areas. The Republic of Armenia (RA) is known for its frequent flood cases that result in material loss, destructions, mud runoffs, landslides and unfortunately, death (Vardanyan 2005, 2009). The number of various natural hazard types that occur on the territory of the RA exceeds 15, the most common of which are hails, strong winds, earthquakes, snowfall, floods, mud-flows debris and rockfalls, and landslides. Floods constitute up to 9% of all natural hazard events occurring during 1997–2003. This impact needs to be considered thoroughly (Hovhannisyan 2014). Therefore, floods are considered as one of the most severe and most frequent water-induced natural disasters, causing major damage to habitat, infrastructures, and properties worldwide – regardless of geographical or hydrological locations and having direct economic impacts (Pandey & Nguyen 1999; Chang et al. 2008; Jongman et al. 2012). However, unlike other natural disasters, floods are somehow predictable because of the main preconditions for flood formation. The main preconditions are considered a sharp increase in air temperature and the intense precipitation simultaneously, in the case of a permanent snow cover. Continuous but varying precipitation ultimately causes the flow of a river to exceed a threshold, such that it breaches the river bank or previous flood restoration work, resulting in flooding (Dulal et al. 2007). Furthermore, the likelihood of flooding is increased by lack of any proper development plan, land use changes (Hirabayashi et al. 2013), the random building of infrastructures in floodplains, and the blocking of rivers (Bathellos et al. 2018).

Many complex factors influence the dynamics and impacts of a flood formation, which must be addressed by a multidisciplinary approach and considerable holistic efforts. Some physical factors include basin geography and steepness, soil characteristics, vegetation cover and makeup, land use, and location of urban features such as roads, buildings, and houses. The basin geography is important, especially for the mountainous regions where rainfall is easily transferred and channeled down to streams and rivers thanks to gravity. This setting can cause water levels to rapidly increase, thus creating a higher risk for flooding (Pollak 2009).

According to Balasubramanian (2005), flooding of rivers is due to both climatic and physiographic factors. The dominant climatic factors are precipitation and temperature. The notable physiographic factors are slopes and aspects of the catchment. Although relationships between changes in floods and changes in other hydrological components (e.g., precipitation are annual discharge) are complex (Hirabayashi et al. 2013), the mentioned key parameters were analyzed in this study. Due to highly vulnerable climate conditions and complicated topography, the study area is characterized by great spatiotemporal variability in flood occurrences in the context of climate change (Vardanyan 2009; Hovhannisyan 2014; Galstyan et al. 2015; Galstyan et al. 2016), representing a major challenge for the assessment of those events for the study area. The geographic location, the variety of relief forms, the compound geological structure, the allocation in an active seismic zone, and the collisions of various atmospheric fronts create appropriate conditions for the occurrence of natural disasters, in particular floods. The natural hazards become much more active and often cause substantial economic damage and numerous human casualties in RA during the last few decades. For example, between 2000 and 2005, the following climate-related economic losses were reported in the agriculture sector: drought – 67 million US$ (10% of gross agriculture product); frost damage to fruit production and viticulture – 25 million US$; and impacts of hail, floods, and frost on crop yields – 15 million US$ (Magnus et al. 2008). Flood events threaten more than 30% of the country’s
area, and the average annual damage to the population and socio-economic system is about 4.6 million US$. During the spring rivers flooded agricultural lands, settlements, roads, railways, destroying bridges and coastal barriers (Hovhannisyan 2014).

The negative impact of global climate change on the Earth is evident everywhere, including the RA. It is particularly expressed by the increasing vulnerability of ecosystems, frequent natural disasters, observed extreme climate and hydrologic values, desertification, droughts, and other phenomena and risks. It is impossible to find any sector of the economy which is not affected by climate change (Hovhannisyan 2014; Armenia’s Third National Communication on Climate Change 2015). The increasing frequency and intensity of extreme weather phenomena such as flood events is also an expected result of climate change. It is worth mentioning that different methods have been developed to analyze, predict, and manage the flood events (Fotovatikhah et al. 2018).

Thus, climate change impact on flood events availability within a drainage area needs the trend analysis of air temperature and precipitation data. Statistical trend analysis of those data can be carried out by both parametric and non-parametric tests. Parametric tests assume that the hydro-meteorological data used for trend analysis are distributed normally and non-biased (Praveenkumar & Jothiprakash 2020). On the other hand, nonparametric tests have the advantage of working with air temperature and precipitation data, as normal distribution is not a pre-condition. The Mann–Kendall (MK) trend test is a widely used nonparametric method for computing trends of a given time series data (Mann 1945; Kendall 1970) which is applied in this study. For hydro-meteorological analysis, the MK trend test is used by a few scientists (Westphal et al. 2011; Galstyan et al. 2015; Galstyan et al. 2016), for air temperature and precipitation, but never for flood events trend detection in the RA.

Moreover, this work copes with the matter by presenting linear and nonparametric trend analyses, as well as applying Geographical Information System (GIS)-based mapping, which could serve as a solid basis for the future predictions. GIS mapping approach is applied by the Institute of Geological Sciences of the National Academy of Sciences of RA to study the hazard level categories. According to this institution, there are four classifications: categories Extreme, High, Middle, and Low (Final Report for The Development of Flooding Hazard Map/ GIS Layer of Armenia 2014).

Overall, besides the traditional methods which are used in this work, computational intelligence techniques, a non-linear regression tool is also widely implemented as an artificial neural network for the prediction of water resource variables, such as flood events prediction and management. In the last two decades, researchers have investigated proposals to overcome disadvantages associated with traditional models. As a result, hydrologists adopted data-driven and computational intelligence techniques in the stream-flow forecasting discipline (Wu & Chau 2013; Taormina & Chau 2015; Fotovatikhah et al. 2018). In the further scientific studies, these up-to-date techniques would be applied as the main tool of our research works.

A catalogue of flood events of the last three decades (1994–2019) has been analyzed to support our study. These data, along with meteorological and geomorphic parameters, such as slopes and aspects, were evaluated to record the temporal and spatial distribution of flood events for the study area. The GIS tool was used to perform complex analysis, processing, evaluation of the meteorological data, along with the geomorphic parameters and flood events. In recent years, flood susceptibility and hazard mapping have been done through extensive application of remote sensing (RS) data and GIS tools (Chapi et al. 2017).

Thereby, the study of flood formation factors and the most flood-prone areas in Armenia are considered as the main objective of this work, taking into account the actuality of the issue and the referenced findings above. Although there are many studies on flood formation of rivers and their risk assessments for RA, still complex analyses in combination with thematic mapping are missing. Moreover, climate change studies, that are rather comprehensive in Armenia, are not somehow linked to transformations of a flood phenomenon. Therefore, the specific objectives of this study are (1) to explore and evaluate air temperature and atmospheric precipitation trends, (2) to analyze temporal dynamics and spatial distribution of flood events, (3) to classify the flooding zones according to the observed number of floods in each river basin, and (4) to identify the impact of slopes and aspects on flood events in the river basins.
STUDY AREA

The RA is a typical mountainous country in the South Caucasus located in a northeastern part of the Armenian Highlands. The high mountains and deep gorges, broad river valleys and volcanic plateaus are following each other in the country. The average height above sea level (a.s.l.) is 1,830 m (Figure 1). The highest altitude of the country is the volcanic peak of Mount Aragats (4,090 m a.s.l.). The lowest altitude is in the lower reaches of the Debed river – 380 m. About 90% of the country is located up to 1,000 m a.s.l., approximately 75% – up to 1,500 and over (Bagdasaryan 1971).

