Regional Climate Change Impacts Study for the South Caucasus Region

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Acknowledgements

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Executive Summary

This report represents the first cooperative study on the impacts of climate change and adaptation in the South Caucasus involving all three countries in the region - Armenia, Azerbaijan and Georgia. The study has considered four areas for investigation: (1) recent historical and projected climate change, (2) impacts of climate change on transboundary river basins, (3) impacts of climate change on crop water and irrigation requirements in critical agricultural areas, and (4) the effect of climate change on urban heat stress in selected cities in the region.

Climate change is already occurring in the South Caucasus. In all three countries there is strong evidence of increased warming over the last century. At country-level, Armenia, Azerbaijan and Georgia all show statistically increasing trends in mean annual temperature, mean daily minimum temperature and mean daily maximum temperature, though there are no trends in mean annual precipitation nor the number of wet days per year. In terms of meteorological stations, about half in Armenia and Azerbaijan and about one quarter in Georgia show statistically significant trends in annual temperature. The evidence concerning annual precipitation is less convincing, although there are stations in Armenia and Azerbaijan that have experienced precipitation declines. In Georgia there are no signs of decline in annual precipitation, but two stations in the southwestern part of the country show an increase in precipitation. This study also represents the first examination of extreme climate indices. Almost all the meteorological stations in all three countries have recorded increases in the duration of warm spells – either consecutive days above 25 ºC or consecutive nights higher than 20 ºC. However, there is no strong evidence that the maximum time gap between rainfall events is changing in the South Caucasus.

This study carries on the work on future climate projections presented in the Second National Communications of Armenia, Azerbaijan and Georgia with regard to the Framework Convention on Climate Change by assessing climate projections from a set of coarse-scale General Circulation Models. All four models that simulate historical climate reasonably well in the region project declines in precipitation for all three countries: 20 – 31% in Armenia, 5-23% in Azerbaijan, and 0 – 24% in Georgia by the end of the century (A2 emissions scenario). From this assessment, there is no further support for projections of increased precipitation in Azerbaijan at the end of the century. **The evidence seems to suggest that with the exception of one model result the South Caucasus it will continue to become drier this century**. This report is a cautionary note about relying on one climate model future, one climate model projection. **All climate models are in agreement that the South Caucasus will become warmer**. Across the four selected GCMs, the projected change in mean annual temperature is: 1.1 ºC – 1.9 ºC, 1.0 ºC – 1.6 ºC, 0.9 ºC – 1.9 ºC for Armenia, Azerbaijan and Georgia, respectively (A2 emissions scenario). By 2100, the increase may be dramatic: 4.4 ºC-5.5 ºC, 3.6 ºC-4.1 ºC, and 4.1 ºC-5.5 ºC, respectively, for the three countries (A2 emissions scenario).

Water supply is likely to decrease in important transboundary basins. Future streamflow was assessed for the transboundary Alazani (Ganikh) (Azerbaijan/Georgia), Khrami-Debed (Armenia/Georgia) and the Aghstev (Armenia/Azerbaijan) River Basins. Due to the projected decline of precipitation and increase in temperatures, by the end of the century, streamflow is projected to decline dramatically: 26 - 35%, 45 – 65%, and 59 – 72% in the Alazani (Ganikh), Khrami-Debed and Aghstev Basins, respectively. In Alazani, at least, even very modest increases in water demand of even 10% - through increased agricultural water demand and population growth - will likely lead to shortfalls in the summer (August) by 2050. Most of the water in these Basins is used in agriculture, therefore increasing water use efficiency by employing such methods as advanced micro-irrigation technologies (e.g. sprinklers and drip irrigation) will help ameliorate the decreasing water availability. Additional adaption measures include demand-side conservation measures and possibly an increase of storage to address increased variability and shortfalls in high demand (i.e. summer) months. For effective climate change adaptation planning in these Basins, it is imperative that trans-national river management plans are enacted that include comprehensive water accounting.

Substantially more water will be required in the future in critical agricultural areas to maintain the current cropping pattern due to a likely decrease of precipitation and an increase of temperature. Future crop water and irrigation requirements were projected for the main crops in three important agricultural regions in the South Caucasus, namely the Ararat Valley (Armenia), the Belakan region (Azerbaijan), and the Dedoplistskaro region (Georgia). In the Ararat Valley, by the end of the century, the crop water requirements (CWR) for winter wheat and vegetables is projected to increase 19 – 22% and 19 – 23%, respectively, compared to 1967 – 1982, while the irrigation water requirement (IWR) is projected to increase 35% - 36% and 38% - 42% for winter wheat and vegetables, respectively. In Belakan, there is expected to be only a slight increase in CWR. However, IWR is projected to increase from nearly zero to approximately 50 mm and 110 mm for spring wheat and pasture, respectively (2076 - 2100 vs. 1998 – 2010). Lastly, for Dedoplistskaro by 2100, irrigation requirements for winter wheat, pasture and sunflower are expected to increase 114%, 82%, and 50%, respectively, compared to 1991 – 2005. Regardless of the exact quantitative projections on CWR and IWR it is clear that maintaining the current compliment of crops in these regions will require significantly more water, which may not be available (see above). There are many adaption actions that can be undertaken, most notably the use of advanced micro-irrigation methods to conserve water (above), investments in drought-tolerant crops, the cultivation of less water-intensive and higher-valued crops (e.g. fruits and vegetables), measures to increase soil fertility and reduce soil erosion and reduce productivity losses (in Dedoplistskaro and Belakan), and crop, income and landscape diversification. All of these measures require significant investment in agricultural research and extension services by the respective national governments and the international community.

Urban heat stress may be a significant climate change-induced health issue in the South Caucasus. The projected change in the Heat Index was evaluated for three cities in the South Caucasus: Baku, Azerbaijan; Tbilisi, Georgia; and Vanadzor, Armenia. For Baku and Tbilisi, there is expected to be a dramatic increase in the number of 'dangerous' days by mid-century – roughly a trebling of days compared to present. While in Vanadzor, the increase in the absolute number of 'dangerous' days is rather small, although there is projected to be a sevenfold increase in the number of warm days between 2020 and 2040 compared to the present period. However, there needs to be more research into the current level of acclimation in these cities and how this urban heat stress may translate into increased mortality. As the South Caucasus is relatively urbanized and heat stress is likely to be the most serious climate change-related health issue, all the countries need to enact adaptation plans that address: reducing exposure to heat in urban areas (e.g. infrastructure measures), adopting preventive public health measures (e.g. surveillance and early warning systems) and ensuring the preparedness of the healthcare system and other care providers to respond to heat waves.

Climate change in the South Caucasus is a transnational challenge. Further regional co-operation would be beneficial in a number of areas, and future programs could include: the formulation of transboundary river management plans; the exchange of climate and hydro-meteorological data, the development of Early Warning Systems for natural disasters and seasonal forecasting; and the sharing of lessons learned in climate change adaptation projects, such as water conservation, natural disaster management and agriculture.

Chapter 1: Historical Climate and Future Climate Change

Summary

Climate change is already occurring in the South Caucasus. On the country-average scale, Armenia, Azerbaijan and Georgia all show statistically increasing trends in mean annual temperature, mean daily minimum temperature and mean daily maximum temperature over the last century, though there are no trends in mean annual precipitation, nor the number of wet days per year. About half of the meteorological stations in Armenia and Azerbaijan and about one quarter in Georgia show statistically significant trends in annual temperature. The evidence for trends in annual precipitation is less convincing, although there are stations in Armenia and Azerbaijan that have experienced precipitation declines. In Georgia, there are no decreasing trends in annual precipitation, but two stations in the southwestern part of the country show increasing trends in precipitation. Almost all the meteorological stations have recorded increases in the duration of warm spells – either consecutive days above 25 ºC or consecutive nights higher than 20 ºC. There is no strong evidence that the maximum duration between rainy days is changing in the South Caucasus. The economic losses suffered as a result of climate-related natural disasters and climate-influenced land use change, such as erosion, are significant in the region: at least $2.7 billion over the last 30 years.

In the Second National Communications to the UN Framework Convention on Climate Change, all three countries presented projections for the change in precipitation and temperature. All the climate models are in accord that the mean annual temperature will increase significantly by the end of the century (A2 emission scenario): 1.8 ºC-5.2 ºC and 3.5 ºC-4.9 ºC, in western and eastern Georgia, respectively; 4 ºC - 5.1 ºC in Armenia; and 3 ºC-6 ºC in Azerbaijan. However, there is a discrepancy when it comes to precipitation. One Regional Climate Model (PRECIS using the ECHAM 4 General Circulation Model) projects increases in mean annual precipitation in western Georgia and Azerbaijan, while other models (PRECIS using HadCM3, MAGICC/SCENGEN) for Georgia project declines. Projections from a set of coarse-scale General Circulation Models were assessed to extend the analyses in the Second National Communications. All four reliable models in the Region project declines in precipitation for all three countries: 20 – 31% in Armenia, 5- 23% in Azerbaijan, and 0 – 24% in Georgia by the end of the century (A2 emissions scenario). From this assessment, there is no further support for projections of increased precipitation in Azerbaijan at the end of the century. The evidence seems to suggest that with the exception of one model result (PRECIS/ECHAM4 in Azerbaijan) the South Caucasus will continue to become drier this century. The region is expected to become significantly warmer. By 2050, the projected change in mean annual temperature is: 1.1 ºC – 1.9 ºC, 1.0 ºC – 1.6 ºC, 0.9 ºC – 1.9 ºC for Armenia, Azerbaijan and Georgia, respectively, across the set of selected GCMs; by, 2100, it is projected to be 4.4 ºC – 5.5 ºC, 3.6 ºC – 4.1 ºC, and 4.1 ºC – 5.5 ºC, respectively (A2 emissions scenario).

Given the recent climate and projected climate change in the South Caucasus, further regional cooperation on climate and hydrometerological data exchange would be an important step for adaptation planning and building climate resilience in the Region.

Study Region

Figure 1 shows the three countries of the South Caucasus: Armenia, Azerbaijan and Georgia. The region is very topographically and climactically heterogeneous, including humid, coastal areas on the Black Sea; warm temperate areas; mountains; dry, subtropical plains; and semi-desert/steppe areas. Figure 2 shows the main Köppen-Geiger climate zones of the region. The country-averaged mean annual precipitation is 444 mm, 527 mm, and 955 mm, respectively in Azerbaijan, Armenia and Georgia (Table 1.1), while the country-averaged mean annual temperature is 6.3 °C, 7.0 °C, and 11.5 °C, respectively in Armenia, Georgia and Azerbaijan (Table 1.2) (See Appendix I – CRU Dataset). There is a distinct spring rainfall peak in April – June in all three countries (Figure 3), and a July-August peak in temperature (Figure 4).

Figure 1. The Caucasus Region

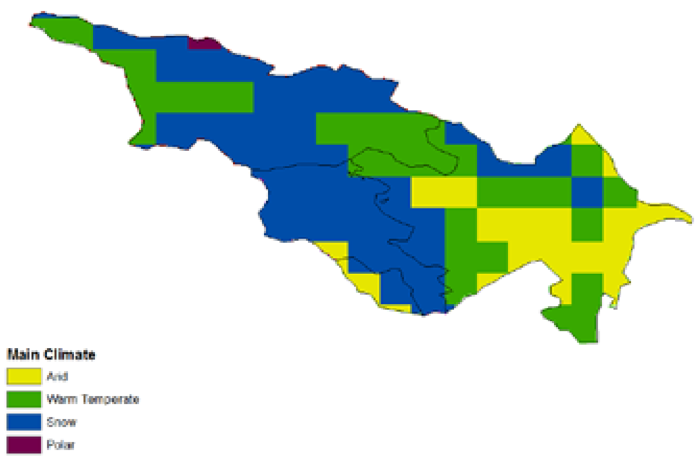

Figure 2. Köppen-Geiger climate classification for the South Caucasus (1976 – 2000[1]).

[1] The Kopper-Geiger classification is based on temperature and precipitation, using temperature data from the CRU TS 2.1. dataset (Climatic Research Unit (CRU) of the University of East Anglia, United Kingdom) and precipitation data from the GPCC Full v4 dataset (Global Precipitation Climatology Center (GPCC) at the German Weather Service. See [1].

Table 1.1. Historical precipitation (mm) for the South Caucasus (1901 – 2006).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean Annual
Armenia	21.5	24.6	41.3	60.0	85.4	73.5	49.7	37.1	36.0	41.3	34.1	22.7	527.1
Azerbaijan	24.9	25.7	40.4	49.8	56.1	50.7	30.2	25.1	37.2	42.5	35.4	25.9	444.0
Georgia	61.2	56.9	63.7	81.1	105.9	112.5	88.9	77.2	81.0	82.3	73.1	70.7	954.6

Table 1.2. Historical temperature (°C) for the South Caucasus (1901 – 2006).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Mean Monthly**
Armenia	-8.6	-6.7	-0.9	6.3	11.5	15.6	19.7	19.6	15.0	8.3	1.5	-5.2	6.3
Azerbaijan	-1.0	0.1	4.3	10.7	16.1	21.2	24.3	23.9	19.3	12.6	6.3	0.8	11.5
Georgia	-5.7	-4.6	0.1	6.9	12.0	15.5	18.6	18.6	14.4	8.7	2.7	-3.1	7.0

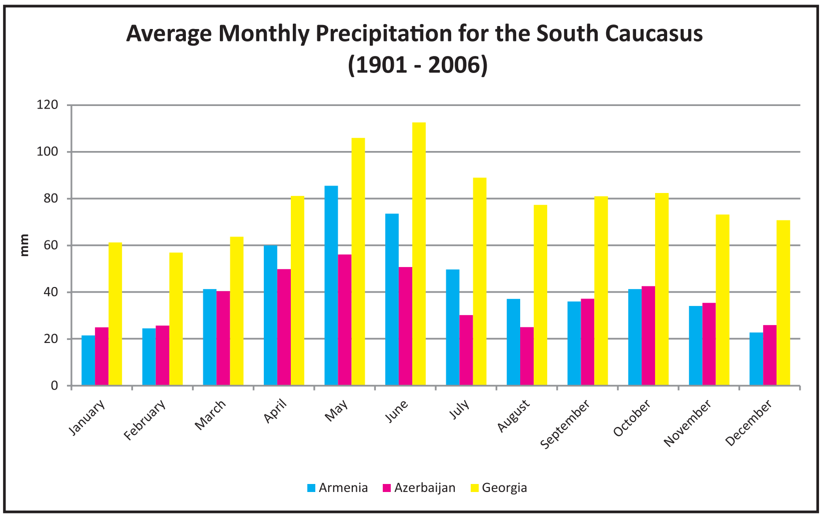

Figure 3. The monthly precipitation distribution in the South Caucasus. The values are the country (spatial) mean.

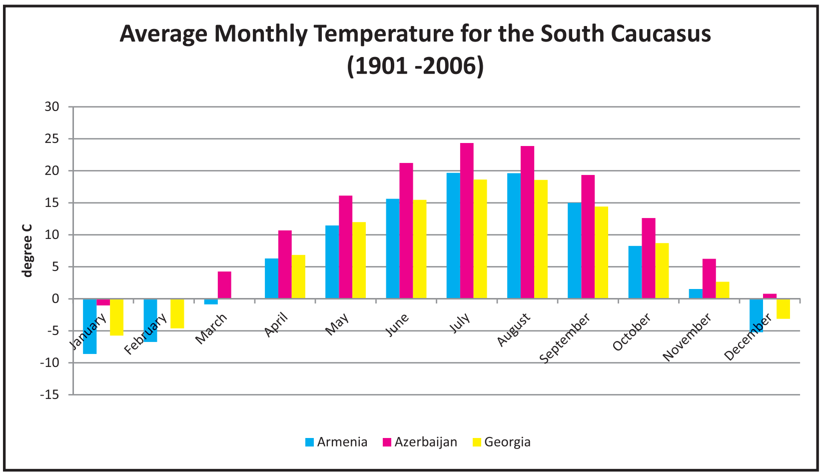

Figure 4. The monthly temperature distribution in the South Caucasus. The values are the country (spatial) mean

Recent Climate Change

Annual Temperature and Precipitation

Before analyzing projections of future climate change, it is instructive to assess how climate has changed historically in the region. Analyzing a global, gridded dataset of climate (See Appendix I, CRU Dataset), one can see that there are clear statistically significant year-to-year trends in mean annual temperature, mean daily minimum temperature and mean daily maximum temperature over the period 1901 – 2006 (Table 1.3). However, there are no statistically significant trends in mean annual precipitation and the number of wet days (i.e. number of days with precipitation > 0.1 mm) for the region. Even though these global data are informative, they are derived from spatial interpolation of meteorological station data. Thus, it is preferable to analyze the data from meteorological stations directly.

Table 1.3. Mann-Kendall trend analysis of historical precipitation and temperature for the South Caucasus (Blanks indicate no statistically significant trends.). Significance is set at the 95% level (α = 0.05). See Appendix II.

	Annual Precipitation	**Number of Wet Days Per Year**	**Mean Annual Temperature Per Year**	**Mean Daily Minimum Temperature Per Year**	**Mean Daily Maximum Temperature Per Year**
Armenia			**Increasing**	**Increasing**	**Increasing**
Azerbaijan			**Increasing**	**Increasing**	**Increasing**
Georgia			**Increasing**	**Increasing**	**Increasing**

Historical precipitation and temperature data from 30, 21, and 14 meteorological stations in Armenia, Georgia, and Azerbaijan, respectively, were analyzed for two time periods (Table 1.4, Figure 4)[2]. Figure 5 shows the change in mean annual temperature across the whole record of observation (See Table 1.4) compared to the baseline period of 1961 - 1990. For most of the region the change in temperature is in the range of 0 – 1.5 °C, while in some parts of

[2] Data obtained from the National Environmental Agency, Ministry of Environment Protection of Georgia; Armenian State Hydro-meteorological Service under the Ministry of Emergency Situation

Georgia and Azerbaijan, the change exceeds 1.5 °C, although the paucity of data in Azerbaijan does not allow one to make robust conclusions. Comparing mean annual precipitation across the two periods, parts of the South Caucasus, have experienced increases in precipitation, most notably the Black Sea region of Georgia (> 90 mm), while much of Armenia (except for Lake Sevan) and eastern Azerbaijan have experienced decreases. In parts of eastern Azerbaijan, for example, annual precipitation has decreased by 60-90 mm when compared to the baseline (Figure 6).

