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Indexing the Environmental Vulnerability of Mountain Streams in Azerbaijan

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1

A simple environmental vulnerability assessment scheme is developed and illustrated using several streams in Azerbaijan as examples. Vulnerability of a river ecosystem is defined in terms of a combined impact of pressure factors such as water withdrawals, pollution, climate change impact on flow variability, and land use. These factors are used to measure the sensitivity of various elements/components of the system to impacts. The choice of these indicators may vary from area to area and depends on the nature of man-made and natural conditions. Each factor is characterized and quantified using a specific indicator and score. The total vulnerability score is estimated as a sum of the scores of all indicators. Most of the streams studied in Azerbaijan were found to be very vulnerable or extremely vulnerable, according to the developed scheme. The overall approach is straightforward and transparent. Conclusions are made about the vulnerability and/or resiliency of streams, to be taken into consideration when planning for water-sources development for the future.

Keywords: *Small streams; environmental vulnerability index; water withdrawal; pollution; environmental flow; land use; indicator assessment; Azerbaijan.*

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Introduction

Small rivers of the Kura basin of Azerbaijan experience significant pressure due to intensive water withdrawals for irrigated agriculture, energy production, and domestic needs. Under natural conditions, most of the small streams in the region have stopped flowing only in exceptionally dry years. However, due to progressive water withdrawals from the 1980s onward, most of these streams now dry up regularly. As a result, the connectivity of small streams with the mouths of larger rivers is lost. This affects migration of sturgeon from the Caspian Sea to spawning grounds (Barannik et al 2004). The Caspian Sea accounts for some 90% of the world's sturgeon population. Sturgeon are the main source of black caviar, more than 85% of which is produced by Caspian countries (Williot et al 2002). Small streams in Azerbaijan are also highly impacted by pollution from the mining industry, agriculture, and domestic water use (Suleymanov et al 2010).

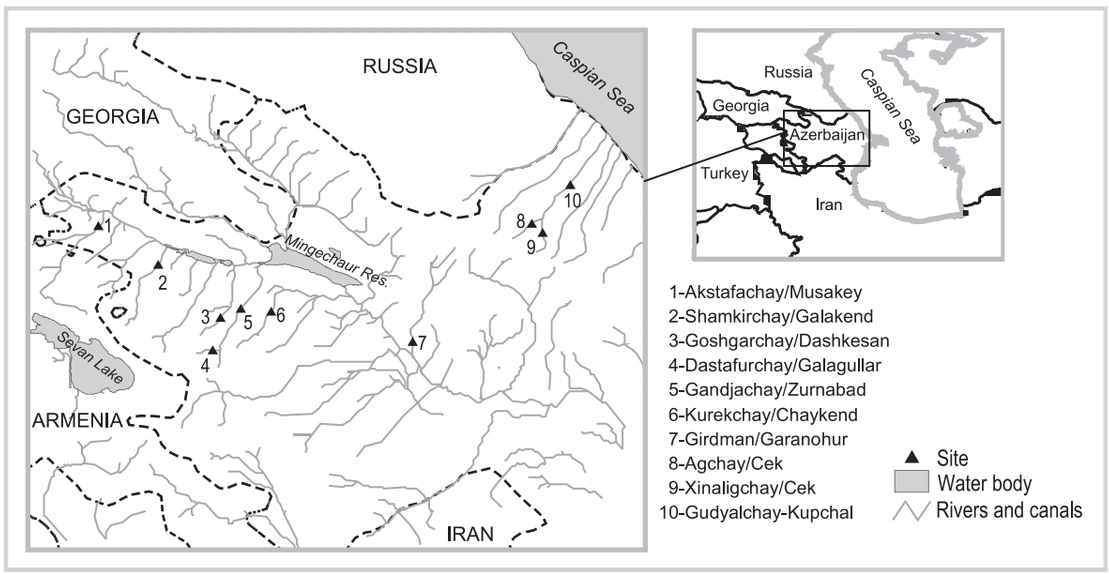
The Caspian Environmental Programme specifies that future development of resources of the Caspian Sea should be environmentally sustainable and that all natural resources, including fish, should be carefully managed and protected (CEP 2002). To help implement this noble task, it is important to evaluate in a clear and transparent way the levels of anthropogenic pressure and environmental vulnerability of small streams. Comprehensive and yet simple indices of environmental vulnerability due to various factors can be used to guide the appropriate management interventions.