The RA has been adopted as a study area thanks to the following factors: first of all, the negative impact of global climate change is studied rather comprehensively in the RA (Armenia’s Third National Communication on Climate Change 2015; Galstyan et al. 2015). Secondly, during the last decades, flood events became more frequently observed in the RA (Hovhannisyan 2014). Thirdly, the damage caused by floods calls for immediate attention due to its increasing trend as well. Thus, the study of spatial and temporal

Figure 1 | Geographic locations of the meteorological stations used in the study. Major river basins of the RA.
distribution analyses of flood events in the context of climate change in Armenia is considered an urgent topic for the responsible ministries and relevant specialists.

Armenia is a country of climate contrasts. Due to complicated topography and microclimatic particularities, significant climate diversity is observed through neighboring small watersheds. The country includes almost all climatic types starting from arid subtropical to cold mountainous (Nersisyan 1964).

According to Armenia’s Third National Communication on Climate Change (2015), the average annual air temperature for the given 1920–2014 period is 5.5 °C (it is below zero at altitudes above 2,500 m a.s.l.). The highest annual average temperature is 12–14 °C. The summer is hot in valleys and temperate in mountains: the average temperature at the end of July is 16.7 °C, while in the Ararat valley it ranges between 24 and 26 °C. The recorded absolute maximum temperature is 43.7 °C. Winters are cold. January is the coldest month, with an average temperature of 6.7 °C. The recorded absolute lowest temperature is −42 °C. Winters in the northeastern and southeastern parts of the country are temperate. The average annual precipitation amounts to 592 mm which has rather uneven distribution throughout the country. The most arid zones are the Ararat Valley and Meghri region, with annual precipitation of around 200–250 mm. The highest precipitation is observed in high mountainous areas: approximately 1,000 mm/year. The average precipitation in Ararat valley does not exceed 32–36 mm in the summer months.

The average annual wind speed in RA has uneven distribution and varies in the range of 1.0–8.0 m/s. Mountain winds are quite prevalent in some regions, particularly in the Ararat valley. In summer, gusts of wind reach 20 m/s and over (Armenia’s Third National Communication on Climate Change 2015).

In the RA, the rivers belong to the Araks (76.4% of the territory) and the Kur (23.6%) river basins (Figure 1). There are 380 rivers with more than 10 km length in the country. The main sources of water in the rivers are snow and rainwater, which constitute an average of 54%, and for individual rivers (Aghstev, Pambak), they reach 65–70%. For the rivers located in volcanic areas, underground supply plays a significant role (Baghdasaryan 1981). The water resources of Armenia are formed very unevenly in terms of spatial and seasonal distribution. They are scarce, particularly in the densely populated Hrazdan River watershed in the central part of RA. Around 50% of the total volume of the rivers’ runoff is subject to significant annual variations: the flow in water-scarce years amounts to less than 65% of the average. In addition to annual variations, there are also significant seasonal variations in the river flow. Around 55% of the total river runoff on average comes from spring snow melts and rainfall. The ratio for maximum to minimum flow can reach 10:1. In most of the rivers in Armenia, the maximum flow has shown a 3–5% declining trend, except for Aghstev, Hrazdan, Marmarik, and Dzkanget Rivers, where a very small increase in the maximum flow is observed. In recent decades (1975–2005), the intensity and frequency of hazardous hydro-meteorological phenomena have increased. In the last 30 years, the total number of hazardous hydro-meteorological phenomena (as well as floods) increased by 1.2, and in the last 20 years it increased by 1.8 per year (Second National Communication on Climate Change (SNCCC 2010)).

In the basin of the Kura river, 15 mm and more precipitation are sufficient for flood formation, while in the basin of the Araks river it is 20 mm and more (Margaryan 2007). The reason lies in differences of geologic formation – in the Kura river basin, sedimentary and metamorphic rocks are prevailing, while the Araks river basin is mostly covered by volcanic rocks (Baghdasaryan 1971).

In the RA, the maximum precipitation is observed in spring months and early summer, due to which river flooding mostly coincides with this period. At the beginning of April, in most of the cases, air temperature increases, heavy rains in the high-altitude zone cause snow melting and the rivers’ levels rise sharply, and the flow of the rivers grows accordingly.

The flood period of the rivers begins in the second half of March and continues until June, and sometimes until July. The average duration of the flood period is 80–120 days (maximum 150 days and minimum 60 days). On the territory of the RA, on average, about 58% of 6.9 million m³ river runoff forms in the spring months. For this period, due to a sharp increase in temperature and seasonal heavy rains, the water levels in rivers may rise by 100–150 cm during a day. The largest daily fluctuations reach up to 3–5 m for large rivers – Araks, Akhuryan, and Debed and 1.5–2 m for smaller rivers (Hovhannisyan 2014).
The hydrometric and hydrological features of the relatively large rivers of the RA are shown in Table 1. As could be observed, the average altitude of the river catchments is more than 2,000 m a.s.l., which means that the stability of the rivers’ level mostly depends on the melting snow, which, on the other hand, depends on temperature variations during a year.

As typical mountainous rivers, they have different water discharge supply during the year (for example, snow melting from low elevations to the top of the mountains continues for months and thus provides yearlong runoff even if the rain is not sufficient). Thus, instability of the river’s level, in this case, depends on precipitation, which varies from time to time and from place to place.

## MATERIALS AND METHODS

### Materials

The official meteorological data of the Armenian Hydrometeorological Center (air temperature and precipitation data)