Table 1.4. List of meteorological stations analyzed in the South Caucasus (Note: The periods covered by the weather stations in each country vary, and within each country, many stations had missing values for various years. Not all stations had complete records for the period listed). See Figures 5 and 6 for their locations.

Armenia (1935 – 2008)	**Georgia (1936 – 2005)**	**Azerbaijan (1950 – 2005)**
1. Amasia	1. Lentehki	1. Sheki
2. Gyumri	2. Ambrolauri	2. Zakatala
3. Tashir	3. Kutaisi	3. Oguz
4. Stepanavan	4. Poti	4. Guba
5. Odzun	5. Samtredia	5. Shakhbuz
6. Ijevan	6. Mta-Sabueti	6. Lankaran
7. Dilijan	7. Goderdzi	7. Lerik
8. Shorja	8. Bakhmaro	8. Agstafa
9. Sevan	9. Khulo	9. Griz
10. Vanadzor	10. Batumi	10. Dashkasan
11. Aparan	11. Sachkhere	11. Gadabey
12. Talin	12. Abastumani	12. Alibay
13. Aragac	13. Gori	13. Yardimli
14. Hrazdan	14. Tsalka	14. Nakhchivan
15. Fantan	15. Akhaltsikhe	
16. Gavar	16. Tbilisi	
17. Armavir	17. Telavi	
18. Amberd	18. Pasanauri	
19. Ashtarak	19. Kvareli	
20. Yerevan agro	20. Saqara	
21. Yerevan arabkir	21. Dedoplistskaro	
22. Artashat		
23. Ararat		
24. Masrik		
25. Yeghegnadzor		
26. Vorotan		
27. Sisian		
28. Goris		
29. Kapan		
30. Megri		

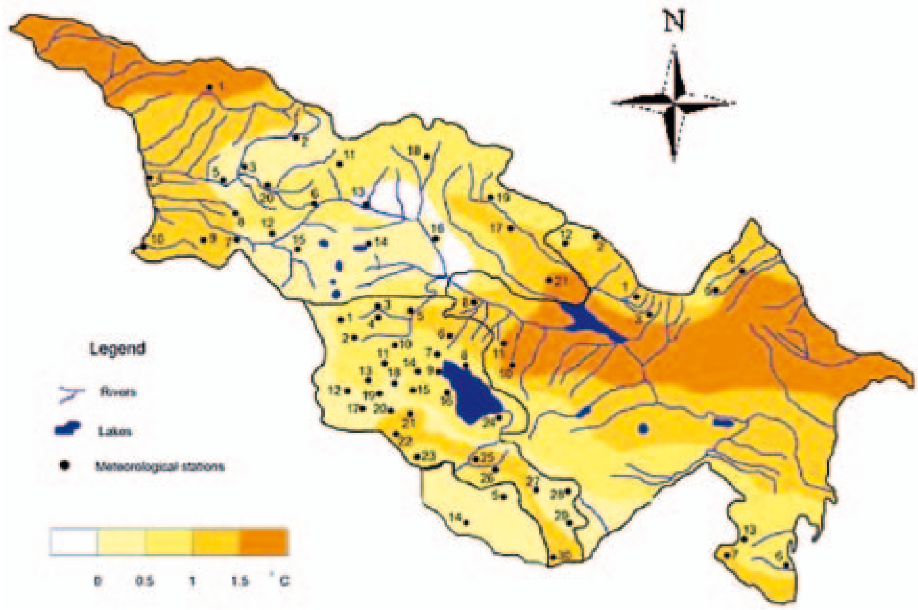

Figure 5. The change in mean annual temperature (°C) in the South Caucasus. The change is the averaged value across the whole record of observation compared to the baseline period of 1961 – 1990. The continuous values on the map are derived by ploting isoterms for equal values of anomalies and taking into account general features of relief.

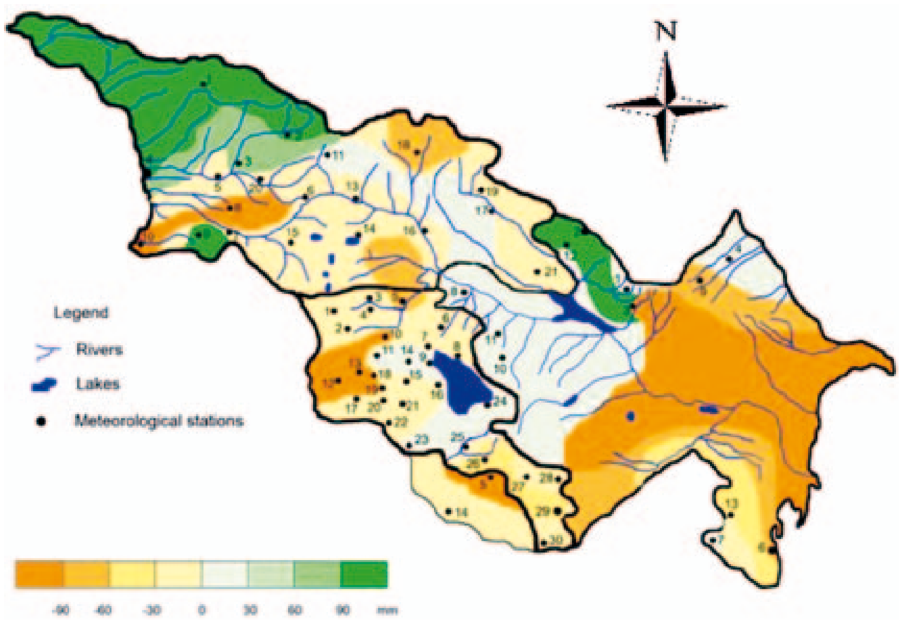

Figure 6. The change in mean annual precpitation (mm) in the South Caucasus. The change is the averaged value across the whole record of observation compared to the baseline period of 1961 – 1990.

The above comparison of two time periods does not actually gauge whether there are statistically significant trends in annual temperature and precipitation. Indeed, because the baseline period is in the middle of the range of the entire historical period, it is unclear whether the changes are due to the years prior to or after the baseline period. Once again, Mann-Kendall trend analysis was performed on the annual temperature and precipitation data of the meteorological stations in the South Caucasus (Table 1.5 – 1.7). Approximately half of the stations in Armenia and Azerbaijan show statistically significant trends in annual temperature, although fewer in Georgia do so. The evidence for trends in annual precipitation is less convincing, although there are stations in Armenia and Azerbaijan that have recorded precipitation decreases. Only one in Armenia – Lake Sevan, has recorded an increase in precipitation over time. In Georgia there are no decreasing trends in annual precipitation, but two stations in the southwestern part of the country (Ogerzi and Khulo) show increasing trends in precipitation.

Table 1.5. Mann-Kendall trend analysis of historical annual precipitation and temperature for the meteorological stations in Armenia (1935 – 2008). (Blanks indicate no statistically significant trends.). (Not all stations had complete records for the period listed.) Significance is set at the 95% level (α = 0.05). See Appendix II.

Meteorological Station	Annual Precipitation	Annual Temperature
Amasia		**Increasing**
Amberd	**Decreasing**	
Aparan		**Increasing**
Aragac	**Decreasing**	
Ararat		
Armavir		
Artashat		**Increasing**
Ashtarak		
Dilijan		
Fantan		
Gavar		**Increasing**
Goris		
Gyumi		**Increasing**
Hrazdan		**Increasing**
Ijevan		**Increasing**
Kapan		**Increasing**
Masrik		
Meghri		**Increasing**
Odzun		
Sevan	**Increasing**	
Shorja		
Sisian		**Increasing**
Stepanavan		
Talin	**Decreasing**	
Tashir		
Vanadzor	**Decreasing**	**Increasing**
Vorotani	**Decreasing**	**Increasing**
Yeghegnadzor		**Increasing**
Yerevan Agro		
Yerevan Arabkir		**Increasing**

Table 1.6. Mann-Kendall trend analysis of historical annual precipitation and temperature for the meteorological stations in Azerbaijan (1950 – 2005). (Blanks indicate no statistically significant trends.). (Not all stations had complete records for the period listed.) Significance is set at the 95% level ($\alpha = 0.05$). See Appendix II.

Meteorological Station	Annual Precipitation	Annual Temperature
Agstafa		
Alibay	**Decreasing**	
Dashkasan		**Increasing**
Gadabey		**Increasing**
Griz		
Guba		**Increasing**
Lankaran		**Increasing**
Lerik		
Nakhchivan	**Decreasing**	
Oguz		
Shakhbuz	**Decreasing**	
Sheki		**Increasing**
Yardimli		
Zagatala		**Increasing**

Table 1.7. Mann-Kendall trend analysis of historical annual precipitation and temperature for the meteorological stations in Georgia (1959 – 2005). (Blanks indicate no statistically significant trends.). (Not all stations had complete records for the period listed.) Significance is set at the 95% level (α = 0.05). See Appendix II.

Meteorological Station	Annual Precipitation	Annual Temperature
Abastumani		**Increasing**
Akhaltsikhe		
Ambrolauri		
Bakhmaro		
Batumi		
Dedoplistskaro		
Goderzi	**Increasing**	**Increasing**
Gori		
Khulo	**Increasing**	
Kvareli		
Lentheki		
Mta_sabueti		
Pasanauri		**Increasing**
Poti		
Kutaisi		
Sachkhere		
Samtredia		
Saqara		
Tbilisi		**Increasing**
Telavi		**Increasing**
Tsalka		

It is not simply changes in annual temperature and precipitation that are important, but whether there is a change in precipitation and temperature extremes. Three extreme climate indices were evaluated for the region using the RClimMDex (1.0) software. This software provides a user-friendly interface to compute indices of climate extremes. It computes all 27 core indices recommended by the CCl/CLIVAR Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) as well as some other temperature and precipitation indices with user defined thresholds. The 27 core indices include almost all the indices calculated by RClimDex. The current version of RClimDex has been developed under R 1.84, therefore it should run with R 1.84 or a later version. Thus, the following extreme climate indices were evaluated through the application of RClimMDex: C*DD*, or the maximum number of consecutive dry days per year; *SU25*, or the number of days where the daily maximum exceeds 25 ºC; and *TR20*, or the number of days where the daily minimum exceeds 20 ºC (Table 1.8). There is a clear trend in the values of *SU25* across Armenia and Georgia: 24 of 29 stations in Armenia and 12 of 21 stations in Georgia have statistically significant positive trends. Thus, the duration of warm spells is increasing in Armenia and Georgia. The pattern is not as robust for *TR20*, but there are a number of stations where there is an increasing trend. For Azerbaijan, the duration of periods of warm nights is increasing, but the dataset is limited. Finally, there is little evidence across the countries that the maximum interval between rainfall events is changing (Tables 1.9 – 1.11). It should be noted, though, that this is only one measure of rainfall variability.

Table 1.8. Extreme climate indices investigated for the South Caucasus

Index	**Explanation**
CDD	Maximum consecutive number of dry days per annum , where a dry day is one with < 1mm of precipitation
SU25	Number of days per annum where the daily maximum >25ºC
TR20	Number of days per annum where the daily minimum >20ºC

Table 1.9. Mann-Kendall trend analysis of climate extremes for the meteorological stations in Armenia (1935 – 2008) (Blanks indicate no statistically significant trends.). (Not all stations had complete records for the period listed.) Significance is set at the 95% level (α = 0.05). See Appendix II.

Meteorological Station	**CDD**	**SU25**	**TR20**
Amasia		**Increasing**	
Amberd			
Aparan		**Increasing**	
Aragac	**Increasing**		
Ararat		**Increasing**	**Increasing**
Armavir		**Increasing**	
Artashat		**Increasing**	**Increasing**
Ashtarak		**Increasing**	
Dilijan		**Increasing**	
Fantan		**Increasing**	
Gavar	**Decreasing**	**Increasing**	
Goris		**Increasing**	
Gyumi		**Increasing**	
Hrazdan		**Increasing**	
Ijevan		**Increasing**	**Increasing**
Kapan		**Increasing**	
Masrik		**Increasing**	
Meghri		**Increasing**	**Increasing**
Odzun		**Increasing**	**Increasing**
Sevan		**Increasing**	
Shorja		**Increasing**	
Sisian			
Stepanavan		**Increasing**	
Talin			
Tashir			
Vanadzor		**Increasing**	
Yeghegnadzor		**Increasing**	**Increasing**
Yerevan Agro		**Increasing**	
Yerevan Arabkir		**Increasing**	**Increasing**

Table 1.10. Mann-Kendall trend analysis of climate extremes for the meteorological stations in Azerbaijan (1970 – 2000). (Blanks indicate no statistically significant trends.). Significance is set at the 95% level (α = 0.05). See Appendix II.

Meteorological Station	CDD	SU25	TR20
Dashkasan			**Increasing**
Lankaran			**Increasing**
Sheki		**Increasing**	**Increasing**

Table 1.11. Mann-Kendall trend analysis of climate extremes for the meteorological stations in Georgia (1959 – 2005). (Blanks indicate no statistically significant trends.). (Not all stations had complete records for the period listed.) Significance is set at the 95% level (α = 0.05). See Appendix II.

Meteorological Station	CDD	SU25	TR20
Abastumani		**Increasing**	
Akhaltsikhe		**Increasing**	
Ambrolauri		**Increasing**	
Bakhmaro			
Batumi			
Dedoplistskaro		**Increasing**	
Goderzi			
Gori			
Khulo		**Increasing**	
Kvareli		**Increasing**	
Lentheki			**Increasing**
Mta_sabueti		**Increasing**	
Pasanauri		**Increasing**	
Poti		**Increasing**	**Increasing**
Qutaisi			**Increasing**
Sachkhere			
Samtredia			**Increasing**
Saqara		**Increasing**	
Tbilisi			**Increasing**
Telavi		**Increasing**	**Increasing**
Tsalka		**Increasing**	

Climate-Related Natural Disasters and Economic Losses

When it comes to climate-related natural disasters, there are not any trends in the number of disasters, the number of people affected, nor the economic losses suffered[3]; however, the post-Soviet Union records are short. Over the last 30 years, climate-related economic losses – either from natural disasters or slower onset phenomena such as erosion – have totaled at least $2.7 billion (Table 1.12).

3 Climate-related disasters include: drought, flood, extreme temperature, mass movement dry, mass movement wet, storm and wildfire. See [2]

Table 1.12. Summary of reported economic losses linked to climate in the South Caucasus 1978-2007 [3].

Country	Year	Cause	Cost million US$
Armenia	2000-2005	Drought, frost, floods on agriculture	107
Armenia	Sept 2006	Drought/forest fires	9
Azerbaijan	1978-1995	Caspian Sea, floods and coastal erosion	2000
Azerbaijan	July 1997	Floods/erosion	50
Azerbaijan	2000-2007	Floods and erosion (est. 70 mill/year)	490
Georgia	1995- 2009	Floods/erosion (landslides, mudflow)	650
Total			**2659**

Future Climate Projections

The Second National Communications for the three countries [4,5,6] used PRECIS (Providing Regional Climates for Impact Studies) [7], a Regional Climate Model, and MAGICC/SCENGEN [8], a regional climate scenario generator. PRECIS is a dynamic downscaling model with a spatial resolution of 25 km. x 25 km. that uses two global, coarse-scale Global Circulation Models (GCMs) (ECHAM4 and HadAM3P) to supply boundary conditions (Box 1). The MAGICC/SCENGEN modeling system comprises two models: the MAGICC component projects global mean temperature and the levels of the sea rise based on various socioeconomic and emission scenarios, while SCENGEN uses the MAGICC results, plus outputs from a selection of GCMs, to 'pattern scale' to a regional scale (spatial resolution of 2.5 º x 2.5º). That is, the relationship between the change in global mean annual temperature and some change in a variable of interest (e.g. change in monthly/annual precipitation) that is derived from each individual GCM – the normalized pattern of change – is multiplied by the global mean temperature change (from MAGICC) to generate regional-scale projections.

For Georgia, the PRECIS model projects a mean annual precipitation change by the end of the century (2070 – 2100 compared to 1961 – 1990) for western and eastern Georgia of -30 mm and -70 mm using the HadAM3P 'mother model', and 36 mm and -72 mm, respectively, using ECHAM4 (A2 emissions scenario). The 'best' GCM [4] using MAGICC/SCENGEN (Version 5.3) projects declines of -110 mm and -106 mm for western and eastern Georgia, respectively, by 2100 (A2 emissions scenario). The projections for changes in mean annual temperature by the end of the century for western and eastern Georgia range from 1.8 ºC – 5.2 ºC and 3.5 – 4.9 ºC, respectively, with MAGICC/SCENGEN at the high end of the range. For Armenia, on average MAGICC/SCENGEN projects mean annual precipitation declines of 10 – 27% (A2) by 2100, while PRECIS (using HadAM3P) projects declines of 9%. The projected change in temperature by 2100 for the two modeling approaches ranges from 4 ºC - 5.1 ºC. Lastly, for Azerbaijan, using PRECIS (ECHAM4), mean annual rainfall is projected to increase 20 – 80% from west to east by 2100, with the exception of Nakhchivan (the land-locked part of Azerbaijan), where it is projected to decrease by 20%. Likewise, PRECİS projects an increase in mean annual temperature of 3 ºC – 6 ºC across the country.

