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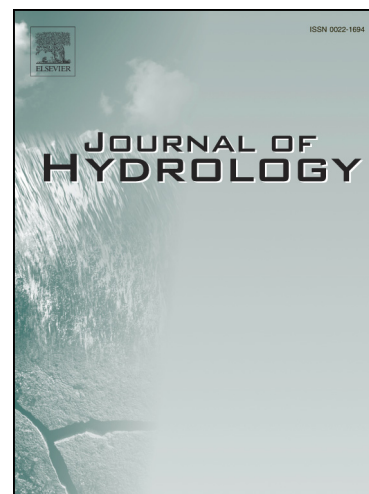
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## Trends in the Hydrologic Regime of Alpine Rivers

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## 1 **Abstract**

2 This paper describes a trend analysis performed on 177 streamflow time series collected over  
3 the Alps in Central Europe. The analysis covers several facets of the Alpine hydrologic  
4 regimes, including winter droughts and spring snowmelt flows, both in terms of severity and  
5 timing of occurrence. Statistical trend tests are applied at a local scale (i.e. on a site-by-site  
6 basis) and at a regional scale (seeking a common trend for sites within the same hydro-  
7 climatic region). The overall results indicate a trend toward less severe winter droughts, and  
8 consistent changes in the timing of snowmelt flows. However, a more in-depth analysis at the  
9 scale of hydro-climatic regimes reveals more contrasted changes. While most glacial- and  
10 snowmelt-dominated regimes show a decreasing trend in the severity of winter droughts,  
11 contrasted trends are found for mixed snowmelt-rainfall regimes in the Southeastern Alps.  
12 Changes in the timing of snowmelt flows (earlier start and increased duration of the snowmelt  
13 season) mostly affect glacial- and snowmelt-dominated regimes. Lastly, glacial regimes show  
14 an increase in the volume and the peak of snowmelt flows.

15

16 **Keywords:** Streamflow, Trend analysis, Alps, Snowmelt, Droughts, Spring onset.

17

## 18 Introduction

### 19 **1.1. Detecting trends in hydrologic series**

20 Trend analyses have received widespread attention in the hydrologic and climate communities  
21 (see e.g. Kundzewicz *et al.*, 2005; Moberg and Jones, 2005; Svensson *et al.*, 2005; Pujol *et*  
22 *al.*, 2007; Hannaford and Marsh, 2008; Stahl *et al.*, 2010; Hodgkins and Dudley, 2011;  
23 Giuntoli *et al.*, 2013 for recent examples). Trend analysis is indeed a useful preliminary step  
24 to assess the existence of significant changes in hydro-climatic series, before attempting to  
25 understand their possible causes (Merz *et al.*, 2012). The detection of trends within hydrologic  
26 series raises several challenges. Firstly, the inter-annual variability of hydrologic series is  
27 generally very large, especially in the extreme domain, hence restricting the power of  
28 statistical tests to detect trends based on relatively short series. Secondly, many catchments  
29 are impacted by direct anthropogenic influences, such as water withdrawal or hydro-  
30 electricity production, which may create artificial trends in addition to climate trends. Lastly,  
31 ensuring the homogeneity of streamflow measurements over several decades is difficult:  
32 rating curves may change or gauging stations may be relocated, thus creating spurious trends  
33 in the time series (Lang *et al.*, 2010). Specific testing procedures (Kundzewicz and Robson,  
34 2000; Parey *et al.*, 2007; Renard *et al.*, 2008) and thoroughly-reviewed datasets of  
35 undisturbed catchments (Hannah *et al.*, 2011; Burn *et al.*, 2012; Whitfield *et al.*, 2012) are  
36 required to face these challenges.

### 37 **1.2. Observed trends in hydro-climatic variables in the Alps**

38 Many studies have investigated the existence of trends in cryospheric variables over the  
39 world. Chapter 4 of the IPCC report (2013) provides an overview of these studies. We focus  
40 here on reviewing trend analyses for hydro-climatic variables in the Alpine region.

41 Stewart (2009) presents an overview of the changes in snowpack and snowmelt-related flows  
42 in the Alps and in other mountainous areas of the world. Focusing on the Alps, an overall  
43 decrease in snow cover is observed during the 20<sup>th</sup> century for low- and mid-elevations.  
44 Trends are less significant at higher elevations, and snowpack even increased due to higher  
45 precipitation totals. Auer *et al.* (2007) and Brunetti *et al.* (2006; 2009) describe an analysis of  
46 several climate variables over the Alpine region based on the HISTALP dataset. A general  
47 increase in annual temperature and air pressure is observed during the 20<sup>th</sup> century. Trends in  
48 precipitation are spatially more variable: for instance, annual totals increase in the northwest  
49 but decrease in the southeast. Other studies have focused on national scales and specific  
50 variables. In one such study, Frei and Schär (2001) analyzed 133 raingauges in Switzerland  
51 and found an increase in the frequency of intense events in winter and autumn during the 20<sup>th</sup>  
52 century.

53 Trend analyses on streamflow variables have often been performed at a relatively small  
54 spatial scale, for specific sub-regions within the Alpine area (see Viviroli *et al.*, 2011 for an  
55 overview). Birsan *et al.* (2005) analyzed 48 gauging stations in Switzerland, and found  
56 increases in winter, spring and autumn streamflow. Castellarin and Pistocchi (2012) used 17  
57 stations in the Swiss Alps observing upward trends in annual streamflow maxima. In the  
58 French Alps, Giuntoli *et al.* (2012) observed decreasing high flow volumes from high-  
59 elevation catchments. In the same region, Renard *et al.* (2008) also observed an earlier timing  
60 of snowmelt-related flows, less severe winter droughts and an increase in annual flow for  
61 highly glacierized catchments. For the latter catchments, Pellicciotti *et al.* (2010) found  
62 similar results in Switzerland (see also Casassa *et al.*, 2009 for other mountainous areas of the  
63 world). The results for highly glacierized catchments seem consistent with what is expected in  
64 a warming climate, as described by Huss *et al.* (2008).

65 The study of Bard *et al.* (2012) is one of the few analyses covering the whole Alpine region  
66 for streamflow variables, but was restricted to high flows. Results showed an increase in the  
67 volume and peak of snowmelt flow for glacial regimes, and an earlier start of snowmelt flow.  
68 Lastly, the European-wide study of Stahl *et al.* (2010), based on 441 small undisturbed  
69 catchments, encompassed about 110 catchments in the Alpine region; trends toward less  
70 severe winter droughts were detected in most of them.

### 71 **1.3. Objectives**

72 The objective of this paper is to assess the existence of trends affecting hydrologic regimes in  
73 the Alps. The analysis described herein is unique in several respects. Firstly, it uses an  
74 extended and thoroughly-reviewed dataset of daily streamflow series covering most of the  
75 Alpine region. Secondly, it uses hydrologic indices adapted to the peculiarities of snowmelt-  
76 influenced catchments, and describing low, medium and high flows. Lastly, it operates at both  
77 local and regional scales, enabling a comprehensive assessment of the detected trends  
78 consistency.