### Table 1 | The hydrometric and hydrological features of the relatively large rivers of the RA

<table>
<thead>
<tr>
<th>No.</th>
<th>River – Hydrometric station</th>
<th>Catchment area (km²)</th>
<th>The average altitude of the catchment area (m)</th>
<th>The average annual runoff of river water (m³/s)</th>
<th>Extreme maximum runoff (m³/s)</th>
<th>Monitoring time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Debed – Ayrum</td>
<td>3,740</td>
<td>1,770</td>
<td>33.2</td>
<td>759</td>
<td>19.05.1959</td>
</tr>
<tr>
<td>2</td>
<td>Dzoraget – Gargar</td>
<td>1,450</td>
<td>1,860</td>
<td>15.4</td>
<td>395</td>
<td>19.05.1959</td>
</tr>
<tr>
<td>3</td>
<td>Pambak – Meghrut</td>
<td>1,070</td>
<td>1,920</td>
<td>7.89</td>
<td>109</td>
<td>14.06.1963</td>
</tr>
<tr>
<td>4</td>
<td>Pambak – Tumanyan</td>
<td>1,370</td>
<td>2,000</td>
<td>10.4</td>
<td>171</td>
<td>23.06.1976</td>
</tr>
<tr>
<td>5</td>
<td>Aghstev – Dilijan</td>
<td>303</td>
<td>3.11</td>
<td>53.1</td>
<td>31.05.1978</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Aghstev – Ijevan</td>
<td>1,270</td>
<td>1,800</td>
<td>9.54</td>
<td>177</td>
<td>1990</td>
</tr>
<tr>
<td>7</td>
<td>Akhuryan – Akhurst</td>
<td>1,060</td>
<td>2,100</td>
<td>9.93</td>
<td>182</td>
<td>18.04.1968</td>
</tr>
<tr>
<td>8</td>
<td>Karkachun – Gharibjanyan</td>
<td>1,020</td>
<td>2,020</td>
<td>1.04</td>
<td>79.4</td>
<td>27.03.1964</td>
</tr>
<tr>
<td>9</td>
<td>Qasakh – Vardenis</td>
<td>441</td>
<td>2,300</td>
<td>1.26</td>
<td>151</td>
<td>12.04.1972</td>
</tr>
<tr>
<td>10</td>
<td>Gegharot – Apagats</td>
<td>40</td>
<td>3,100</td>
<td>0.96</td>
<td>18.7</td>
<td>19.07.1933</td>
</tr>
<tr>
<td>11</td>
<td>Sevjar – Tarunik</td>
<td>1,560</td>
<td>1,410</td>
<td>14.37</td>
<td>43.6</td>
<td>06.05.1966</td>
</tr>
<tr>
<td>12</td>
<td>Marmarik – Hankavan</td>
<td>94</td>
<td>2,430</td>
<td>1.65</td>
<td>51.3</td>
<td>26.04.1960</td>
</tr>
<tr>
<td>13</td>
<td>Dzknaget – Tsogayvugh</td>
<td>85</td>
<td>2,220</td>
<td>1.1</td>
<td>28.1</td>
<td>06.05.2007</td>
</tr>
<tr>
<td>14</td>
<td>Gavaraget – Noradus</td>
<td>467</td>
<td>2,430</td>
<td>3.8</td>
<td>49</td>
<td>03.07.1997</td>
</tr>
<tr>
<td>15</td>
<td>Argichi – Verin Getashen</td>
<td>384</td>
<td>2,470</td>
<td>5.6</td>
<td>171</td>
<td>17.04.1968</td>
</tr>
<tr>
<td>16</td>
<td>Masrik – Tsovak</td>
<td>685</td>
<td>2,310</td>
<td>4.1</td>
<td>20.3</td>
<td>30.04.1969</td>
</tr>
<tr>
<td>17</td>
<td>Azat – Garni</td>
<td>326</td>
<td>2,420</td>
<td>4.8</td>
<td>83.9</td>
<td>09.05.1963</td>
</tr>
<tr>
<td>18</td>
<td>Vedi – Urtasdzor</td>
<td>329</td>
<td>2,090</td>
<td>1.9</td>
<td>53.8</td>
<td>11.09.1974</td>
</tr>
<tr>
<td>19</td>
<td>Arpa – Jermuk</td>
<td>180</td>
<td>2,790</td>
<td>5.3</td>
<td>91</td>
<td>17.05.1983</td>
</tr>
<tr>
<td>20</td>
<td>Arpa – Areni</td>
<td>2,040</td>
<td>2,110</td>
<td>16.9</td>
<td>340</td>
<td>01.04.1969</td>
</tr>
<tr>
<td>21</td>
<td>Elegis – Shatin</td>
<td>458</td>
<td>2,350</td>
<td>6.95</td>
<td>207</td>
<td>30.06.1997</td>
</tr>
<tr>
<td>22</td>
<td>Daliget – Borisovka</td>
<td>136</td>
<td>2,780</td>
<td>1.37</td>
<td>46.6</td>
<td>14.05.1967</td>
</tr>
<tr>
<td>23</td>
<td>Vorotan – Vorotan</td>
<td>2,020</td>
<td>2,280</td>
<td>22.6</td>
<td>300</td>
<td>18.04.1968</td>
</tr>
<tr>
<td>24</td>
<td>Gorisget – Goris</td>
<td>85</td>
<td>2,180</td>
<td>0.95</td>
<td>46.4</td>
<td>18.06.1967</td>
</tr>
<tr>
<td>25</td>
<td>Voghi – Kajaran</td>
<td>120</td>
<td>2,840</td>
<td>3.27</td>
<td>43.9</td>
<td>04, 05, 21, 24.07.1960</td>
</tr>
<tr>
<td>26</td>
<td>Voghi – Kapan</td>
<td>685</td>
<td>2,380</td>
<td>11.1</td>
<td>133</td>
<td>15 and 16.05.2010</td>
</tr>
<tr>
<td>27</td>
<td>Meghriget – Meghri</td>
<td>274</td>
<td>2,200</td>
<td>3.5</td>
<td>87.5</td>
<td>12.04.1956</td>
</tr>
</tbody>
</table>
were used for this study. The observed flood data were provided by the Information Provision and Statistics Center of Ministry of Emergency Situations of Armenia (MES).

The atmospheric precipitation and air temperature dynamics data (annual and monthly averages) were compared and evaluated for the period of 1994–2019 from 37 meteorological stations in Armenia. The selected stations’ geographic location is provided in Figure 1. The meteorological stations supervised by the Armenian Hydrometeorological Center were selected to cover all climatic zones in the country. These locations were chosen against the following criteria: data reliability, quality, and the temporal representativeness.

The elaborated study period (1994–2019) depended on the data availability in terms of record length and spatial coverage. The short period is explained by the fact that the flood cases registration started from 1994. On the other hand, the air temperature and atmospheric precipitation data have been available since the end of the 19th century. However, elaboration of this period is based on the fact that all analytical parameters have a unified format of registration and common period. From our point of view, it was preferable to choose the same period, even if it is short.

The datasets used for analyses were checked for data quality, screened for data errors, and the correlation had been calculated and performed by the Armenian Hydrometeorological service before giving them to us. The human regulated watersheds, e.g., one of the largest rivers in the central part of Armenia – the Hrazdan river basin with an area of 2,310 km² – were excluded from this study.

Methods

The methodological approach applied in this study consists of the following logical steps: the temporal statistical analysis, the spatial statistical analysis, and the evaluation of flood-prone areas in Armenia (Figure 2). For spatial distribution analyses, the ArcGIS toolbox was applied. The ArcGIS toolbox is an integrated application and provides a reference for the toolboxes to facilitate user interface in ArcGIS for assessing and organizing a collection of geoprocessing tools, models, and scripts (Chapi et al. 2017).