4 Based on comparisons with the CRU dataset – See Appendix 1

Box I. General Circulation Models and Climate Downscaling

General Circulation Models (GCMs) are spatially-explicit, dynamic models that simulate the three-dimensional climate system using as first principles the laws of thermodynamics, momentum, conservation of energy and the ideal gas law. GCMs divide the world into a grid, and each equation is solved at each grid cell across the entire globe, at a fixed time interval (usually 10 -30 minutes), and for several layers of the atmosphere. Due to the computational burden, GCMs typically have spatial resolutions of 1-4 degrees (~100 – 400 km), although there is at least on very high-resolution GCM (< 20 km. resolution), but the ocean dynamics are not fully coupled with the atmospheric dynamics [9]. The coarseness of the spatial resolution means that several aspects of climate dynamics that have smaller spatial scales are imperfectly incorporated and averaged over the entire grid cell, such as topography, clouds and storms [10].

The term **climate downscaling** is an umbrella terms that includes two disparate techniques: **Regional Climate Models (RCMs) ('dynamic downscaling'), such as PRECIS,** and **'empirical downscaling' [10]**. **RCMs** simulate climate dynamically at much finer scales (10 – 50km.). The atmospheric fields simulated by a GCM (surface pressure, temperature, winds, water vapor) are inputted as boundary conditions for the RCM, and the "nested" RCM then simulates the smaller-scale climate. They have been shown to realistically simulate regional climate features such as orographic precipitation, interaction with water bodies, extreme climate events, seasonal and diurnal variations of precipitation across different climate regimes and regional scale climate anomalies, such as that associated with the El Nino Southern Oscillation [11]. However, RCMs are sensitive to the errors of the "mother" models which specify the boundary conditions and the choice of initial conditions (e.g. soil moisture). Finally, the results are sensitive to the model domain and resolution: ideally the domain should be large enough to model mesoscale atmospheric conditions, and resolution small enough to contain the detailed topography or the size of storms. Increasing the domain or decreasing the spatial resolution comes with computation costs.

Empirical downscaling relies on determining statistical relationships between large-scale atmospheric variables (e.g. strength of airflow, humidity) with local response variables, such as daily precipitation. Changes in those large-scale variables under climate change (as simulated by GCMs) can be translated into changes in the local predictor variables. There is a plethora of downscaling software available. However, access to predictor variables for calibration continues to be a major impediment to their use. Even if GCM outputs are available, further processing may be necessary. Empirical downscaling, of course, relies on having good observational data, the reliability of predicting the local variable from change in the large-scale forcing and the constancy of that relationship with climate change. In one global study of daily precipitation, empirical downscaling performed relatively poorly in near-equatorial and tropical locations where convective processes dominate, but adequately reproduced seasonal precipitation and the phase of daily precipitation in mid-latitude locations [12]. In general the downscaling techniques for this study at least seem to underestimate large rainfall events. In general, empirical and dynamic downscaling methods have similar skill. **With the increased interest in climate downscaling – whether empirical downscaling or RCMs – one point needs to be considered: if one does not have confidence in the GCMs, then one should not do downscaling [13]. Downscaling should only be performed in regions where the GCMs are in general agreement.**

However, there is some skepticism concerning the result for Azerbaijan. It is important to explore a range of possible climate futures and to not rely upon one model (PRECIS). Increasing spatial resolution does not necessarily mean greater model accuracy, and all RCMs are subject to the errors of the GCMs that supply the boundary conditions. Whilst RCMs provide climate projections at a smaller spatial scale, they may not necessarily simulate better the local climate, nor provide more accurate future projections (Box I).

Thus, nine global GCMs presented in the IPCC AR4 outputs were further assessed. Firstly, they were analyzed to determine which ones adequately simulate historical climate in the South Caucasus (Appendix III). Nearly all of the models capture the seasonal summer temperature peak (June-July-August); however, when it comes to precipitation, only three models simulate the seasonal distribution reasonably well with the spring precipitation peak: HadCM3, GFDL 2.1 and GISS ER (Appendix IV). These three GCMs, plus ECHAM5 which simulates the spatial pattern of temperature well (not shown), were selected to provide future climate projections for the region.

Table 1.13 shows the future projections of changes in mean annual precipitation from this set of models. All of them project that all three countries will experience precipitation declines in the future: 20 – 31% in Armenia, 5- 23% in Azerbaijan, and 0 – 24% in Georgia by the end of the century (A2 emissions scenario) (See Appendix V). From this assessment, there is no further support for projections of increased precipitation in Azerbaijan at the end of the century. The evidence seems to suggest that with the exception of one model result (PRECIS/ ECHAM4 in Azerbaijan) the South Caucasus will continue to become drier this century. The region is expected to become significantly warmer. By 2050, the projected change in mean annual temperature is: 1.1 ºC – 1.9 ºC, 1.0 ºC – 1.6 ºC, 0.9 ºC – 1.9 ºC for Armenia, Azerbaijan and Georgia, respectively, across the set of selected GCMs; by, 2100, it is projected to be 4.4 ºC – 5.5 ºC, 3.6 ºC – 4.1 ºC, and 4.1 ºC – 5.5 ºC, respectively (A2 emissions scenario) (Table 1.14).

Table 1.13. The country spatial means of the projected change in mean annual precipitation for the South Caucasus across the best set of GCMs (A2). See Appendix III for the methodology.

Model		Armenia (%)	Azerbaijan (%)	Georgia (%)
HadCM3	Percent Change (2030 - 2049 vs. 1980 - 1999)	-4	0	-2
	Percent Change (2080 - 2099 vs. 1980 - 1999)	-22	-10	-11
ECHAM5	Percent Change (2030 - 2049 vs. 1980 - 1999)	-6	3	2
	Percent Change (2080 - 2099 vs. 1980 - 1999)	-20	-5	0
GFDL 2.1	Percent Change (2030 - 2049 vs. 1980 - 1999)	-8	1	1
	Percent Change (2080 - 2099 vs. 1980 - 1999)	-31	-15	-24
GISS ER	Percent Change (2030 - 2049 vs. 1980 - 1999)	-2	-4	-2
	Percent Change (2080 - 2099 vs. 1980 - 1999)	-20	-23	-20

Table 1.14. The country spatial means of the projected change in mean annual temperature for the South Caucasus across the best set of GCMs (A2). See Appendix III for the methodology.

Model		Armenia (°C)	Azerbaijan (°C)	Georgia (°C)
HadCM3	Change (2030 - 2049 vs. 1980 - 1999)	1.8	1.3	1.7
	Change (2080 - 2099 vs. 1980 - 1999)	5.5	4.1	5.5
ECHAM5	Change (2030 - 2049 vs. 1980 - 1999)	1.4	1.1	0.9
	Change (2080 - 2099 vs. 1980 - 1999)	5.2	4.0	4.3
GFDL 2.1	Change (2030 - 2049 vs. 1980 - 1999)	1.1	1.0	0.9
	Change (2080 - 2099 vs. 1980 - 1999)	4.4	3.6	4.1
GISS ER	Change (2030 - 2049 vs. 1980 - 1999)	1.9	1.6	1.9
	Change (2080 - 2099 vs. 1980 - 1999)	4.8	4.1	4.8

Extreme Climate Indices

The future projections (2020 – 2050) for two extreme climate indices (*SU25* and *TR20*) were assessed for the meteorological stations in the South Caucasus, using the RClimMDex 1.0 software and projections from the PRECIS RCM (B2 emissions scenario; ECHAM4 supplying the boundary conditions). The future distribution of daily temperature was first corrected by regressing the simulated (GCM-derived) series of daily temperature on the observed values. By mid-century under even a low emissions scenario (B2), almost all the meteorological stations in the South Caucasus will experience increases in both indices. The periods of warm days and nights will become longer, in some cases by 30 (*SU25*) or 40 (*TR 20*) days (Tables 1.15 – 1.17). Extreme precipitation indices still need to be projected for several climate models.

Table 1.15. Future projections of the change in the extreme climate indices for Armenia (averages of 2020 –2050 vs. 1935 – 2005). The projections are for the B2 emissions scenario using the PRECIS Regional Climate Model (ECHAM 4 as the boundary conditions)

Stations	**SU 25**	**TR 20**
Aparan	17	27
Armavir	12	37
Gyumi	27	3
Hrazdan	17	27
Kapan	30	0
Gavar	28	0
Sevan	20	18
Vanadzor	25	0
Yerevan Arabkir	12	36

Table 1.16. Future projections of the change in the extreme climate indices for Azerbaijan (averages of 2020 –2050 vs. 1970 – 2005). The projections are for the B2 emissions scenario using the PRECIS Regional Climate Model (ECHAM 4 as the boundary conditions)

Stations	**SU 25**	**TR 20**
Dashkasan	11	0
Lankaran	27	19
Sheki	15	11

Table 1.17. Future projections of the change in the extreme climate indices for Georgia (averages for 2020 –2050 vs. 1970 – 2005). The projections are for the B2 emissions scenario using the PRECIS Regional Climate Model (ECHAM 4 as the boundary conditions)

Stations	SU 25	TR 20
Ambrolauri	24	5
Batumi	24	36
Gori	19	23
Lentheki	17	0
Pasanauri	1	0
Poti	2	44
Qutaisi	17	26
Sachkhere	24	5
Tbilisi	18	33
Telavi	25	27
Tsalka	26	4

Regional Cooperation on Climate and Hydrometeorological Data

Greater investments in weather and climate services in the South Caucasus will help build climate resilience in the region. Robust climate and hydrometeorological datasets are necessary for the formulation of adaptation plans in every sector. The investments, such as in Early Warning Systems, for example, can help buffer the impacts of extreme events (e.g. floods and droughts), and they generally pay for themselves many times over. Typically, the ratio of the economic benefits to the costs of national meteorological services is in the range of 5–10 to 1 [14].

In order to foster regional cooperation and further add-value to climate and hydrometeorological data being collected by each country separately, a regional web-based platform for sharing climate and climate-related data would be very useful. This initiative could be elaborated in several steps:

1. **The Immediate Term**
   The three countries of the South Caucasus (Armenia, Azerbaijan, Georgia) could share these data (some of which have been done as part of this report):
   - Over at least the last 50 years, monthly precipitation and temperature means for every weather station in each country.
   - Measures of extremes for each weather station, such as *CDD*, *SU25*, *TR20*
   - Climate-related natural disaster data, such as geo-referenced Geographic Information System maps on flood and drought extent for each year.
   - River discharge and lake level monthly data, particularly for critical (i.e. transboundary) resources.

2. **The Near Term (6 months – 18 months)**

This would include plans to ensure that this data-sharing is web-based, sustainable and efficient:

- A web-based portal for data exchange should be developed. Various issues need to be discussed and resolved in a series of workshops, such as: data format compatibility, server site and hosting (e.g. Environment and Security Initiative (ENVSEC) or the Regional Environmental Centre for the Caucasus), different levels of access for data uploading/downloading and the public versus national hydrometeorological services (data suppliers), and importantly, financial resources to create and maintain the data portal.
- Other datasets related to climate could be included in the regional data-sharing, such as: land use, cropping patterns, soil type/soil degradation, and forest cover/forest types.

3. **The Medium Term (1 year onwards)**

- Technical workshops should be held to exchange regional expertise in seasonal forecasting and to discuss the feasibility, needs and modalities regarding Early Warning Systems for the Region, particularly in relation to drought.

Chapter 2 – The Impact of Climate Change on Transboundary Water Resources

Summary

Future water availability for three transboundary river basins in the South Caucasus was assessed for the Alazani (Ganikh), Khrami-Debed and the Aghstev River Basins. Due to projected declining precipitation and increasing temperatures, by the end of the century, streamflow is projected to decline dramatically: 26 - 35%, 45 – 65%, and 59 – 72% in the Alazani (Ganikh), Khrami-Debed and Aghstev Basins, respectively. In the Alazani, at least, very modest increases in water demand of even 10% - through increased agricultural water demand and population growth, for example - will likely lead to shortfalls in the summer (August) by 2050. Most of the water in these Basins is used in agriculture, so increasing water use efficiency by employing such methods as advanced micro-irrigation technologies (e.g. sprinklers and drip irrigation) is a necessity when dealing with decreasing water availability. Additional adaptation measures include demand-side conservation measures and possibly increased storage to address increased variability and shortfalls in high demand (i.e. summer) months. For effective climate change adaptation planning in these Basins, it is imperative that trans-national river management plans are enacted.

Study Sites

The future water availability with climate change of three critical trans-national river basins was explored: the Alazani (Ganikh), Khrami-Debed and the Aghstev River Basins. The Alazani (Ganikh) River spans the territories of Georgia and Azerbaijan, and it has a length of 375 km and a catchment area of 11,600 km^2 [15]. The total area of the Khrami-Debed basin is 8340 km^2, of which 3790 km^2 is in Armenia and 4550 km^2 in Georgia. In the Armenian section of the basin, the major river is the Debed (178 km long), while in Georgia, it is the Ktsia-Khrami (201 km long). The population of the basin is about 710,000. The Aghstev River basin is located in the northern part of Armenia and the western part of Azerbaijan. The Aghstev River is 85 km long, and its catchment area totals 1730 km^2 (Figure 7) [16].

Figure 7. The location of the three trans-boundary river basins in the South Caucasus.

Methodology and Results

The previous chapter has shown that it is quite likely that the South Caucasus will experience declines in mean annual precipitation, which would have implications for streamflow and water resource management. Two different methodologies were employed to assess the water resources of the three basins in the region. For the Alazani (Ganikh), the WEAP model (Version 2.2054) was used (See Appendix VI) [17], while for the other two, a regression method was used to relate climate (i.e. precipitation and temperature) to streamflow.

Alazani (Ganikh) River

Figure 8 shows the schematic for WEAP for the Alazani (Ganikh) River. The Alazani (Ganikh) is the second largest river in eastern Georgia, mainly used for irrigation (~60,000 ha of cropland in Georgia). The WEAP model was first calibrated with historical data from 1966 - 1990. Because the elevations of meteorological stations differ from the larger sub-catchments that they represent, observed precipitation and temperature values were modified to represent the climate over the entire sub-catchment. Precipitation data from nearby meteorological stations were used, and the values were spatially interpolated using a standard relationship between precipitation and elevation to derive the historical climate for the entire sub-catchment. The temperature was modified according to the relationship between elevation and temperature in the nearby Aragvi watershed in eastern Georgia. From the available data, the calibration of the model was performed for years 1966-1990. The WEAP model requires not only data on water supply, but of course, demand as well. Water consumption in Georgian was estimated from data provided by the Ministry of Natural Resources and Environmental Protection of Georgia for 2006. The data, however, are not disaggregated by sector (e.g. agricultural, municipal, industrial water demand). Since no data were available for the water consumption on Azerbaijan territory, it was estimated during calibration. Table 2.1 shows the results of the calibration for the sub-catchments of the Alazani (Ganikh). The modeled streamflow is well-correlated with the actual streamflow in the sub-catchments.

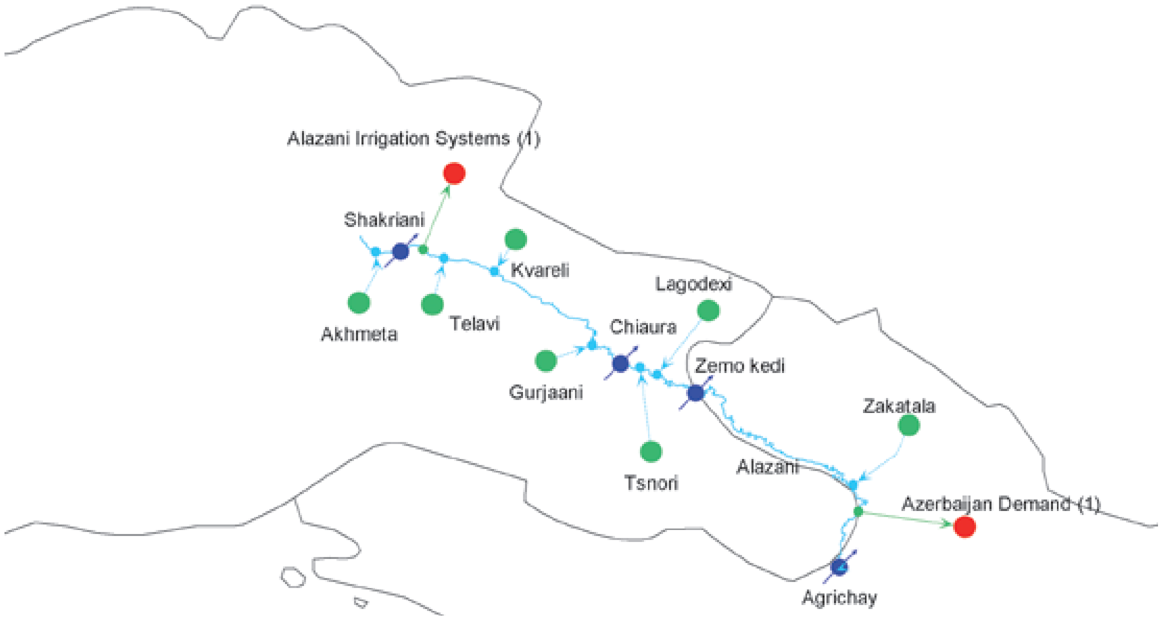

Figure 8. WEAP schematic of the Alazani (Ganikh) River Basin. The green circles show sub-catchments represented by meteorological stations, the red ones are demand sites, and the blue ones are streamflow gauges. The black lines indicate political boundaries. (The upper left corner is Georgia, while the lower left corner is Azerbaijan.).

Table 2.1. Model performance for different sub-catchments. The correlation refers to the correlation between the observed and historical streamflows. Agrichay is in Azerbaijan, while the others are in Georgia.