79 The paper is organized as follows. Section 2 describes the dataset of daily streamflow series  
80 and its properties. Section 3 describes the methods used to analyze the evolution of  
81 hydrologic regimes, and more precisely the definition of hydrologic indices and the statistical  
82 setup for trend detection. The results are presented in Section 4 and discussed in Section 5. In  
83 Section 6 the main outcomes of this work are summarized.

## 84 **2. The AdaptAlp Dataset**

### 85 **2.1. Daily streamflow series and associated catchments**

86 The dataset used in this paper was gathered within the EU Alpine Space Programme project  
87 AdaptAlp, and is therefore named after it. The AdaptAlp dataset contains daily streamflow



88 series for snowmelt-influenced catchments located in the Alps. As described in Bard *et al.*  
89 (2012), the strategy used to gather these series involves extensive quality checks in order to  
90 meet the following requirements: (a) the gauging station has been active over a period of at  
91 least 40 years; (b) the station controls a largely “undisturbed” catchment where direct  
92 anthropogenic influences can be neglected; (c) the daily streamflow series is free from any  
93 major non-homogeneity due to measurement issues.

94 Data quality has been assessed through a first round of analysis investigating changes  
95 affecting low, medium and high flows over the whole available period for each gauging  
96 station. In particular, step-change tests (Pettitt 1979) were used to highlight suspicious  
97 stations. For example a significant step change occurring on the same date for many  
98 hydrologic indices may be indicative of a measurement inhomogeneity (e.g. due to station  
99 relocation, change in the measurement sensor or method, etc.). The results from this first  
100 round of analysis were discussed with the data producers. Following this discussion, stations  
101 were excluded from the dataset whenever a specific cause for the detected change could be  
102 identified (typically, station relocation, building of some hydraulic structure influencing the  
103 river flow, etc.). Some of the stations were judged appropriate only for a specific flow range.  
104 As an example, some stations are only usable for high flow analyses because measurement  
105 issues and/or minor direct influences compromise their suitability for low flows.

106 This selection strategy yields a total of 177 series from six countries<sup>1</sup> (Austria, France,  
107 Germany, Italy, Slovenia and Switzerland, see Fig. 1a). Amongst these 177 series, 140 are  
108 suitable for high flow analyses, 134 for low flow analyses and 126 for all flow ranges.  
109 Figure 1b shows the effective record length (i.e. after the removal of missing values), with  
110 most stations providing between 40 and 50 years of daily data. A few series are effectively  
111 shorter than 40 years (due to missing data), while a few others are very long, with more than

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<sup>1</sup> The names of the 177 gauging stations are given in the online material.

112 80 years of data. Note that the series may appear quite short compared to other meteorological  
113 variables. For instance, in the HISTALP project (Auer *et al.*, 2007), many series span the  
114 whole 20<sup>th</sup> century for variables such as air pressure, temperature or precipitation. Such long  
115 series are unfortunately scarcely available for streamflow data: while long series of water  
116 stages do exist, the same is not true for rating curves that estimate the stage-discharge  
117 relationship, thereby reducing the availability of reliable streamflow data. At the time of  
118 writing of this paper, 169 time series from the Adaptalp dataset have been made available  
119 through the Global Runoff Database Center<sup>2</sup>.

120 The station elevations range mostly between 400 and 1200 m.a.s.l. (Fig. 1c). The dataset  
121 comprises catchments of varied size, the majority of which have an area between 100 and  
122 1000 km<sup>2</sup> (Fig. 1d). Around twenty catchments have a significant part of their area covered by  
123 glacier, however precise quantification was not available for all of them. Lastly, Figure 1f  
124 shows the data availability, and suggests that the period 1961-2005 provides the best trade-off  
125 for analyzing as many stations as possible over a 40 years long common period.

## 126 **2.2. Hydrologic regimes and hydro-climatic regions**

127 Although all catchments in the AdaptAlp dataset are influenced by snowmelt, they still span a  
128 significant diversity of hydrologic regimes. The catchments are clustered into homogeneous  
129 hydrologic regimes to allow regime-specific analyses. Nine regimes are defined as presented  
130 in Figure 2; they range from pure glacial and snowmelt regimes to mixed snowmelt-rainfall  
131 regimes. The regimes clustering is performed by applying the Kohonen algorithm (Wehrens  
132 and Buydens, 2007) to the inter-annual monthly streamflow (standardized by the inter-annual  
133 mean) computed for each station. The Kohonen algorithm was chosen because it imposes

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<sup>2</sup>(GRDC: [http://www.bafg.de/GRDC/EN/Home/homepage\\_node.html](http://www.bafg.de/GRDC/EN/Home/homepage_node.html))

134 continuity between clusters, thus mimicking the continuous shift from glacial regimes to  
135 mixed snowmelt-rainfall regimes. Loosely speaking, hydrologic regimes are hence sorted by  
136 decreasing values of the annual solid/liquid precipitation ratio. Also note that the naming of  
137 each hydrologic regime is based on the interpretation of each cluster rather than on a detailed  
138 analysis of the dominant flow processes: this may not suffice to distinguish between e.g.  
139 glacial melt and snowmelt from high-elevation regions (Koboltschnig and Schoner, 2011).

140 As seen in Figure 3 pure glacial- and snowmelt-dominated regimes are found in the heart of  
141 the Alps. These hydrologic regimes are mainly controlled by the storage of precipitation as  
142 snow and ice during the cold months, with the lowest flows occurring between December and  
143 February (see Fig. 2). While the highest flows occur during spring and summer. The month  
144 with the highest flow ranges between April for composite 1 regimes to July for glacial  
145 regimes, owing to snow and ice melt and summer precipitation (Birsan *et al.*, 2005). On the  
146 other hand, mixed snowmelt-rainfall regimes are found in pre-alpine regions and behave  
147 differently, exhibiting two low flow seasons: during the winter when part of the precipitation  
148 is stored as snowpack, and during the summer due to a combination of earlier snowpack  
149 shortage, lack of precipitation and high evapotranspiration. For these regimes, high flows are  
150 mainly driven by snowmelt during the spring and by abundant precipitation in autumn.

151 Similarly to the hydrologic regimes, the Alpine area also spans a diversity of climatic regions.  
152 The four climatic regions defined in the HISTALP project (Auer *et al.*, 2007) are used  
153 (Fig. 3). This classification is based on climatic variables including normalized air pressure,  
154 air temperature, precipitation, cloudiness, and sunshine duration.

155 The climatic and hydrologic classifications are complementary because the former creates  
156 homogenous regions based on the main climate forcing, while the latter ensures the  
157 homogeneity of the hydrologic regimes at the catchment scale. Therefore, both classifications

158 are combined to create homogeneous hydro-climatic regions, grouping catchments with  
159 similar hydrologic behavior and forced by similar climatic drivers.

## 160 **3. Methods**

### 161 **3.1. Streamflow indices**

162 The present study focuses on specific properties of Alpine rivers like winter low flows or  
163 spring and summer snowmelt-induced high flows. This is achieved by defining several  
164 hydrologic indices that are described in this section.