The MATLAB was used for temporal statistical analysis (standard deviation, correlation coefficient, the fitting formula, slope of trend, etc.) and graph representation. The recent progress in computational science MATLAB software gave highly accurate results (Martin 2015). The presence of trends for air temperature, precipitation, and flood events were assessed by means of the linear trends. In addition, the significance of trends in the air temperature, precipitation, and flood events was tested by the MK trend test method. The significance level was determined by the statistic Z and P-value. In this study, confidence level >95% is considered significant (|Z| > 1.96). The time series shows an increasing trend when statistic Z is greater than 0, while the trend is decreasing when Z is less than 0. The Z values of ±1.96 and ±1.64 are equal to the confidence levels of 0.05 and 0.1, respectively. Based on these confidence levels, in this work, the detected trend could be classified into three zones according to the Z-value (as in all cases, it was greater than 0): (1) \( Z \in (0 \text{ to } 1.64) \), indicating no significant increasing trend; (2) \( Z \in (1.64 \text{ to } 1.96) \), indicating weak increasing trend; and (3) \( Z \geq 1.96 \), indicating the significant increasing trend (Mann 1945; Kendall 1970). P-values tested the statistical significance of the studied variables. The MK test results were obtained using the «Kendall» package in R Studio 3.7 programming language.

Thus, for analyzing the trend detection and statistical significance of the studied parameters, the above-mentioned methodology gave accurate and reliable results. The flowchart of the methodology is illustrated in Figure 2.

The records of past floods since 1994 available in the MES database were used. This information was classified as required and used to create different types of maps. As a primary step, a temporal statistical analysis was performed to identify trends in air temperature, precipitation, and flood events during the study period. Then, the spatial distribution of flood events was examined in the territory of RA. Additionally, to identify the seasonal distribution of flood events, these parameters were analyzed for each month.

Thus, 191 flood cases were analyzed during the set period of time (1994–2019), and the following background information was used to get the detailed results: Datum of the flood event; Slopes of the mountain; Aspects of the mountain; and Location of the area affected. The selection of these physical-geographical parameters and the determination of the class numbers, as well as their boundary values, are based on the literature (Pradhan 2010). An
available Digital Elevation Model (DEM) was used to get the appropriate maps. DEM is the digital representation of the land surface elevation with respect to any reference datum. DEMs are used to determine terrain attributes such as elevation at any point, slope and aspect. Nowadays, GIS applications depend mostly on DEMs (Balasubramanian 2017). To get a representable physical-geographical map, such as slopes or aspects, DEM is highly applicable and recommendable for the mountain terrain of Armenia. The GIS powerful analytic and demonstrative possibilities are satisfactory for this specific study. Thus, here the use of a \( z \)-factor was essential to correct slope calculations when the surface \( z \) units were expressed in units different from the ground \( x, y \) units.

Based on the data, the vulnerable zones were classified and mapped, applying the ‘Reclassify’ tool from the Arc Toolbox. If a range of values was to be reclassed, the ranges should not overlap except at the boundary of two input ranges. Where overlapping occurred, the higher end of the lower input range was inclusive, and the lower end of the higher input range was exclusive. For example, if two ranges were specified, such as reclassifying values 1–5 as 100 and values 5–10 as 200, an input value less than or equal to 5 would be assigned the value 100 in the output, and an input value that was larger than 5, such as 5.01, would be assigned to 200.

Moreover, using the ‘Extract by Mask’ tool from the same section of the Arc Toolbox made it possible to identify the matching territories according to our classification, which were considered the most vulnerable zones. In this case, the automatic classification was selected as a basis. Thus, areas having a slope up to 5\(^\circ\), conditional flat areas and southern aspects of mountains were considered to be the risky flood areas.

Thus, according to the principal approach, layers of two risk assessment factors must be compared and the matching areas should be considered as the most dangerous zones for flooding in Armenia.

RESULTS AND DISCUSSION

Results

Although the occurrence of flooding is often associated with atmospheric precipitation, it has been acknowledged that
this does not occur alone. Hoyt & Langbein (1939) noted meteorological, physiographic, and climatic influences on flood occurrence, including precipitation, temperature, topography, and soil characteristics (Modrick & Georgakakos 2015). Most of the hydrological studies focusing on floods were based on morphometric parameters of the catchment area. The location, topography, and climate of the region lead to hydro-meteorological hazards, including flood occurrences (Azmeri et al. 2016).

As the primary goal of the study was temporal trend analysis and spatial distribution of flood events in the context of climate change, the climate change analyses were carried out in the study area. According to the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007), climate change is mainly described by air temperature and precipitation changes. Thus, those two factors were taken as key parameters which showed the climate change and could influence the flood formation processes.

On the other hand, as for the physical-geographical parameters, slope and aspects were chosen because of the fact that Armenia is a mountainous country and favorable conditions for flooding depend not only on climate conditions but also on the appropriate slopes and aspects (Pradhan 2010; Bathrellos et al. 2018). This approach is applicable for the mountainous countries (such as for Turkey and Iran), where the intensity of floods increases in the case of the high slope topographic structure of the area (Kaya et al. 2017).

According to the ‘Second National Communication on Climate Change in Armenia’, deviations of annual air temperature and precipitation, recorded in Armenia in 1935–2007 from the average for 1961–1990, were estimated. Thus, air temperature deviations since 1994 have been only positive and reached their peak of 2.1 °C in 1998, which is the hottest year registered in Armenia in the entire observation period. In the last 80 years, the average annual temperature increased by 0.85 °C, and annual precipitation decreased by 6%. In summer months, the average air temperature has increased by 1 °C, while in winter months, temperature increase has not been observed. During the last 15 years, anomalies of summer temperatures were positive, summers were extremely hot in 1998, 2000, and 2006, and the summer of 2006 was the hottest in Armenia in the entire period of 1929–2007. On the other hand, studying the atmospheric precipitation data after 1990 we have noticed an increasing (10.8%) trend according to the data taken from meteorological stations (SNCCC 2010).

Thus, studying flood occurrence series changes in the context of global climate change and making our survey much more effective and clearer, the temporal trends of air temperature and precipitation were studied. Moreover, the temporal and spatial distribution analyses were done for flood occurrences during the period 1994 to 2019 for finding out the most flood vulnerable areas in the territory of Armenia.

The temporal trend analysis of air temperature, atmospheric precipitation, and flood occurrences series

Analyzing the multiannual changes of air temperature and atmospheric precipitation over the past three decades and the noticeable presence of changes forced us to analyze in spatial terms. Armenia, being a mountainous country, having relief diversity and complicated climatic conditions, made it even more challenging to study floods. In addition to slopes and aspects of the mountains, air temperature and amount of atmospheric precipitation are considered to be one of the most essential factors to create flooding.

As a result of the study of air temperature and atmospheric precipitation changes in Armenia, it became evident that noticeable changes were observed not only for the average annual values of air temperature and precipitation but also for the monthly average values (from 3 to 8 months). As the floods were observed from March to August, the values of air temperature and atmospheric precipitation were aligned for that period of the year. Moreover, their changes were characterized from 1994 to 2019 (Figures 3 and 4).