The aim of this study is threefold: (1) to quantify environmental conditions of small mountain streams in Azerbaijan by developing an environmental vulnerability index, (2) to suggest ways in which resilience of such small streams can be enhanced, and (3) to fill the data and methodology gap in the research field.

Study area and data

Several right and left tributaries of the Kura River and streams that directly flow into the Caspian Sea are considered in this study (38–41°N; 44–50°E). All of them are located in northwestern and northern parts of Azerbaijan (Figure 1). The highest point of the study area—Mount Bazardüzü (41°13′14″N; 47°51′28″E)—has an altitude of 4466 m, while the lowest point is at 28 m below the mean sea level. Mountain territories of Azerbaijan have a temperate and cold climate. The climate is characterized by dry summers and temperate winters. Mean annual precipitation is up to 864 mm in high and middle lands, and less than 250 mm on plains. Approximately 70–80% of annual precipitation falls during winter; and 50–60% of the annual flow volume occurs during April–June, triggered by the intensive snowmelt and rains (Mamedov 1989). Irrigation takes place largely on plains. Over the past 60 years, the area of the cultivated land has considerably increased. Grain, wheat, vegetable, and fruits are the main crops produced here (Fatullayev 2003).

FIGURE 1 Study area. (Map by authors)



The study area has a rather sparse hydrological observational network. Most of the observational points are located in the low and middle basins, and records start in the late 1960s and early 1970s. Annual and monthly flow time series from 1949 to 2009 were used from 10 hydrological stations, together with average monthly values of dissolved oxygen, pH, total nitrogen, and total phosphorus for the period 2007–2009. In streams where mines are sources of additional pollution, data on metal concentration were also collected.

Methods

Environmental vulnerability

UNDRO (1982) defined vulnerability as the degree of loss to a given element or a set of elements at risk resulting from occurrence of a natural phenomenon of a given magnitude. Mitchell (1989) suggested that vulnerability is the potential for loss. Downing et al (2001) termed vulnerability as the function of sensitivity to present climate variability, the risk of adverse climate change, and resilience to adapt. IPCC defined vulnerability as the extent to which a natural or social system is susceptible to sustaining damage from climate change (IPCC 2006). A similar definition was proposed by Luers et al (2003). Most of these definitions address climate change only. Yet some authors consider vulnerability to include susceptibility of ecosystems (Metzger et al 2006). The concept of vulnerability developed by Schröter et al (2005) broadens this term and considers other global changes (eg land-use changes) as well. Ecosystem resilience is the opposite of vulnerability and reflects the ability of an ecosystem to withstand this combined impact (Xiaolei et al 2011).

The choice of vulnerability indicators is important for analysis. The choice of these indicators may vary from area to area and depends on the nature of man-made and natural conditions (Kulshreshtha 1993).

In this study, vulnerability of a river ecosystem is defined in terms of a combined impact of pressure factors such as water withdrawals, pollution, climate change impact on flow variability, and land use. Each factor can be characterized and quantified using a specific indicator. The total vulnerability score is estimated as the sum of scores of all indicators.

The highest score of each indicator is 6. High indicator scores mean that the ecosystem has a high level of vulnerability in terms of this indicator. The total maximum vulnerability score—in terms of all indicators—is 30. Total scores are categorized (albeit subjectively) as extremely vulnerable (>25), very vulnerable (21–25), vulnerable (16–20), marginal (11–15), resilient (6–10), and very resilient (=5). The details of each indicator are briefly described next (Table 1).

Water withdrawals

From the management perspective, the flow in a river can and should be seen as the sum of two components:

$$Q = Qenv + Qww, \quad (1)$$

where Q is the total discharge on a certain day, month, or year, Qenv is environmental flow during the same period, and Qww is environmentally acceptable water withdrawal. Environmental flow refers to the flow variability in a river that sustains freshwater ecosystems (Smakhtin and Anputhas 2006). It is that part of the flow that ideally

TABLE 1 Main indicators of the vulnerability scoring and relevant values.