Streamflow gauge	**Correlation**	**Relative error (%)**
Shakriani	0.7	14%
Chiaura	0.8	8%
Zemo Kedi	0.9	10%
Agrichay	0.9	8%

To project future streamflow, climate projections of temperature and precipitation from MAGICC/SCENGEN (Version 5.3) (2020 – 2050; HadAM3P) and PRECIS (2070 – 2100, HadAM3P) were used (See Chapter 1). Tables 2.2 and 2.3 show the precipitation and temperature projections for meteorological stations in the Alazani (Ganikh) Basin from the PRECIS model (See Chapter 1 – Figure 5 and Table 1.4). By the end of the century, mean annual precipitation is projected to decrease from 4 – 12% across the Basin, which will translate into reduced water supply. Moreover, this will be exacerbated by mean annual temperature increases of around 5 ^{o}C, which will lead to higher rates of evapotranspiration. When these projections are coupled with WEAP to derive estimates of future streamflow, the results are quite stark: a 26 – 35% decrease in mean annual streamflow by 2100. The results for mid-century are rather curious – declines of 38 – 59% - but MAGICC/SCENGEN (not shown) projects steeper declines in precipitation than PRECIS.

Table 2.2. Simulated and projected mean annual precipitation (mm) for the different meteorological stations of the Alazani (Ganikh) River (PRECIS HadAM3P).

	Akhmeta	Telavi	Kvareli	Gurjaani	Tsnori	Lagodekhi	Zakatala
1960-1990 (mm)	755	776	977	786	598	967	959
2070-2100 (mm)	703	716	925	755	550	850	857
Change (%)	-7%	-8%	-5%	-4%	-8%	-12%	-11%

Table 2.3. Simulated and projected mean annual temperature (ºC) for the different meteorological stations of the Alazani (Ganikh) River (PRECIS HadAM3P).

	Akhmeta	Telavi	Kvareli	Gurjaani	Tsnori	Lagodekhi	Zakatala
1960-1990 (ºC)	12.3	12.2	12.8	12.8	13	13.1	12.8
2070-2100 (ºC)	17.7	17.1	18.6	18	18.3	18.4	17.6
Change (ºC)	5.4	4.9	5.8	5.2	5.3	5.3	4.8

Table 2.4: The change in 30 years average of mean annual streamflow at different points of the Alazani (Ganikh) (in million m3)

Streamflow gauge	Baseline 1960-1990 (million m3)	Change 2020 – 2050 vs Baseline (million m3)	Change 2070 – 2100 vs. Baseline (million m3)	Change 2020 – 2050 vs. Baseline (%)	Change 2070 – 2100 vs. Baseline (%)
Shakriani	1336	-508	-356	-38%	-27%
Chaiura	1874	-821	-482	-44%	-26%
Zemo kedi	3118	-1439	-873	-46%	-28%
Agrichay	35012	-2060	-1229	-59%	-35%

These results above assume a constant water demand in the future; however it is likely to grow for a variety of reasons, most notably, increased irrigation demand due to increases in temperature and decreases in precipitation (See Chapter 3). It is difficult to forecast future water demand, but three scenarios were considered: increases of 10%, 30% and 50%. Results indicate that even for modest increases in water demand (i.e. 10%) by 2050 there will be unmet demand in August for both countries, as well as in March and in April for Azerbaijan. That is, water supply will not be able to satisfy water demand. By 2100, there will be unmet demand in both countries for June and August. This has serious implications for agriculture, as these are critical months for crop production.

Table 2.5. Unmet average monthly water demand (million m^3) on the Georgian side of the Alazani (Ganikh) (2020-2050)

Demand Increase scenarious	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10%	0	0	0	0	0	0	0	2.5	0	0	0	0
30%	0	0	0	0	0	0	0	4.5	0	0	0	0
50%	0	0	0	0	0	0	0	6.6	0	0	0	0

Table 2.6. Unmet average monthly water demand (million m3) on the Azerbaijani side of the Alazani (Ganikh) (2020-2050)

Demand Increase scenarios	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10%	0	0	0.6	0.2	0	0	0	21.5	0.2	0.7	0	0
30%	0	0	2.3	1.5	0	0	0.3	37.5	1.5	1.2	0.1	0
50%	0	0	5.7	5.6	0	0	1.4	54.9	5.9	2.0	1.7	0

Table 2.7. Unmet average monthly water demand (million m3) on the Georgian side of the Alazani (Ganikh) (2070-2100)

Demand Increase scenarious	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10%	0.00	0.00	0.00	0.00	0.00	0.01	0.00	1.07	0.00	0.00	0.00	0.00
30%	0.00	0.00	0.00	0.00	0.00	0.04	0.00	2.39	0.00	0.00	0.00	0.00
50%	0.00	0.00	0.00	0.00	0.00	0.09	0.00	3.78	0.00	0.00	0.00	0.00

Table 2.8. Unmet average monthly water demand (million m3) on the Azerbaijani side of the Alazani (Ganikh) (2070-2100)

Demand Increase scenarios	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10%	0	0	0	0	0.0	0.5	0.0	8.9	0.0	0	0	0
30%	0	0	0	0	0.0	1.7	0.0	19.8	0.2	0	0	0
50%	0	0	0	0	0.0	4.1	0.0	31.4	0.8	0	0	0

Khrami-Debed and Aghstev River Basins

Figures 9 and 10 show the locations of meteorological stations on the Khrami-Debed and Aghstev Rivers. Approximately 70 – 80% of the water in these basins is used for agriculture[5]. In both basins, there has been a distinct temperature increase from 1991 – 2006 compared to 1961 - 1990, ranging from 0.2 – 0.6 ºC in the Aghstev to 0.5 – 0.7 ºC in the Khrami-Debed (Tables 2.9, 2.10). All of the meteorological stations in the Aghstev have recorded modest declines in precipitation across the two periods (-3 - -6%), while in the Khrami-Debed the record is more mixed, with changes in precipitation of -9 – 10% [16] (Tables 2.11, 2.12).

5 Vahagn Tonoyan, UNDP. Pers comm.

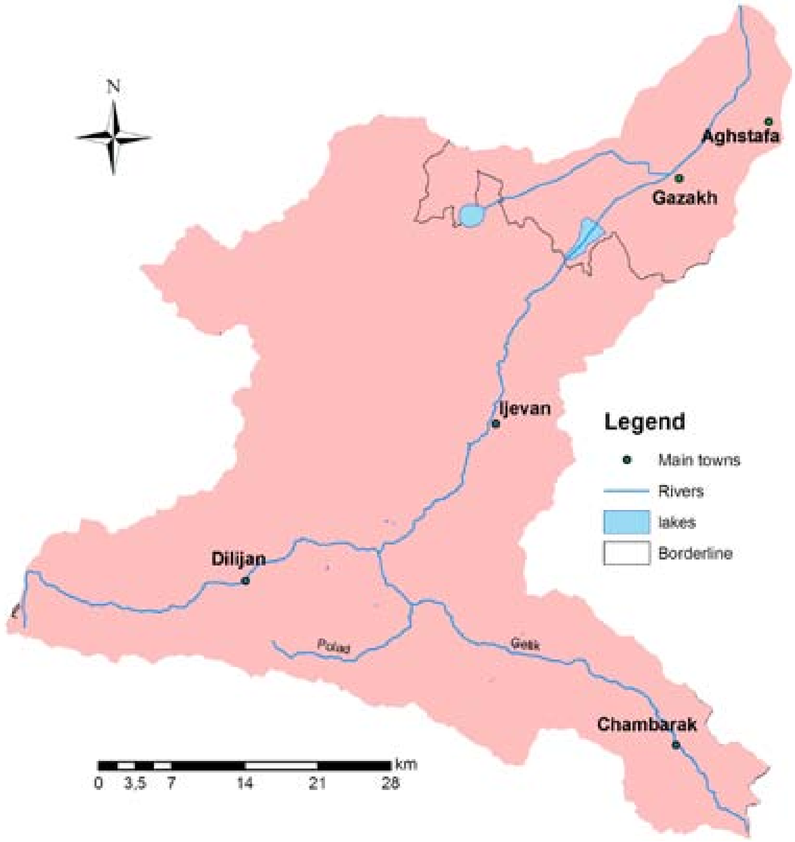

Figure 9. The location of meteorological stations on the Aghstev River. The gray line indicates the border between Azerbaijan and Armenia.

Figure 10. The location of meteorological stations of the Khrami-Debed River Basin. One can see the two major rivers, The Khrami (Ktsia) and the Debed, and the tributaries of the Debed, the Dzoraget and Pambak Rivers. The grey line indicates the border between Georgia and Armenia.

Table 2.9. Mean annual temperature for meteorological stations in the Aghstev Basin

Meteorological station	Mean Annual Temperature (°C) 1961- 1991	Mean Annual Temperature (°C) 1991 -2006
Dilijan	8.1	8.8
Ijevan	11.2	11.8
Aghstafa	12.6	13.1

Table 2.10. Mean annual temperature for meteorological stations in the Khrami-Debed Basin.

Meteorological station	Mean Annual Temperature (°C) 1961- 1991	Mean Annual Temperature (°C) 1991 -2006
Bolnisi	13.2	13.6
Tzalka	6.8	7.0
Gardabani	14.2	14.6
Stepanavan	7.0	7.5
Tashir	5.9	6.3
Vanadzor	7.8	8.5
Pushkin passage	3.5	4.1

Table 2.11. Mean annual precipitation for meteorological stations in the Aghstev Basin.

Meteorological station	Mean Annual Precipitation (mm) 1961- 1991	Mean Annual Precipitation (mm) 1991 -2006	Change (%)
Dilijan	653	635	-3
Ijevan	583	549	-6
Aghstafa	363	349	-4

Table 2.12. Mean annual precipitation for meteorological stations in the Khrami-Debed Basin.

Meteorological station	Mean Annual Precipitation (mm) 1961- 1991	Mean Annual Precipitation (mm) 1991 -2006	Change (%)
Bolnisi	514	494	-4
Tzalka	709	646	-9
Gardabani	403	423	5
Stepanavan	688	645	-6
Tashir	683	753	10
Vanadzor	569	558	-2
Pushkin passage	799	733	-9

In order to explore how climate change will affect river flows on both major river systems, data were collected from 3 hydrological stations in the Aghstev and 5 hydrological stations on the Khrami-Debed Basins. In the former, these included the Barkhudarli (Azerbaijan; for the years 1976 – 1991) and Ijevan (Armenia; 1961 – 2006) sites on the Aghstev Rivers, as well as the Voskepar (Armenia; 1961 – 2006) site on the Kirants River (Figure 11). For the Khrami-Debed Basin, the sites included: Sadakhlo on the Debed River (Georgia; 1977-1992), Yeddikilisia on the Khrami River (Georgia; 1950-1992); Ayrum on the Debed River (Armenia; 1954-2006), Tumanyan on the Pambak River (Armenia; 1950-2006) and Gargar on the Dzoraget River (Armenia; 1950-2006) (Figure 12). In order to project future streamflow, historical streamflow was regressed on historical climate:

$\mathbf{S} = a\mathbf{P} - b\mathbf{T} + c,$

Where **S** is the annual flow (million m^3), **P** is precipitation (mm), **T** is temperature (^{o}C), *a* and *b* are coefficients, and *c* is an error term. The climate data were obtained from the nearest meteorological station to each hydrological station. Historical precipitation and temperature were found to be good predictors of streamflow, as the correlation coefficient ranged from 0.76 to 0.83.

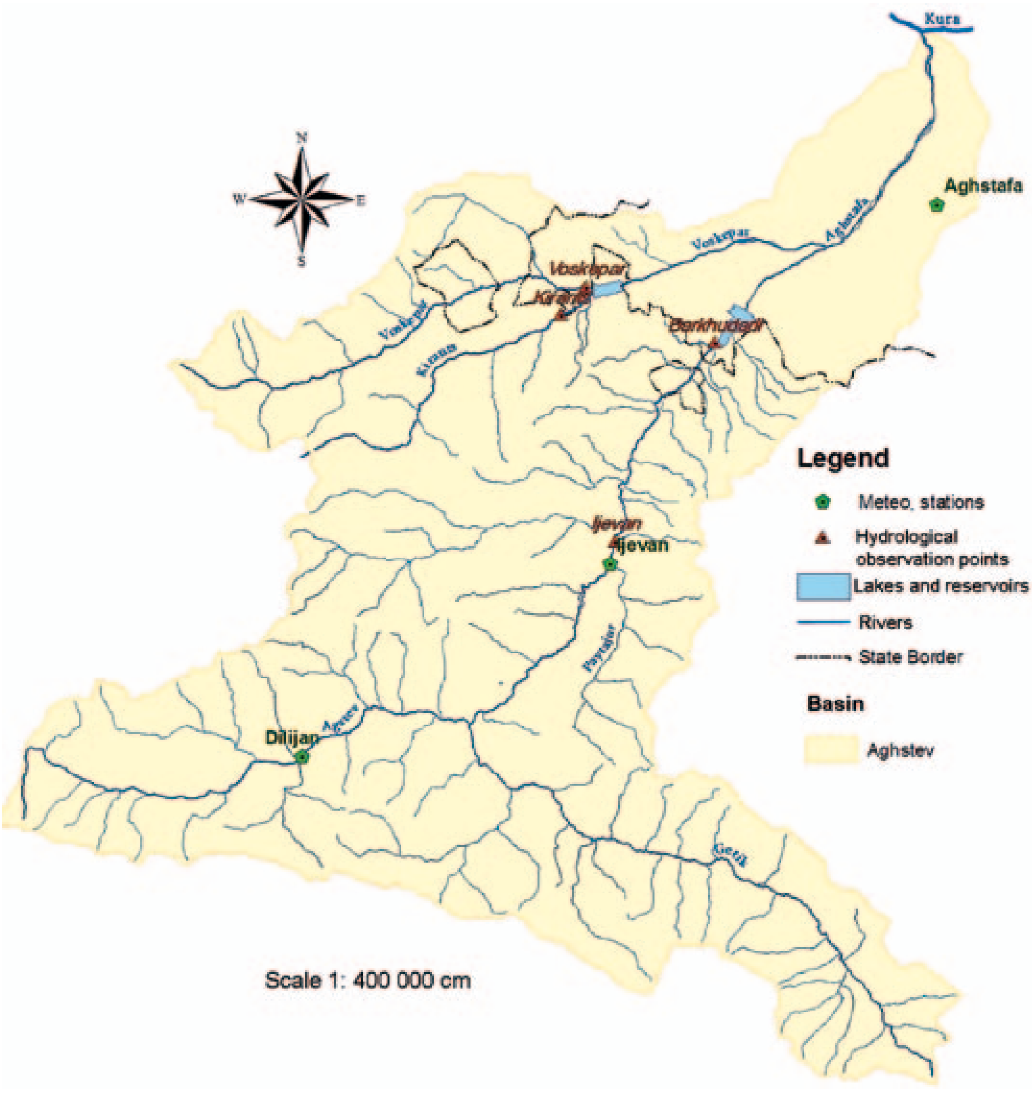

Figure 11. The Aghstev Basin, including major tributaries and meteorological and hydrological stations.

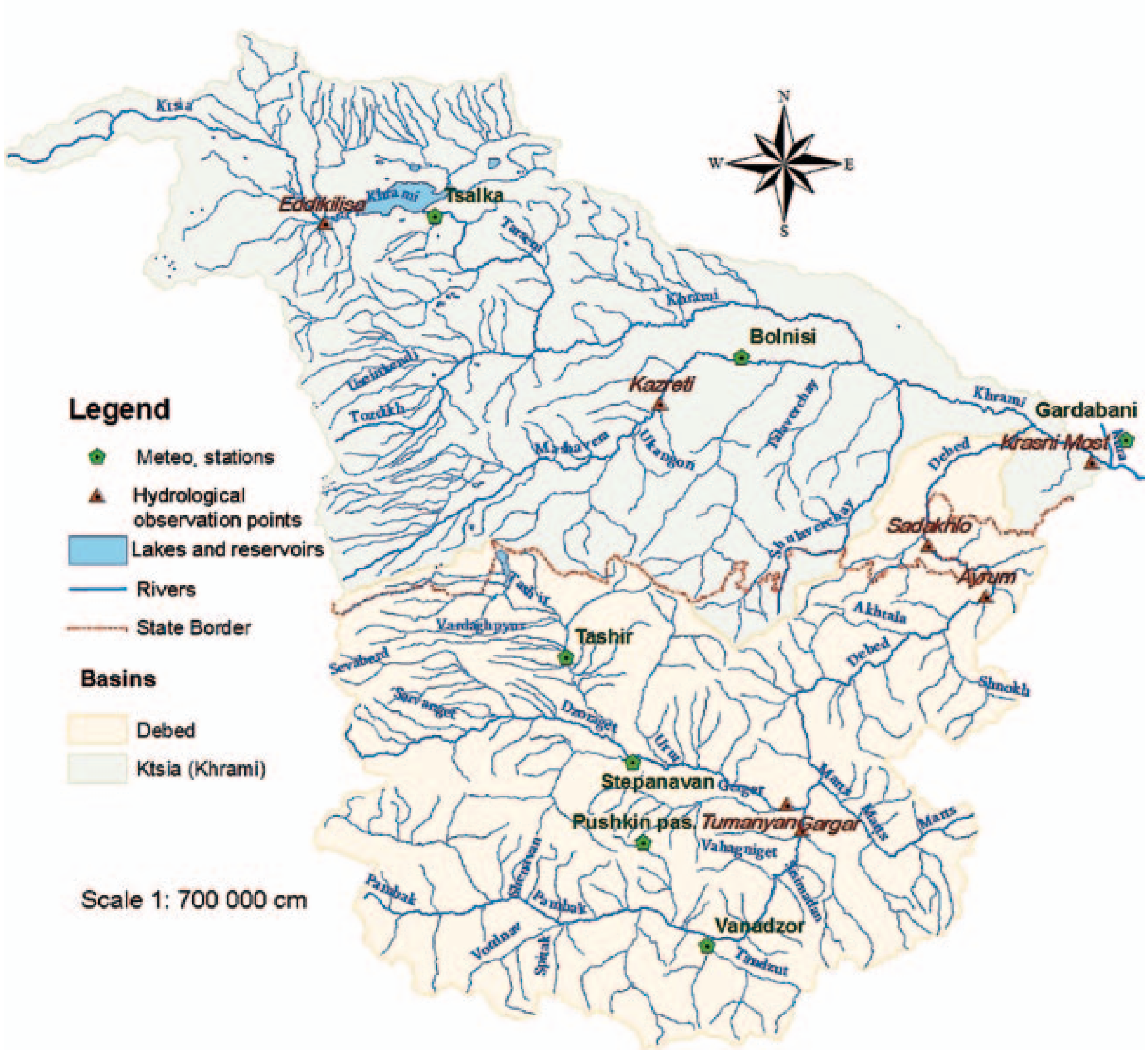

Figure 12. The hydrological stations in the Khrami-Debed Basin, including major tributaries and meteorological and hydrological stations.