According to the analyses, the average air temperature from March to August increased by about 1.5 °C, while the average annual values of air temperature were approximately 1.4 °C for the same period. Thus, the average value of air temperature grew remarkably not only annually but also for March–August. Precipitation was also a primary factor in the flood formation process. The values of precipitation from March to August grew by about 2.7% (or 10.43 mm), while the annual precipitation increased by about 10.8% (or 60 mm) (Figure 4). Accordingly, during the flooding period, precipitation increased insignificantly,
but, on the other hand, precipitation in autumn and winter increased noticeably. Therefore, in winter, more snow cover was formed in the high mountains, which melted, and spring precipitation caused more favorable conditions for flood formation.

**The temporal trend analysis of flood events**

Simultaneously, with air temperature and precipitation, flood events data were examined during the same study period (Figure 5). In Figure 5, the normalized data were used for comparing and highlighting the correlation. For obtaining the normalization of the data, we divided each of them to their maximum values. Thus, the correlation coefficient between annual precipitation and flood cases is a bit more (0.66) than with III–XI months (0.65). The expected higher correlation coefficient depends on the intensity of the precipitation, which was not studied in this paper because of the data unavailability. However, for flood formation, the precipitation intensity is very important, especially for mountainous regions. Further, irregular and intense rainfall may result in higher runoff, as well as snow-melt from the catchment area (Jain & Singh 2020).

In contrast, the correlation between temperature and flood events is almost impossible to find (with III–XI months, it is 0.34, with an annual temperature of 0.2).

From all the above, it could be concluded that even the correlation is not very significant, but as illustrated in Figure 5, the connections among these variables are visible. For instance, during 2009–2011, the flood events number increased, but as the temperature was higher in 2010, the flood events decreased compared with 2009 and 2011. In this case, flood events variation is undoubtedly repeating precipitation variation.

Thus, a total number of 191 flood events were recorded in all drainage basins of Armenia in 1994–2019. Figure 6 shows the temporal distribution of flood occurrences during that period. The number of flood events reached its maximum value (50) in 2011. That value was high (29) in 2009 and was relatively high (28) in 2007. In 2011, flood events were four times higher than the average occurrence during the study period (the average case of floods during the study period was 7.35 cases/year). In the 1990s, a total of 13 flood events were recorded, while in the 2000 and 2010s, 99 and 79 were observed, respectively. There were 127 observed flood events from 2005 till 2011. This number constitutes 66.5% of the overall flood events studied over 25 years.
For the study period, flood events increase from 2003 until 2011 (only 2006 and 2008 are excluded: 5 and 3 events, respectively). Flooding was particularly significant in 2003, in early April, when unprecedented air temperature increase and heavy rains in the high-altitude zone led to rapid snow melting and a sharp rise in river levels. Heavy precipitation, its long-lasting character coupled with increasing temperature and the simultaneous outflow of snow melting in high-altitude zones contributed to the formation of floods, which, in turn, led to the activation of landslides and other slope processes, with flood damage of approximately 3.1 million Armenian drams (Hovhannisyan 2014).

The highest damage value was in Lori region, mainly caused by the Debed river.

In spring 2004, a sharp increase in air temperature was observed in the Aragatsotn region. On March 5, within a few hours, the temperature rose by 10–12°C, while at the same time, heavy rainfall and a stormy wind began to contribute to the intensive melting of accumulated snow on the slopes of mount Aragats, which led to a sharp increase of river levels. The rise of the Hrazdan river level by 1.5–2.5 m caused significant damage to the surrounding villages, the central districts of Hrazdan city and a number of buildings in Yerevan city. Flood damage in 2004 amounted to approximately 1.5 billion drams (Hovhannisyan 2014).

In 2005, floods were observed in Ararat, Armvir, Gegharkunik, and Kotayk regions. In the Kotayk region, the Hrazdan river flood damaged the Arzakan-Yerevan water supply system, and the Getar river partially destroyed several houses in the village of Mayakovksy. In 2007 in the territory of the RA, 28 flood events were registered, most of which were observed in May. Some of the cases were observed in April (due to heavy snowfall) and June (due to heavy rainfall). From 2009 to 2011, a large amount of flood events were observed (in total 42% of the overall flood events during the study period). Most of the flood events were recorded in May and June. A significant part of them were observed in Vayots Dzor and Lori regions.

During 2010 and 2011, 41 flood events were registered. As a result, only 15 cases were recorded in March of 2010. Most of the floods were observed in Lori, Ararat, Syunik, Shirak, and Kotayk regions.

According to the ‘Second National Communication on Climate Change’, the intensity and frequency of hazardous hydro-meteorological phenomena (including floods) increased in recent decades (1975–2005). In the last 30 years (at that time from 1975 to 2005), the total number of hazardous hydro-meteorological phenomena increased by 1.2 cases, and in the last 20 years (at that time from 1985 to 2005) by 1.8 cases/year (SNCCC 2010).

Obviously, in this case, there was a trend of increasing flood occurrences over the last three decades. In the last 25 years (at that time from 1994 to 2019), the total number of flood events increased by 5.6 cases.

In addition to annual variations, there were also significant seasonal variations in the river flow. Figure 7 presents the seasonal distribution of flood events from 2011 to 2019 (the time series were short as there were no monthly recorded data before that period). During that period, there were 57 events and the statistical analysis proved that the largest number of flood events was in May (25). High values of flood occurrences were observed in June (15) and in April (10). Thus, out of the observed 57 cases, 50 happened in those 3 months. This could be explained by the fact that 40% of annual precipitation was observed

![Figure 6](https://example.com/figure6.png)

**Figure 6** | The annual distribution of flood events from 1994 to 2019.

![Figure 7](https://example.com/figure7.png)

**Figure 7** | The monthly distribution of flood events during 2011–2019.
from April to June. Moreover, during this period, heavy precipitation and snow melting (as the temperature was gradually increasing) were happening at the same time. Heavy precipitation is also considered one of the most significant reasons for the mountainous snow melting process. They are often associated with an air-mass process in the warm period (April–October). The contributions of circulation types during the heavy precipitation events are associated with the cyclonic activities. It is worth noting that those synoptic processes are known to be flood generating systems (Gevorgyan 2015).

Thus, it appeared that increasing air temperatures and precipitation contributed to the growth of river water discharge. Therefore, the risk of possible floods increased. As a result, the snow was not accumulated in many river basins and from time to time, it melted due to increasing air temperature in winter. It gradually melted from early spring, and the possibility of an extreme maximum runoff in early spring increased the risk of the occurrence of floods as well.

According to the results gained from linear trend analysis, we have increasing trends for all studied parameters. For deeper understanding and to obtain appropriate results, we applied the MK nonparametric test to analyze the temporal trend significance of air temperature, precipitation, and flood events.

**The temporal trend analysis using MK nonparametric test**

Trend analysis of the observed air temperature, precipitation, and flood events data was carried out using the MK test and the results are shown in Table 2. If the used data have values $P < 0.05$, they are statistically significant. As it is given in Table 2, the statistical analysis of the data showed that $P$ is 0.07 and 0.2 for annual air temperature and atmospheric precipitation, respectively. It was only statistically significant for III–IX-month temperature (0.02). The statistical analysis of the flood events showed that $P$ is equal to 0.14 and it is not statistically significant.