Vulnerability indicators					Total score	Vulnerability category
Water withdrawals	Pollution	Land-use changes	Flow regime	Climate changes		
6	6	6	6	6	**>25**	Extremely vulnerable
5	5	5	5	5	**21–25**	Very vulnerable
4	4	4	4	4	**16–20**	Vulnerable
3	3	3	3	3	**11–15**	Marginal
2	2	2	2	2	**6–10**	Resilient
1	1	1	1	1	**0–5**	Very resilient

should be "pre-allocated" (reserved) for environmental purposes. Naturally, in order to estimate environmentally acceptable water withdrawals, it is first necessary to estimate environmental flows. A discussion of environmental flow assessment methods is beyond the scope of this paper, but details can be found in the most recent review by Acreman and Dunbar (2004). For the purpose of illustration, as well as to keep the focus on the region in this study, monthly environmental flows are estimated according to the scheme proposed by Abbasov and Smakhtin (2009):

$$\mathrm{Qenv} = (\mathrm{Xi}/\mathrm{X})\mathrm{Q} * \mathrm{env}, \qquad (2)$$

where Xi is the basin precipitation from the beginning of October to the end of March for year i, X is the long-term mean precipitation for the same period, and Q*env is the environmental minimum base flow for a calendar month, assumed to be equal to the naturally observed minimum flow for this calendar month.

The simple indicator of the pressure of water withdrawals on the river ecosystem is the water withdrawal pressure index (WWP):

$$\mathrm{WWP} = 1 - \mathrm{Qenv}/\mathrm{Qobs}. \qquad (3)$$

WWP can be calculated using daily or monthly flow time series, depending on data availability and the needs of

TABLE 2 The scoring system for assessment of vulnerability from water withdrawals.

WWP index values	Ecosystem condition	Vulnerability score	Vulnerability level
<−1	• Totally deteriorated • Water withdrawals significantly exceed permissible levels • Ecosystem water needs are not satisfied • Small rivers go dry	6	Extremely vulnerable
−1 to −0.5	• Bad • Water withdrawals exceed permissible levels • Ecosystem needs partially/temporarily not satisfied • Most of small rivers go dry	5	Very vulnerable
−0.5 to 0	• Poor • Water withdrawals exceed permissible levels • There is no sufficient water to support ecosystem needs	4	Vulnerable
0	• Fair • Water withdrawals are equal to permissible levels • Ecosystem needs are marginally supplied • There are no additional opportunities to increase withdrawals	3	Marginal
>0 to 0.5	• Sufficient • Ecosystem needs are supported	2	Resilient
0.5 to 1	• Good • Additional opportunities to increase water withdrawals exist	1	Very resilient

Mountain Research and Development mred-32-01-02.3d 20/1/12 20:14:04 3 Cust # 11-00012

TABLE 3 Ecosystem evaluation scoring for pollution.

BOD_5[a)] (mg/L)	DO[a)] (mg/L)	NH_3 (mg/L)	NO_3 (mg/L)	PO_4 (mg/L)	TSS (mg/L)
1–2	<2	<0.25	<0.1	<0.1	0–150
2–3	2–3	0.25–0.5	0.1–0.25	0.1–0.25	150–300
3–4	3–4	0.5–1.5	0.25–0.5	0.25–0.5	300–450
4–5	4–5	1.5–2.5	0.5–1.0	0.5–1.0	450–600
5–6	5–6	2.5–5	1–1.5	1–2	600–800
>6	>6	>5	>1.5	>2	>800

practice. Negative values of WWP point to undesirable conditions in a river, since they mean that there is not sufficient water to support ecosystem needs, and that water withdrawals exceed environmentally acceptable limits. Values lower than −1 could be indicative of extreme pressure from withdrawals. Positive values are indicative of reasonable ecological conditions of various degrees. Using WWP, it is possible to determine the scores for changed conditions of stream ecosystems (Table 2).

Pollution

Excessive pollution challenges the ability of streams to perform self-purification and to dilute more pollutants, thus increasing vulnerability of streams (Kazemi and Hosseini 2011). Vulnerability scoring is in a direct relationship with water quality. The latter is defined by concentrations of constituents that change quickly as a result of pollution (Chapman 1992); these are 5-day biochemical oxygen demand (BOD_5), dissolved oxygen (DO), pH, total suspended solids (TSS), total dissolved solids (TDS), ammonia (NH3), nitrate (NO_3), and total phosphate (PO_4) (Tebbutt 1998). For example, some microorganisms resulting from pollution use oxygen. Therefore, low DO levels indicate high oxygen demand, which may be the result of pollution. In Azerbaijan, DO levels change as a result of loads of NH_3, NO_3, and PO4 resulting from domestic and agricultural sources. In some river basins with mines, pollution by metal contaminants (Al, Fe, Cu) has also been categorized, and the same scoring was used.

