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Multi-annual hydro-climatic trends in the Dunajec Basin (Polish Carpathians)

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Abstract. Owing to changing climate conditions, this study analyses potential hydro-climatic trends for the most recent 60 years (1956–2015). The study area is situated in the mountain basin of the Dunajec River in the Polish Carpathians. The focus of the study was to evaluate multi-annual trends in mean monthly river flow for each season of the year as well as to compare the direction of these trends with potential trends in seasonal values of surface air temperature and precipitation. An increase in minimum flow ($p < 0.05$) during the winter was identified for sites located along the upper and middle course of the Dunajec River, while no trends in winter flow were found at the studied lower-course site. An increase in spring flow is significant ($p < 0.1$, weak evidence) at the upper-course site only. Moreover, an increase in maximum flow was found for autumn at the studied middle-course and downstream sites ($p < 0.05$ and $p < 0.1$, respectively). Increasing trends in mean and maximum air temperature ($p < 0.005$) were identified for the spring and summer, together with an increase in minimum summer air temperature ($p < 0.005$). Precipitation shows an increasing tendency in maximum values for spring, but a decrease in minimum values for summer ($p < 0.05$), as well as a decrease in maximum values for winter ($p < 0.1$). Overall, the revealed trends imply discernible, multi-annual changes in hydro-climatic conditions for the studied mountain basin.

1. Introduction

Mountain river catchments are typically areas with considerable freshwater resources resulting from orographic precipitation and substantial, multi-annual snow pack accumulation. Exploring the impact of climate change on water resources in mountain regions seems therefore particularly important for adequate water management and planning. Changing climate conditions with atmospheric warming of 0.12°C per decade (1951–2012) [1] observed worldwide, and induced changes in freshwater resources and riverine ecosystems have been extensively studied during the last few decades [2–13]. Owing to the strong co-variability of air temperature and precipitation, which is manifested in negative correlations over continental land in summer and positive correlations in winter at high latitudes [14], precipitation changes seem inevitable. It seems also clear that the observed and modelled changes in precipitation [15–16] and river flow are not expected to be spatially uniform over larger areas [17] and often do not extend beyond large natural hydro-climatic variability. Moreover, land use and land cover changes and other forms of human activity (e.g., dam and reservoir construction, road construction, water diversion) affect the water cycle as well [18–20]. In this context, identifying hydro-climatic



trends, especially multi-annual, may provide valuable information on ongoing changes, which can be utilised for future remedial actions mitigating adverse climate change impacts on freshwater resources.

The aim of this study is to: (1) assess potential multi-annual (60-year) trends in river flow (Q) for each season of the year; (2) compare the direction of these trends with potential trends in seasonal values of surface air temperature (T_a) and precipitation (P) for a mountain basin in the Polish Carpathians. The assessment of trends in the studied hydro-climatic variables (Q , T_a , P) can facilitate more realistic management and planning of existing freshwater resources at the catchment scale. It can also help in preparing adequate strategies limiting potential adverse impacts of climate change in crucial water source (mountain) regions.

2. Materials and methods

2.1. Study area

The research was conducted on the Carpathian river Dunajec, the right-bank tributary of the upper Vistula River in southern Poland (figure 1). The source tributary—Czarny Dunajec—begins in the Western Tatra Mountains (Poland), and the largest tributary—Poprad—begins in the High Tatra Mountains (Slovakia). The Dunajec River is 247 km in length. Its basin covers an area of 6804 km² [21], with the highest peak (Gerlach: 2655 m) being located in the High Tatra Mountains, and the lowest elevation at the Dunajec River mouth (174 m a.s.l.). The drainage basin is underlain by highly permeable aqueous carbonate rocks as well as impermeable crystalline and metamorphic rocks [22].