For annual temperature, the test shows a weak increasing trend in the RA, whereas the linear trend shows a visible increasing trend (Figure 3). III–IX-month temperature shows a significant increasing trend which was also observed according to the linear trend. The annual and monthly precipitation (III–XI month) shows no significant increasing trend. Similarly, flood events data shows similar trend results, which is in conflict with the result observed when applying linear as shown in Figure 6.

However, the increasing number of floods during the last three decades (even though it is not significant), enforce us to study the spatial distribution of observed floods paying attention to the slopes and aspects of the area. In this case, it could be possible to find out the most dangerous places where flooding was very usual and where the most vulnerable places are.

### Spatial distribution of flood events in Armenia

However, changes in temperature in various regions of RA and in different seasons of the year show different trends. Spatial distribution of annual precipitation changes in Armenia is quite irregular; northeastern and central (Ararat valley) regions of the country have become more arid, while the southern and northwestern parts and Lake Sevan basin have had a significant increase in precipitation in the last 70 years (SNCCC 2010). This kind of change enforces us to analyze the spatial distribution of flood events, taking into consideration climate change influences on different flood formation factors.

Furthermore, a spatial analysis of the flood occurrences was carried out. In the RA, in 1994–2019, overall 191 floods were observed, which were distributed unevenly (Figure 8) and needed further explanation.

**Table 2** | The trend analyses of studied parameters for the period 1994–2019.

<table>
<thead>
<tr>
<th>Measured parameters</th>
<th>Z</th>
<th>P-value</th>
<th>Test Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual temperature</td>
<td>1.7633</td>
<td>0.07785</td>
<td>Weak increasing trend</td>
</tr>
<tr>
<td>III–IX-month</td>
<td>2.2756</td>
<td>0.02287</td>
<td>Significant increasing trend</td>
</tr>
<tr>
<td>temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual precipitation</td>
<td>1.2784</td>
<td>0.2011</td>
<td>No significant trend</td>
</tr>
<tr>
<td>III–IX-month</td>
<td>0</td>
<td>1</td>
<td>No significant trend</td>
</tr>
<tr>
<td>precipitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood events</td>
<td>1.4652</td>
<td>0.1429</td>
<td>No significant increasing trend</td>
</tr>
</tbody>
</table>

The bold trend is significant at the 0.05 level based on the MK trend test.
The three drainage basins in Armenia (Kura, Araks, and Lake Sevan basins) are divided into 14 sub-basins: Azat, Akhuryan, Aghstev, Arpa, Debed, Tributaries of Kur, Hrazdan, Meghriget, Voghji, Vorotan, Selav Mastara, Rivers flowing into Lake Sevan, Vedi, and Kasakh river. The spatial distribution of flood events in each drainage basin was examined (Table 3). A spatial database was created, and ArcGIS 10.7 software was used to process the collected data.

Table 3 shows the spatial distribution of flood events expressed as the number of events per drainage basin during the study period. The observed data which were expressed in percentages made the image more visible and provided a clear understanding of every river basin separately. Most of the floods were located in the drainage basin of the Hrazdan River.

Thus, the analysis revealed that the highest value of flood events was observed in the Hrazdan river basin.
dangerous (Figure 8). The more dangerous their degree of risk: less dangerous, dangerous, and more
river basins could be divided into three zones, according to fl
that more in-depth surveys could avoid further risks
covers about 22% of the country
basins could be subdivided into three groups
Therefore, combining the above-analyzed values, the river
the fact that fl
No. The river basin
fl
26.7% – and then in the Debed river basin – 19.4% – but no
flooding was observed in the Meghriget river basin, and in
the Kasakh river basin there was one case. As was expected,
out of 15 surveyed river basins, 50% of floods were observed
only in two river basins (the Hrazdan and the Debed river
basins). Those two river basins covered 22% of the country’s
area.

One of the objectives of the study was to analyze the
spatial distribution of flood events and to classify the flood-
ing zones according to the observed number of floods in
each river basin (Figure 8). The main purpose of this map
was visualization of the geographical distribution of flood
occurrences in Armenia in each river basin separately.
Therefore, combining the above-analyzed values, the river
basins could be subdivided into three groups – based on
the fact that flooding risk depends on the number of
floods in the area. Thorough analyses show that the studied
river basins could be divided into three zones, according to
their degree of risk: less dangerous, dangerous, and more
dangerous (Figure 8). The more dangerous flooding area
covers about 22% of the country’s territory, which means
that more in-depth surveys could avoid further risks
caused by floods. The river Hrazdan is most regulated, as
there are reservoirs to solve the flooding problem. Moreover,
this river flows through Yerevan city (the capital of
Armenia), and it is characterized by underground flows in
some places. These circumstances make it more difficult to
compile comprehensive research on flood discharges. Con-
clusively, it is essential to study the form of the terrain,
which already contributed to the occurrence of flooding.

The less dangerous areas were the southern edge of the
country, the south, southwest, and southeast of Aragats
mountain (Figure 8). The southern edge of the country had
different factors which could prevent the flood formation
processes. First of all, the existing forest landscape
(Baghdasaryan 1971) which controlled the surface runoff.
The second factor was considered relief condition; slope
degrees were more than 20° (Figure 9(b)), which means
less flood favorable conditions according to our study
(Table 5). As for the south, southwest, and southeast of Ara-
gats mountain, the most significant factor here is a massive
volcanic shield and deep river canyons (such as the Kasakh
river).

Naturally, there are two types of factors that affect flood-
ing: stable and variable (changing from time to time and
from place to place). We have already studied two important
factors, air temperature and precipitation, which were con-
sidered important for flood formation. On the other hand,
the stable flood creator factor is relief, which has a significant
role in the formation of runoff and, hence, flooding in rivers.

Thus, the geomorphological setting of an area affects
flood occurrences. Lowland morphology, gentle slopes and
flat areas create favorable conditions for flooding (Pradhan
2010; Bathrellos et al. 2018). That is why the slope and
aspect of the study area were examined as important flood
formation processes. The selection of these geomorphologi-
cal parameters and the determination of the categories
adopted for slope and aspect were done based on the litera-
ture (Pradhan 2010; Bathrellos et al. 2018), which was also
applicable for the relief of the RA. Hence, the slope map
was classified into the following five categories: 0–5°, 5–
10°, 10–20°, 20–30°, and 30–70° (Figure 9(b)). The aspect
map shows the slope direction and identifies the flat areas
that have no slope. Thus, the aspect map was categorized
into nine classes: flat, north, northeast, east, southeast,
south, southwest, west, and northwest (Figure 9(a)).

