Flood regimes in the Southern Caucasus: the influence of precipitation on mean annual floods and frequency curves

J. V. Sutcliffe, F. A. K. Farquharson, E. L. Tate and S. S. Folwell

ABSTRACT

Relations between mean annual flood estimates and basin area and precipitation, as well as dimensionless flood frequency curves, have been derived from a number of groups of gauging stations in the southern Caucasus. Total precipitation and its seasonal distribution are extremely variable at this location. The importance of antecedent soil moisture deficit (closely linked to the seasonal distribution of precipitation) in determining the shape of flood frequency curves is discussed through previous empirical studies and recent sensitivity analyses. The varying shape of regional curves from the southern Caucasus is related to the variations in soil moisture deficit.

Key words | basin characteristics, dimensionless flood frequency curves, mean annual flood, soil moisture deficit, Southern Caucasus

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NOMENCLATURE

k	shape parameter
q	flood peak discharge
u	location parameter
α	scale parameter
AAR	basin mean annual precipitation
AREA	area of basin
FSEE	factorial standard error of estimate
GEV	general extreme value distribution
MAF	mean annual flood
PWM	probability weighted moments

INTRODUCTION

Flood records are available at a large number of stations covering the southern Caucasus where the annual precipitation and its seasonal distribution are extremely variable. This provides a rare opportunity to study the effect of this seasonal distribution, in addition to total precipitation, on the magnitude of the mean annual flood and, in particular, the shape of the flood frequency curve. In this geographical example it is possible to take advantage of the fact that the seasonal distribution is uniform over several regions but can also vary greatly between regions, while the mean annual precipitation is exceptionally variable. Thus the relation between the mean annual flood and the basin area and mean annual precipitation, and also the dimensionless flood frequency curves, can be compared over areas where the total precipitation and seasonal distributions are both different.

DIMENSIONLESS FLOOD FREQUENCY CURVES

Methods of flood frequency estimation have, in recent years, become linked to estimation of the mean annual flood (MAF) from records of annual maximum series, or from peaks over threshold series in the case of shorter records. Regional dimensionless curves, to scale the mean flood to the magnitude corresponding to a lower frequency or longer

doi: 10.2166/nh.2008.025

return period (NERC 1975; Meigh *et al.* 1997), are also available. The use of regional curves has been shown to overcome the problem of estimating the slope and skewness of the frequency curve from the usually short period of record at a single site.

The method is based on the premise that the range of events experienced at a single measuring station can be expanded by incorporating the floods measured at the stations, which may be considered homogeneous in hydrological terms. The choice of a regional set of records has developed from a geographical region, based on proximity, to the choice of basins having similar characteristics. The choice of characteristics may in practice be limited in some areas by the availability of maps from which to choose other basins with similar characteristics to the basin where the flood estimate is required, so that in practice the choice may be based on basin area and annual precipitation alone.

However, it is important to establish which characteristics most affect the shape of flood frequency curves, so that an appropriate choice of stations is sampled and grouped together. This paper aims to contribute to this discussion.

Once the choice of regional station set has been established, there remain the choices of statistical distribution and of fitting method before the set of flood records can be converted to a choice of dimensionless frequency curves. In this study, the choice has been made of the General Extreme Value distribution and the method of Probability-Weighted Moments, on the grounds that the combination has been tested on flood records in many parts of the world and that it has the ability to fit most sets of annual maximum data without being markedly affected by outliers or extreme floods which may occur in the dataset. It has been found (Lu & Stedinger 1992) that "the GEV-PWM method is relatively robust and can perform better than other at-site and regional estimation methods with homogeneous and mildly heterogeneous regions".

The method has been described elsewhere (NERC 1975, pp. 41–52), but the sets of annual maximum records are rendered dimensionless by dividing each series by its mean annual flood. A GEV distribution

$$F(q) = \exp\left\{-\left[1 - \frac{k(q-u)}{\alpha}\right]^{1/k}\right\} \qquad (1)$$

is then fitted by PWM. In Equation (1), u is a location parameter, α is a scale parameter and k is a shape parameter. The regional distribution is used to provide the multiplier to apply to the mean annual flood at the project site to estimate the flood of a given return period.

Factors affecting the flood frequency curve

There are several factors which affect the flood frequency curve, and which therefore have to be taken into account when choosing basins which are likely to be homogeneous. These include statistical analyses of large datasets, regional studies over wide areas and synthetic studies using realistic models of storm events, antecedent conditions and runoff processes.

During the investigations leading up to the Flood Studies Report (NERC 1975), the flood records for over 500 stations sampling all parts of the UK were assembled together with basin characteristics which were used to estimate the mean annual flood in the absence of flood records at a site. The useful characteristics were basin area and channel slope, stream frequency and soil index, mean annual rainfall or net short-term rainfall less mean soil moisture deficit and fractions of urban or lake-fed basin. However, the shape of the flood frequency curve was more closely related to the variability of flood events. A regression of coefficient of variation (CV) on basin characteristics showed that the climate factors of annual or short-term net rainfall were most influential, although only a fraction of the variance was explained.

Whereas annual rainfall had been used in earlier comparisons of flood statistics with basin characteristics, it was felt that net short-term rainfall would be a more direct indicator of flood potential. After a statistical analysis of daily rainfall records and soil moisture deficit series, already assembled by the Meteorological Office, a map was produced of daily rainfall less soil moisture deficit, of 5-year return period (Beran & Sutcliffe 1972; NERC 1975). A map of effective mean soil moisture deficit covering the UK was derived from analysis of 200 stations, and could be used with maps of 5-year daily rainfall to derive an index of flood-producing rainfall. This had the advantage of reducing the exponent of the rainfall term in MAF regressions from unrealistic values to nearer unity.

The investigations presented in this current paper may be coupled with recent research on statistics of extreme rainfall (Koutsoyiannis 2004*a*,*b*) to explain the importance of soil moisture deficit statistics in flood frequency curves. In the first paper, Koutsoyiannis notes that theoretical analyses show that the Gumbel distribution (EV1) is quite unlikely to apply to hydrological extremes such as daily rainfall. In the second paper (Koutsoyiannis 2004*b*) it is reported that the extreme value type II (EV2) is a more consistent choice. An extensive empirical investigation of 169 available long-term rainfall records from Europe and the US suggest that a typical value of the GEV parameter k is -0.15. If a series of typical soil moisture deficit (SMD) values is subtracted from annual maximum daily precipitation values with such a distribution, the mean annual precipitation (MAR) is reduced by the SMD and the dimensionless curve is steepened. This illustrates the importance of soil moisture deficit and its seasonal variation on flood frequency curves.

A number of investigations in many parts of the world have confirmed the importance of climate factors in defining the shape of dimensionless flood frequency curves. These curves range from being extremely steep in arid and semiarid regions around the world (Farquharson *et al.* 1992) to more linear and gentle slopes in areas where climates are dominated by short seasons of rainfall surplus, as in West Africa (Farquharson *et al.* 1993) and in snowmelt areas. Indeed, a worldwide comparison of flood curves and climate (Meigh *et al.* 1997) revealed that the multiplier $q(500)$, or the ratio of 500-year flood to mean annual flood, is inversely related to mean annual rainfall. There are some anomalous areas where the flood curves are much steeper than would be expected from the rainfall regime; these include Sri Lanka. Sutcliffe & Farquharson (1998) suggest that this steepness is related to the variety of dates of annual maxima, which in turn is related to the fact that floods are caused by one of two different monsoon systems.

Evidence from sensitivity analysis

Valuable insights into the factors affecting flood frequency curves have been obtained by sensitivity analysis based on continuous simulation (Hashemi *et al.* 2000; Franchini *et al.* 2000). A rainfall generation model was based on storms originating from a Poisson process at a given rate, generating a random number of storm cells divided into convective and stratiform types with differing duration and intensity. A time series of potential transpiration was represented by an autoregressive (AR(n)) model, in which a value at a given time is based on a linear combination of n prior values, with a seasonal component. A lumped rainfall-runoff model was used to simulate flood frequency curves, using the generated rainfall and potential transpiration components, with soil moisture capacity distributed over the basin and interflow component and routing defined by further parameters.