#### 165 **3.1.1. Flow duration curve percentiles**

166 The first group of indices is obtained by using percentiles  $Q_x$  of the annual flow duration  
167 curve, with  $x = 10\%$ ,  $25\%$ ,  $50\%$ ,  $75\%$ ,  $90\%$  and  $100\%$ . This approach was used in a similar  
168 analysis by Lins and Slack (1999) and Birsan *et al.* (2005). It has the advantage of describing  
169 the whole spectrum of flows observed each year, by using an ensemble of percentages  $x$   
170 between 10 and 100. For these indices, we use the 126 stations that are suitable for all flow  
171 ranges.

#### 172 **3.1.2. Winter low flows**

173 Low flows are defined using a threshold approach (e.g. Fleig *et al.*, 2006): a low-flow  
174 threshold that equals the 15% percentile of the inter-annual flow duration curve is computed  
175 for each station. Three indices describing the drought severity are then defined as illustrated  
176 in Figure 4a: the volume deficit, the drought duration and the minimum streamflow ( $A_{min}$ ).  
177 The volume deficit is calculated as the cumulative difference between the actual flow and the  
178 low flow threshold. In addition, three timing indices describing the drought timing are  
179 calculated: the drought “start” is defined as the date at which the cumulated volume deficit  
180 reaches 10% of the total volume deficit. Similarly, the drought “center” and the drought “end”

181 correspond to 50% and 90% of the total volume deficit. These timing indices are similar to  
182 the “center of mass” defined by Stewart *et al.* (2005). For these indices, we use the 134  
183 stations that are suitable for low flows.

### 184 **3.1.3. Spring and summer high flows**

185 In order to focus on snowmelt-related streamflow occurring during spring and summer, the  
186 daily time series are filtered to remove isolated rainfall-induced peaks: this is achieved using  
187 the base flow separation (BFS) method proposed by Tallaksen and Van Lanen (2004). A  
188 similar filtering was also used by Hodgkins and Dudley (2011) for base flow trend detection.  
189 Given the alpine character of the studied catchments, the filtered series is interpreted as  
190 snowmelt-induced base flow. Six indices are then extracted from the filtered series (Fig. 4b).  
191 The base flow maximum ( $A_{max}$ ) and volume describe the snowmelt intensity. Similarly, as in  
192 section 3.1.2, high flow timing is described with the indices “start”, “center” and “end”,  
193 defined as the dates at which 10%, 50% and 90% of the base flow volume is reached. Lastly,  
194 the time between the snowmelt “start” and “end” gives an indication on the duration of the  
195 snowmelt-induced flows. For these indices, we use the 140 stations that are suitable for high  
196 flows.

### 197 **3.1.4. Calculation time windows**

198 The extraction of all hydrologic indices defined in sections 3.1.1-3.1.3 is not based on  
199 calendar years (from 1<sup>st</sup> of January to 31<sup>st</sup> of December) but on selected time windows which  
200 depend on the target index and hydrologic regime. Table 1 summarizes the time windows  
201 chosen in this study. Time windows are based on the annual regime shown in Figure 2: for  
202 high flow indices, the time window starts and ends on the months with the smallest  
203 streamflow (and *vice versa* for low flow indices). Consequently, calculation time windows are

204 centered on the spring-summer runoff peak for high flows and on the coldest period for low  
205 flows.

### 206 **3.1.5. Remark on timing indices**

207 The timing of snowmelt flow is an important property of Alpine catchments, and it has been  
208 studied by several authors (Stewart *et al.* 2005). However, the use of “center of mass” or  
209 “center of volume” indices has been criticized by Dery *et al.* (2009) and Whitfield (2013).  
210 This metric is sensitive to the runoff volume variation and to the choice of calculation time  
211 window. It is also unable to capture changes associated with two or more dominant flow  
212 components. In the context of this paper, it is worth making a few considerations on the  
213 limitations of timing indices. First of all, our stations are strongly driven by snowmelt. For all  
214 regime types, snowmelt-induced volume contributes to most of the annual runoff volume,  
215 even for mixed snowmelt-rainfall regimes where the snowmelt induced runoff is still more  
216 important or is fairly equivalent to the runoff produced by autumnal precipitation (Fig. 2).  
217 Secondly, calculation time windows are specific to the target streamflow index and are  
218 centered either on the low or high flow period. Lastly, for high flows the base flow separation  
219 method is used in order to remove runoff induced by rainfall events and to only consider  
220 snowmelt-induced base flow.

## 221 **3.2. Statistical tests**

222 Trend detection is performed by applying statistical tests to the time series of hydrologic  
223 indices defined in the previous section 3.1. All testing procedures are detailed in Appendix 1.

### 224 **3.2.1. At-site tests**

225 The Mann-Kendall trend test (Mann, 1945; Kendall, 1975) is used for at-site trend detection.  
226 This test was selected because it is distribution-free, i.e. it does not require making any

227 distributional assumption. However, this test does assume data independence, which may not  
228 be the case for some of the indices used in this study (especially low-flow indices). Therefore,  
229 the “modified” Mann-Kendall (MMK) test proposed by Hamed and Rao (1998) is  
230 implemented. We favored this test over possible alternatives such as prewhitening (see e.g.  
231 Von Storch and Navarra 1999) because Monte Carlo experiments (not detailed here)  
232 suggested that the MMK test performs at least equally well in general, and is even more  
233 powerful in some cases (e.g. strong autocorrelation, Renard 2006).

### 234 **3.2.2. Field significance**

235 When applying a statistical test to a large number of series with a 10% error level, a detection  
236 rate of about 10% of significant trends is expected, even in absence of any change in the  
237 series. Therefore, at-site testing is complemented by an evaluation of field significance, which  
238 answers the following question: what is the minimum number of significant at-site trends  
239 ensuring that these trends are not due to chance? The Bootstrap procedure proposed by  
240 Douglas *et al.* (2000), specifically designed to account for the spatial correlation within a  
241 dataset, is used for this purpose. Field significance is evaluated for each hydrologic regime,  
242 and for the whole dataset.

### 243 **3.2.3. Regional consistency**

244 Although an assessment of field significance is necessary to qualify detected trends at a  
245 regional level, it does not allow evaluating the trends consistency within a homogenous  
246 hydro-climatic region. As an illustration, a region affected by numerous trends both in upward  
247 and downward directions can be “field significant” despite a lack of consistency in detected  
248 trends. However, in the context of climate-related trend detection, one would expect that  
249 catchments with similar behavior and located in the same climatic region will respond in a  
250 similar way to the evolution of climate forcings. Consequently, the trends consistency is

251 studied by applying the regional test proposed by Renard *et al.* (2008) at the scale of the  
252 hydro-climatic regions defined in section 2.2. In a nutshell, this test attempts to detect a  
253 common trend for a set of stations located in the same hydro-climatic region. It is a stringent  
254 test since it requires consistency, and will therefore not detect strong at-site trends that are not  
255 consistent across the region. On the other hand, it is powerful for detecting small but  
256 consistent trends that would be otherwise missed by at-site tests.

## 257 **4. Results**

258 All tests described in section 3.2 are applied with an error level of 10%. At-site tests are  
259 applied to series restricted to the common period 1961-2005, leading to the analysis of 126 to  
260 140 stations (depending on the stations quality for low, medium, or high flows). Field  
261 significance is then evaluated for all stations and for each hydrologic regime separately (see  
262 Table 2). Lastly, the period of study for the regional consistency test is region-specific in  
263 order to optimize the number of stations available for each hydro-climatic region. However,  
264 these periods broadly cover the same period 1961-2005. For a given station, years with a  
265 missing value rate exceeding 0.5% are excluded from the series.