<table>
<thead>
<tr>
<th>No.</th>
<th>The river basin</th>
<th>Number of floods in the river basin</th>
<th>Number of floods expressed in % in the river basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Azat</td>
<td>9</td>
<td>4.7</td>
</tr>
<tr>
<td>2</td>
<td>Akhuryan</td>
<td>13</td>
<td>6.8</td>
</tr>
<tr>
<td>3</td>
<td>Aghstev</td>
<td>17</td>
<td>8.9</td>
</tr>
<tr>
<td>4</td>
<td>Arpa</td>
<td>24</td>
<td>12.6</td>
</tr>
<tr>
<td>5</td>
<td>Debed</td>
<td>37</td>
<td>19.4</td>
</tr>
<tr>
<td>6</td>
<td>Tributaries of Kur</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>Hrazdan</td>
<td>51</td>
<td>26.7</td>
</tr>
<tr>
<td>8</td>
<td>Meghriget</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>9</td>
<td>Voghji</td>
<td>4</td>
<td>2.1</td>
</tr>
<tr>
<td>10</td>
<td>Vorotan</td>
<td>5</td>
<td>2.6</td>
</tr>
<tr>
<td>11</td>
<td>Selav Mastara</td>
<td>3</td>
<td>1.6</td>
</tr>
<tr>
<td>12</td>
<td>Rivers flowing into Lake Sevan</td>
<td>20</td>
<td>10.5</td>
</tr>
<tr>
<td>13</td>
<td>Vedi</td>
<td>6</td>
<td>3.1</td>
</tr>
<tr>
<td>14</td>
<td>Kasakh</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>15</td>
<td>The total number of floods</td>
<td>191</td>
<td>100.0</td>
</tr>
</tbody>
</table>
The aspect identifies the downslope direction of the maximum rate of change in value from each cell to its neighbors. It could be thought of as the slope direction. The values of each cell in the output raster indicate the compass direction that the surface faces. It is measured clockwise in degrees from 0 (due north) to 360 (again due north), coming full circle. Flat areas having no downslope direction are given a value of –1. Figure 9 shows the slope and aspect maps and their categories.

The lowest and flattest areas were mainly located in the low stream of drainage basins of the Hrazdan, the Vedi (which flows through the Ararat valley), the Arpa, the Aghstev, the Debed rivers, and in Lake Sevan coastal zone. Generally, the lowest and flattest places of river basins, in this case, also in Armenia, are considered one of the densest populated areas. Thus, flooding damage is much higher and more diverse in these valleys than anywhere else.

As is already mentioned, according to the analyses, we separated nine different aspects and the flood occurrences in each aspect (Table 4). The ‘Select by location’ tool is used from the Arc Toolbox to calculate the number of floods on each side. Thus, maximum floods are seen in flat and southern aspects (29.8 and 21.5%, respectively). This means that more than half of the observed floods are located in the flat and south aspects.

The appearance of more floods in the south aspects of the mountains in the RA is mostly conditioned by the southeastern invasion of warm air masses from the Arabian deserts in early spring (Surenyan 2010), that creates favorable conditions for the intensive snow melting.

![Figure 9](image-url) | The thematic maps of the two geomorphological parameters: (a) aspects and (b) slopes.

<p>| Table 4 | The flood occurrences in different aspects of the mountains during the 1994-2019 period (with numbers and percentages) |
|---|---|---|</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>Aspects</th>
<th>The number of floods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flat</td>
<td>57</td>
</tr>
<tr>
<td>2</td>
<td>North</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Northeast</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>East</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>Southeast</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>South</td>
<td>41</td>
</tr>
<tr>
<td>7</td>
<td>Southwest</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>West</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>Northwest</td>
<td>21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>191</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
process. Moreover, the south aspects have more floods because of more sunlight energy. Hence, the snow melting process (mostly at the beginning of spring, simultaneously increasing air temperature and occurring rain) was happening much more intensively than in other aspects of the mountains. It is worth mentioning here that the southern aspects of the mountains are windward side and get more precipitation than the other aspects (Galstyan et al. 2015). This is especially noticeable in the northern and the northeastern part of the country, where the most flood events were registered.

As a result, it was discovered that 50% of the observed floods occurred in the flat areas and southern aspects during the last three decades (Figure 10(a)). Furthermore, they cover only 13% of the territory in Armenia. Mainly located in the lower parts of the valleys, the largest area was Ararat valley and the valleys located on the southern slopes of the mountain.

On the other hand, studying the slope case, it became clear that there are some regularities here as well. Almost 66% of floods are observed at the slopes up to 5°, which covered 34.6% of the country’s area, mostly with a dense population (Figure 10(b)). The second regularity is class of slope from 5° to 10°, where almost 20% of the flood occurrences are happening (Table 5). Hence, it could be said that less sloped mountains are less risky. Based on these results, the maps were drawn to see the position of flat, southern aspects and slopes up to 5° separately (Figure 10(a) and 10(b)).

However, this was considered insufficient and it was decided to evaluate the joint impacts of the slopes and aspects (Figure 11). Thus, we combined those two values

Table 5 | The flood occurrences in different slopes of the mountains during the 1994–2019 period (with numbers and percentages)

<table>
<thead>
<tr>
<th>No.</th>
<th>Slopes</th>
<th>The number of floods</th>
<th>The number of floods expressed in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Up to 5°</td>
<td>126</td>
<td>66.0</td>
</tr>
<tr>
<td>2</td>
<td>5–10°</td>
<td>39</td>
<td>20.4</td>
</tr>
<tr>
<td>3</td>
<td>10–20°</td>
<td>22</td>
<td>11.5</td>
</tr>
<tr>
<td>4</td>
<td>20–30°</td>
<td>4</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>More than 30°</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>191</td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 10 | (a) The location of flat and southern aspects and (b) the location of slopes up to 5°.
to evaluate the slopes and aspects that impact the observed river floods in Armenia.

The areas with slopes <5 and flat and southern aspects were combined to identify the lowest, flattest areas having the southern aspect of the study area. This was accomplished by the intersection tool of ArcGIS 10.7.

Approximately 5% of the territory in Armenia was considered as the most vulnerable flooding zone. This is not a large number, but it is located mostly in the central parts of the country (the lowest and southern slopes of Aragats mountain), lowest parts of Ararat valley, upper stream of the Debed river, and lower areas of some other valleys. In these areas, the flood formation processes are very active and experience the most serious and frequent floods in Armenia.

**DISCUSSION**

Though the data performed and analyzed in this study were taken from reliable and official sources some uncertainties could be found. The standard deviations from air temperature and precipitation were low which indicated that the data points tended to be close to the mean, while the standard deviation for flood events was higher than mean. This indicated that the data points were spread out over a wider range of values. The uncertainties that may affect the findings of this study were connected with flood events data. The possible explanation was the fact that the official data were registered only from the residential area (such as villages or cities), where flood events have been observed. Thus, the flood events that happened in nonresidential areas were missing in this study.

The analyses of the annual distribution of flood occurrences demonstrate an increasing trend for the period 1994–2019 according to the linear trend. Meanwhile, the applied MK nonparametric test shows no significant increasing trend. Similarly, precipitation data show no significant trend results, but for annual air temperature, the increasing trend is weak significantly (for III–IX-month air temperature, it is significant).

It turned out that during the study period, the maximum flood occurrences are noticed from 2005 to 2011, which constitutes almost 66.5% of the observed data.