The parameters of the rainfall and potential transpiration models were calibrated to the conditions of southeast UK, where rainfall is distributed fairly uniformly but summer storms are more convective and where potential transpiration has a stronger seasonal distribution. The sensitivity of the flood frequency curves, standardized by the mean or not, was tested by increasing or decreasing individual parameters. It was noted that changes in rainfall or evaporation parameters affect the shape of the frequency curve by effecting changes in the soil moisture regime. The analysis suggests that the soil moisture regime (and in particular the probability of soil moisture content at the storm arrival time) can be considered as a unifying link between the changes in the parameters and their effects on the frequency curves, consistent with the physical mechanism through which their influence is exercised. The rainfall-runoff model parameters defining interflow also affect the frequency curve by altering the soil moisture regime. In short, these analyses confirmed that climate statistics, through soil moisture regime, play a key role in the shape of the dimensionless flood frequency curve.

The object of the present paper is to apply this insight to the south Caucasus region, and investigate the way in which rainfall amount and seasonal distribution together affect flood frequency curves in a relatively small region in which there is a remarkably wide variation in climate. The variations in precipitation amount and distribution in different parts of the region are shown to affect the shape of the frequency curves and also the timing of the flood events themselves. The southern Caucasus is thus used as an outdoor laboratory to demonstrate the importance of climate variability in influencing dimensionless flood frequency curves.

THE SOUTHERN CAUCASUS

Because of the topography and the precipitation regimes, the Southern Caucasus (comprising the republics of Armenia, Azerbaijan and Georgia) presents an excellent opportunity to investigate the effect of precipitation amount and seasonal distribution on flood magnitudes and frequency curves. The topography is very striking, ranging from coastal plains adjoining the Black Sea and Caspian Sea to impressive mountain chains reaching up to 5,000 m which form a barrier from coast to coast. As a result, the precipitation is exceptionally variable both in annual total and in seasonal distribution. The average annual precipitation varies from less than 200 mm to over 4,000 mm, with a wide range of seasonal distribution from single winter and summer wet seasons to bimodal distributions. The basic records, discussed below, allow the effect of total precipitation and seasonal distribution on flood frequency curves to be studied using a very wide range of examples.

Topography

The area of study (Figure 1) forms a parallelogram bounded by two immense mountain ranges, the Greater Caucasus range to the north and the Lesser Caucasus to the south, completed by the Black Sea to the west and the Caspian Sea to the east. The Greater Caucasus, whose watershed forms the northern political boundaries of Georgia and Azerbaijan and runs from west to east, is the more distinct and continuous feature, rising to an elevation of 4,000–5,000 m over most of its length. The Lesser Caucasus, which runs parallel to the Greater Caucasus but does not coincide so closely with the political boundaries, is more broken and is crossed by a number of rivers including the Araks river and

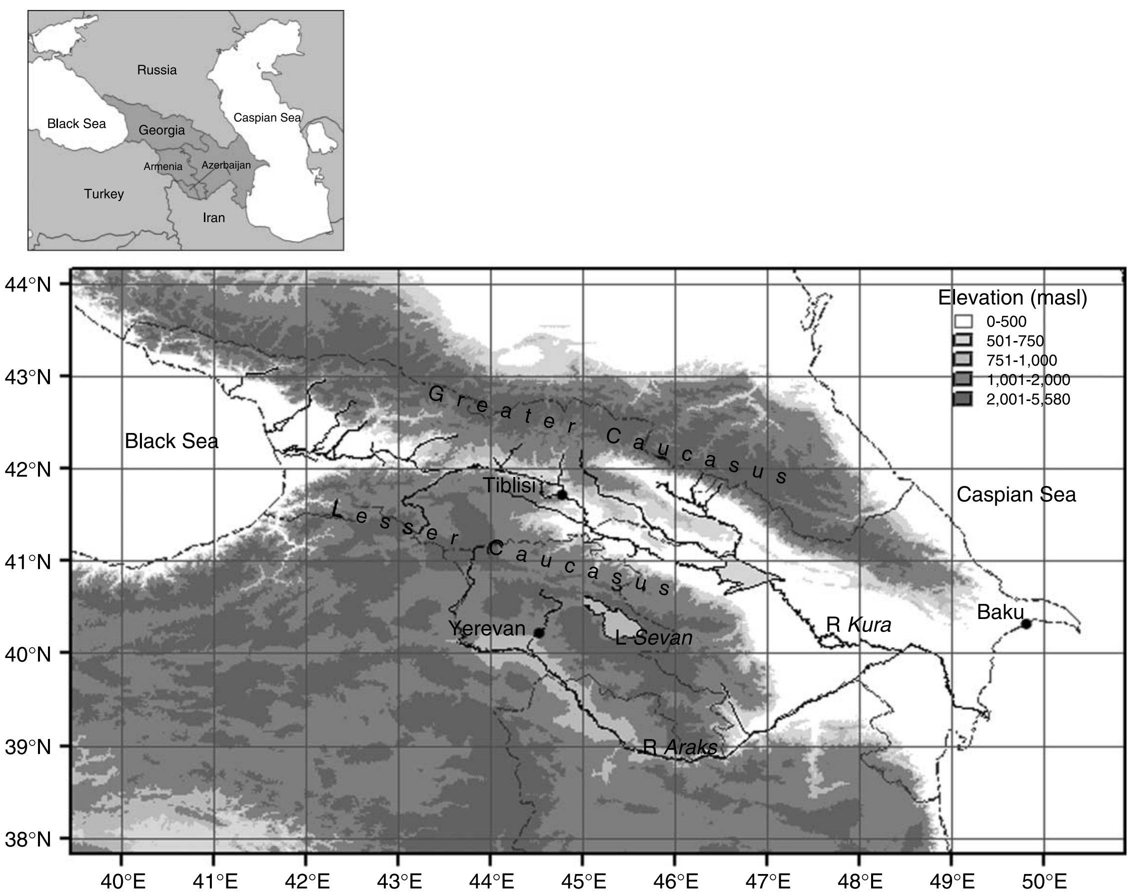

Figure 1 | Location map and topography of study area.

several tributaries. However, it includes a number of massifs which rise to 3,000–4,000 m and separates two distinct climate zones within Armenia.

Between these two ranges, the area between the Black Sea and the Caspian Sea is broken up into a number of discrete topographic units by high ground such as the Likhi range in Georgia, linking the two major ranges west of Tbilisi. The lowland plain near the Black Sea coast is open to maritime influence but eastern Georgia and Armenia are isolated by high ground. Within Azerbaijan, the plain near the Caspian Sea covers a much wider area than the western plain, but is flanked to the north and southwest by the eastern flanks of the two Caucasus ranges. As a result of the mountainous landscape and the features dividing up the central plateau, there are many rivers draining the three countries in a complex pattern (Figure 1), but most of their basins are comparatively small by world standards.

Precipitation

The precipitation regime of the southern Caucasus region reflects the mountainous and isolated topography. According to Lydolph (1972, pp. 200–201), the precipitation has the most complex distribution of any region in the former USSR. The mean annual precipitation over the region is illustrated in Figure 2. The extreme spatial variability of precipitation totals is evident, but the variety of seasonal distribution is equally important.

In western Georgia the combined influence of the Black Sea and the orographic effect of the topography is evident. To the north of the Black Sea lowland, where the average annual precipitation is about 1,500 mm, the annual average precipitation rises to 2,000–3,000 mm on the southern slopes of the Greater Caucasus. To the south of the lowland, the average precipitation rises to 4,000 mm on the high ground to the east of Batumi. In eastern Georgia, beyond the barrier formed by the Likhi range, the mean precipitation varies in general between 600 and 1,000 mm, although it reaches 1,600 mm along the crest of the mountains north of Tbilisi.