In order to score ecosystem condition, 10 categories were used, and each category was worth 1/10. The total vulnerability score was taken as the rounded value of the sum of categories. Depending on the region, the number of categories may be arbitrary, but in all cases, 10 categories are sufficient to evaluate ecosystem conditions. Because the level of some compounds directly depends on water temperature, scoring was conducted for all 12 months of the year (Table 3).

Flow variability

Flow variability is the main determinant of ecosystem functioning; changes in flow variability lead to ecological changes in a stream. The absolute amount of permissible water withdrawals in a small stream is naturally smaller than in a large river. Therefore, in small streams, the probability that water withdrawals may exceed environmentally acceptable limits is higher than in large rivers. Larger rivers may therefore have more potential to be resilient than smaller streams. Moreover, there is a direct relationship between permissible water withdrawals and flow variability. It means that in a single river/stream, the low-flow periods are more vulnerable than high-flow periods.

Vulnerability of streams due to flow variability was approximated in this study by the simplified standard deviation (S) of mean monthly flows. The developed indicator is a transferred form of the deviation from the mean yearly flows, and we consider that it successfully illustrates interannual flow distribution, such that

$$s=\sqrt{\frac{1}{12}\sum_{1}^{12}\left(\frac{q_i}{q_m}-1\right)^2}, \qquad (4)$$

where q_i is mean monthly flow, in m^3/c, and q_m is mean annual flow, in m^3/c. In the extreme, and obviously hypothetical, case of constant flow throughout the year, S = 0. The scoring categories for S are listed in Table 4.

Climate change

Due to climate change, flow variability, and hence S values, may change. For example, due to early melting of snow cover, winter flow of some rivers in Azerbaijan may gradually increase. This will result in decreasing S values. Thus Equation 4 allows future projections of hydrological impacts to be accounted for.

Also, studies of the small streams of Azerbaijan suggest that there is a gradual increase in the annual temperature accompanied by a steady decrease in precipitation (Abbasov 2001; Mansimov 2004; Mahmudov 2006; Renssen et al 2007). To account for such trends in this study, a simple linear trend approach is used:

$$Q=aT+b, \qquad (5)$$

where Q is discharge in m^3/c, T is a time (year), a is a slope coefficient, and b is the intercept. If the slope coefficient is significantly positive, it is an indication of an increasing trend. Negative values of the slope indicate decreasing trends. Hence, the sign of the slope coefficient defines the

TABLE 3 Excented.

TDS (mg/L)	As (mg/L)	Ca (mg/L)	Pb (mg/L)	Vulnerability score	Vulnerability level
<0.1	<0.0005	<0.0005	<0.01	1	Extremely vulnerable
0.1–0.5	0.0005–0.001	0.0005–0.001	<0.01–0.02	2	Very vulnerable
0.5–1.0	0.001–0.015	0.001–0.015	<0.01–0.05	3	Vulnerable
1–1.5	0.015–0.02	0.015–0.02	0.05–0.1	4	Marginal
1.5–2	0.002–0.03	0.002–0.03	0.1–0.5	5	Resilient
>2	>0.03	>0.03	>0.05	6	Very resilient

trend direction. Extrapolation of the slope allows approximations of the long-term mean flow for the future *X* years to be made. In this study, an arbitrarily selected 20-year horizon was used for such extrapolations.

There are many approaches to evaluate significance of the linear trends (eg Helsel and Hirsch 1992; Devore 2004). The P-value approach is one of the most used methods. The P-value is a parameter ranging from zero to one. Lesser values of P indicate an increased probability that the trend is significant. In hydrology and meteorology, it suffices to say that P-values less than 0.01 are statistically significant. If the P value is greater than 0.01, we should suggest that the significance of the trend is low (McBean and Motiee 2008).