The monthly distribution of flood events demonstrates that for the studied period, floods used to be observed from March to September. For the 2010–2019 timeframe, almost 88% of flood events occurred from April to June. Moreover, May data contains the most flood events, while June is the second month with many flood records (Figure 7).

The study area is subdivided into 14 sub-basins to examine the spatial distribution of flood events (Table 3). Most occurrences are recorded in the central and northern parts of the study area and specifically in the drainage basin of Hrazdan and Debed rivers.

According to our research, almost 66% of floods are observed at the slopes up to 5° and about half of the floods are observed in flat and southern aspects (51.3% or 15,258 km²), although some of the results do not correspond to the basic pattern that we have discovered. A clear example is the results obtained for Aragats mountain. As was already mentioned, the southern, southwestern, and southeastern slopes of Aragats mountain are considered less dangerous flood-prone areas. Whereas,
According to the research, we can state that the southern slopes of the mountains in Armenia are considered more flood vulnerable than the other slopes. The main reason for this dissonance is the flood data source. As the inhabitants of the high slopes of Aragats mountain are quite sparse, the number of flood events registered is relatively small.

The flat and less sloped areas are located in the central, northern parts of the country, and the coastal area of Lake Sevan (Figure 11), where many flood cases were observed. Usually, when a flood occurs, the lowest and flattest areas will be flooded first. This lowland morphology of the plain and the narrow passages along the river course, such as the Debed, the Hrazdan, and the Kasakh gorges, are the main reasons for the flooding. On the other hand, in the northeastern part of Armenia, yearly precipitation is almost twice higher than in the central part of the country, thus, in that area, the flood occurrence is mostly connected with heavy precipitation from April to June (during 25 years in the Debed and the Aghstev rivers, there were 54 flood events).

The observed spatial distribution of flood events also depends on the spatial variability of the distribution of frequency of heavy precipitation events. Higher values of frequency of heavy precipitation events (greater than 10–15%) could be seen mainly in the northern and northeastern humid regions of Armenia. Heavy precipitation events of convective origin were observed rarely (less than 5%) in southwestern and southern semi-arid regions of Armenia (Gevorgyan 2013).

Furthermore, other reasons favoring the flood genesis due to human activities are bridges with inappropriate height and the construction by the farmers of ‘handy’ barriers in the river channel for the storage of irrigation water. The best example of this is the river Hrazdan, which is more or less regulated by people.

In the study area, the endogenic processes, such as active tectonics, do not seem to be affecting the flooding hazard within a short period of time. On the other hand, exogenic processes, such as climate change, may significantly influence the formation of future flood events. Expected climate changes will cause annual and seasonal temperature increase and will bring precipitation changes in Armenia. According to the ‘Medium Impact Scenario’, the average annual air temperature will increase by 2.6 °C during the next 50 years starting from 2012. On the other hand, it is forecasted that precipitation will decrease, even though (also according to our study) during the 1980–2012 period it increased by 11.5 mm, and during III–XI months almost by 19.3 mm (Ahouissoussi et al. 2014).

Comparing our results with a similar study in Europe (IPCC 2007; Transboundary Floods 2005; Hirabayashi et al. 2013; Bathrellos et al. 2018), it was clear that changing climate both increased and decreased the flooding risks in different river basins. Analyzing the long-term temporal evolution of flood discharges and their drivers (temperature and precipitation) for different parts of Europe (Blösch et al. 2019), it was clear that based on the seven studied hotspots in four regions (Northern Iberia, Central Balkans, Southern Finland, and Western Russia), flood and temperature changed similarly to Armenia. Moreover, only in Northern Iberia and Central Balkans, the discussed tree parameters (air temperature, precipitation, and flood events) changed in the same pattern as in Armenia. From this point of view, it was difficult to identify any factor that forms flood, which would be the same for all regions, with the exception of climate change, which, in our opinion, was the main factor.

In addition to air temperature and the amount and intensity of precipitation changes, slopes and aspects are considered to be among the most important flood determinants. Although we found out that only 5% of the study area (which is equal to 1,500 km²) was more vulnerable to flooding, the possible temperature and precipitation changes will certainly increase in this area.

Overall, in the RA, the frequency and destructive force of flood events and economic damage caused by them have increased in recent years. According to some researchers (Stepanyan et al. 2011), natural cycles, which are manifested by global climate change and considered its consequences, also play an important role in the formation of flood events in the RA.

**CONCLUSIONS AND RECOMMENDATIONS**

This paper provided the review of factors that affect the temporal and spatial distribution of flood events in the
context of global climate change in the RA. The average annual air temperature and atmospheric precipitation increased during the same period. There was a clear growth potential of flood occurrences. Consequently, it could be concluded that the degree of flooding risk in the river basins drastically increased due to the increase in average annual and seasonal air temperatures and precipitation. The number of flood events reaches its maximum value in the year 2011, while May contains the most flood events. In the last 25 years (from 1994 to 2019), the total number of flood events increased by 5.6 cases, especially for the 2000s. The analysis of the spatial distribution of the floods proves that around half of the 191 flood events are recorded in the conditional flat areas and southern slopes of the mountains of the study area (22% of the country’s territory or almost 6,500 km²). There is a certain amount of clustering of flood events in the areas having up to 5-degree slope. These areas are located in the central, northern parts of the country, and the coastal area of Lake Sevan. Thus, if we evaluate all the above-mentioned factors, it will become evident that 5% of the RA’s territory (or 1,500 km²) is considered the most flood-prone area. The result revealed the crucial information on the most flood vulnerable areas in Armenia.

This study demonstrates that the applied methodology is successful for analyzing temporal trends and spatial distribution of flood events. The used approach successfully determined the high-risk flood zones. This implies that this methodology can be scaled-up for flood analysis or flood mapping in similar mountainous regions where slope and aspects play a significant role in the flood formation process. Furthermore, the results provide solid analytic background information for land use planning at a local scale, leading to the discovery of the safe and nonsafe areas for urban and rural activities. The appropriate land use planning along with the selection of the proper constructions is essential to prevent and mitigate the consequences of flood occurrence in areas prone to flooding.

There is a likelihood that the risk of flood events will continue in the coming years as an effect of climate change. Despite a number of actions and plans executed in the past few decades, there is still much to be done. More concerted efforts are required in the direction of climate change management. Plans related to the control of flood effects in the RA need to be intermingled with climate change management efforts by employing better planning policy. There is also a need to learn from the experiences gained in the past. Consequently, considerable territories of the RA will appear at flood risk, which will require significant extra costs. Proper land use for specific areas (i.e., agricultural usage, residential areas, etc.) have to be determined. The study results will be communicated to the Ministry of Emergency Situations of Armenia (Disaster Management Agency) to guide the disaster risk reduction activities of floods. In the future studies and analytic projects integration of MATLAB, the MK test and GIS should be applied. To foster improvements of this methodology related to flood analyses, it is planned to implement a systematic mapping so as to gain a more detailed classification of the related works and to present a useful guide to aid in the future flood management plans. The only limitation for now is considered flood events data registration methodology, which must be more operative and accurate.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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