Finally, projected precipitation and temperature from the set of GCMs that seem to simulate the historical climate the best for the South Caucasus Region (ECHAM5, GFDL 2.1, GISS ER, HadCM3 - See Chapter 1) were used to project future streamflow for both Basins. The results averaged across the four GCMs for 2011 – 2040, 2041 – 2070 and 2071 - 2100 are presented in Table 2.13 and 2.14. By 2040, mean annual streamflow is projected to decline 11 – 14% in the Aghstev Basin and 9 – 11% in the Khrami-Debed. By 2100, dramatic declines are expected: 59 – 72% in the Aghstev and 45 – 62% in the Khrami-Debed.

Table 2.13. Projected mean annual streamflow and change relative to 1961- 1990 for hydrological stations in the Aghstev Basin. The results are the average of the results from four GCMs ((ECHAM5, GFDL 2.1, GISS ER, and HadCM3 - See Chapter 1)

Hydrological Station	**1961 - 1990**	**2011-2040** million m3 (%)	**2041-2070** million m3 (%)	**2071-2100** million m3 (%)
Barkhudarli (Aghstev River)	255	225 *(-12)*	177 *(-31)*	104 *(-59)*
Ijevan (Aghstev River)	286	255 *(-11)*	196 *(-31)*	108 *(-62)*
Voskepar (Kirants River)	67	58 *(-14)*	42 *(-37)*	19 *(-72)*

Table 2.14. Projected mean annual streamflow and change relative to 1961- 1990 for hydrological stations in the Khrami-Debed Basin. The results are the average of the results from four GCMs ((ECHAM5, GFDL 2.1, GISS ER, and HadCM3 - See Chapter 1)

Hydrological Station	**1961 – 1990** million m3 (%)	**2011-2040** million m3 (%)	**2041-2070** million m3 (%)	**2071-2100** million m3 (%)
Ayrum (Debed River)	1054	937 *(-11)*	669 *(-37)*	402 *(-62)*
Gargar (Dzoraget River)	480	427 *(-10)*	343 *(-29)*	215 *(-55)*
Sadakhlo (Debed River)	924	819 *(-11)*	585 *(-37)*	365 *(-61)*
Tumanyan (Pambak River)	336	300 *(-11)*	240 *(-29)*	160 *(-53)*
Yeddikilisa (Khrami River)	267	242 *(-9)*	201 *(-25)*	147 *(-45)*

Adaptation Options

These analyses indicate that all three river basins will experience dramatic declines in streamflow and concomitantly water availability by the end of this century. The first step in any water resource planning is effective monitoring of water usage in the basins; however, adequate water accounting is not common [18]. Since these basins are mostly used for irrigation, increasing agricultural water productivity is paramount. Typically, half of the water used in inefficient flood irrigation is lost due to evaporation. Advanced micro-irrigation technology, such as sprinklers and drip irrigation, can reduce water consumption by 30 to 70% [19]. These technologies are not employed in three river basins, but could be adopted to drastically reduce water use. Other water conserving techniques include mulching and conservation tillage. These all divert water that would otherwise evaporate unproductively. Other interventions, such as rainwater harvesting, create more water for individual users, but simply capture water that would otherwise be available elsewhere in the basins and do not increase total water supply. It is important to note that increases in agricultural water efficiency must be coupled with limits on overall water consumption. Where water demand exceeds water consumption – as is likely in these Basins by the end of the century – there are only two options: water pricing or the enforcement of strict water quantity limits. Tradable water rights have been successful in the developed world (e.g. the United States and Australia), but they require strong institutional capacity, regulation and governance [18].

At the level of the municipality (household and businesses), demand-side conservation measures, such as water metering, rainwater harvesting (but see above), higher efficiency appliances (e.g. faucets and toilets), and wastewater re-use are good adaptation strategies for declining water supply [20]. Additional water storage can help mitigate against low season summer flows where demand is high and address increasing variability, while not increasing aggregate supply. In the Alazani (Ganikh), reasonable future demand scenarios indicate shortfalls in the summer (June and August). In Armenia at least, there is the potential to increase storage by building new dams and reservoirs to increase capacity by 1 to 2 billion cubic meters. But constructing dams well is difficult, and all the tradeoffs (e.g. environment) need to be carefully assessed. Interconnections with Lake Sevan can increase water supply in the Aghstev and Khrami-Debed Basins [16], but the ecological impacts need to be properly studied. As these rivers are important for hydropower, it is vital that redundancies are in place in the power sector to accommodate likely decreases in power generation.

Finally, and most importantly, as all of these basins are transboundary, regional cooperation of all three countries is *sine qua non* for effective climate change adaptation in these basins, given the likely decline in water availability. Adaptation planning will only succeed if there are joint water management plans.

Chapter 3 – The Impact of Climate Change on Agricultural Water Demand

Summary

Future crop water and irrigation requirements were projected for the main crops in three important agricultural regions in the South Caucasus, namely the Ararat Valley (Armenia), the Belakan region (Azerbaijan), and the Dedoplistskaro region (Georgia). In the Ararat Valley, by the end of the century, crop water requirements (CWR) for winter wheat and vegetables are projected to increase 19 – 22% and 19 – 23%, respectively, compared to 1967 – 1982, while irrigation water requirement (IWR) is projected to increase 35% - 36% and 38% - 42% for winter wheat and vegetables, respectively. In Belakan, there is expected to only be a slight increase in CWR, but IWR is projected to increase from near zero to about 50 mm and 110 mm for spring wheat and pasture, respectively (2076 - 2100 vs. 1998 – 2010). This result may be conservative, as it is based on climate projections from the Hadley PRECIS Regional Climate Model, where precipitation is projected to decrease only slightly in the region. Lastly, for Dedoplistskaro by 2100, irrigation requirements for winter wheat, pasture and sunflower are expected to increase 114%, 82%, and 50%, respectively, compared to the 1991 – 2005.

The increase in water requirements in all the regions is driven both by decreasing precipitation and increasing temperatures (and concomitantly evapotranspiration). All climate models concur that the South Caucasus will become substantially warmer. Regardless of the exact quantitative projections on CWR and IWR it is clear that maintaining the current suite of crops in the regions will require significantly more water, which may not be available. There are many adaptation measures that can be enacted, most notably the use of advanced micro-irrigation methods to conserve water. Additionally, the countries need to invest in drought-tolerant crops and consider growing less water-intensive and higher-valued crops (e.g. fruits and vegetables), which would require investments in agricultural research and extension services. Dedoplistskaro and Belakan suffer from severe degradation; measures to increase soil fertility and erosion can ameliorate losses in crop productivity. Finally, crop, income and landscape diversification should be promoted in the regions.

Study Sites

Agriculture is important economically in the South Caucasus. As a percentage of GDP, its contribution (value-added) is modest – 21%, 8% and 10% in Armenia, Azerbaijan and Georgia, respectively, but as a source of employment, it is very significant. The percentage of people employed in the agricultural sector as a percentage of total employment is 46%, 39%, and 53%, in Armenia, Azerbaijan and Georgia, respectively [21].

Given the increasing temperatures and likely declining precipitation in the South Caucasus region, it is important to assess whether there will be increased water demands in agriculture. Crop water and irrigation requirements were explored in one critical agricultural region in each country: the Ararat Valley (Armenia), the Belakan region (Azerbaijan), and the Dedoplistskaro region (Georgia) (Figure 13) [22]. The Ararat Valley is the most important agricultural area in Armenia [4]. The Dedoplistskaro region is under threat from desertification and was selected as one of the priority regions for consideration in Georgia's Second National Communication [5]; Belakan also suffers from the same set of problems and is the Azerbaijani extension east of Dedoplistskaro.

Figure 13. The location of the three agricultural areas in the South Caucasus

Methodology and Results

CropWat (Version 4.3) (Appendix VII) was used to calculate crop water and irrigation requirements for the main crops in each agricultural area. CropWat is a software program developed by the United Nations Food and Agricultural Organization to calculate evapotranspiration, crop water requirements and irrigation requirements (Appendix VII). *Crop water requirement* is defined as the total amount of water that must be supplied to a plant in order to avoid water stress. It is the amount needed to compensate for the amount of water that is *consumed*, i.e. evapotranspirated, by a crop. *Irrigation water requirement* for crop production is the amount of water, in addition to rainfall, that must be applied to meet a crop's evapotranspiration needs without a significant reduction in yield [23].

In the Ararat Valley of Armenia, data from two meteorological stations were used (Artashat and Armavir – Figure 5, Table 1.4) to calculate historical crop water requirements (*CWR*) and irrigation water requirements (*IWR*) for winter wheat and vegetables (generically, but would include such things as onions) for two periods where climate data were continuously available: 1967-1982 and 1994-2009. Mainly due to increasing monthly maximum and minimum temperatures, the crop water requirement has increased in the order of 10% across the two time periods (Tables 3.1, 3.2). The *IR* increases by a greater amount, because it is a function of precipitation as well as the *CWR*, and its increase reflects decreases in precipitation in the Ararat Valley (See Chapter 1).

Table 3.1. Crop Water Requirements (CWR) and Irrigation Requirements (IR) for winter wheat and vegetables during their vegetation periods (Artashat station)

Years	Winter wheat		Vegetables	
	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)
1967-1982	539	398	336	269
1994-2009	582	463	365	307

Table 3.2. Crop Water Requirements and Irrigation Requirements for winter wheat and vegetables during their vegetation periods (Armavir station)

Years	Winter wheat		Vegetables	
	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)
1967-1982	533	407	324	260
1994-2009	577	438	354	285

The next step is to project future *CWR* and *IWR* for the Ararat Valley using temperature and precipitation for the periods 2011-2040 and 2071-2100. For the former period, projections from the set of "best" GCMs from Chapter 1 were used (A2), while for the latter period, the Hadley PRECIS model (A2) was used. The "delta" method was employed to project future maximum and minimum temperature and precipitation for each month. That is, the historical values were adjusted by the change in mean temperature and precipitation between the future period and the baseline period of 1960 and 1990 for each month to derive the maximum and minimum future values. For relative humidity and wind speed the average values for existing observations in the 1960-1990 baseline were used, while sunshine duration is only a function of latitude.

Tables 3.3 – 3.5 show the projection in water requirements for both future periods. For winter wheat, the *CWR* in 2011 – 2040 is projected to be 9 – 15% greater in the Ararat Valley compared to 1967 – 1982 across the GCMs. For vegetables, *CWR* is projected to increase 10 – 17% across climate models. There are only marginal differences between the projections of the set of GCMs. By the end of the century, *CWR* for winter wheat and vegetables is projected to increase 19 – 22% and 19 – 23%, respectively, compared to 1967 - 1982 while *IWR* is projected to increase 35% - 36% and 38% - 42% for winter wheat and vegetables, respectively.

Table 3.3. Crop Water Requirements and Irrigation Requirements for winter wheat and vegetables during their vegetation periods (Artashat station)

Period	Winter wheat		Vegetables	
	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)
1967-1982	539	398	336	269
1994-2009	582	463	365	307
HadCM 2011-2040	594	493	372	341
GISS ER 2011-2040	595	493	373	337
ECHAM 2011-2040	586	461	368	312
GFDL 2011-2040	594	462	372	303

Table 3.4. Crop Water Requirements and Irrigation Requirements for winter wheat and vegetables during their vegetation periods (Armavir station)

Years	Winter wheat		Vegetables	
	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)
1967-1982	533	407	324	260
1994-2009	577	438	354	285
HadCM 2011-2040	615	506	379	331
GISS ER 2011-2040	616	520	380	341
ECHAM 2011-2040	606	486	374	314
GFDL 2011-2040	615	486	379	306

Table 3.5. Crop Water Requirements and Irrigation Requirements for winter wheat and vegetables during their vegetation periods (Artashat station). The projections are based on the Hadley PRECIS (HadAM3P) model.

Years	Winter wheat		Vegetables	
	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)
1967-1982	539	398	336	269
1994-2009	582	463	365	307
2071-2085	635	493	395	325
Change vs. 1967 - 1982 (%)	18%	24%	18%	21%
2086-2100	641	537	400	370
Change vs. 1967 - 1982 (%)	19%	35%	19%	38%

Table 3.6. Crop Water Requirements and Irrigation Requirements for winter wheat and vegetables during their vegetation periods (Armavir station). The projections are based on the Hadley PRECIS (HadAM3P) model.

Years	Winter wheat		Vegetables	
	Total CWR (mm)	**IR (mm)**	**Total CWR (mm)**	**IR (mm)**
1967-1982	533	407	324	260
1994-2009	577	438	354	285
2071-2085	645	505	394	317
Change vs. 1967 - 1982 (%)	21%	24%	23%	22%
2086-2100	651	552	398	369
Change vs. 1967 - 1982 (%)	22%	36%	23%	42%

For the Belakan region of Azerbaijan, two crops were considered: wheat and pasture. The requisite data on wind speed and humidity were derived from two meteorological stations in the region (Zakatala and Belakan) (See Figure 5, Table 1.4 for Zakatala) to calculate historical *CWR*. The baseline period of 1998-2010 for Zakatala and 1983-1990 for Belakan were chosen due to data availability. Because daily sunshine duration was unavailable, data from a nearby meteorological station in the Kakheti Region were used instead. Table 3.7 shows the projected change in crop water and irrigation requirements in the future, using precipitation and temperature projections from the Hadley PRECIS model (HadAM3P; A2 emissions scenario). It should be noted that the PRECIS projections are conservative, and precipitation is projected to decrease by only 5% in Zakatala and very little in Belakan. However, the increases in temperature (and hence evapotranspiration) lead to increased water requirements.

Table 3.7 Crop Water Requirements and Irrigation Requirements for wheat and pasture during their vegetation periods for Belakan. The projections are based on the Hadley PRECIS (HadAM3P) model.

Years	Winter wheat		Spring wheat		Pasture	
	Total CWR (mm)	**IR (mm)**	**Total CWR (mm)**	**IR (mm)**	**Total CWR (mm)**	**IR (mm)**
1998-2010	327	0	348	0	681	105
2061-2075	334	52	367	110	735	161
2076-2100	335	48	369	109	739	154
Change vs. 1998 - 2010 (%)	2	--	6	--	9	47%

In the predominately arid subtropical Dedoplistskaro region in East Georgia on the border with Azerbaijan, agriculture is mainly animal husbandry and the cropping of wheat and sunflower. The climate data were obtained from the Dedoplistskaro meteorological station (Figure 5, Table 1.4) for 1961 – 2005. Table 3.8 shows the historical irrigation requirements for winter wheat, sunflower and pasture. By 2100, irrigation requirements for the three crops are expected to become severe: an increase of 114%, 82%, and 50% for winter wheat, pasture and sunflower, respectively, compared to the 1991 – 2005 period (Table 3.9) [5].

Table 3.8. Average Irrigation Requirements for selected crops in Dedoplistskaro.

Years	Winter wheat	Sunflower	Pasture
	IR (mm)	IR (mm)	IR (mm)
1961-1975	163	229	296
1976-1990	147	243	292
1991-2005	133	249	288

Table 3.9. Crop Water Requirements and Irrigation Requirements for wheat and pasture during their vegetation periods in Dedoplistskaro. The projections are based on the Hadley PRECIS (HadAM3P) model.

Years	Winter wheat		Sunflower		Pasture	
	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)
2061-2075	499	285	547	368	936	515
2076-2100	484	272	553	398	929	534

For both Belakan and Dedoplistskaro, it will be important to explore water requirements using climate projections from models other than PRECIS.

Adaptation Options

These focal agricultural areas in the South Caucasus will require much more irrigation to maintain the mix of crops grown; indeed, based on the analysis in Chapter 3 of some select transboundary basins, water availability (streamflow) is likely to decline in the South Caucasus. Increasing irrigation efficiency through the use of micro-irrigation technologies, such as sprinklers and drip irrigation, and other soil moisture conservation techniques, such as mulching and conservation tillage, can ensure that irrigation water is used more effectively (See Chapter 3).

In the Dedoplistskaro region, currently about 80% of the pastureland is degraded, and 65% suffer from wind erosion, resulting in a decrease of productivity of 40-70% [36]. A similar picture exists in Belakan. Climate change will likely exacerbate this, due to increasing temperatures and declining, more variable precipitation (Chapter 1). There are several recommended adaptation measures that could help mitigate the combined effects of land degradation and climate change in these areas:

1. The improvement and rehabilitation of irrigation systems to expand capacity and more importantly increase efficiency (in conjunction with micro-irrigation)
2. The planting of windbreaks to reduce erosion.
3. Measures to increase productivity, such as weed control, ploughing and seeding of degraded areas with new seed types, and the removal of stones in pastures.
4. Ameliorating soil fertility through the use of gypsum in alkali soils and chemical fertilizers (nitrogen, sulfur, phosphorus, etc.) in saline soils.