In the Armenian plateau, the annual precipitation is less variable than in Georgia, and averages about 500–800 mm in general; however, it increases to some extent with elevation. The total rises to around 1,000 mm on areas of high ground both north and south of Lake Sevan, and falls to less than 300 mm in the valley of the Araks to the west of Yerevan.

In Azerbaijan, on the western shore of the Caspian Sea, the total precipitation is low with the annual average at 240 mm at Baku and less than 300 mm over most of the

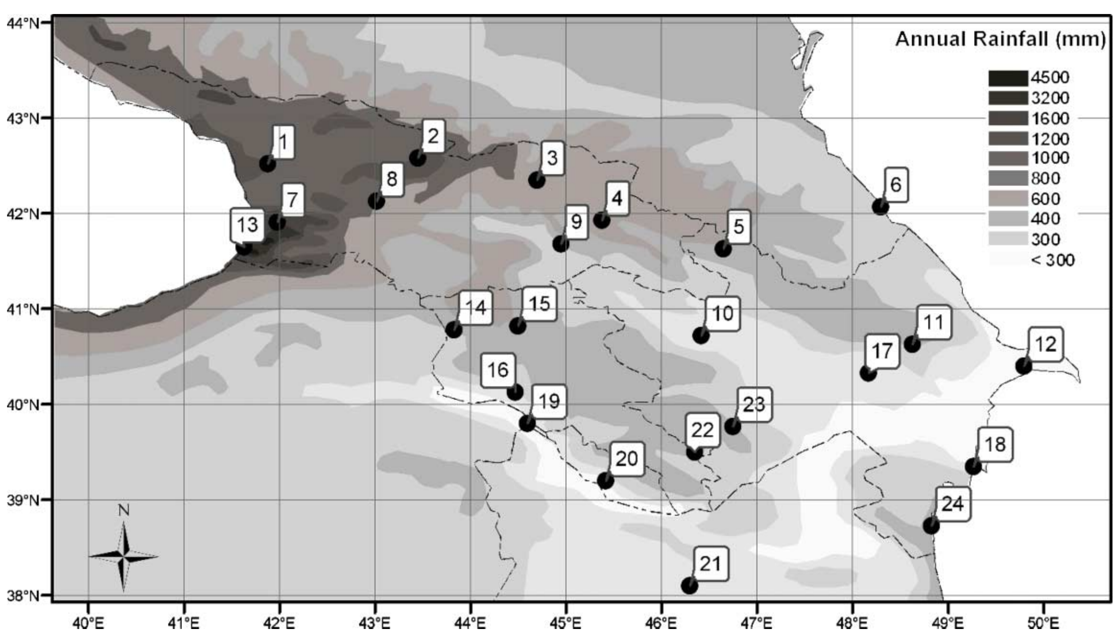

Figure 2 | Annual average precipitation for the southern Caucasus (inset figures relate to rain gauges shown in Figure 3).

coastal plain. However, the precipitation increases with elevation over areas of higher ground, especially near the coast. To the north, where the Greater Caucasus approaches the Caspian Sea, the mean precipitation reaches 1,600 mm from 600 mm in the foothills. Where the Talysh range approaches the sea to the south of the coastal plain, the precipitation also increases to a maximum of 1,600 mm. Inland, where the Lesser Caucasus reaches an elevation of 3,500 m south of the river Kura, the precipitation rises to about 900 mm.

Seasonal distribution of precipitation

The seasonal distribution of precipitation varies in western Georgia; in the southwest the distribution has a maximum in September–December and a minimum in May. In the northwest, however, the distribution is less variable but has a minimum around May and a maximum in winter. In eastern Georgia, the distribution is highly seasonal although the maximum occurs in May, the opposite to the western area. There is also an indication of a bimodal distribution at Tbilisi, with a second smaller maximum in September–October. Within a relatively small area, the distribution is therefore very variable both in terms of total and seasonal pattern.

In Armenia, the seasonal distribution is less variable than in Georgia but the variations are important. To the south of the Lesser Caucasus range there are two maxima (the higher about April and a lesser peak around October–November) with a drier season around August–September. To the north of the range, by contrast, there is a single peak around May. This difference is reflected in the vegetation, as the precipitation in the north occurs during the summer and allows woodland to flourish. The runoff from the north is lower than the south, where grassland is generally dominant. The difference in terms of mean annual runoff is about 100 mm; this difference is reflected in flood frequency curves.

In Azerbaijan, the precipitation has maxima in October and March and a minimum in July. The seasonal distribution over the wider region is shown by monthly histograms in Figure 3. The seasonal distribution at selected stations is illustrated by means of histograms of mean monthly precipitation from January to December. The stations are laid out schematically according to position, with those adjacent to the Black Sea on the left and those near the Caspian Sea to the right, and their positions are shown on Figure 2. It will be seen that there are a number of similarities between groups of adjacent stations as well as varying patterns across the region.

There is a distinctive pattern common to several stations near the Black Sea coast or on the coastal plain such as Sakara. They have a minimum in May and high precipitation throughout the period June–December, with totals decreasing during the period January–April. Over the inland plateau, there are two distinct distributions. There is a wide area from north of the Greater Caucasus through eastern Georgia to northeast Armenia, north of the Lesser Caucasus, which is dominated by a single precipitation season with a maximum in May and June and relatively light precipitation in winter. Much of southern Armenia, by contrast, has two wet seasons (around April and October) and a relatively dry period around August. This pattern extends south towards Dil Duc and Tabriz. Towards the eastern part of the study area over western Azerbaijan and the Caspian Sea coastal plain, the precipitation patterns show that there are maxima around May and October. This is similar to the distribution at Yerevan, with minima around July. In contrast to the climate at the Black Sea end of the region, the early months generally have more precipitation than the autumn months.

There are therefore about four different precipitation patterns in the southern Caucasus. The account in Lydolph (1972) attributes the pattern along the Black Sea coast to the interaction between cyclonic storms in the winter and thunderstorms in the summer. Inland from the Black Sea, the primary control shifts to summer thunderstorms with a general time progression from east to west of thunderstorm activity. The eastern part of the region receives more activity in April and May, and the western part in September. However, in terms of flood generation, the timing of the precipitation distribution may be more important than the meteorological causes. The exception is that thunderstorm activity is more likely to produce storms of high intensity than cyclonic storm activity.

It is evident that the whole region experiences great variation in the distribution of precipitation, both in annual total and in seasonal distribution. The seasonal distribution