266 Trend magnitudes are only presented for significant detections and are averaged either across  
267 all stations or by hydrologic regime type. They are computed with the formula proposed by  
268 Sen (1968). For indices representing a discharge or a volume metric, trends are normalized by  
269 the mean index value and are expressed as the total variation over the 1961-2005 period in  
270 percent. For timing indices, trends are expressed as absolute values, quantifying the change  
271 over the period 1961-2005 as a number of days.

272 While the results related to floods have already been presented by Bard *et al.* (2012), this  
273 paper provides a general overview of the trends detected on the three components of the



274 hydrologic regime of alpine rivers: low, medium and high flows. An additional analysis based  
275 on a subset of 22 long series covering the period 1925-2005 is also presented in section 4.4.

#### 276 **4.1. Percentiles**

277 Figure 5 maps the trends detected with the at-site test, while Figure 6 shows the result of the  
278 field significance evaluation (at the scale of hydrologic regimes) and of the regional  
279 consistency test (at the scale of hydro-climatic regions). Note that there are very few Italian  
280 stations in Figure 5: this is due to extended periods of missing values in the 1980s,  
281 corresponding to a reorganization of the hydrological services. By restricting the analysis to  
282 the common period 1961-2005, those stations could not be considered in the analysis.  
283 However, Italian stations are included in the regional analysis (Fig. 6, mostly in the southwest  
284 climatic region), as region-specific periods allow for more flexibility in the station selection.

##### 285 **4.1.1. Lower percentiles (Q10, Q25)**

286 Figure 5 shows a general increase in lower percentiles Q10 and Q25, with averaged trend  
287 magnitudes of 11% and 12% for all stations. This increase is particularly noticeable for  
288 glacial-influenced regimes (Table 2), with more than 60% of significant upward trends, and  
289 trend magnitudes of 26% and 31%. This increase holds to a lesser extent for snowmelt and  
290 composite regimes. The increasing trend is generally consistent at the scale of hydro-climatic  
291 regions (Fig. 6), especially in the northwest region. However, mixed snowmelt-rainfall  
292 regimes show the opposite behavior, with decreasing lower percentiles, especially in the  
293 southeast region.

##### 294 **4.1.2. Annual Median flow (Q50)**

295 The annual median flow shows no clear general behavior over the whole Alpine region  
296 (Fig. 5). However, a clear increase appears for glacial regimes (Table 2), with 77% of

297 significant upward trends and a trend magnitude of 36%. This increase is also found at the  
298 regional scale for snowmelt 1 regimes in both western regions (Fig. 6), but it is not field-  
299 significant (only 13% of at-site significant trends). Lastly, for composite 2 and snowmelt-  
300 rainfall 2 regimes the annual median flow is significantly decreasing with trend magnitudes of  
301 respectively 1% and 16%, but the regional consistency tests are not significant.

### 302 **4.1.3. Higher percentiles (Q75, Q90, Q100)**

303 Results for the higher percentiles are broadly similar to those of the annual median flow: no  
304 clear change appears over the Alps (Fig. 5), but some changes are field significant or  
305 regionally consistent at a smaller scale. In particular, upper percentiles increase for glacial  
306 regimes with moderate trend magnitudes of 17% and 15% (Table 2 and Fig. 6). Conversely,  
307 upper percentiles decrease for snowmelt-rainfall 1 and snowmelt-rainfall 2 regimes with trend  
308 magnitudes of 28% and 15% respectively.

## 309 **4.2. Winter low flows**

310 The low flow indices complete the description provided by the lower percentiles of section  
311 4.1.1, with a characterization of winter low flows more focused on drought events. Results for  
312 low flows are presented similarly to section 4.1: in Figure 7 the trends detected with the at-  
313 site test are mapped with numbers provided in Table 2. Figure 8 shows the evaluation of field  
314 significance and regional consistency.

### 315 **4.2.1. Severity**

316 Winter drought severity appears to decrease overall (Fig. 7a-c): volume deficit (a) is indeed  
317 significantly decreasing for 25% of stations (Table 2), with a trend magnitude of 39% and  
318 drought duration (c) for 26% of stations with a reduction of 21 days on average. Annual  
319 minimum (b) is significantly increasing for 25% of stations with a trend magnitude of 16%

320 overall. These results are expressed in Figure 8 at the scale of the hydro-climatic regions:  
321 glacial, snowmelt-glacial and snowmelt 1 and 2 regimes present a clear signal toward less  
322 severe droughts: decrease in the drought duration and volume deficit and rise of the minimum  
323 streamflow value. This signal is reinforced by regionally significant trends in both western  
324 regions. Trend magnitudes are important for all regimes except snowmelt-rainfall ones:  
325 drought duration decreases on average by 25 days and volume deficit by 47%. This signal is  
326 less visible for composite 1 and snowmelt-rainfall 2 regimes, but is confirmed by the regional  
327 analysis for composite 1 regimes in the northwest region, and snowmelt-rainfall 2 regimes in  
328 the southeast region. Conversely, snowmelt-rainfall 1 regimes present an opposite trend  
329 toward more severe winter droughts with volume deficit increasing by 10%.

#### 330 **4.2.2. Timing**

331 Trends in timing indices are scarce, with the exception of the drought end (Fig. 7f), which  
332 tends to occur earlier for 21% of stations (Table 2) by 8 days on average overall. However,  
333 this trend is particularly marked for glacial, snowmelt-glacial and snowmelt 1 and 2 regimes,  
334 with a timing shift of 15 days on average. Moreover, it is also detected at the scale of hydro-  
335 climatic regions for snowmelt 2 and snowmelt 3 regimes (Fig. 8). The opposite trend is found  
336 for snowmelt-rainfall 1 and 2 regimes where winter droughts are shifted later in the season by  
337 22 days on average. This result is regionally consistent for the southeast region.

### 338 **4.3. Spring and summer high flows**

#### 339 **4.3.1. Intensity**

340 At-site results do not reveal any generalized change for high flow intensity (Fig. 9a-b).  
341 However, glacial regimes show significant trends: both snowmelt volume and annual  
342 maximum are significantly increasing for 93% and 47% of the stations (Table 2), with trend  
343 magnitudes of 29% and 21% respectively. Regional results (Fig. 10) confirm these

344 observations, with regionally consistent upward trends detected on these indices for glacial  
345 regimes. On the other hand, a field-significant decrease of the snowmelt annual maximum by  
346 an average magnitude of 16% is found for composite and snowmelt-rainfall regimes, but it is  
347 not regionally consistent.