5. Increasing storage during the May – October months.

In all three areas, there needs to be increased efforts and financing for breeding drought resistant crops, particularly wheat. The choice of crops in these areas may need to be reconsidered; higher-valued fruit and vegetable crops are more water-efficient than wheat, but, of course, shifting away from wheat cultivation brings its own problems and issues related to food security [24]. A recurring theme in climate change adaptation is diversification – diversifying landscapes and income can help buffer against climate impacts. Farmers can increase the types of production on the farm by, for example, integrating livestock, horticulture and specialized agriculture. Diversifying landscapes include the techniques of ecoagriculture, which can reduce vulnerability to natural disasters (including drought), reduce soil erosion, and enhance farm income and productivity, while also conserving biodiversity. Examples include silvopastoral systems (quite relevant to Dedoplistskaro and Belakan) that integrate trees with pastureland and improve the sustainability of cattle production and diversify and increase farmers' incomes. Such systems are particularly useful as climate-change adaptation measures, because trees retain their foliage in most droughts, providing fodder and shade and thus stabilizing milk and meat production [18].

Agricultural research and extension is critical for the adaptation to climate change in the agricultural sector. Certainly the international aid community needs to do more: the share of official development assistance for agriculture dropped from 17 percent in 1980 to 4 percent in 2007, despite estimates that rates of return to investment in agricultural research and extension are high (30–50 percent) [18].

Chapter 4 – The Impact of Climate Change on Urban Heat Stress

Summary

The projected change in the Heat Index was evaluated for three cities in the South Caucasus: Baku, Azerbaijan; Tbilisi, Georgia; and Vanadzor, Armenia. For Baku and Tbilisi, there is expected to be a dramatic increase in the number of 'dangerous' days by mid-century – roughly a trebling of days compared to the past. While in Vanadzor, the increase in the absolute number of 'dangerous' days is rather small, there is projected to be a seven-fold increase in the number of warm days between 2020 – 2040 and the past period. There needs to be more research into the current level of acclimation in these cities and how this urban heat stress may translate into increased mortality. As the South Caucasus is relatively urbanized and the heat stress is likely to be the most serious climate change-related health issue, all the countries need to enact adaptation plans that address: reducing exposure to heat in urban areas (e.g. infrastructure measures), adopting preventive public health measures (e.g. surveillance and early warning systems) and ensuring the preparedness of the healthcare system and other care providers to respond to heat waves.

The most serious climate change-related health issue in the South Caucasus is likely to be urban heat stress. More than half the population in each country live in urban areas (64%, 52%, 53%, respectively in Armenia, Azerbaijan, Georgia) [18], and they all have a large, old housing stock dating back to the time of the Soviet Union. Three major cities were selected in the Region: Baku, Tbilisi and Vanadzor (Figure 14).

Figure 14. The focal cities considered in the urban health analysis.

Methodology and Results

The goal of this analysis was to project how the Heat Index (HI) will change in the future for three focal cities. HI is a correction of actual air temperature by the relative humidity [25] and is a useful measure of thermal comfort for humans (Table 4.1). (The index really is only meaningful when the air temperature is at least 72 ºF (22.2 ºC) and the relative humidity is at least 30%.) The World Health Organization has classified HI in terms of its public health danger (Table 4.2).

Table 4.1. The relationships between the Heat Index and temperature and relative humidity. The entries of the matrix are the values of the Heat Index. The colors from green to dark red represent: "warm", "very warm", "hot", "very hot" and "extremely hot" days.

RH (%)	Temperature (°C)															
	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
90	28,04	30,73	33,75	37,08	40,72	44,68	48,95	53,54	58,45	63,67	63,67	75,06	81,22	87,71	94,51	101,6
85	27,85	30,22	32,89	35,87	39,14	42,71	46,58	50,76	55,22	59,99	65,06	70,43	76,1	82,07	88,34	94,91
80	27,67	29,74	32,1	34,74	37,67	40,88	44,37	48,14	52,21	56,54	61,17	66,08	71,28	76,75	82,51	88,56
75	27,48	29,28	31,36	33,69	36,3	39,17	42,31	45,72	49,39	53,33	57,53	62,01	66,75	71,76	77,03	82,57
70	27,29	28,86	30,67	32,73	35,04	37,6	40,41	43,47	46,78	50,34	54,15	58,21	62,52	67,08	71,89	76,95
65	27,11	28,46	30,03	31,84	33,88	38,66	38,66	41,41	44,38	47,58	51,02	54,69	58,59	62,73	67,09	71,69
60	26,93	28,08	29,45	31,03	32,83	34,84	37,07	39,52	42,18	45,05	48,14	51,44	54,96	58,69	62,64	66,81
55	26,74	27,73	28,92	30,31	31,89	33,67	35,64	37,81	40,18	42,75	45,51	48,47	51,63	54,98	58,53	62,28
50	26,56	27,42	28,45	29,66	31,05	32,62	34,36	36,29	38,39	40,68	43,14	45,78	48,59	51,59	54,77	58,12
45	26,38	27,13	28,03	29,09	30,32	31,7	33,24	34,94	36,81	38,83	41,02	43,36	45,86	48,52	51,34	54,33
40	26,21	26,86	27,67	28,61	29,69	30,91	32,28	33,78	35,43	37,22	39,14	41,21	43,42	45,77	48,27	50,9
35	26,02	26,63	27,36	28,2	29,17	30,26	31,47	32,8	34,26	35,83	37,53	39,34	41,28	43,34	45,53	47,83
30	25,84	26,42	27,09	27,87	28,75	29,73	30,82	32	33,28	34,67	36,16	37,75	39,44	41,24	43,13	45,13

Note: Exposure to full sunshine can increase HI values by up to 10°C

Table 4.2. The classification of the heat index in terms of public health impacts.

Fahrenheit	Celsius	Notes
80-90°F	27-32°C	Caution – fatigue is possible with prolonged exposure and activity
90-105°F	32-41°C	Extreme caution – sunstroke, heat cramps, and heat exhaustion are possible
105-130°F	41-54°C	Danger – sunstroke, heat cramps, and heat exhaustion are likely; heat stroke is possible
over 130 ˚F	over 54 ˚C	Extreme danger – heat stroke or sunstroke are likely with continued exposure

For all three cities, historical temperature and humidity data were obtained from 1955 – 1970 and 1990 – 2006 (or slightly later for Tbilisi (2007) and Vanadzor (2009)) in order to calculate the historical HI values. In order to project future HI, daily climate projections (daily temperature and relative humidity) from the PRECIS model (using ECHAM as the boundary GCM - see Chapter 1) (B2 emissions scenario) for the period 2020 – 2049 were used. The five important months for heat stress were considered: May, June, July, August and September. Tables 4.3 – 4.5 show the results for the three cities. For Baku and Tbilisi, there is expected to be a dramatic increase in the number of 'dangerous' days by mid-century – roughly a trebling of days compared to 1990 – 2006(7). In Baku, for example, it is projected that by mid-century there will be about 120 days that are 'dangerously' hot, or the majority of days in the May – September period. For Vanadzor, however, which has a more temperate climate than the other two cities, the increase in the absolute number of 'dangerous' days is rather small, although there is projected to be a seven-fold increase in the number of warm days between 2020 – 2040 compared to 1990 – 2009.

This analysis is only the first step in evaluating the climate change, urban heat and health nexus. Firstly, each population responds differently (mortality-wise) to heat, so it will be important to characterize the current level of acclimation in each city – and across the South Caucasus. Secondly, the Heat Index is an imperfect metric and may not best capture heat risk. Other metrics, such as the Wet Blub Globe Temperature (WGBT), the distribution of hot days or the duration of heatwaves may be better correlated with mortality. This needs further exploration.

Table 4.3. The projected change in the number of 'dangerous days' for Baku by mid-century. The number of dangerous days is the sum across each period.

	Baku		
	1955-1970	1990-2006	2020-2049
Normal	508	872	1037
Warm	463	607	1063
Very Warm	331	749	1858
Hot	13	63	539
Very Hot	0	0	3
Extremely Hot	0	0	0
Total number of dangerous days	344	812	2400

Table 4.4. The projected change in the number of 'dangerous days' for Tbilisi by mid-century. The number of dangerous days is the sum across each period.

	Tbilisi		
	1955-1970	1990-2007	2020-2049
Normal	1338	1349	1525
Warm	796	843	1161
Very Warm	310	545	1527
Hot	4	17	287
Very Hot	0	0	3
Extremely Hot	0	0	0
Total number of dangerous days	314	562	1814

Table 4.5. The projected change in the number of 'dangerous days' for Vanadzor by mid-century. The number of dangerous days is the sum across each period.

	Vanadzor		
	1955-1970	1990-2009	2020-2049
Normal	2192	2942	3700
Warm	17	116	784
Very Warm	0	2	16
Hot	1	0	0
Very Hot	0	0	0
Extremely Hot	0	0	0
Total number of dangerous days	1	2	16

Public Health Responses and Adaptation Options

There are basically three general measures that can be taken to reduce the risks of mortality from heat waves: (1) changing the urban environment to reduce exposure, (2) adopting preventive public health measures and (3) ensuring the preparedness of the healthcare system and other care providers.

The first measure is the most effective, but the most resource and capital-intensive. The goal would be to reduce the effective heat stress to which the urban population is exposed by: increasing green space (including green roofs), designing buildings to be cooler (e.g. improving insulation, air-conditioning, etc.) and using building/paving materials with a higher albedo. However, it should be noted that quick fixes, such as mobile or central air-conditioning, evaporative coolers, dehumidifiers and electric fans are useful in the short term, but they are carbon-intensive and may not reach the most vulnerable populations [26].

The second measure entails the establishment of a health action plan, both at the national and sub-national levels. It would include several components, such as [27]:

- An early warning system for heat waves.
- A health information plan to issue warnings to relevant stakeholders and the public.
- A communication campaign, including health education materials for the public and others.
- The establishment of systems for real-time data collection on heat-related syndromes, hospital admissions and mortality.
- An epidemiologic surveillance for heat-related morbidity and mortality.
- Enhanced surveillance of heat-related morbidity and mortality during the summer time.
- Some type of surveillance of especially at-risk individuals, based on census data, in collaboration with social services, etc.
- Periodic monitoring and evaluation of systems and interventions.

It is important to investigate the nature of current heat-related mortality. It may be the case that the excess mortality during heat waves simply represents the early deaths of those who would have died within several days, weeks, or months in the absence of a heat wave (e.g. the elderly and the sick). This is known as the "harvest effect" [28]. It may be the case that an increased incidence of hea twaves in the future with climate change will not necessitate new public health expenditures, only the distribution of those resources across various public health programs.

Lastly, ensuring the preparedness of the healthcare system and other care providers will involve [27]:

- Guidelines for practitioners on the diagnosis and treatment of heat-related issues.
- Advisories for practitioners on medications and other collateral risk factors for heat-related risk.
- Guidance to hospitals and care homes on how to minimize heat-related risk for patients.
- Capacity-building of healthcare practitioners (revise curricula, specific training, etc).
- Enhancement of healthcare service delivery capacities prior to heat waves.
- Promotion or the mandating that large healthcare and other care providers have a plan in place to prepare for and respond to heat waves.
- Inspection of adequacy of buildings, facilities and resources to deal with heat.

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Appendix I. CRU Dataset

These data are from the Climate Research Unit of the University of East Anglia, United Kingdom (CRU TS 3.0) (the so-called CRU data). This dataset is the most comprehensive and reputable global dataset of historical climate [29]. On a 0.5º basis (~50 km at the equator) worldwide for the period 1901 – 2006, the dataset contains: monthly mean precipitation, mean temperature, mean daily minimum temperature, mean daily maximum temperature and number of wet days (number of days with precipitation > 0.1 mm). The data were obtained from the CGIAR-Consortium for Spatial Information (http://csi.cgiar.org/cru_climate.asp).

Software and Data Processing

Analyses of the CRU data were done using the statistical programming package, R 2.11.0, and ArcGIS 9.3 and its scripting language Python 2.4.1. The country delineations were derived from a raster (0.033 degree resolution) originally obtained from the World Bank Development Economics Spatial Group. Spatial averages for climate variables were derived by using the zonal analysis operation in ArcGIS 9.3.

Appendix II. Mann-Kendall Trend Analysis

Mann (1945) [30] first suggested using Kendall's Tau as a test for a trend in variable *Y* over time (*T*). The Mann-Kendall test can be stated most generally as a test for whether *Y* values tend to increase or decrease with *T* (monotonic change). To perform the test, Kendall's S statistic is computed from the *Y, T* data pairs:

$S = P - M,$

where P = the number of $Y_i < Y_j$ for all $i < j$

M = the number of $Y_i > Y_j$ for $i < j$

Then,

$$\tau = \frac{S}{n(n-1)/2}$$

For n > 10

$$\sigma_s = \sqrt{(n/18)*(n-1)*(2n+5)}$$

$$Z_S = \begin{cases} \frac{S-1}{\sigma_S} & if \quad S > 0 \\ 0 \quad if & S = 0 \\ \frac{S+1}{\sigma_S} & if \quad S < 0 \end{cases}$$

The null hypothesis is rejected at significance level α if $|Z_s| > |Z_{\alpha/2}|$, where $|Z_{\alpha/2}|$ is the critical value from standard normal distribution.

Mann-Kendall trend analysis is common in environmental science [31]. The Mann-Kendall tests were done in R 2.11.0 with the package Kendall.

Appendix III. General Circulation Models (GCMs)

GCMs used in the analysis. The columns indicate in which variable calculations the model was used. GCMs vary in the variables and scenarios for which they have output. All GCMs were utilized when model outputs were available. Only the A2 emissions scenario, probably the most plausible, was considered [32].

Model ID	Institution, Country	Spatial Resolution
CGCM3.1(T47)	Canadian Center for Climate Modelling and Analysis, Canada	~2.8° x 2.8°
CSIRO-Mk3.0	Australia's Commonwealth Scientific and Industrial Research Organisation, Australia	~1.9° x 1.9°
ECHAM5/MPI-OM	Max-Planck-Institut for Meteorology, Germany	~1.9° x 1.9°
ECHO-G	Meteorological Institute, University of Bonn, Germany; Meteorological Research Institute of KMA, Korea; Model and Data Groupe at MPI-M, Germany	~3.9° x 3.9
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory, USA	2.0° x 2.5°
GISS-ER	Goddard Institute for Space Studies, USA	4.0° x 5.0°
INM-CM3.0	Institute for Numerical Mathematics, Russia	4.0° x 5.0°
MIROC3.2 (medres)	National Institute for Environmental Studies, Japan	~2.8° x 2.8°
UKMO-HadCM3	UK Met. Office UK	2.5° x 3.75°

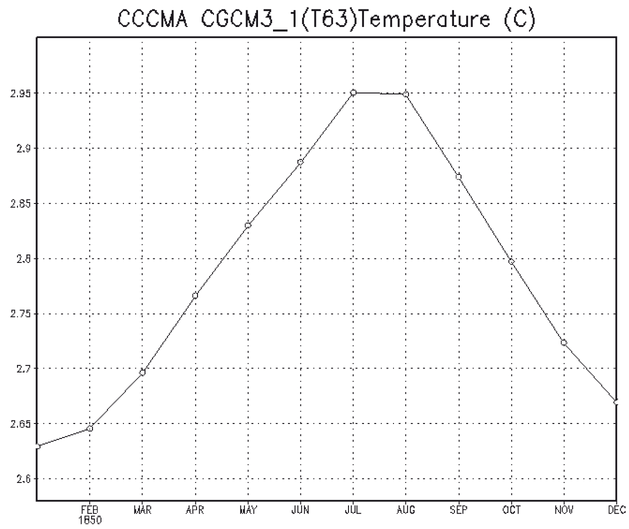
The source for all model outputs was the World Climate Research Programme's Coupled Model Intercomparison Project (Phase 3): https://esg.llnl.gov:8443/ . See also the IPCC Fourth Assessment Report for more details [33].

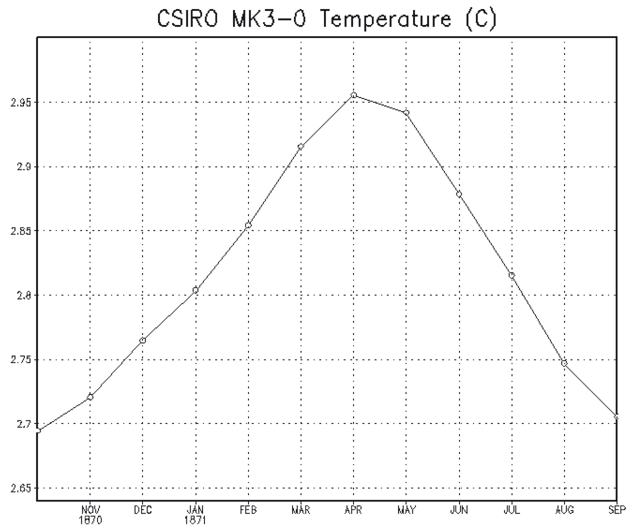
Zonal Analyses

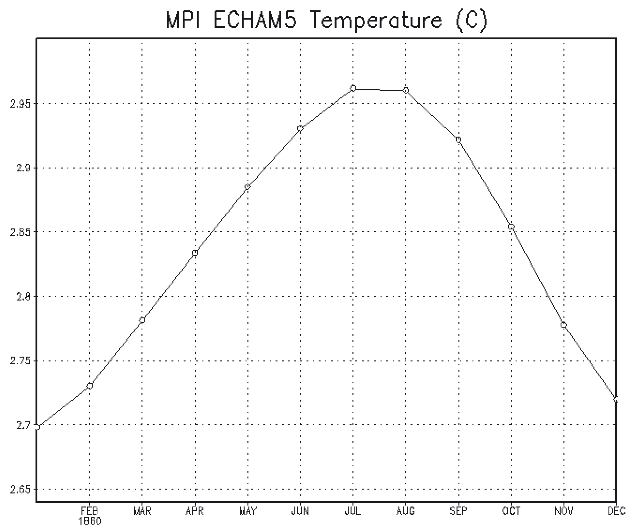
The analyses in Tables 13 and 14 were done using the statistical programming package, R 2.11.0, and ArcGIS 9.3 and its scripting language Python 2.4.1. The former was used to access and manipulate the GCM output files, while the latter was used to generate the country-averaged values. The country delineations were derived from a raster (0.033 degree resolution) originally obtained from the World Bank Development Economics Spatial Group.