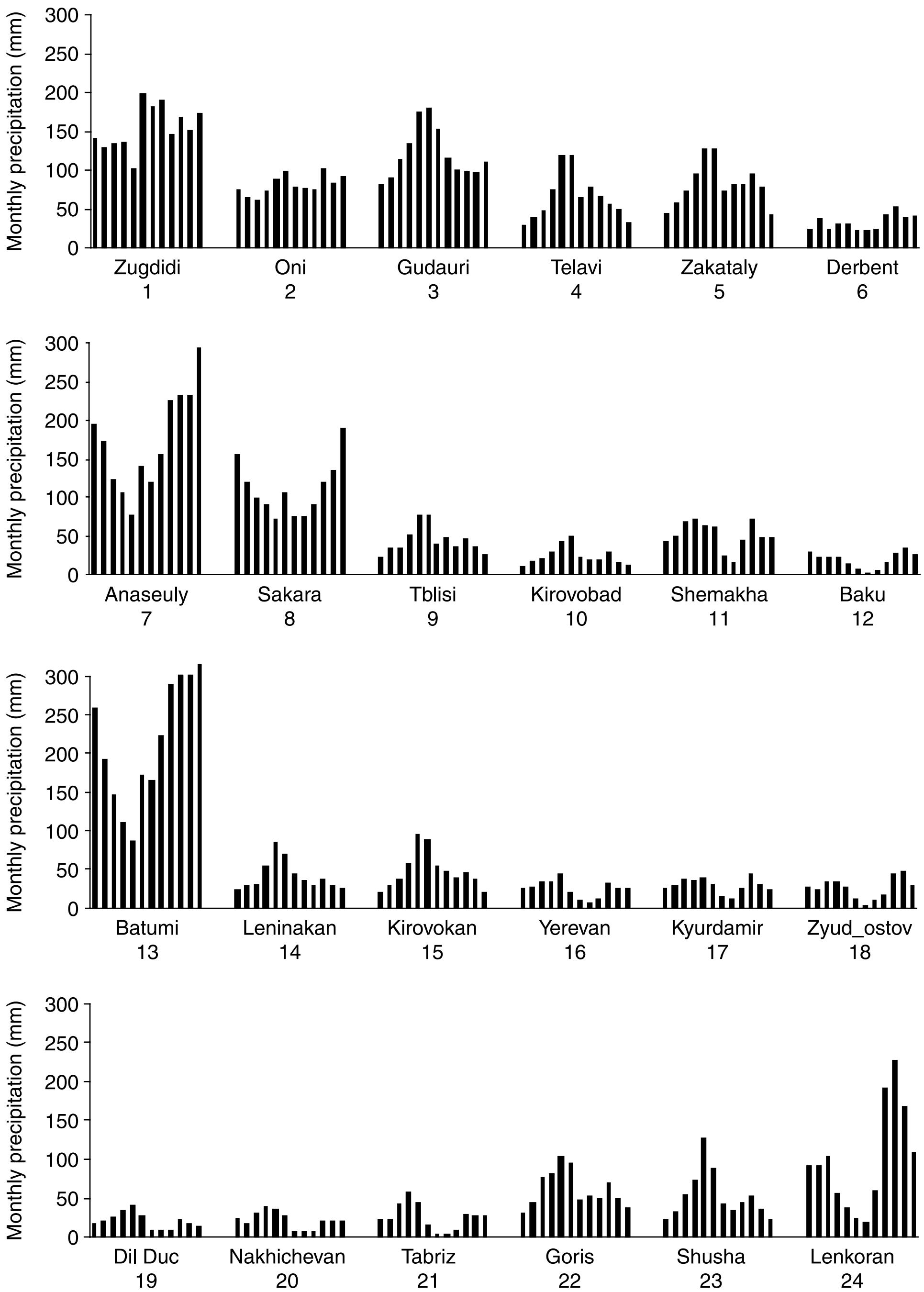

Figure 3 | Mean monthly precipitation distribution for January–December (at locations shown in Figure 2).

is important in terms of flood incidence not only through the influence of snowmelt, but because the annual cycle of basin soil moisture deficit largely determines the proportion of the precipitation which gives rise to immediate runoff. The comparison of precipitation distribution with flood incidence, in terms of seasonal timing and the shapes of flood frequency curves, should throw considerable light on the dependence of flood regime on both total and seasonal precipitation. The unusual nature of the hydrology of the southern Caucasus allows both annual precipitation and its seasonal distribution to be studied in terms of their influence on the magnitude of the mean annual flood and the dimensionless flood frequency curve, using records from a wide range of climates situated within a relatively small area.

Flood records

The incidence of floods in the Caucasus region can be deduced from the annual maximum series of flow records. These records, assembled for different design purposes (e.g. dam safety projects, Spasic-Gril 2005), total over 230 gauging stations with over 8,000 station-years of record. These provide a good sample of flood distribution over the region (see Figure 4).

Just over 100 records for Armenia, distributed throughout the country, were collated for a countrywide investigation of flood frequencies. Annual maximum instantaneous flows were assembled for available gauging stations. The records include the dates of the maxima and the corresponding mean daily flows, which give an indication of the shape of the flood response. An appraisal of the basic data in conjunction with a map of gauging stations revealed that the incidence of high skewness of the annual series, or the presence of outliers in individual records, was quite random, with high values scattered through the records with no apparent pattern. This suggested that high storms and floods occurred at random over the network.

The data from Armenia were divided into eight basin groups and analysed by the methods used in earlier investigations (Farquharson *et al.* 1992, 1993). The mean annual flood for each station was derived as the arithmetic mean of the annual maximum series. Each annual maximum flood series was converted into a dimensionless series by division by the mean annual flood. Dimensionless flood frequency curves using the General Extreme Value (GEV) statistical distribution were fitted by Probability Weighted Moments (PWM). The basic information about these records, including the station number and area, the years of record, the mean annual flood, the annual average precipitation estimated from a countrywide isohyetal map and the parameters of the GEV distribution (u, α, k), have been collated in a countrywide file. The individual

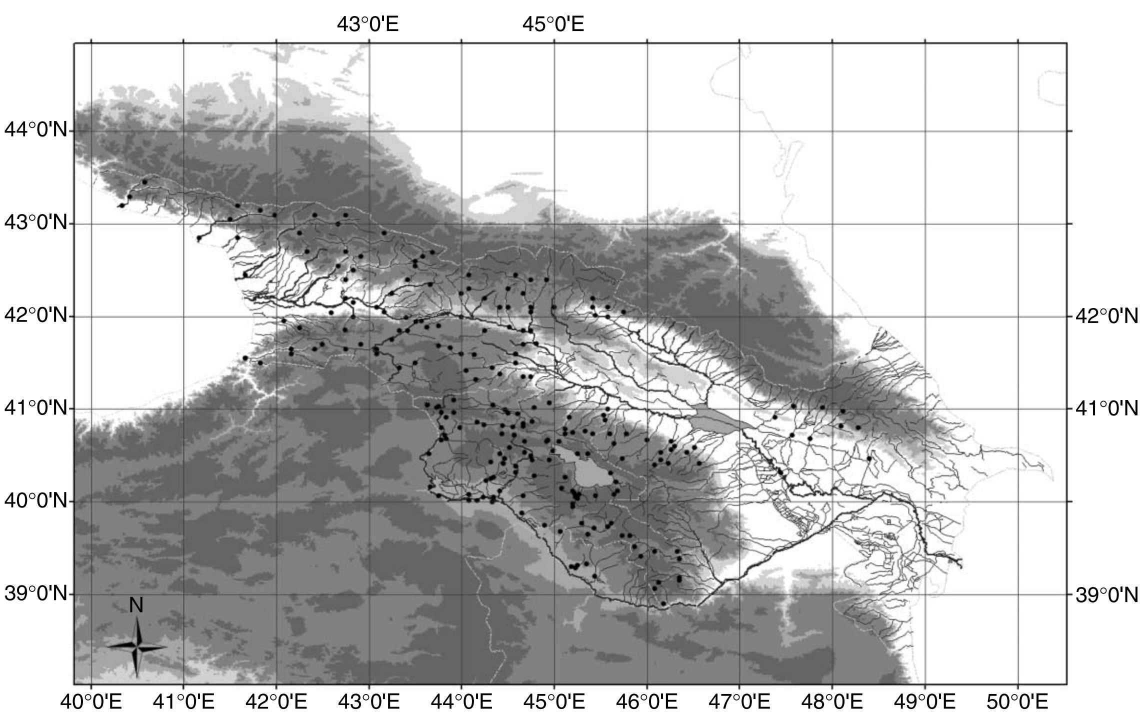

Figure 4 | Gauging stations used in the study.

frequency curves were combined into group curves. The dates of annual maxima have been extracted from the station records, and these have been analysed by means of histograms of flood incidence, described below. These are generally dominated by late spring dates, indicating a combination of snowmelt and summer storms.

The records for Georgia come from several sources. For a dam safety project (Spasic-Gril 2005), a statistical study similar to the Armenian study used stations in eastern Georgia. Other studies used records from wider areas. Records were also obtained from a countrywide publication (Government Water Register 1987). The annual maximum flow series, including dates for the years 1957–1980 were listed for a number of gauging stations. All the records were numbered from this yearbook; there are 105 records, well spread out over the whole country. There is an isohyetal map of Georgia, from which annual average precipitation values have been estimated for all the basins with flood series. A countrywide file has been compiled by the authors listing the basin areas, estimated rainfall, number of years of record, mean annual flood and flood statistics (u, α, k and $q(200)$), as well as the dates of the annual maximum flood series.