Land-use change

Land-use change is one of the major factors that may affect natural flow variability of small streams (Ward et al 2008). The scoring in this study takes into consideration the main land-use impacts on flow in Azerbaijan—deforestation, agriculture, and urbanization. Mass removal of vegetation decreases infiltration and evapotranspiration, leaving a larger percent of incoming precipitation to generate surface runoff (Mohapatra and Singh 2003). The removal of vegetation also makes steep slopes much more susceptible to sheet erosion due to removal of roots that otherwise stabilize the soil column (Balyuk and Kondratyev 2004). Increasing area of cultivated land may adversely affect soil cover and water quality (Hall et al 1999; Zalidis et al 2001). Urbanization impacts interannual flow distribution (Hall et al 1999).

Catchment land-use changes may be detected and evaluated by comparing spatial data from different years. In this study, old topography maps and contemporary satellite images of the area were compared. Old maps represent official data from 1956 of the State Geodesy and Cartography Committee of the USSR. Satellite images represent Google Earth data of 2008, from which land-use maps were generated. Changes in areas of forests, urbanized territories, and agricultural lands may be estimated using basic ARC View software.

The scoring system for assessing vulnerability due to land-use change is presented in Table 5. Each one of the three main land-use impacts considered—deforestation, agricultural land expansion, and urbanization—was scored separately, and each has a maximum score of 2. There are 6 categories for each impact, and, therefore, each category is

TABLE 4 Flow variability scoring categories.

S values	Natural flow regime	Vulnerability score	Vulnerability level
>0.6	• Big difference in volume of monthly flows • High level of seasonal allocation • In some months, rivers naturally go dry • Rivers are mainly fed by melting snows or seasonal rains	6	Extremely vulnerable
0.5–0.6	• Considerable difference in volume of monthly flows • Seasonal allocation is considerable • Rivers are mainly fed by melting snows or seasonal rains	5	Very vulnerable
0.3–0.4	• Difference in volume of monthly flows fairly high	4	Vulnerable
0.2–0.3	• Difference in volume of monthly flows is not high	3	Marginal
0.1–0.2	• Relatively equal allocation of monthly flows	2	Resilient
<0.1	• Highly regulated, monthly flows are not much different from mean yearly flows	1	Very resilient

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TABLE 5 Ecosystem evaluation scoring for land-use changes.

Deforestation (%)	Agriculture (%)	Urbanization	Vulnerability score	Quality and vulnerability level
>30	>30	>20	6	Extremely vulnerable
26–30	26–30	16–20	5	Very vulnerable
21–25	21–25	11–15	4	Vulnerable
16–20	16–20	6–10	3	Marginal
11–15	11–15	1–5	2	Resilient
<10	<6–10	<1	1	Very resilient

worth 2/6. The combined total impact score was calculated as the round sum of the three individual impact scores. The maximum total score is therefore 6.

Results

Water withdrawals

In most summer months, WWP values are negative (Figure 2), indicating bad ecosystem conditions and in-stream flows not resilient enough to satisfy ecosystem requirements.

According to the ecosystem evaluation scoring for water withdrawals, in most of the summer months of 2008, ecosystem conditions in the Girdmanchay at Qaranohur were not satisfactory, since water withdrawals significantly exceeded permissible amounts. Only in some winter months (January and February) did the conditions improve. There is hardly much potential for more water withdrawal. In December, March, and April, ecosystem requirements were marginally supplied, and stream ecosystems can be evaluated as marginal.

There is a large spatial variability in WWP. WWP values of high mountain sites (eg Xinaliq at 1950 m) differ from those at lowland sites (eg Kupchal at 736 m). These changes are better seen in the Figure 3, where both spatial and temporal variations of WWP are illustrated. The withdrawals have fluctuated at the high end from 1983 until present time. For example, by 1996, an insignificant drop in WWP can be observed, which may be the result of the economic slowdown in the previous years, associated with the collapse of the USSR.

Pollution

According to the scoring scheme, water quality in some of the streams can be evaluated as extremely vulnerable. For example, observed BOD_5 values in the Akstafachay River at Musakey in July of 2008 were 5.5 mg/L, which is almost three times higher than maximum acceptable concentration levels.

FIGURE 2 Water withdrawal pressure index in the Girdmanchay River at Qaranohur and Kurakchay-Chaykend, 2008.