#### 348 **4.3.2. Timing**

349 The snowmelt duration has significantly increased for 49% of the stations (Fig. 9c and  
350 Table 2) with a trend magnitude of 19 days, mostly owed to an earlier shift in the snowmelt  
351 “start” (Fig. 9d). Glacial regimes show significant trends in the snowmelt onset that occurs  
352 earlier, with a small magnitude of 6 days, whereas duration does not significantly increase.  
353 On the contrary, snowmelt-glacial, snowmelt 1 to 3 and composite 1 regimes exhibit  
354 significant decreasing trends for the snowmelt “start” and “center” indices, with average shifts  
355 of 10 and 7 days, and increasing trend for the snowmelt “end” index by 11 days. For these  
356 regimes, the snowmelt duration consequently increases with a trend magnitude of 23 days. At  
357 the scale of hydro-climatic regions (Fig. 10), the same results are observed particularly for  
358 snowmelt 1 to 3 and composite 1 regimes, with a significant increase of the snowmelt  
359 duration and an earlier onset of the melting season.

#### 360 **4.4. Analysis of long series over the period 1925-2005**

361 In order to assess the stability of detected trends over different time periods, the at-site  
362 analysis is repeated for two 40-year periods: 1925-1964 and 1965-2005. Only 22 series  
363 (mapped in Fig. 3) are long enough to cover the extended period 1925-2005, thus precluding  
364 an analysis of the regional consistency at the scale of hydro-climatic regions.

365 Figure 11 shows the results of the at-site trend analysis. Generally, the results over the long  
366 period 1925-2005 are similar to the main results observed for the whole dataset over the  
367 1961-2005 period described previously. Overall, lower percentiles are the most impacted by

368 significant decreasing trends, whereas higher percentiles are found significantly increasing for  
369 snowmelt-rainfall 1 regimes. For low flow indices, snowmelt regimes show a significant trend  
370 toward an earlier drought end, a decrease in drought duration and volume deficit.  
371 Furthermore, contrasted changes are observed for the annual minimum. Snowmelt-rainfall 1  
372 regimes show results toward less severe winter drought with a clear increasing signal in the  
373 annual minimum. However, the drought “end” is found to be shifted earlier, in contrast to the  
374 trends observed over the period 1961-2005. For high flow indices, there is a good agreement  
375 between the main analysis over the 1961-2005 period and results from the 22 long stations  
376 over the 1925-2005 period: snowmelt timing indices “start” and “center” significantly  
377 decrease and snowmelt duration increases significantly except for two stations. Contrasted  
378 changes can be observed for the snowmelt “end” and no clear trend is found for the snowmelt  
379 annual maximum and volume.

380 Regarding the influence of the time period, slightly more significant trends are detected over  
381 the period 1925-2005 than over the two sub-periods: 1925-1964 and 1965-2005 (among  
382 which the 1925-1964 period accounts for more significant changes). The detection of  
383 significant trends in opposite directions for the two sub-periods would imply a strong  
384 inconsistency and an oscillating behavior of the hydrologic indices. This is rarely observed  
385 (Fig. 11), but 7 exceptions were found. Among these 7 cases, 5 are not significant over the  
386 1925-2005 period. Series with significant trends in only one sub-period are more frequent (26  
387 cases) than series with consistent trends over both sub-periods (7 cases).

388 A particular behavior can be observed for station DE043, with significant increasing trends  
389 for almost all percentiles over the period 1925-1964, and even a contradiction in the sub-  
390 periods trends for the snowmelt annual maximum. However, these changes could not be  
391 explained by any historical change of the gauging station.

392 These results suggest that the period of analysis (which has been selected in this paper based  
393 on data availability rather than on a particular climate-related assumption) plays an important  
394 role in the outcome of the trend analysis. Alpine regimes do not seem to have evolved  
395 uniformly over time, which calls for further analysis to further understand the main drivers of  
396 hydrologic variability in the Alps.

## 397 **5. Discussion**

### 398 **5.1. Interpreting the results of trend tests**

399 Meaningful trend detection in climate variables requires a good-quality dataset. For this  
400 reason, extensive efforts have been made to use a consistent non-influenced streamflow  
401 dataset in the AdaptAlp project. However, spurious trends might also be detected if unrealistic  
402 assumptions are made by the test. The detection of a significant trend does not prove beyond  
403 doubt that a trend actually exists in the data: firstly because of the error level, secondly  
404 because what might be rejected is one of the hypotheses used to build the test rather than the  
405 null hypothesis. The main questionable assumption relates to the treatment of autocorrelation.  
406 Indeed, the local Mann-Kendall test used in this paper assumes that autocorrelation, if present,  
407 follows a simple first-order autoregressive structure (AR(1)). Should the data be affected by a  
408 more complex dependence structure (for instance, Long-Term Persistence LTP), spurious  
409 trends might be detected unduly. This is a difficult issue that, in our opinion, has no clear  
410 solution so far. Indeed, while testing procedures adapted to LTP-data have been developed  
411 (Cohn and Lins, 2005; Hamed, 2008), these tests make the assumption that data are either  
412 LTP or independent. When applied to data presenting only Short-Term Persistence (STP)  
413 (e.g. AR(1)), those tests lose their power to detect a trend because they will blame it on  
414 spurious LTP. Quoting Jaruskova (1997): *“if the finite part of a time series is observed, it is*  
415 *impossible to distinguish between a stationary series with the positive dependence between*

416 *the neighbouring observations and a sequence of independent variables with the slowly*  
417 *changing mean*". In other words, for a given time series of observations, one can always build  
418 a stationary model with complex LTP dependence structure or a simple STP model with some  
419 complex non-stationarity that will fit the data equally well. Therefore, this choice has to be  
420 made beforehand (using physical considerations if possible), but one should acknowledge that  
421 subsequent results are conditioned to this choice.

422 Finally, in accordance with the review provided by Hall *et al.* (2014) on the understanding of  
423 flood regime changes in Europe, we followed a three-step approach by focusing on: (i) trend  
424 analysis of individual time series, (ii) field significance of an ensemble of local stations, and  
425 (iii) analysis of consistent regional trends. This threefold strategy helps building confidence in  
426 the trend detection and highlights general trends at the scale of hydrologic regimes and hydro-  
427 climatic regions. Field significant results were found for all major changes observed.  
428 Moreover, they are reinforced by the regional consistency test, which provides information on  
429 the spatial consistency of detected trends. The regional consistency test is the most stringent  
430 (because trends have to be consistent across the hydro-climatic region to be detected),  
431 therefore fewer significant trends are found compared with field-significant results at the scale  
432 of hydrologic regimes. Nevertheless, trends that are both regionally consistent and field  
433 significant are found in 55%, 54% and 42% of the cases for annual percentiles, low flow and  
434 high flow indices, respectively (Fig. 6, Fig. 8 and Fig. 10).

435 In a few cases, field significance and regional consistency tests do not yield the same  
436 conclusion. Two opposite situations are identified:

- 437 1. A regionally consistent trend is detected, but field significance is not reached. In this  
438 case, it is likely that the trend is too small to be detected by at-site tests, and the  
439 number of detections is therefore too small to reach field significance. However, if this

440 small trend is consistent across the hydro-climatic region, the regional consistency test  
441 may be able to detect it because it is much more powerful than at-site tests in this case.