For Azerbaijan, 29 records were located in the mountainous areas northeast and southwest of the central valley. Average basin precipitation values are variable but relatively high compared to the southern and eastern parts of the country. The flood series have been analysed in the same way as the other records.

To summarize, we have 102 records in Armenia, 105 in Georgia and 29 in Azerbaijan; the record length averages 40 years in Armenia and 30 years in Georgia and Azerbaijan. With the great variety of precipitation values and seasonality (Table 1 and Figure 3), this distribution (Figure 4) provides a good sample from which to study the effect of climate on flood series.

Seasonal distribution of floods

The seasonal aspect of floods in the Caucasus has long been noted. As Leo Tolstoy observed in 1852: "in the Caucasus rivers are apt to overflow in July" (Tolstoy 1852). However, in the south Caucasus at least, this seasonality varies regionally and provides a useful clue to flood frequency distribution.

The months of occurrence of annual maximum floods were displayed in histograms showing the number occurring in each calendar month. These graphs showed that flood distribution is indeed highly seasonal, but the seasonality varies with location. A broad summary of the regional climate characteristics is given in Table 1.

For example, in northern Armenia the floods occurred in April or May but also later, as in stations 6 and 20 (Figure 5). In southern Armenia, the floods were even more concentrated in April and May (stations 74 and 102). This difference corresponds to the single precipitation season in the north and the two seasons to the south. Comparison of the peak and daily floods and their dates provided a basis for separating snowmelt floods from rainfall storm events. This information for northern Armenia, where precipitation and floods extend through the summer, showed the difference between early snowmelt events and later rainfall events. Figure 6 from Station 6 (3,740 km^2 and 476 m) and Station 20 (94 km^2 and 1,814 m) illustrates the importance of rainfall events to the flood frequency curves. In southern Armenia, the spring and autumn precipitation means that there are fewer floods after the April/May period as autumn soil moisture deficits are likely to be high and the flood

Table 1 | Summary of main climate characteristics

Region	Stations	AAR	Precipitation distribution
Armenia southwest	60	500–1,000	Bimodal April/October
Armenia northeast	42	600–1,000	Unimodal May/June max.
Georgia west	64	1,200–2,000+	Autumn/winter max.
Georgia east	41	600–1,200	Summer max.
Azerbaijan southwest	19	500–800	May/October
Azerbaijan northeast	10	500–1,600	October/May

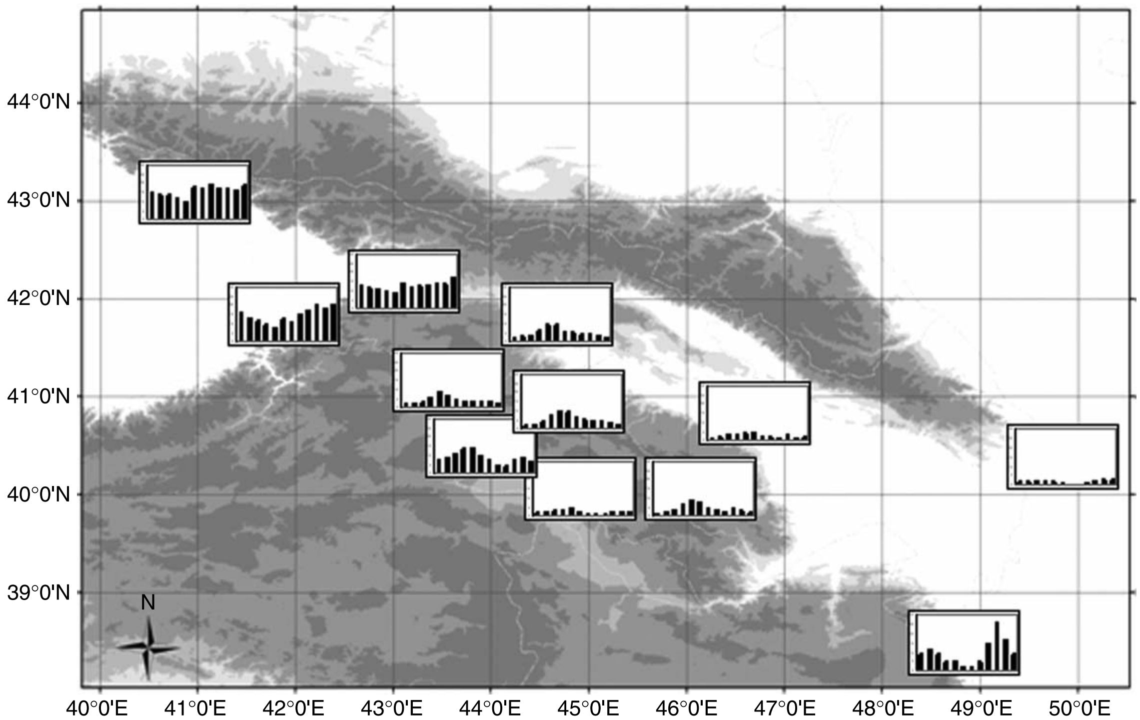

Figure 5 | Seasonal distribution of annual maximum floods at typical stations.

frequency curves are less skewed. In this case, the effect of the seasonal precipitation on dimensionless frequency curves is simply explained.

In Georgia, the distribution of floods is geographically more complex in accordance with the seasonal distribution of precipitation. In northwest Georgia, in the basins of the Kodori and adjacent streams (1–47), floods are distributed between May and September (station 10) with incidence varying somewhat within that range at different stations. Further east, over an area ranging from Kutaisi to Telavi, the floods are spread over a longer period (station 56) with peaks in the spring. In southwest Georgia, on the other hand (station 83), floods are spread between February and September with a peak in October. In a limited area of south central Georgia (102–125, 151–156), the distribution is similar to northern Armenia, with peaks at a maximum in April and May. The difference between northwest and southwest Georgia is due to the precipitation seasonality, as is the similarity between southern Georgia and northern Armenia.

In northern Azerbaijan, the distribution of annual maximum floods has a typical maximum in May and June, but the flood season extends over some seven months up to October (Station 78). This results from the autumn precipitation and the variation of soil moisture deficit.

It is important to take these different flood distributions into account when grouping stations into regions to derive joint frequency curves. It is important to note the correspondence between seasonal distributions of precipitation and flood incidence.

FLOOD ANALYSIS: MEAN ANNUAL FLOOD

The records described provide annual flood series at stations where basin area and mean annual precipitation have been estimated, and where groups of stations in larger river basins share a similar seasonal distribution. This section describes the analyses of these flood records and the conclusions which may be drawn. The results are given in some detail, as they may be useful locally and also illustrate the process of region selection. They provide empirical support, based on measured floods, to some of the