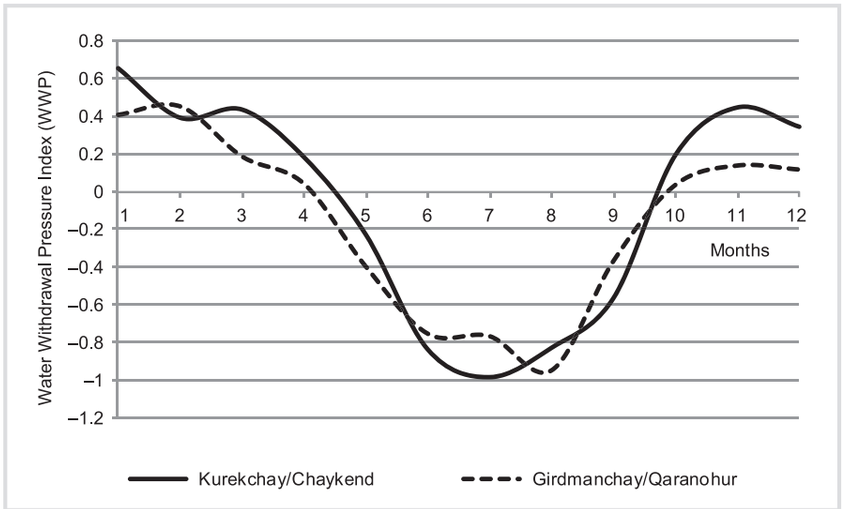

FIGURE 3 Variation of WWP values in various years and at different elevations.

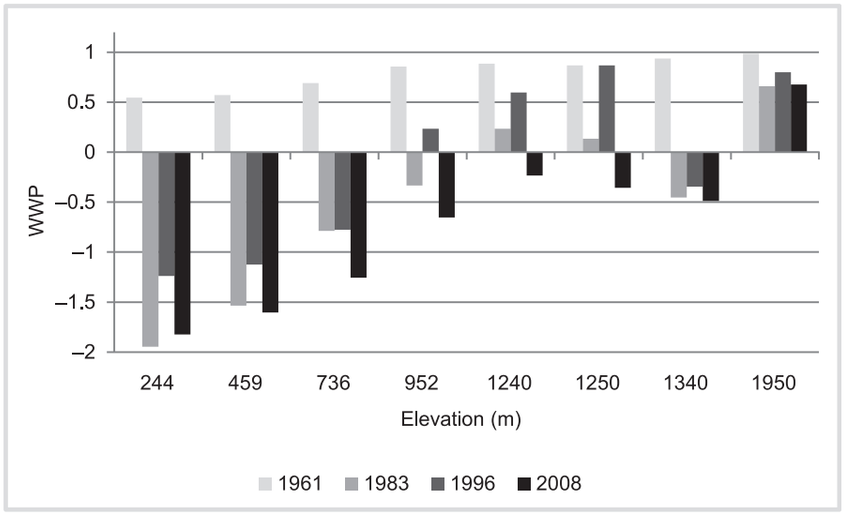

FIGURE 4 Linear trends of February (A), August (B), and annual flows (C) in the Candjachay at Zurnabad.