442 2. Field-significant trends are detected, but they are not regionally consistent. This  
443 suggests that trends are numerous but not consistent. This might be partly explained  
444 by a non-homogenous region, i.e. catchments within the region may have different  
445 behaviors that have been overlooked by the clustering methodology. Another  
446 explanation is that rivers of the same region are impacted differently over time and  
447 thus evolve in different ways. This highlights the difficulty of catchment classification  
448 and construction of homogenous climatic regions in a changing context (Krasovskaia  
449 and Gottschalk, 2002).

## 450 **5.2. Comparison with previous studies and attribution**

451 A coherent picture can be drawn for catchments that are highly influenced by snow and  
452 glacier melt, which have evolved more drastically than other hydrologic regime types.

453 For glacial regimes, changes are more numerous for lower and medium percentiles than for  
454 upper percentiles (Table 1), which are still field significant. Similar results have been  
455 obtained by Birsan *et al.* (2005) where significant trends were generally observed in low  
456 flows. Thus winter droughts are shorter and less severe, and spring and summer base flow  
457 increase. Pellicciotti *et al.* (2010) also found significant positive trends in annual streamflow  
458 for highly glacierized catchments of the Alps, caused by increasing flows in spring and  
459 summer. The study concludes that glaciers are still in a phase of enhanced contribution to the  
460 total streamflow of their catchment.

461 For snowmelt-glacial and snowmelt 1 to 3 regimes, a trend toward less severe winter droughts  
462 is found. These results are consistent with previous findings, in particular those of the  
463 European-wide analysis of Stahl *et al.* (2010). The winter drought timing is not affected



464 except for the “end” which appears to occur earlier. Similar results were observed by Birsan  
465 *et al.* (2005), who showed a general increase in winter runoff for alpine catchments in  
466 Switzerland. Snowmelt-induced base flow is increasing for rivers that are highly dependent  
467 on snow (snowmelt-glacial, snowmelt 1 regimes), and snowmelt duration is found to increase  
468 for all the regime types except snowmelt-rainfall 2. According to Birsan *et al.* (2005),  
469 increase in winter and spring streamflow is related to changes in temperature rather than  
470 changes in precipitation. The study suggests that temperature increase in winter, spring and  
471 summer induces a shift in the freezing level with more liquid precipitation during winter, and  
472 an earlier and enhanced melt in spring and summer. These results are also consistent with  
473 trends found in other mountainous areas of the world. In particular, the trend toward earlier  
474 snowmelt flow was also a key finding of Stewart *et al.* (2005) over western North America.

475 This clear signal on the evolution of winter low flows and spring-summer high flows tends to  
476 disappear as the snowmelt influence loses its predominance over other hydrologic flow  
477 components. For composite 1 regimes, results tend to be consistent with previous findings. On  
478 the contrary, composite 2 regimes show a different behavior with significant increases in  
479 winter drought severity (volume deficit and duration), as well as significant decreases in the  
480 snowmelt-induced base flow volume. At the end of the Alpine hydrologic spectrum,  
481 snowmelt-rainfall regimes show an overall decrease of all percentiles, particularly in the  
482 southeast region for lower percentiles. This overall decrease in the percentiles comes from  
483 streamflow decrease during the spring and summer periods as it can be observed in the  
484 evolution of seasonal percentiles (results not presented here). These results are consistent with  
485 the decreasing trends observed for the southern and eastern borders of the Alps by Stahl *et al.*  
486 (2010), and with the decrease of precipitation, particularly during the summer, observed in  
487 long time series of this region by the HISTALP study (Auer *et al.*, 2007). Regarding low  
488 flows, snowmelt-rainfall regimes tend to be affected by later winter droughts, but show

489 contrasted changes in terms of intensity, with more severe winter droughts for snowmelt-  
490 rainfall 1 regimes and less severe droughts for snowmelt-rainfall 2 regimes. Conversely,  
491 summer droughts tend to occur earlier for both regimes, whereas summer droughts tend to be  
492 more severe for snowmelt-rainfall 2 regimes (results not presented in this paper).

493 As already mentioned, a number of previous studies have demonstrated the link between the  
494 evolutions of hydrologic regimes with observed changes in temperature. While a general  
495 increase in temperature is observed in the Alps during the 20<sup>th</sup> century (e.g. Auer *et al.*, 2007),  
496 changes in precipitation patterns appear to be more complex. Moreover, empirical  
497 comparisons between streamflow trends and forcing variables like precipitation and  
498 temperature are difficult to interpret and possibly misleading for two main reasons. First, the  
499 complex filtering role of the catchment makes it difficult to determine the expected  
500 streamflow response from a given trend in forcing – in particular, a trend in precipitation or  
501 temperature should not be expected to identically match what is detected in streamflow.  
502 Second, the evolutions affecting distinct forcing variables might compensate each other. As a  
503 rough illustration, increasing temperatures and precipitation might (at least partly and  
504 temporarily) compensate each other and create no apparent trend in streamflow (at least at the  
505 annual scale). Long-term analysis on the Rhone, the Rhine, the Danube and the Po, performed  
506 by Zampieri *et al.* (2015), showed that earlier spring streamflow timings are mostly explained  
507 by the change of precipitation seasonality and its increasing liquid proportion in these large  
508 catchments. While the question remains open for smaller alpine catchments, it calls for further  
509 investigation of the role of forcing variables in streamflow trends using some form of  
510 hydrologic modeling (see e.g. Renard *et al.*, 2008; Hundecha and Merz, 2012; Merz *et al.*,  
511 2012), which will be investigated in future work.

## 512 6. Conclusion

513 The objective of this paper was to assess the existence of trends in the hydrologic regime of  
514 Alpine rivers. This was carried out using a dataset of 177 daily streamflow series. Local and  
515 regional statistical tests were applied to various hydrologic indices describing low, medium  
516 and snowmelt-related high flows. The main findings can be summarized as follows:

- 517 • **Winter droughts:**

- 518 ○ Severity tends to decrease for all regimes except snowmelt-rainfall regimes,  
519 with drought durations decreasing by an average of 25 days over 1961-2005  
520 and volume deficits decreasing by an average of 47%.
- 521 ○ For the drought “end” a slight shift is detected toward an earlier occurrence for  
522 all regimes except snowmelt-rainfall regimes, with an average trend magnitude  
523 of 16 days.
- 524 ○ Mixed snowmelt-rainfall regimes in the Southeastern Alps (mostly Slovenian  
525 stations) show an opposite evolution: seasonality seems to be shifted toward  
526 later occurrences, for the drought “start”, “center” and “end” by 22 days on  
527 average. Severity tends to increase for snowmelt-rainfall 1 regimes with a  
528 volume deficit increasing by 10%.

- 529 • **Spring and summer high flows:**

- 530 ○ All regimes show a consistent shift toward an earlier start of snowmelt flow,  
531 with a trend magnitude of 11 days, along with an increase of 18 days in the  
532 duration of the snowmelt season.
- 533 ○ Glacial regimes, in particular, show a consistent behavior with a melting  
534 season shifted by a week earlier, and an increase of 29% in the snowmelt  
535 volume and of 21% in the snowmelt induced base flow maximum.

- 536       • **Medium flows:**
- 537           ○ Glacial regimes show a consistent increase in the annual median flow ( $Q_{50}$ ),
- 538           indicating an enhanced contribution of the glacier to the total streamflow of
- 539           corresponding catchments.