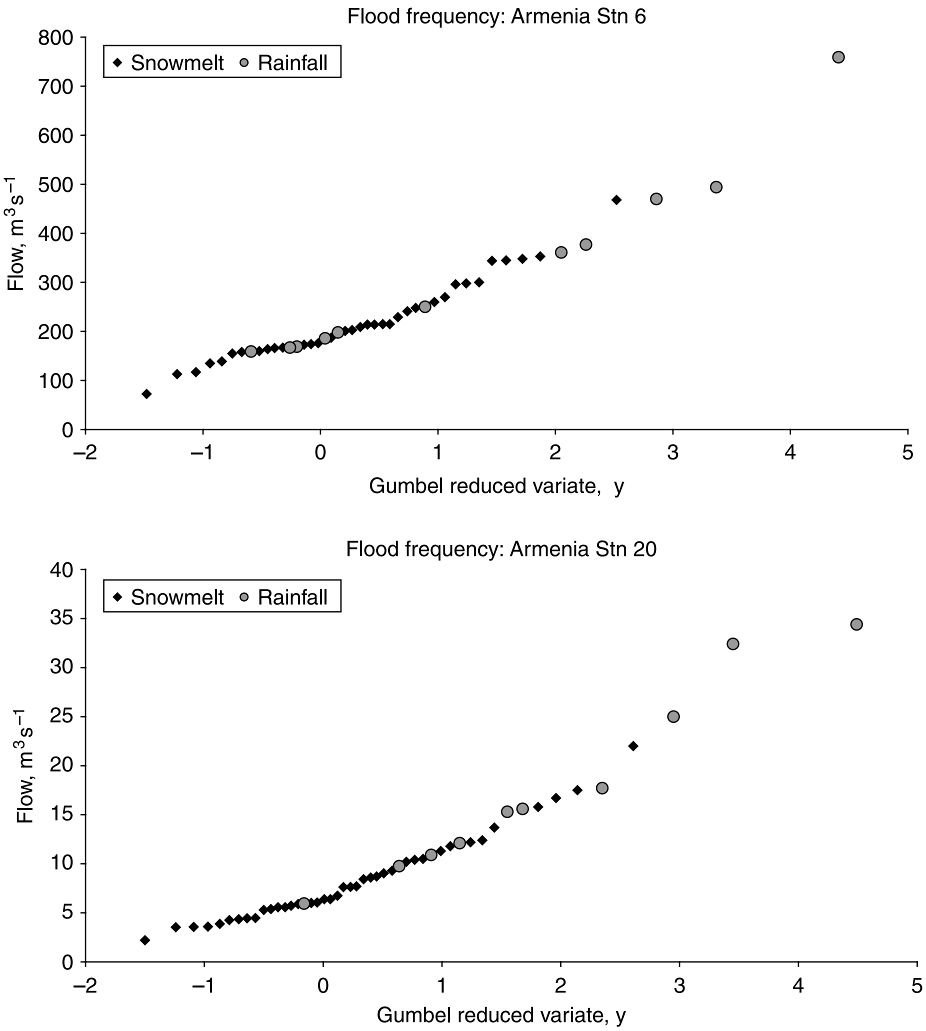

Figure 6 | Flood frequency curves for example stations in northern Armenia, showing rainfall and snowmelt events.

sensitivity analysis based on the simulation studies described in the Sensitivity Analysis section.

The statistics for 230 stations in the three countries were summarized earlier. From these statistics, regressions were carried out in logarithmic form between mean annual flood (MAF, in $m^3 s^{-1}$), basin area (AREA, in km^2), and basin mean annual precipitation (AAR, in mm). For example, in the case of Armenia, the mean annual flood is given by:

$$MAF = 2.529 \times 10^{-6} AREA^{0.782} AAR^{1.764} \quad (2)$$

These countrywide regressions are summarized in Table 2. Three very large basins on the Araks have been omitted from the regression in Armenia as they are unrepresentative. It will be noted that both AREA and AAR are significant predictors of MAF in each of the countries. This is particularly true for Georgia where the range of precipitation is very wide.

For Armenia, where the difference in seasonal precipitation distribution between the northeast and southwest affects mean annual runoff, regressions were carried out for the stations in the northeast and southwest separately (Table 3), and for the whole country. There were small differences between the three regressions and the mean annual flood estimates generally varied little between the two regions, although the predicted MAF was up to 10% higher in the northeast.

In the case of Georgia, the MAF values are compared with AREA in Figure 7. The records are divided between

Table 2 | Regression of MAF on AREA and AAR

Stations	Stn-years	Factor	Constant	Exponent	Std error	R^2	FSEE
Armenia (99)	4027	AREA	0.338	0.733	0.035	0.817	1.697
		AREA	2.529×10^{-6}	0.782	0.031	0.872	1.559
		AAR		1.764	0.274		
Georgia (105)	3325	AREA	0.656	0.765	0.037	0.802	1.838
		AREA	5.427×10^{-5}	0.833	0.022	0.936	1.415
		AAR		1.278	0.087		
Azerbaijan (29)	859	AREA	0.945	0.578	0.086	0.625	1.778
		AREA	8.94×10^{-4}	0.641	0.081	0.709	1.675
		AAR		0.990	0.360		

Table 3 | Armenia: regional regression for MAF

Stns	Stn-years	Factor	Constant	Exponent	Std error	R^2	FSEE
Northeast (36)	1633	AREA	6.7534×10^{-8}	0.8146	0.054	0.872	1.521
		AAR		2.2814	0.832		
Southwest (63)	2394	AREA	2.89594×10^{-6}	0.7756	0.040	0.871	1.595
		AAR		1.7520	0.313		

those where the mean precipitation is above or below 1,000 mm. The sharp difference between the two sets of records emphasizes the range and importance of precipitation in this region. Regression analysis was carried out separately for two categories of basin: those with AAR below 1,000 mm and those with higher mean precipitation. The results are presented in Table 4 and show a similar degree of success as the countrywide analysis in terms of R^2 (the coefficient of multiple determination) and factorial standard error of estimate (FSEE, where 67% of MAF estimates should lie within the range MAF × FSEE and MAF/FSEE).

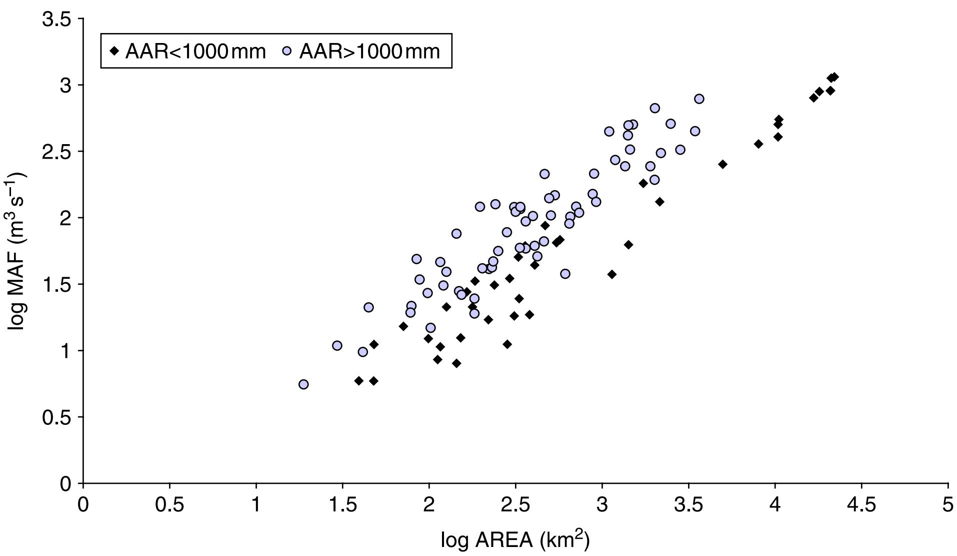

Figure 7 | Georgia: MAF versus AREA (for AAR $<$ 1,000 mm and AAR $>$ 1,000 mm).

Table 4 | Georgia: regional regression for MAF

Stns	Stn-years	Factor	Constant	Exponent	Std error	R^2	FSEE
AAR < 1,000 mm	1437	AREA	7.8435×10^{-4}	0.8031	0.032	0.944	1.493
(41)		AAR		0.9045	0.694		
AAR > 1,000 mm	1888	AREA	1.2401×10^{-5}	0.8852	0.032	0.929	1.356
(64)		AAR		1.4372	0.1688		

The results of regression analysis for the stations in Azerbaijan are presented in Table 2. The results are less precise than for the other countries, because of the smaller number of stations available for analysis (see Meigh *et al.* 1997).

ANALYSIS OF REGIONAL FLOOD FREQUENCY CURVES

The different regions based on climate characteristics may be summarized as in Table 5. The results of fitting Generalized Extreme Value (GEV) distributions to the regional datasets by Probability Weighted Moments (PWM) are summarized in Table 5 and Figure 8.

Some of the differences are readily explicable. The difference in rainfall total between west and east Georgia is very great; in western Georgia, the mean precipitation is about 1,200–2,000 mm with local peaks up to 4,000 mm, while to the east of the ridge dividing the two areas, it falls to about 600–1,200 mm. The difference between the two regional curves reflects this difference clearly. However, when the different basins are studied in greater detail, the picture is more complex than this contrast suggests.