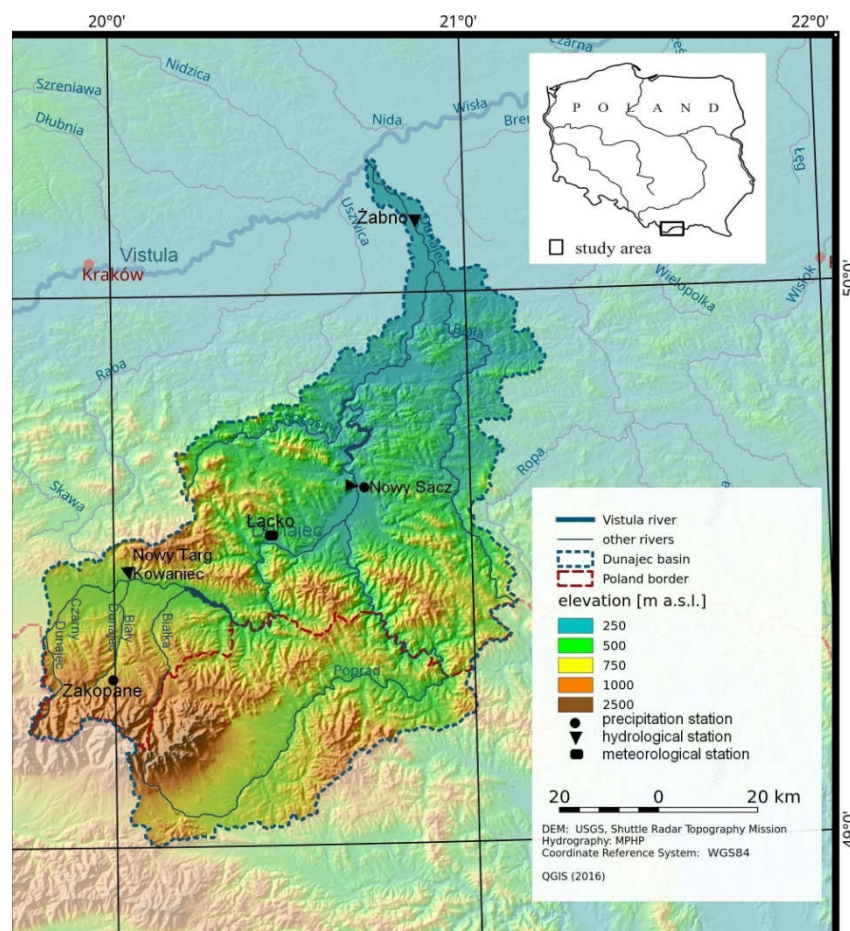


Figure 1. Study area—the Dunajec River Basin with measurement stations considered.

Climate conditions in the study area vary depending on location. In the lower-lying parts of the basin, the air temperature is higher, with an annual mean of 6–8°C, and precipitation totals of 700–900 mm a year. The highest peaks of the Tatra Mountains (2200–2655 m a.s.l.) are characterised by a cold climate, with an annual mean air temperature between –4 and –2°C, and annual precipitation totals reaching 1900 mm [23].

The Dunajec Basin area is 47.8% agricultural, while forests and developed land comprise 46.1% and 5.3%, respectively, and water covers 0.8% [24]. Between the years 1935 and 1949, a complex of two reservoirs (Rożnów and Czchów) was constructed on the Dunajec River, 27 km downstream of the Nowy Sącz gauging site [25]. Subsequently, in the years 1994–1997, a complex of two reservoirs (Czorsztyn and Sromowce Wyżne) was built on the upper Dunajec, approximately 25 km downstream from the Nowy Targ-Kowaniec gauging site.

2.2. Data and methods

The considered river flow data series consist of monthly means for three different gauging sites (Nowy Targ-Kowaniec, Nowy Sącz, Żabno) situated along the upper, middle and lower course of the Dunajec River, respectively (table 1). Mean monthly air temperature at Łącko, and mean monthly precipitation at Zakopane and Nowy Sącz were also taken into account (table 2). The monthly data for the years 1956–2015 (December 1955 – November 2015) were made available for research purposes by the Polish Institute of Meteorology and Water Management—the National Research Institute.

Table 1. Physical characteristics of the study sites [21] and descriptive statistics of mean monthly river flow for the 60-year period (1956–2015).