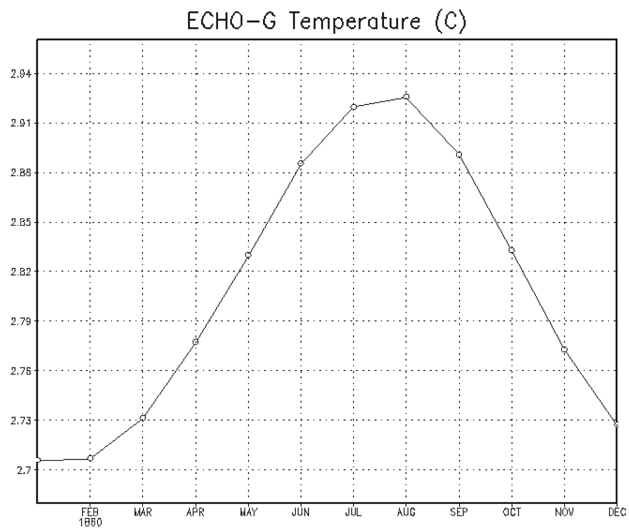
Appendix IV. Evaluation of GCMs.

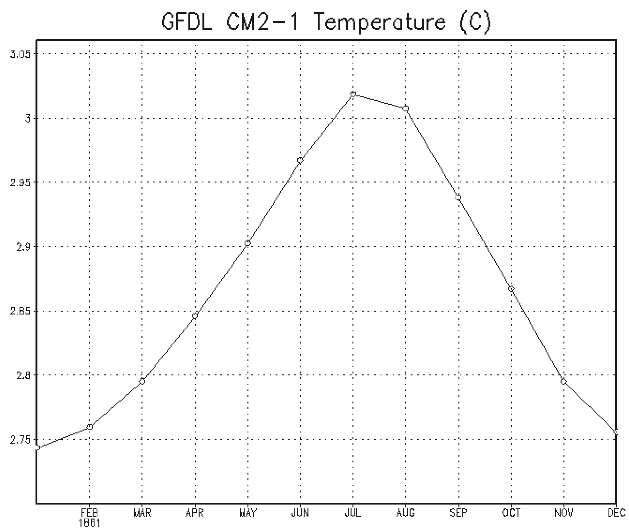
The figures below show the simulation of average monthly precipitation for the South Caucasus for the period 1961 – 1990 [3].

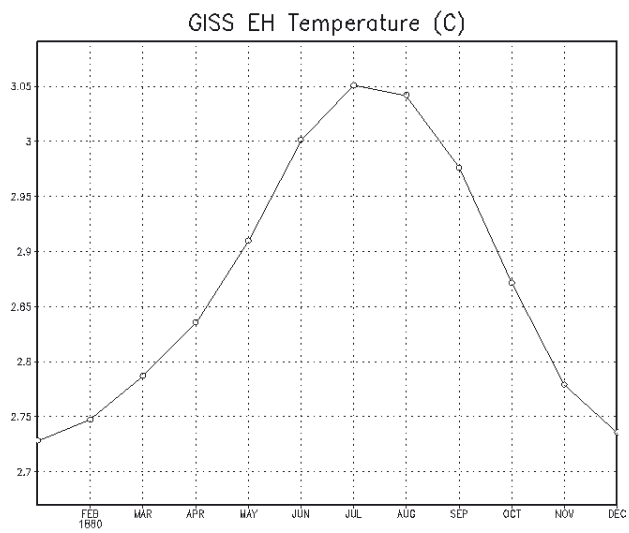




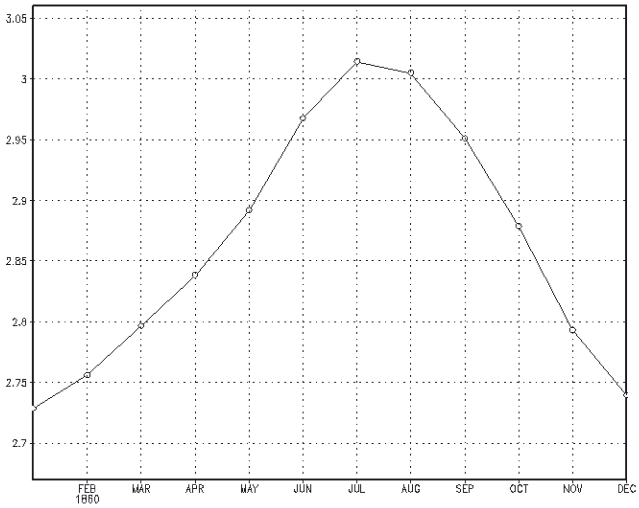




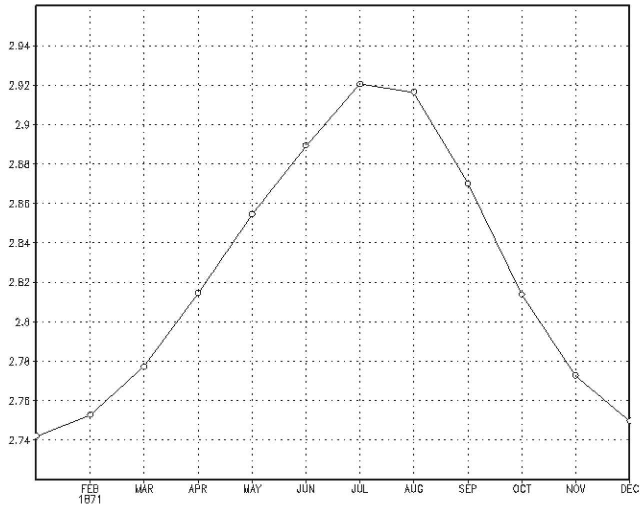




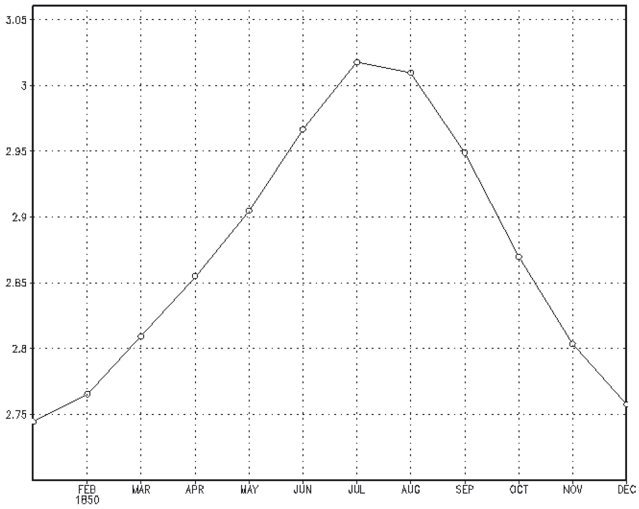
HadCM3 Temperature (C)



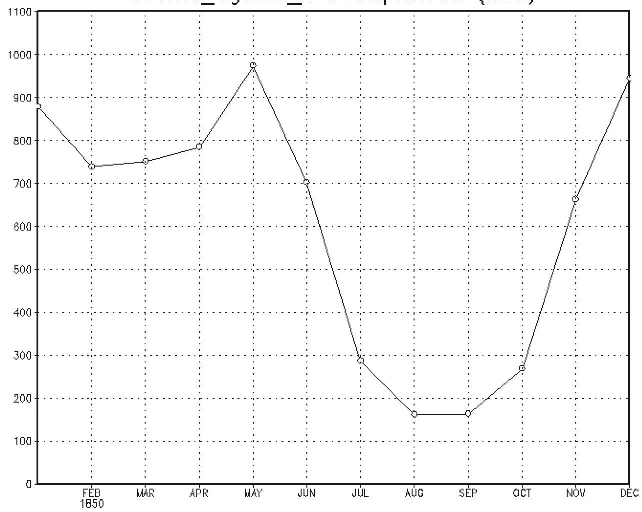
INM CM3.0 Temperature (C)



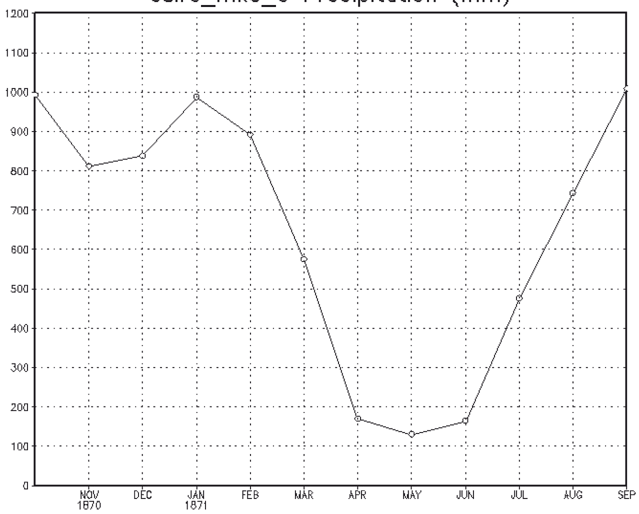
MIROC 3_2 MEDRES Temperature (C)



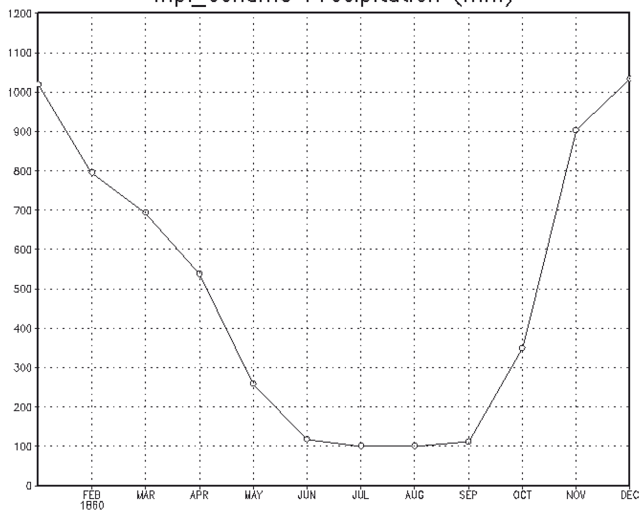
cccma_cgcm3_1 Precipitation (mm)

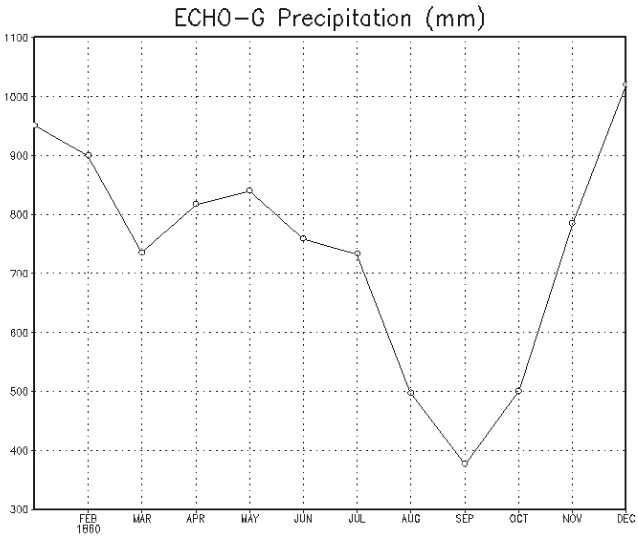


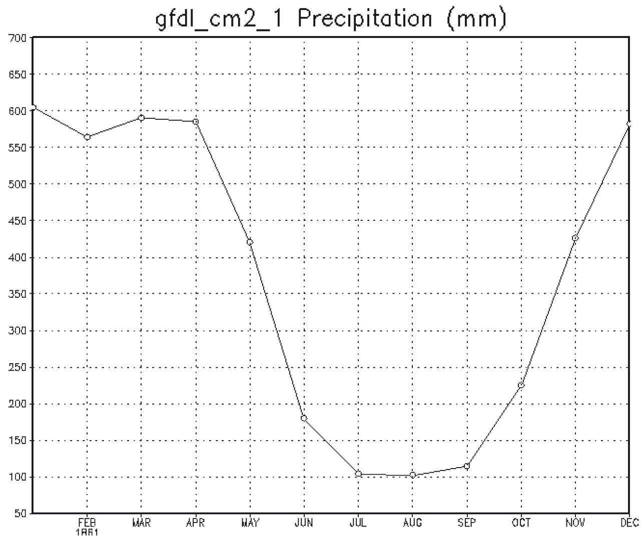
csiro_mk3_0 Precipitation (mm)

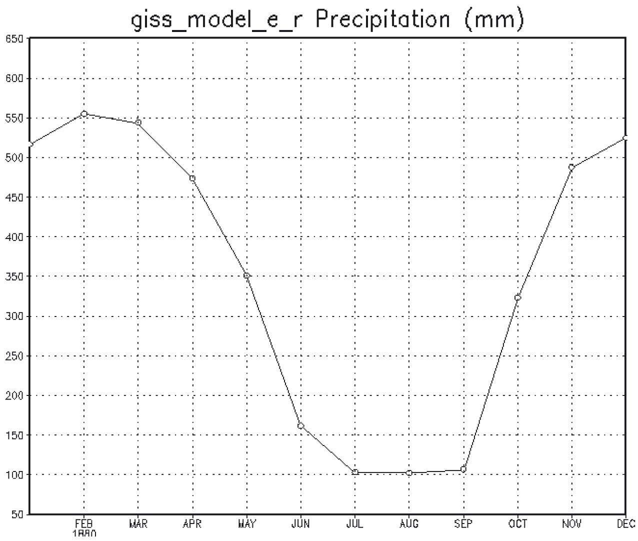


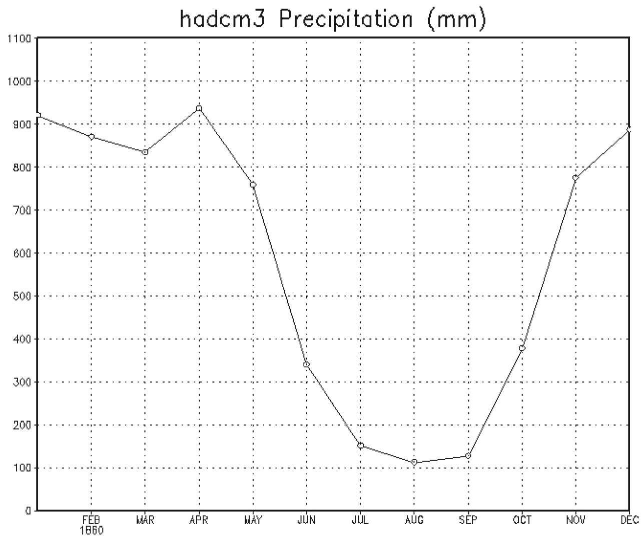
mpi_echam5 Precipitation (mm)

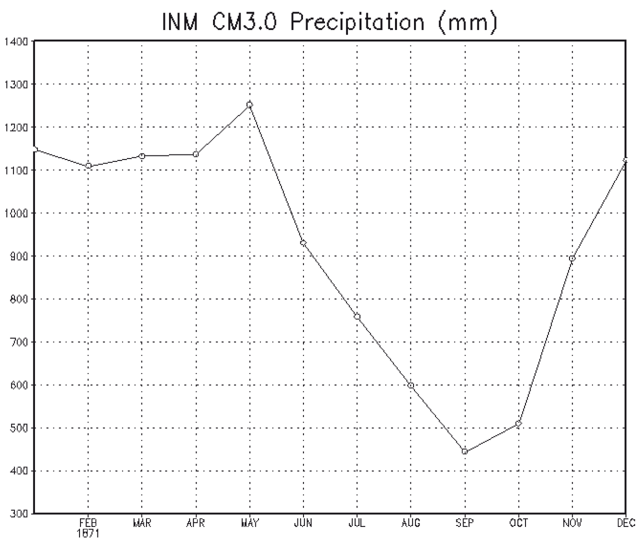


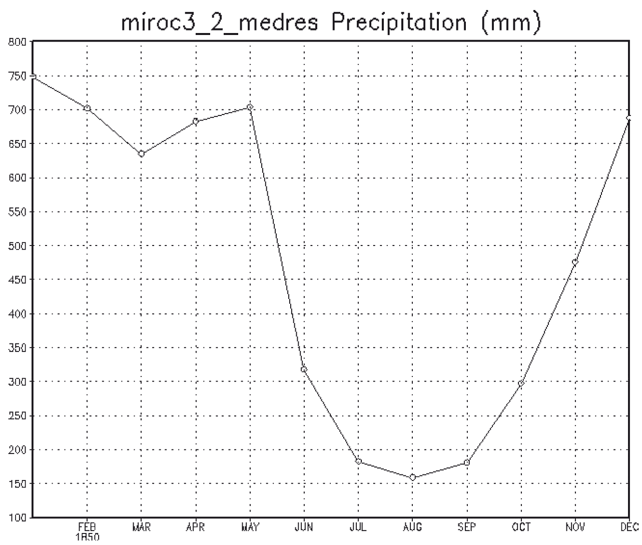

ECHO-G Precipitation (mm)
1100 1000 900 800 700 600 500 400 300
FEB 1860 MAR APR MAY JUN JUL AUG SEP OCT NOV DEC


gfdl_cm2_1 Precipitation (mm)
700 650 600 550 500 450 400 350 300 250 200 150 100 50
FEB 1861 MAR APR MAY JUN JUL AUG SEP OCT NOV DEC


giss_model_e_r Precipitation (mm)
650 600 550 500 450 400 350 300 250 200 150 100 50
FEB 1880 MAR APR MAY JUN JUL AUG SEP OCT NOV DEC


hadcm3 Precipitation (mm)
1100 1000 900 800 700 600 500 400 300 200 100 0
FEB 1860 MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