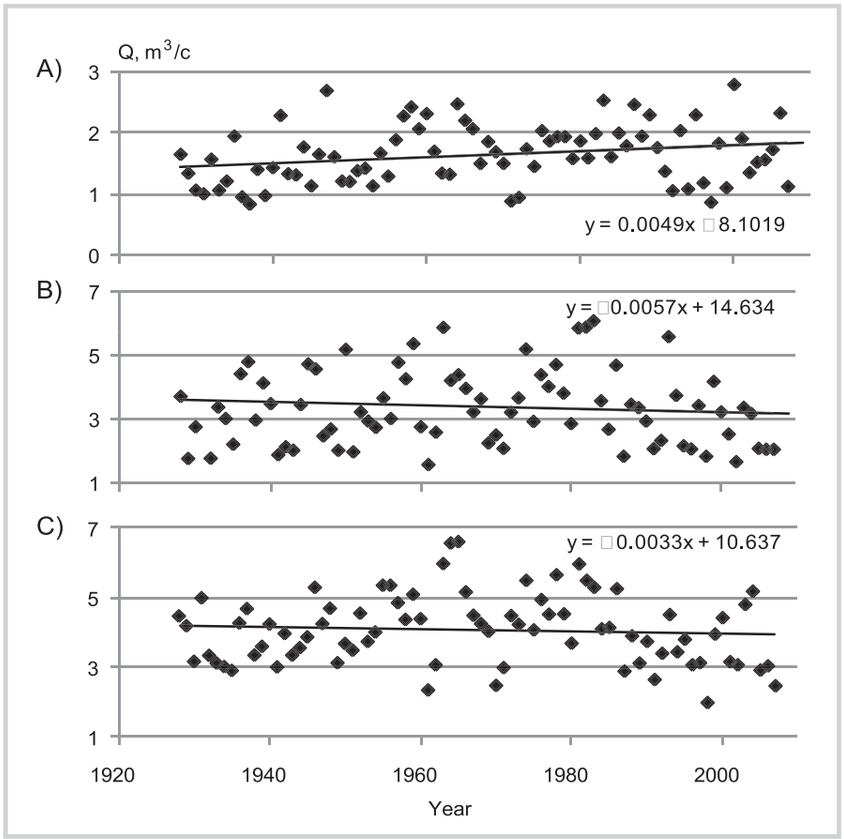

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TABLE 6 Vulnerability scorings for some streams of the study area (July).

River/site	Geographical coordinates	Vulnerability indicators	
		Water withdrawals	Pollution
Candjachay/Zurnabad	40°70′N; 45°91′E	6	5
Dastafurchay/Qaraqullar	40°31′N; 45°92′E	2	1
Shamkirchay/Galakend	40°59′N; 45°72′E	3	2
Goshgarchay/Dashkesan	40°43′N; 45°86′E	3	6
Gudyalchay/Kupchal	41°32′N; 48°38′E	4	2
Girdmanchay/Garanohur	40°78′N; 48°31′E	5	3
Agchay/Cek	41°17′N; 48°12′E	1	1
Xinaligchay/Xinaliq	41°16′N; 48°19′E	1	1

Vulnerability due to pollution significantly changes spatially. High mountain streams are less vulnerable than the streams of middle and lower parts. For example, the vulnerability score for the Dastafurchay Qaraqullar, located in the Candjachay basin at a rather high altitude (1820 m), is much lower than the Candjachay itself. This is a result of limited urbanization in the basin of Candjachay.

Flow variability and climate change

Almost all of the rivers in the study area may be considered "extremely vulnerable" or "very vulnerable" in terms of this indicator. For example, in Candjachay River, standard deviations of S are always more than 0.5. This is an attribute of the flow variability of the streams, which are fed largely by spring snowmelt.

Flow trend analysis illustrates that there are negative (decreasing) trends for the annual and summer flows and positive (increasing) trends for winter flows (Figure 4).

Land-use changes

In the basins of the Candjachay and Kurakchay Rivers, more than 45% of the forest has been removed in the last 70 years (Figure 5). The area of cultivated lands in the basins of these streams in 1956 and 2008 was 7% and 31%, respectively. Urbanization also has a major impact on vulnerability level and changes from 5% in middle altitudes to 12–15% in low altitudes.

According to ecosystem evaluation scoring for land-use changes, the land-use vulnerability level in the Candjachay is considered to be "extremely vulnerable,"

FIGURE 5 Changes in the area of forests, cultivated lands, and urbanized territories over the period 1956 (A) to 2008 (B) in the basins of Kurakchay, Candjachay, and Goshgarchay. (Maps by authors)