540 These results constitute a valuable step toward an improved understanding of the temporal

541 evolution of Alpine hydrologic regimes. In particular, the fact that the trends described above

542 are spatially consistent is an indication that they are climate-related rather than the

543 consequence of measurement issues or direct anthropogenic influences. However, whether

544 these evolutions are linked to climate change or to climate decadal variability remains an open

545 question, which cannot be answered on the sole ground of the analyses described in this

546 paper. Future studies will focus on identifying the role of forcing variables (e.g. precipitation,

547 temperatures) and climate variability (e.g. NAO, ENSO) on the evolution of Alpine

548 hydrologic regimes.

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703 **9. Appendix 1. Description of testing procedures.**

704 Throughout this appendix, the random variables representing a series of observations are  
 705 noted  $X_1, \dots, X_n$ . For regional testing procedures with  $p$  stations, the site  $i$  is denoted using a  
 706 superscript, yielding random variables  $(X_k^{(i)})_{k=1:n, i=1:p}$ .

707 **9.1. Modified Mann-Kendall test**

708 The Mann-Kendall statistic  $S$  is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(X_j - X_i) \quad (1)$$

709 The test statistic  $Z$  is then defined by:

$$Z = \begin{cases} (S-1)/\sqrt{\text{Var}(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ (S+1)/\sqrt{\text{Var}(S)} & \text{if } S < 0 \end{cases} \quad (2)$$

$$\text{with } \text{Var}(S) = n(n-1)(2n+5)/18$$

710 This statistic asymptotically follows a Gaussian distribution  $N(0;1)$  under the  $H_0$  hypothesis  
 711 of no trend (Mann, 1945; Kendall, 1975).

712 The variance  $\text{Var}(S)$  in equation (2) has to be corrected in the following cases:

713 • In the presence of tied values, the variance is computed as:

$$\text{Var}(S) = \left( n(n-1)(2n+5) - \sum_{k=1}^n t_k k(k-1)(2k+5) \right) / 18 \quad (3)$$

714 where  $t_k$  is the number of tied values of extent  $k$ .

715 • In the presence of autocorrelation, the variance is computed as (Hamed and Rao,  
 716 1998):



$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \times \left[ 1 + \frac{2}{n(n-1)(n-2)} \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)\rho_k \right] \quad (4)$$

717 where  $\rho_k$  is the lag- $k$  autocorrelation coefficient. In this paper, we made the additional  
 718 assumption of an order-1 autoregressive dependence structure (AR(1)), in order to avoid  
 719 computing numerous lag- $k$  autocorrelation coefficients with relatively short series. This  
 720 corresponds to replacing  $\rho_k$  by  $(\rho_1)^k$  in equation (4).

## 721 **9.2. Field significance evaluation**

722 Field significance of at-site Mann-Kendall tests is evaluated using the Bootstrap procedure  
 723 suggested by Douglas *et al.* (2000),

724 Repeat for  $m = 1:N_{sim}$ , where  $N_{sim}$  represents the number of bootstrap replicates:

- 725 a) Set  $w_m = 0$ .
- 726 b) Bootstrap the years used in the original data set, yielding a sample  $(y_1, \dots, y_n)$ .
- 727 c) Repeat for  $i = 1:p$ 
  - 728 i) Apply the Mann-Kendall test to the series  $X_{y_1}^{(i)}, \dots, X_{y_n}^{(i)}$
  - 729 ii) If the test is significant, increment  $w_m$ ,  $w_m := w_m + 1$

730 The sample  $(w_m)_{m=1:N_{sim}}$  approximates the distribution of the number of significant results  
 731 amongst  $p$  sites, under the H0 hypothesis that all sites are stationary. Field significance is  
 732 therefore evaluated by comparing the observed number of significant results,  $w_{obs}$ , with an  
 733 empirical quantile computed from  $(w_m)_{m=1:N_{sim}}$ .

## 734 **9.3. Regional consistency test**

735 Let  $\mathbf{X} = (X_k^{(i)})_{k=1:n, i=1:p}$  denote the matrix of data, observed at years  $(y_1, \dots, y_n)$ . We define the  
 736 following quantities:

737 •  $\tilde{\mathbf{X}} = \left( \tilde{X}_k^{(i)} \right)_{k=1:n, i=1:p}$  is the matrix of data transformed by normal score, i.e.:

$$\tilde{X}_k^{(i)} = \phi^{-1} \left( \hat{F}_i \left( X_k^{(i)} \right) \right) \quad (5)$$

738 where  $\phi$  is the cdf of the standard Gaussian distribution and  $\hat{F}_i$  is the empirical cdf of  
739 site  $i$ .

740 •  $\tilde{\mathbf{y}} = \left( \tilde{y}_k \right)_{k=1:n}$  is the vector of centered years, i.e.  $\tilde{y}_k = y_k - \bar{y}$ .

741 •  $\mathbf{I}_p$  is a vertical vector of size  $p$  with all components equal to one.

742

743 With this notation, the following value  $\hat{\beta}$  is an estimator of a common trend affecting all sites  
744 (after transforming data by normal score, see Renard *et al.* (2008)):

745

$$\hat{\beta} = \frac{\mathbf{I}_p^T \left( \tilde{\mathbf{X}}^T \tilde{\mathbf{X}} \right)^{-1} \tilde{\mathbf{X}}^T \tilde{\mathbf{y}}}{\tilde{\mathbf{y}}^T \tilde{\mathbf{y}} \mathbf{I}_p^T \left( \tilde{\mathbf{X}}^T \tilde{\mathbf{X}} \right)^{-1} \mathbf{I}_p} \quad (6)$$

746 The significance of this trend can be assessed using the following deviance statistics, based on  
747 a multivariate Gaussian assumption:

$$Z = -2 \left( \sum_{k=1}^n \log \left( N \left( X_k^{(1)}, \dots, X_k^{(p)} \mid 0, \hat{\Sigma} \right) \right) - \sum_{k=1}^n \log \left( N \left( X_k^{(1)}, \dots, X_k^{(p)}; \hat{\beta} \tilde{y}_k, \hat{\Sigma} \right) \right) \right) \quad (7)$$

748 where  $N(u^{(1)}, \dots, u^{(p)} \mid \boldsymbol{\mu}, \boldsymbol{\Gamma})$  is the pdf of a  $p$ -variate Gaussian distribution with mean  $\boldsymbol{\mu}$  and  
749 variance  $\boldsymbol{\Gamma}$ , and  $\hat{\Sigma}$  is an estimate of the correlation matrix of transformed data  $\tilde{\mathbf{X}}$ ,

750  $\hat{\Sigma} = \frac{1}{n} \tilde{\mathbf{X}}^T \tilde{\mathbf{X}}$ . Under the H0 hypothesis of no trend, the deviance statistics  $Z$  in equation (7)

751 follows a Chi-square distribution with one degree of freedom.

752

753

754 **List of captions**755 **Tables**

756 Table 1. Calculation time windows used for the extraction of hydrologic indices.

757 Table 2. Results of the at-site trend detection. For each regime, numbers give the percentage  
758 of downward/upward trends significant at 10% error level. Bold numbers denote field  
759 significant trends (with 10% regional error level).