	Nowy Targ-Kowaniec	Nowy Sącz	Żabno
Latitude (N)	49°29'13"	49°37'38"	50°07'55"
Longitude (E)	20°03'13"	20°41'14"	20°51'43"
River length (km)	198.6	106.8	17.4
Drainage area (km ²)	681	4341	6735
Mean elevation (m)	1439	1466	1415
Mean basin slope (–)	0.046	0.031	0.027
Exposition	NE	NE	N
Mean flowrate (m ³ s ^{–1})	14.34	65.71	87.49
Minimum flowrate (m ³ s ^{–1})	1.92	8.60	15.11
Maximum flowrate (m ³ s ^{–1})	71.19	333.00	473.00
Median flowrate (m ³ s ^{–1})	11.73	52.31	70.39
Standard deviation of flowrate (m ³ s ^{–1})	10.20	48.51	65.15

Table 2. Characteristics of the study sites [21] and descriptive statistics of mean monthly air temperature (T_a) and mean monthly precipitation totals (P) for the 60-year period (1956–2015).

	Air temperature (°C)	Precipitation (mm)	
	Łącko	Zakopane	Nowy Sącz
Latitude (N)	49°33'35"	49°17'38"	49°37'38"
Longitude (E)	20°26'22"	19°57'37"	20°41'21"
Altitude (m a.s.l.)	366	855	292
Mean T_a / P	7.7	94.1/1128.8 ^a	61.1/733.3 ^a
Minimum T_a / P	–12.8	1.0	0.1
Maximum T_a / P	20.7	439.2	317.0
Median T_a / P	8.0	77.1	45.5
Standard deviation T_a / P	7.4	67.8	48.8

^a Mean annual total precipitation.

Following a visual inspection of monthly data and a quality check, mean, minimum, and maximum values were calculated for each season of the year (1956–2015). Next, trend analysis was carried out on each seasonal series separately in order to assess the strength of potential trends in seasonal values of Q , T_a and P . The non-parametric, 2-sided Mann-Kendall test [26–28] at the significance level α : 0.005 (strong evidence), 0.05 (medium evidence), and 0.1 (weak evidence) was used. The magnitude of trends was determined using Theil-Sen's slope [29–30] as a robust estimate of the slope [28]. Since serial independence is a requirement of the Mann-Kendall test, the trend-free pre-whitening procedure (TFPW) [31] was applied.

3. Results

Increases in minimum Q ($p < 0.05$, medium evidence) were identified for the winter (December–February) for sites located along the upper and middle course of the Dunajec River (figure 2), while no trends in winter Q were found for the studied downstream site (table 3). A weak increase ($p < 0.1$) in mean, minimum, and maximum Q was found for the spring (March–May) at the upper-course site only. Moreover, increases in maximum Q were identified for autumn (September–November) at the studied middle-course and downstream sites ($p < 0.05$ and $p < 0.1$, respectively). No trends in Q were identified for summer (June–August) at either site. An increase in maximum precipitation ($7.6 \text{ mm decade}^{-1}$, $p < 0.05$) was found for spring (figure 3a), while a significant decrease ($-7.1 \text{ mm decade}^{-1}$, $p < 0.05$) in minimum P was identified for the summer at the upstream site (Zakopane) only (figure 3b, table 4). Increases in mean and maximum air temperature ($0.24\text{--}0.30^\circ\text{C decade}^{-1}$, $p < 0.005$, strong evidence) during the spring were followed by increases in mean, minimum, and maximum T_a ($0.35\text{--}0.36^\circ\text{C decade}^{-1}$, strong evidence) during the summer (figure 4, table 5).