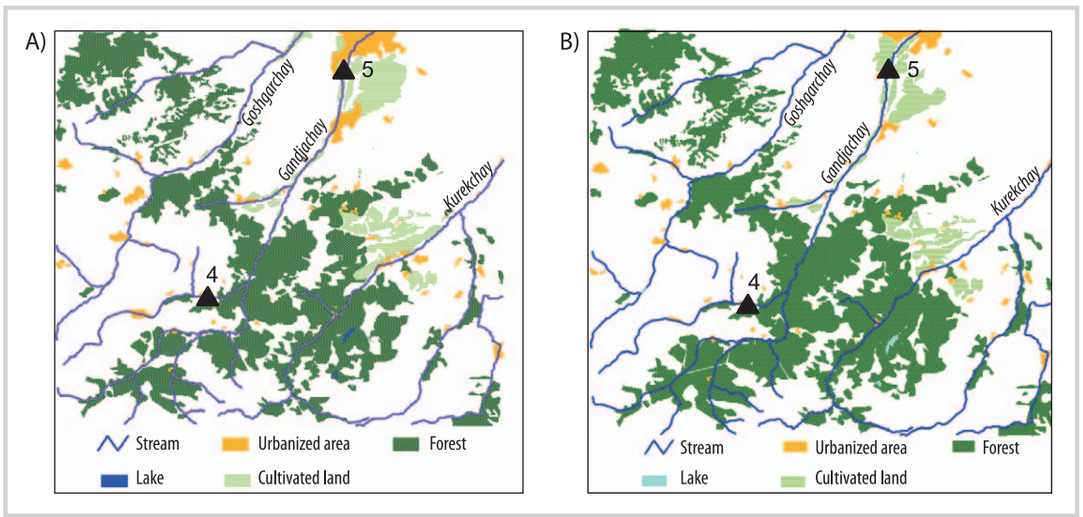

TABLE 6 Excented.

Vulnerability indicators			Total score	Vulnerability category
Land-use changes	Flow regime	Climate changes		
5	6	4	26	Extremely vulnerable
3	4	4	14	Marginal
2	5	5	17	Vulnerable
6	5	5	24	Very vulnerable
3	4	5	18	Vulnerable
4	6	6	24	Very vulnerable
3	2	3	10	Resilient
3	3	2	11	Resilient

since it has only 1 point, and in Kurakchay it is "very vulnerable" with 2 points.

Discussion and conclusions

The main advantage of the vulnerability assessment scheme presented in this paper is that it is both comprehensive (covering several components of vulnerability) and rather straightforward (based on measurable indicators and simple scoring). Direct scoring simplifies evaluation of ecosystem conditions of small streams in a given region. This tool may help identify the streams in the area that are most vulnerable and need urgent improvement and those that are most resilient. This in turn helps to set priorities for investments in management measures. The scheme of conjunctive water use, proposed previously by Abbasov and Smakhtin (2009), requires such comparison since it considers concurrent use of several rivers as a water sources, meaning the environmental conditions of all of the rivers should be evaluated. The developed methodology is generic and therefore may be suitable for other regions, provided the lack of data is addressed appropriately. Depending on local circumstances, the scoring system may be changed. For example, to score pollution level, locally specific contaminants that impact resilience of streams have been taken into account. In other regions, other contaminants may be more relevant, but principles of scoring can remain the same. Therefore, adjustments to the methodology for local circumstances are easy.

Sustainable management of mountain ecosystems requires detailed assessment methods for human-related impacts (Mandal 2007; Behrens et al 2009). These assessment methods may be based on the development of various indices that may easily reflect changes in water sources (Belousova 2009). Because mountain streams are the most important elements that support ecological chains in mountain regions (Mandal 2007), results of this study can be applied in the context of sustainable mountain development in Azerbaijan.

Vulnerability scores range under the impact of various factors, most of which are related to human activity in the region. Water withdrawals, pollution, flow variability, land-use changes, and climate changes have been taken as the main factors (Table 6). To estimate impacts of water withdrawals in the study area, a special indicator (water withdrawal pressure index) has been developed. This index takes into consideration the difference between environmental requirements and observed flows. If environmental requirements are higher than observed flows, the index becomes negative—a reflection of extremely vulnerable condition of a river ecosystem. Positive values of the index are reflective of a resilient, safe condition.

Flow variability also may have varied impact. As a rule, vulnerability of streams during summer is higher than during winter. This means that, in principle, some activities may be shifted to winter, if/when appropriate.

Simple linear trends were used to project flow due to climate change. Positive trends in winter monthly flows and negative trends in summer monthly and annual flows were identified. Linear trends were used just to illustrate the idea of vulnerability assessment due to climate change. However, because there is a broad palette of methods that can help to assess future climate impacts, depending on available data, any such methods may be used.

Vulnerability due to pollution is evaluated in terms of several constituents. Some of them vary for different regions, and also vulnerability of summer months is higher than the vulnerability of winter. This pattern is largely related to changing dilution ability of streams in summer.

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Overall vulnerability depends on the mean altitude of the basins. In high mountains, streams are less vulnerable than those in lowland areas. Although related to mean altitude, this factor has a more anthropogenic interpretation, since human activities are less intensive in the high mountains.

Taking into account the various aspects of vulnerability of streams and understanding its variability seasonally, spatially, and according to altitude may help in the design of environmentally responsible intervention measures in conjunctive use of water from multiple streams.

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