In Armenia, there is a difference in the climate and the flood frequency curves between the northeast and the rest of the country, but the distinction is not as pronounced as in Georgia. The average precipitation in northeast Armenia is somewhat higher than in the south, but the dimensionless frequency curve is also rather higher; however, the difference in seasonal distribution of precipitation, which is illustrated by the marked difference in natural vegetation, explains this contradiction. The precipitation in the northeast occurs in a single season, during the summer, and its incidence spans the snowmelt season and the later period when soil moisture deficit increases. The flood season ranges from the snowmelt period to the period when net rainfall, or rainfall minus soil moisture deficit, is increasingly variable. In southern Armenia, the precipitation season is divided between April/May and the autumn, when the net rainfall is less likely to give rise to floods. As a result of the difference in seasonal distribution in northeast Armenia, the flood frequency curve is therefore slightly steeper in spite of the higher precipitation. This difference is not large, but is sufficient to demonstrate that annual precipitation is not the only variable.

The detailed results of analysis of regional flood frequency curves are summarized in Table 6 for Armenia. The curves for individual basins are given, and there is little difference between the curves for adjacent basins. One curve has been derived from the small basins over the whole country to investigate whether small basins have steeper curves than larger basins; there appears to be little difference. The most significant division appears to be between the NE basins and the rest of the country. These

Table 5 | Statistics of regional dimensionless frequency curves

Region	Stns	Years	*u*	α	*k*	*q*(100)	*q*(200)	*q*(500)
Armenia (southwest)	60	2394	0.735	0.351	−0.1545	3.09	3.61	4.40
Armenia (northeast)	42	1739	0.701	0.369	−0.1932	3.43	4.10	5.13
Georgia (west) (>1,000 mm)	64	1888	0.775	0.293	−0.1637	2.79	3.25	3.94
Georgia (east) (<1,000 mm)	41	1437	0.708	0.331	−0.2392	3.48	4.23	5.44
Azerbaijan (southwest)	19	586	0.668	0.392	−0.2170	3.76	4.56	5.82
Azerbaijan (northeast)	10	273	0.640	0.375	−0.2826	4.18	5.24	6.99

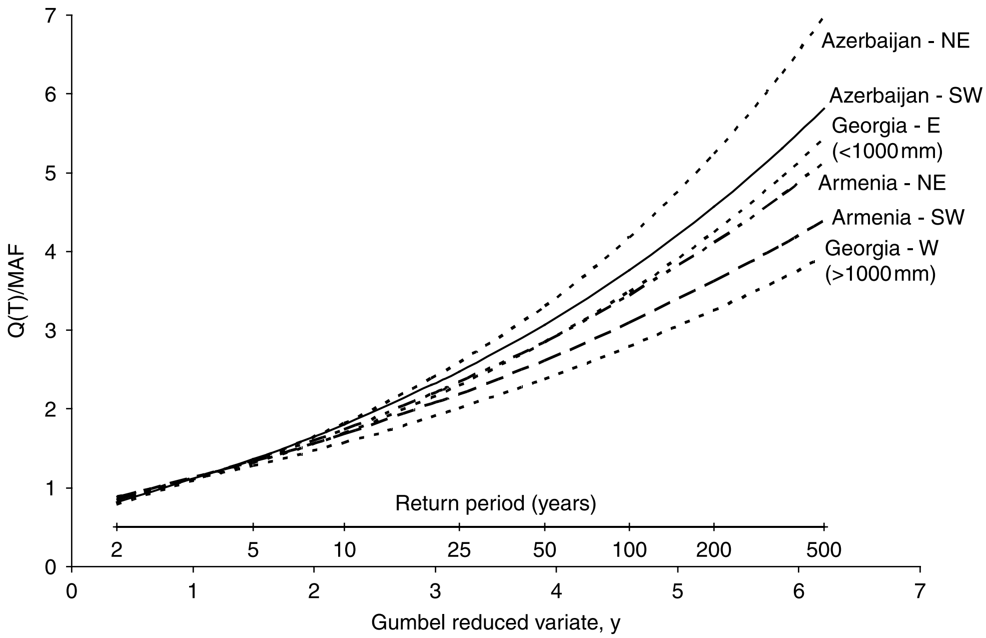

Figure 8 | Regional dimensionless frequency curves (Table 5).

two curves, together with curves for the whole country and small basins, are illustrated in Figure 9.

In fact, the annual rainfall patterns in northeast Armenia, eastern Georgia and western Azerbaijan are relatively similar, and the frequency curves are not dissimilar. Other areas in each country diverge somewhat in rainfall pattern and dimensionless frequency curve.

The equivalent detailed analysis of basins and groups of basins in Georgia is included in Table 7. The individual basin groups are listed, and these are grouped into seven groups by combining similar adjacent basins. These are further combined into five geographical regions and finally into two groups based on annual precipitation values divided at 1,000 mm; these seven curves are illustrated in Figure 10.

Although the marked contrast between the wet western basins and the drier eastern basins is reflected in the broad flood frequency curves, it is also evident that the basins adjacent to the Black Sea (geor1,2,4; see Table 7) receive

Table 6 | Summary of regional flood frequencies in Armenia

Region	Stns	No	Years	Rain	*u*	α	*k*	*q*(200)
Debet	1–15	15	640	741	0.724	0.333	−0.2048	3.91
Agstev	16–27	12	551	710	0.689	0.402	−0.1670	4.11
Ahurian	28, 30–43	15	548	727	0.687	0.376	−0.2077	4.32
Kasah	44–54	11	414	582	0.700	0.361	−0.2071	4.18
Razdan	56–63	8	300	719	0.757	0.316	−0.1644	3.42
Sevan	64–66, 68–80	16	656	630	0.762	0.365	−0.0714	3.11
Arpa	81–94	14	571	736	0.732	0.352	−0.1585	3.65
South	95–99, 101–105	11	453	770	0.717	0.345	−0.1989	3.95
Armenia (northeast)	1–43	42	1739	727	0.701	0.369	−0.1932	4.10
Armenia (southwest)	44–105	60	2394	683	0.735	0.351	−0.1545	3.61
Armenia	1–105	102	4133		0.720	0.358	−0.1718	3.82
Armenia Small	AREA $< 1{,}000\,km^2$	78	3111		0.720	0.365	−0.1625	3.78

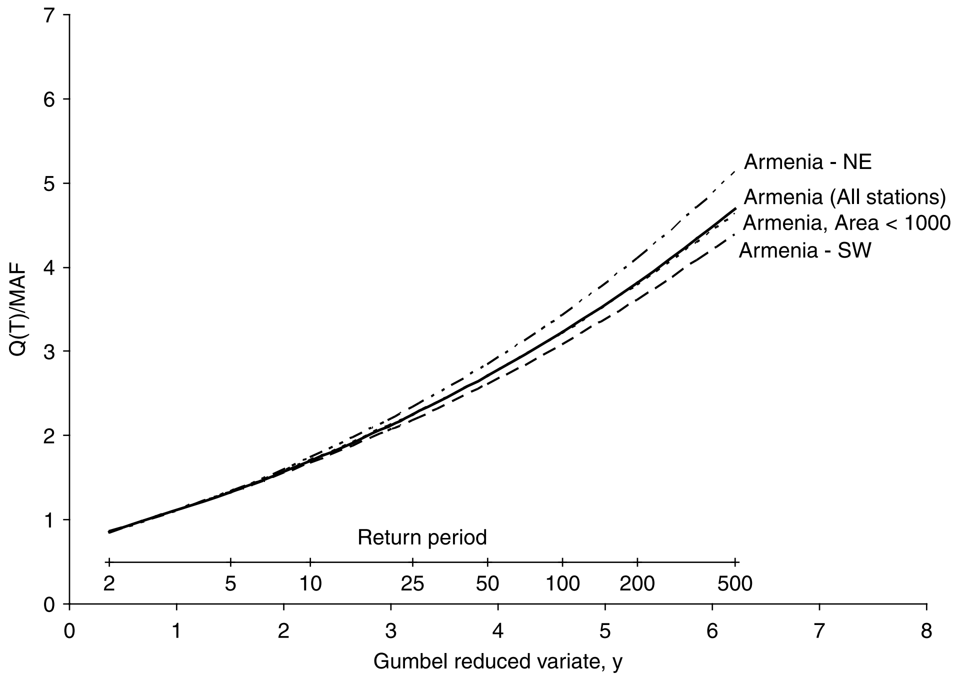

Figure 9 | Regional flood frequency curves for Armenia (Table 6).

storms from the sea which are reflected in the widespread seasonal distributions of the flood regimes. Among the drier basins to the east of the country, the Khrami tributaries in the shadow of the Lesser Caucasus range (geor8) have the most skewed flood frequency curve.