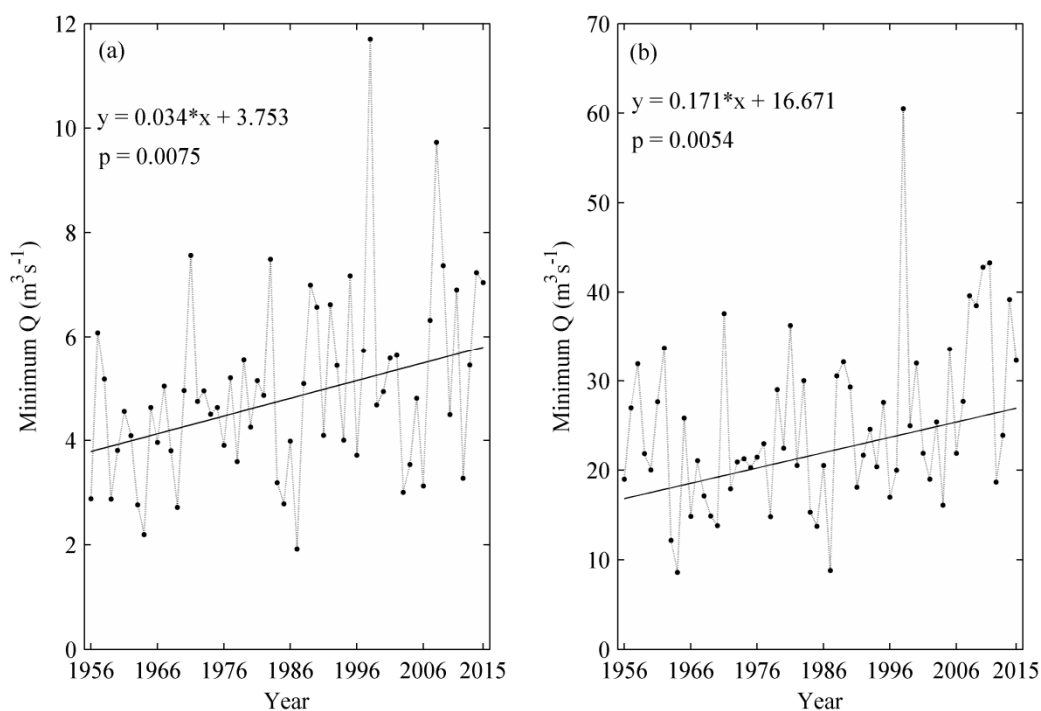


Figure 2. Winter flow rates (Q) at Nowy Targ-Kowaniec (a) and Nowy Sącz (b) with significant trends shown ($p < 0.05$).

Table 3. Rate of change a ($\text{m}^3\text{s}^{-1} \text{decade}^{-1}$) for river flow (Q) in each season of the year (1956–2015) based on Theil-Sen's slope estimation with trend free pre-whitening [31]. Statistical significance of the trends was evaluated via the 2-sided Mann-Kendall test [26-27].

Hydrological station	Q statistic	Winter (Dec–Feb)	Spring (Mar–May)	Summer (Jun–Aug)	Autumn (Sep–Nov)
Nowy Targ-Kowaniec	Mean	0.31*	0.58*	−0.42	0.49
	Minimum	0.34**	0.59*	−0.66	0.27
	Maximum	0.28	1.06*	−0.44	0.73
Nowy Sącz	Mean	1.33	1.33	−0.14	2.49*
	Minimum	1.71**	1.46	−1.10	1.30*
	Maximum	0.81	0.97	0.41	3.78**
Żabno	Mean	1.36	3.71	0.57	2.12
	Minimum	0.79	1.28	−1.49	0.58
	Maximum	2.10	4.57	3.37	4.83*

** Data significant at $p < 0.05$ (medium evidence).

* Data significant at $p < 0.1$ (weak evidence).