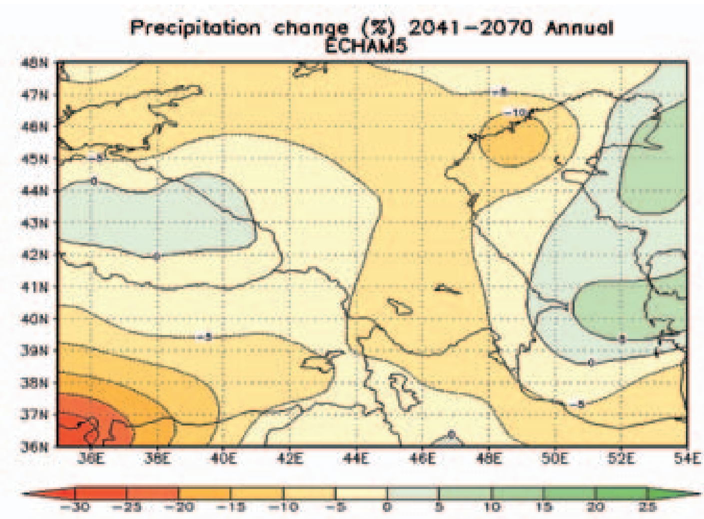

INM CM3.0 Precipitation (mm)
1400 1300 1200 1100 1000 900 800 700 600 500 400 300
FEB 1871 MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

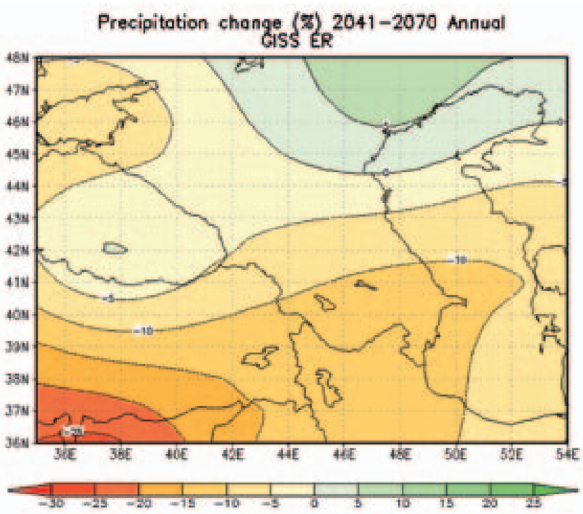

miroc3_2_medres Precipitation (mm)
800 750 700 650 600 550 500 450 400 350 300 250 200 150 100
FEB 1850 MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

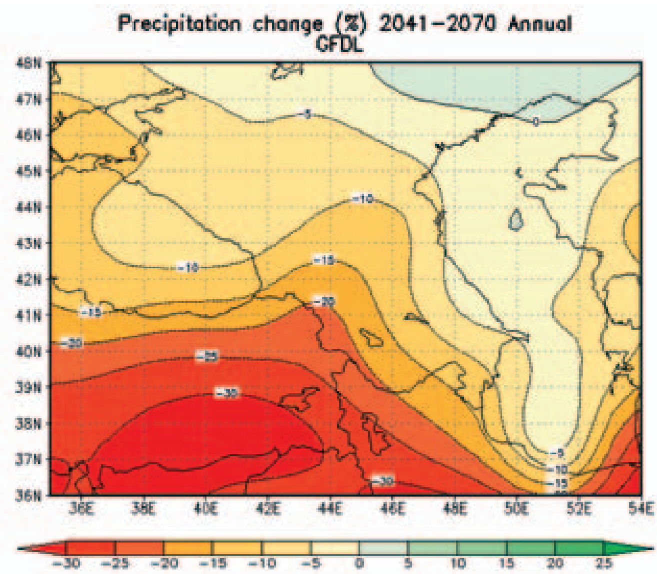
Appendix V. GCM Projections of the change in mean annual precipitation.

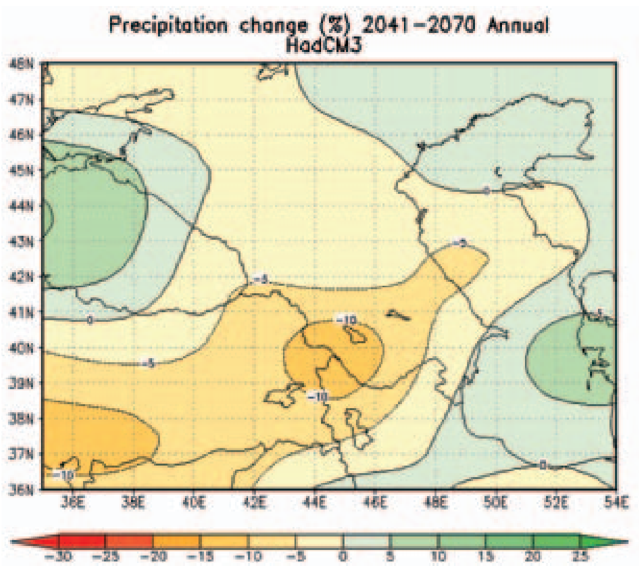
The GCMs represent the set of models that best simulate historical climate in the South Caucasus. Countries delineations are not shown, but two bodies of water bound the region; the Black and Caspian Seas [3].

2041 - 2070

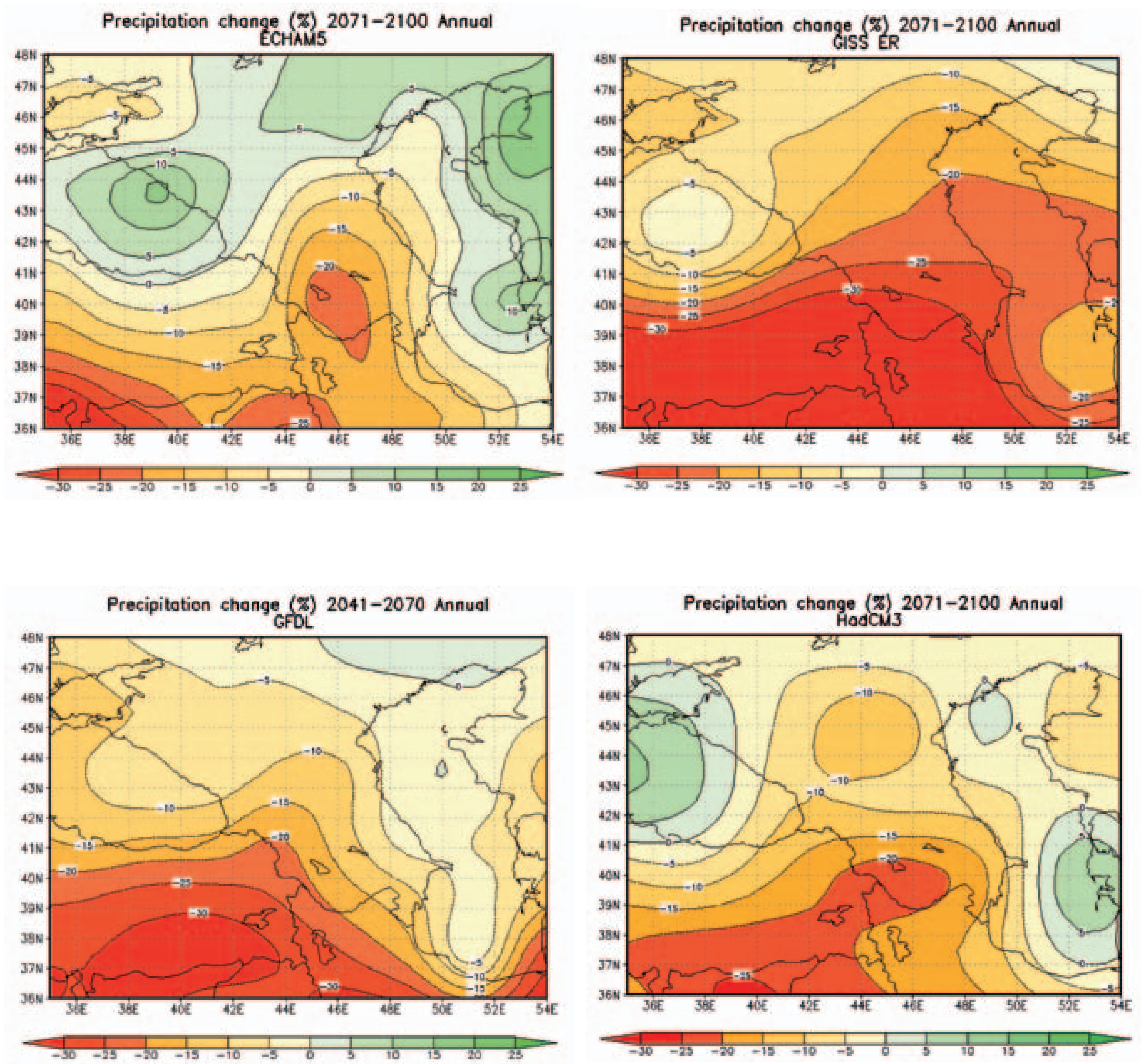








2071 – 2100

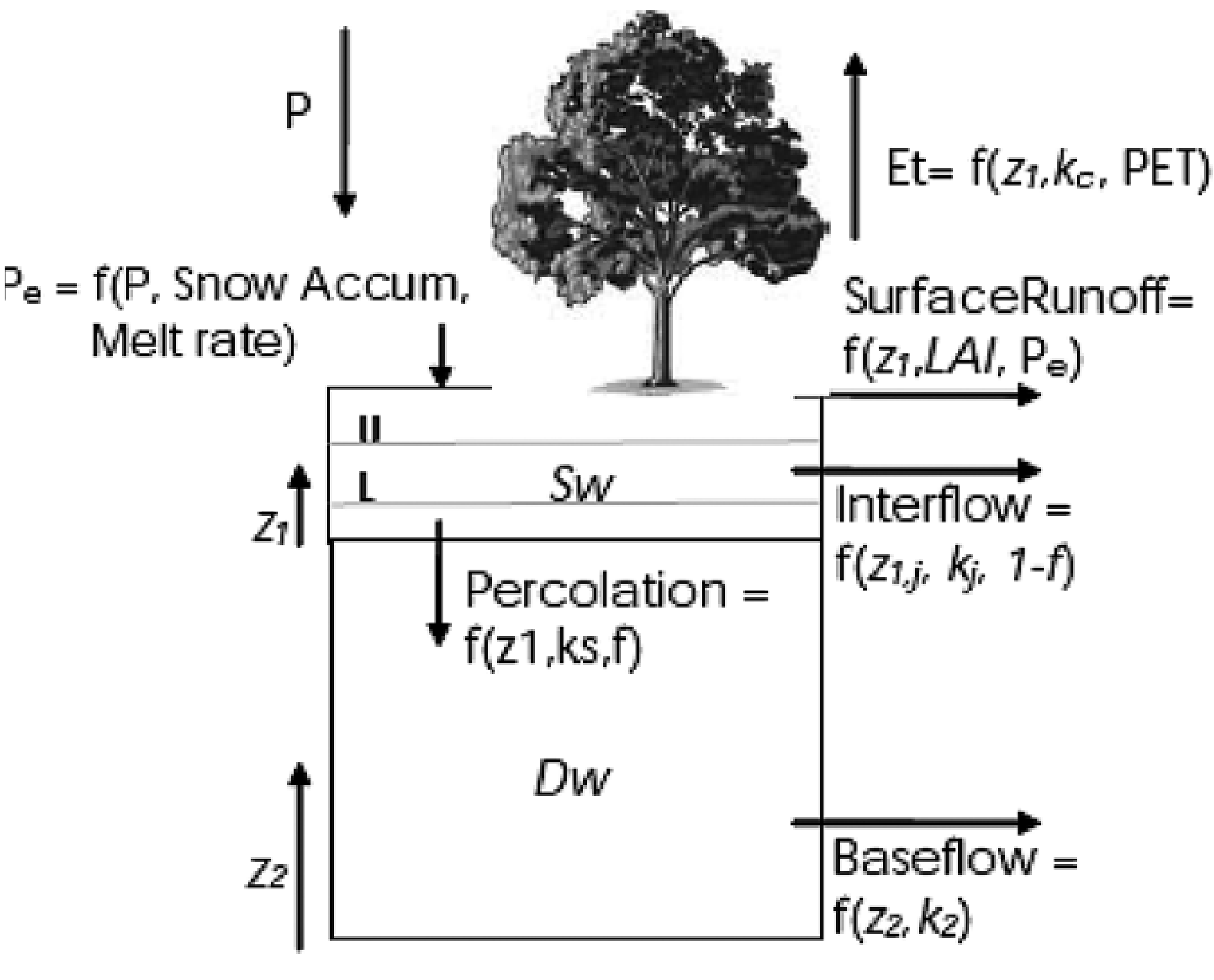


Precipitation change (%) 2071-2100 Annual
ECHAM5
Precipitation change (%) 2071-2100 Annual
GISS ER
Precipitation change (%) 2041-2070 Annual
GFDL
Precipitation change (%) 2071-2100 Annual
HadCM3
48N 47N 46N 45N 44N 43N 42N 41N 40N 39N 38N 37N 36N
36E 38E 40E 42E 44E 46E 48E 50E 52E 54E
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25

Appendix VI. The Water Evaluation and Planning Model (WEAP)

The Water Evaluation and Planning Model (WEAP) [34] is an Integrated Water Resource Management (IWRM) model which integrates water supply generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements. The WEAP model includes an irregular-grid, water balance model that can account for hydrologic processes within a watershed system and can capture the propagating and non-linear effects of water withdrawals for different uses. A one dimensional, 2-storage soil water accounting scheme uses empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff or interflow, and deep percolation (See figure below). WEAP is not spatially-explicit, but spatially-implicit. That is, it does not model the exact real landscape, but the sequence of sub-catchments and demand sites is important. For the Alazani, the basin was first divided into 7 sub-catchments with two demand sites (See Figure below). Each sub-catchment is treated as a "two-bucket" system (See figure below).

Schematic of the two-layer soil moisture store, showing the different hydrologic inputs and outputs for a given land cover or crop type.



For each sub-catchment, a mass balance equation is written as:

$$Sw_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)\, k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t)\, z_{1,j}^{\frac{LAI_j}{2}} - f_j k_j z_{1,j}^2 - (1-f_j)k_j z_{1,j}^2$$

That is, the soil moisture in a sub-catchment is the precipitation that falls minus evapotranspiration and the amount of water that leaves the catchment via surface runoff or sub-surface flows. To calculate streamflow the model needs the following information for every sub-catchment: **Climate variables for the chosen time span (e.g. decade, month, year)**

- **P**, Precipitation (mm)
- **PET**, Evapotranspiration (mm), that can be calculated from mean temperature (°C), relative humidity (%), mean wind velocity(m/s), melting and freezing temperatures (-5 °C and 5 °C by default), geographical coordinates of catchment

- **Various soil/vegetation parameters**

- Area of catchment (km.[2]) and sub-catchments, if catchment is divided by land cover type
- K_c - crop/plant coefficient for each fractional landcover
- z_1, z_2 - relative soil water storage in upper and lower storages at the starting point in time (%)
- D_w - deep water storage capacity (mm)
- S_w - Soil Water capacity (mm)
- k_2 - the conductivity rate of the lower storage (mm/time)
- k_j - an estimate of the upper storage conductivity (mm/time)
- f_j - quasi-physical tuning parameter related to soil, land cover type, and topography that fractionally partitions water either horizontally, f_j or vertically (1- f_j).
- *LAI* - the Leaf and Stem Area Index, with the lowest LAI_j values assigned to the land cover class that yields the highest surface runoff response, such as bare soils.

The number of sub-catchments, their order and area, and climate variables were supplied to WEAP, while for most of the parameters, the model default values are used, or else they are calibrated in the modeling run. Water consumption (demand) at different point of river is specified as monthly values (m^3).

Appendix VII - CropWat Model

CropWat is a program that uses the FAO Penman-Monteith equation to calculate reference crop evapotranspiration [23]. These estimates are used in turn to calculate crop water requirements and irrigation scheduling calculations.

Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (vapor removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Transpiration consists of the vaporization of liquid water contained in plant tissues and vapor removal to the atmosphere.

Evapotranspiration (*ET*) - Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process

Factors affecting evapotranspiration include the following:

- **Weather parameters**: The principal weather parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed. Several procedures have been developed to assess the evaporation rate from these parameters. The evaporation power of the atmosphere is expressed by the reference crop evapotranspiration (ET_o). The reference crop evapotranspiration represents the evapotranspiration from a standardized vegetated surface.
- **Crop factors**: The crop type, variety and development stage should be considered when assessing the evapotranspiration from crops grown in large, well-managed fields. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different *ET* levels in different types of crops under identical environmental conditions. Crop evapotranspiration under standard conditions (ET_c) refers to the evaporating demand from crops that are grown in large fields under optimum soil and water, excellent management and environmental conditions, and achieve full production under the given climatic conditions.
- **Management and environmental conditions**: Factors such as soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management, may limit the crop development and reduce the evapotranspiration. Other factors to be considered when assessing *ET* are groundcover, plant density and the soil water content. When assessing the *ET* rate, additional consideration should be given to the range of management practices that act on the climatic and crop factors affecting the *ET* process. Cultivation practices and the type of irrigation method can alter the microclimate, affect the crop characteristics or affect the wetting of the soil and crop surface. A windbreak reduces wind velocities and decreases the *ET* rate of the field directly beyond the barrier. The effect can be significant especially in windy, warm and dry conditions although evapotranspiration from the trees themselves may offset any reduction in the field, etc.

In order to carry out the crop water requirements calculations CropWat requires:

1. Monthly average reference evapotranspiration (ET_o). If reference evapotranspiration data are unavailable, then climate data (temperatures, humidity, windspeed, sunshine) can be used instead to estimate the reference evapotranspiration using the Penman-Monteith formula.
2. A Cropping Pattern consisting of one or more crop names and the planting date(s). A set of typical crop coefficient data files are provided in the software.
3. Monthly Rainfall data.