In northeastern Azerbaijan, the available stations reveal a lengthy season of flood incidence, with resulting variability of antecedent conditions within the basins. The resulting flood frequency curve (Table 5 and Figure 8) is very steep and curved.

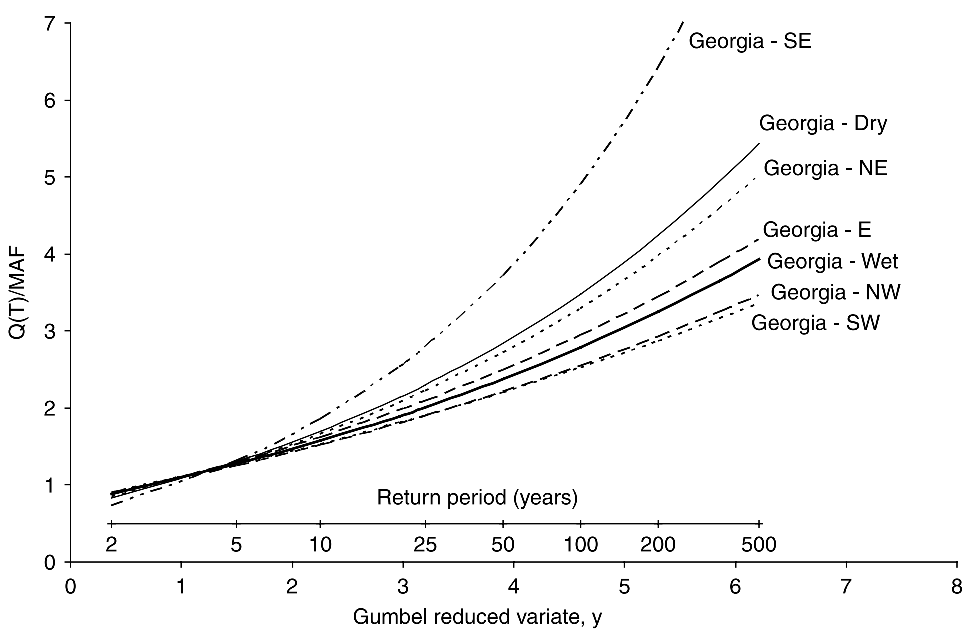

Figure 10 | Summary of regional flood frequency curves for Georgia (Table 7).

Table 7 | Summary of regional flood frequency curves for Georgia

Group	Stations	No.	Years	Rain	u	α	k	$q(200)$
Geor1 Kodori	1–15	9	156	2311	0.785	0.250	−0.2236	2.80
Geor2 Inguri	20–35	6	118	1600	0.769	0.245	−0.2723	3.02
Geor3 Rioni	39–73	22	631	1368	0.809	0.289	−0.0801	2.42
geor4 Adzharis	81–99	11	322	1441	0.781	0.282	−0.1696	3.20
geor5 U Kura mstm	102–10	9	386	706	0.813	0.297	−0.0501	2.61
geor6 U Kura tribs	117–28	12	422	767	0.761	0.310	−0.1655	3.39
geor7 Lr Kura tribs	129–46	13	527	1136	0.749	0.328	−0.1616	3.50
geor8 Khrami tribs	149–68	16	534	706	0.589	0.368	−0.3586	6.41
Geor9 Alazani	170–79	7	229	1428	0.724	0.323	−0.2207	3.97
Combined groups								
Geor1(+2)	1–35	15	274	2027	0.778	0.248	−0.2453	3.47
Geor3	39–73	22	631	1368	0.809	0.289	−0.0801	2.71
Geor4(+5)	81–110	20	708	1110	0.798	0.290	−0.1079	2.87
Geor6(+7)	117–46	25	949	959	0.754	0.320	−0.1633	3.45
Geor8	149–68	16	534	706	0.589	0.368	−0.3586	6.41
Geor9	170–79	7	229	1428	0.724	0.323	−0.2207	3.97
All	1–179	105	3325	1219	0.746	0.309	−0.2008	3.67
Geographical groups								
Northwest	1–73	37	905	1635	0.799	0.276	−0.1335	2.93
Southwest	81–110	20	708	1368	0.798	0.290	−0.1079	2.87
Southeast	149–68	16	534	706	0.589	0.368	−0.3586	6.41
East	117–46	25	949	959	0.754	0.320	−0.1633	3.45
Northeast	170–79	7	229	1428	0.724	0.323	−0.2207	3.97
Climate groups								
Wet (AAR > 1,000 mm)		64	1888	1533	0.775	0.293	−0.1637	3.25
Dry (AAR < 1,000 mm)		41	1437	729	0.708	0.331	−0.2392	4.23

CONCLUSIONS

The analysis has shown that before grouping stations to derive regional frequency curves, it is essential to consider all aspects of the climate and hydrology of the project area. It is important to take into account not only total precipitation but also its seasonal distribution. The example of the south Caucasus has confirmed previous regional studies and synthetic studies to show that a prime determinant of the shape of flood frequency curves is the interaction of storm precipitation and antecedent basin state in terms of soil moisture deficit. A typical storm frequency curve is therefore distorted by soil moisture deficit distribution to provide significantly steeper and skewed dimensionless curves than those of storms alone.

Taking the regional curves from west to east, and treating them in terms of seasonal distribution of precipitation and soil moisture deficit, the precipitation is fairly heavy through the year in northwest and southwest Georgia, so that SMD is not very variable and runoff coefficients are fairly constant. The flood frequency curves are therefore fairly linear and of moderate gradient, although the incidence of storms near the coast has some effect. The southern centre of Georgia is similar to northeast Armenia, where the distribution of precipitation is centred around May/June when the SMD is starting to increase after the winter. The runoff is therefore likely to be more variable and the frequency curve steeper than southern Armenia, where the precipitation is at its maximum in late spring when the SMD is minimal.

In much of eastern Georgia and northeast Azerbaijan, the precipitation is spread through the year but there is a concentration in the autumn. The SMD at the time of flood-producing storms is likely to be higher and more variable than elsewhere. The result is that net precipitation and runoff coefficient are more likely to be low but variable and the resulting flood frequency curve is liable to be steeper and more skewed than in other areas.

Clues to areas of homogeneous flood-producing climates are not only annual average precipitation, given by isohyetal maps, but also correspondence of storm incidence with the seasonal cycle of soil moisture deficit. Indicators are climate incidence and seasonal distributions of floods and even vegetation distribution, which may illustrate differences in flood regime. At the very least, annual average precipitation analogues should be confined to those stations with similar climate seasonality, seasonal flood distribution or even vegetation.

To summarize the findings of this paper, the variable distributions of precipitation and resulting soil moisture deficit interact and lead to a wide variety of regional flood frequency curves as predicted by synthetic predictions. This illustrates the importance of selecting homogeneous regions for flood analysis, not only of total annual precipitation but also its seasonal distribution and links with the annual cycle of soil moisture deficit.

ACKNOWLEDGEMENTS

We thank Professor Enda O'Connell for useful discussions and directing us towards relevant papers. We would also like to thank Ljiljana Spasic-Gril and our colleagues in the various countries for their help, especially Mr Torosyan in Armenia and Mr Baadur Ukleba in Georgia. We also thank anonymous referees for useful comments.

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First received 20 September 2007; accepted in revised form 11 March 2008