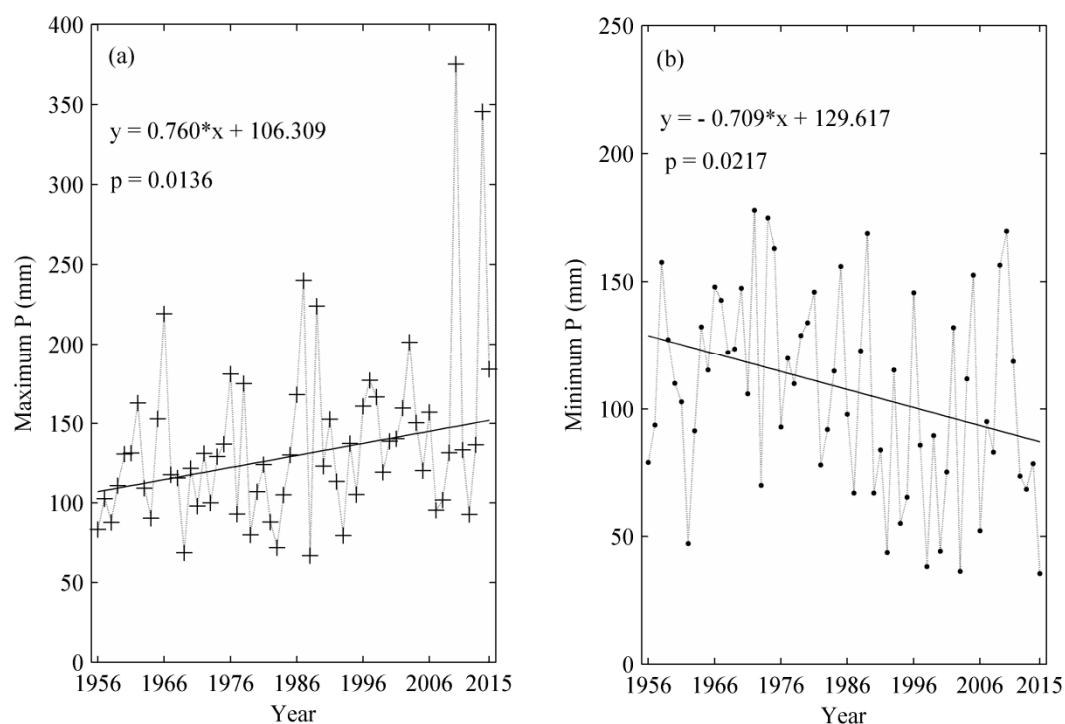


Figure 3. Spring (a) and summer (b) precipitation (P) at Zakopane with significant trends shown ($p < 0.05$).

Table 4. Rate of change a (mm decade⁻¹) for precipitation (P) in each season of the year (1956–2015) based on Theil-Sen's slope estimation with trend free pre-whitening [31]. Statistical significance of the trends was evaluated via the 2-sided Mann-Kendall test [26-27].

Precipitation station	P statistic	Winter (Dec–Feb)	Spring (Mar–May)	Summer (Jun–Aug)	Autumn (Sep–Nov)
Zakopane	Mean	0.2	2.7	−4.3	3.3
	Minimum	0.3	−0.1	−7.1**	1.1
	Maximum	−0.6	7.6**	−3.5	5.0
Nowy Sącz	Mean	−1.0	1.8	−1.3	1.1
	Minimum	−0.1	−0.6	−2.5	−1.1
	Maximum	−1.8*	4.4*	1.0	2.1

** Data significant at $p < 0.05$ (medium evidence).

* Data significant at $p < 0.1$ (weak evidence).

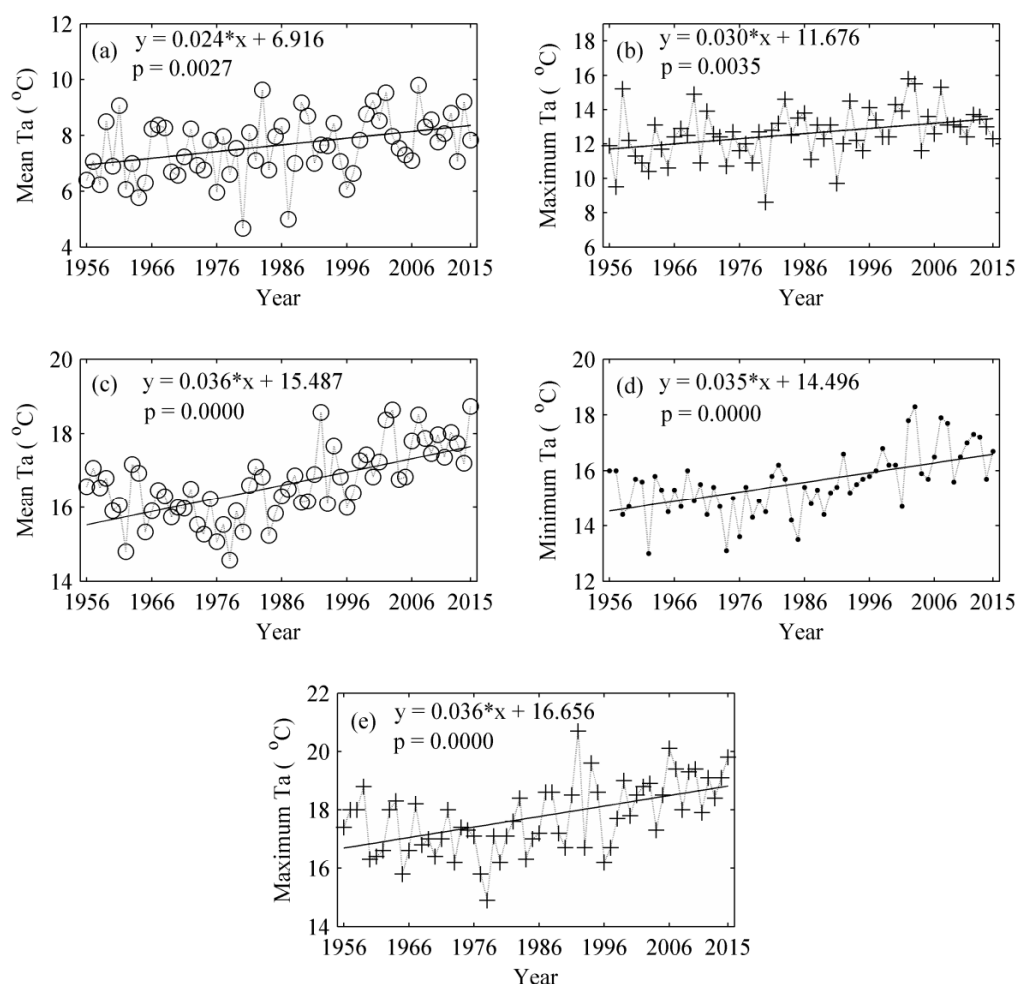


Figure 4. Spring (a–b) and summer (c–e) air temperature (T_a) at Łącko with significant trends shown ($p < 0.005$).

Table 5. Rate of change a ($^{\circ}\text{C decade}^{-1}$) for air temperature (T_a) at Łącko in each season of the year (1956–2015) based on Theil-Sen's slope estimation with trend free pre-whitening [31]. Statistical significance of the trends was evaluated via the 2-sided Mann-Kendall test [26-27].

T_a statistic	Winter (Dec–Feb)	Spring (Mar–May)	Summer (Jun–Aug)	Autumn (Sep–Nov)
Mean	0.14	0.24***	0.36***	0.03
Minimum	0.26	0.18	0.35***	0.06
Maximum	0.03	0.30***	0.36***	0.08

*** Data significant at $p < 0.005$ (strong evidence).

4. Discussion

Direct effects of climate change include changing river flow patterns [15]. In order to make appropriate decisions limiting adverse climate-change impacts on water resources, an evaluation of ongoing changes in river flow, especially multi-annual tendencies, appears vital and necessary. In this study, we focused on a mountain river with such multi-annual flow series relating to the most recent 60 years (1956–2015) as well as on concurrent climatic variables (precipitation and air temperature). The obtained results suggest that river flow tends to be progressively higher during the winter (minimum values of Q shown for sites located along the upper and middle course of the Dunajec River, figure 2), which corresponds with an insignificant increase in minimum winter air temperature (table 5). An increasing trend in spring precipitation (maximum values of P , figure 3a) shows a regional consistency with a change direction in spring P for the neighbouring catchments of the Skawa and Raba Rivers [32], and is in line with the identified increases in P , especially for March and May [33]. The identified increase in spring P is accompanied by progressive warming (mean and maximum values of T_a , figures 4a–b), which extends also to the summer (mean, minimum, and maximum values of T_a , figures 4c–e), in agreement with [34]. On the other hand, summer is the only season when minimum P (table 4) shows a decreasing, statistically significant ($p < 0.05$), tendency consistent with the revealed, significant decreases in summer P for the mentioned nearby catchments [32]. Overall, the stronger and weaker trends revealed imply discernible, multi-annual changes in hydro-climatic conditions for the studied mountain river catchment. Such information appears vital for freshwater resources management, as good management should be based on reliable information about predicted changes in the water cycle on the basis of changes already observed [35].

5. Conclusions

In the conducted analysis relating to changing hydro-climatic conditions in a mountain catchment, multi-annual (60-year) trends for each season of the year (1956–2015) were found with a different level of evidence. For winter, an increase in minimum flow values with medium evidence was identified for sites along the upper and middle course of the Dunajec River. For spring, an increase in air temperature (mean and maximum values, strong evidence) was accompanied by an increase in precipitation (maximum values, medium evidence), while for summer, an increase in air temperature (mean, minimum, and maximum values, strong evidence) was accompanied by a decrease in precipitation (minimum values at Zakopane, medium evidence). For autumn, only an increase in maximum river flow was found with medium evidence. Overall, the revealed trends in multi-annual hydro-climatic series, when carefully considered, can facilitate more realistic management and planning of existing freshwater resources in the studied mountain catchment.

Acknowledgments

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