760

761 **Figures**

762 Figure 1. Summary of the dataset properties. (a) Number of stations per country; (b)  
763 distribution of record length; (c) distribution of station elevation; (d) distribution of catchment  
764 areas; (e) Evolution of the number of available stations; (f) data availability for each station  
765 (colors correspond to Figure 1a).

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767 represent the inter-annual monthly streamflow of one particular station (after standardization  
768 by the inter-annual mean), thick lines represent the within-regime average.

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770 (NW), Southwest (SW), Southeast (SE) and Northeast (NE). Symbols represent the  
771 classification of the stations in the AdaptAlp dataset into nine hydrologic regimes. The 22  
772 stations with the longest records are marked with inscribed black dots.

773 Figure 4. Schematic of streamflow indices: (a) low flows; (b) spring and summer high flows.

774 Figure 5. Results of at-site trend tests ( $\nabla$  = downward,  $\blacktriangle$  = upward, x = not significant; blue =  
775 downward, red = upward) for percentile indices: (a) Q10, (b) Q25, (c) Q50, (d) Q75, (e) Q90,  
776 (f) Q100.

777 Figure 6. Results of the regional test for percentile indices. Rows represent percentile indices,  
778 columns represent hydrologic regimes. Each regime is divided into four squares representing  
779 the four HISTALP climatic regions (NW, SW, SE and NE), thereby representing hydro-  
780 climatic regions. Grey square = non-significant regional trend, red square = significant  
781 upward regional trend, blue square = significant downward regional trend, white square = no  
782 station for this climate/regime combination. ▲ = at-site upward trends are field significant, ▼  
783 = at-site downward trends are field significant, O = at-site trends are not field significant. The  
784 number of stations available for each hydro-climatic region is listed in the first row.

785 Figure 7. Results of at-site trend tests (∇ = downward, ▲ = upward, x = not significant; blue =  
786 downward, red = upward) for low flow: (a) volume deficit, (b) annual minimum, (c) drought  
787 duration, (d) drought “start”, (e) drought “center”, (f) drought “end”.

788 Figure 8. Same as Figure 6 for low flows.

789 Figure 9. Results of at-site trend tests (∇ = downward, ▲ = upward, x = not significant; blue =  
790 downward, red = upward) for high flow : (a) snowmelt volume, (b) snowmelt annual  
791 maximum, (c) snowmelt duration, (d) high flow “start”, (e) high flow “center”, (f) high flow  
792 “end”.

793 Figure 10. Same as Figure 6 for high flows.

794 Figure 11. Stability of detected trends for 22 long series over the period 1925-1965 and over  
795 two distinct sub-periods: 1925-1964, 1965-2005.

796

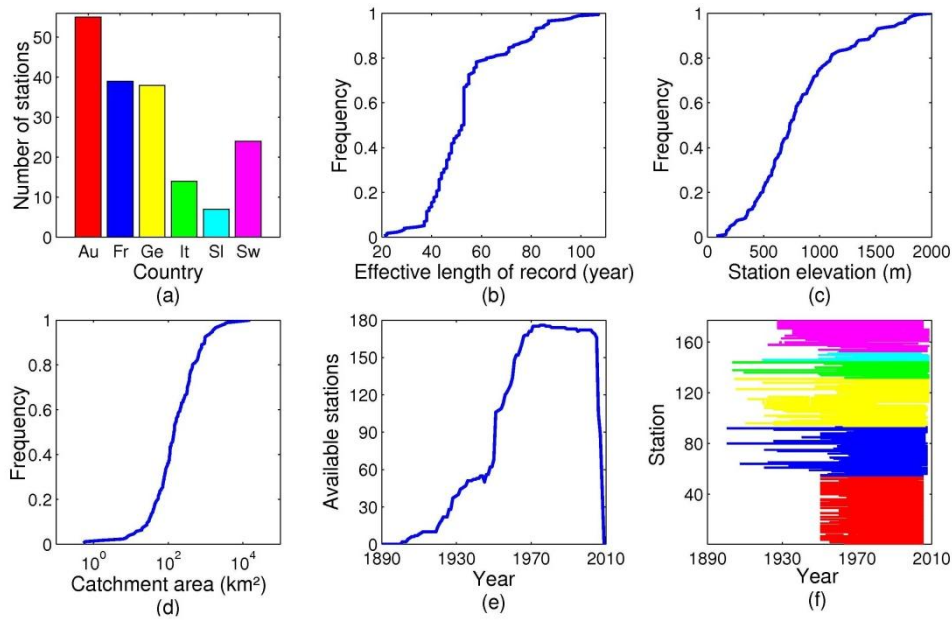
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**Table 1. Calculation time windows used for the extraction of hydrologic indices.**

<b>Hydrologic Regime</b>	<b>Flow duration percentile</b>			
All hydrologic regime types	1 <sup>st</sup> Dec. – 30 <sup>th</sup> Nov.			
	<b>High Flows</b>		<b>Low Flows</b>	
Glacial, snowmelt glacial, snowmelt 1 to 3	1 <sup>st</sup> Feb. – 31 <sup>st</sup> Jan.		1 <sup>st</sup> Jun. – 31 <sup>st</sup> May	
Composite 1 & 2	1 <sup>st</sup> Jan. – 31 <sup>st</sup> Dec.		1 <sup>st</sup> May – 30 <sup>th</sup> Apr.	
	<b>Spring High Flows</b>	<b>Autumn High Flows</b>	<b>Summer Low Flows</b>	<b>Winter Low Flows</b>
Snowmelt rainfall 1 & 2	1 <sup>st</sup> Jan. – 31 <sup>st</sup> Jul.	1 <sup>st</sup> Aug. – 31 <sup>st</sup> Dec.	1 <sup>st</sup> May – 31 <sup>st</sup> Oct.	1 <sup>st</sup> Nov. – 30 <sup>th</sup> Apr.

**Table 2. Results of the at-site trend detection. For each regime, numbers give the percentage of downward/upward trends significant at 10% error level. Bold numbers denote field significant trends (with 10% regional error level).**

	All		Glacial		Snowmelt glacial		Snowmelt 1		Snowmelt 2		Snowmelt 3		Composite 1		Composite 2		Snowmelt rainfall 1		Snowmelt rainfall 2	
<i>Percentile Indices (number of stations)</i>	126		13		5		8		24		17		23		12		6		18	
	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up
Q10	7	<b>25</b>	0	<b>62</b>	0	<b>60</b>	0	<b>38</b>	0	<b>33</b>	0	18	9	<b>22</b>	8	17	<b>33</b>	0	<b>22</b>	0
Q25	8	<b>24</b>	0	<b>62</b>	0	<b>80</b>	0	13	0	<b>21</b>	0	<b>29</b>	13	17	17	<b>25</b>	17	0	<b>22</b>	0
Q50	8	13	0	<b>77</b>	0	20	0	13	0	4	0	6	9	4	<b>25</b>	17	0	0	<b>28</b>	0
Q75	12	10	0	<b>77</b>	0	0	13	0	8	0	18	0	0	4	8	8	<b>67</b>	0	<b>22</b>	0
Q90	<b>15</b>	4	0	<b>38</b>	0	0	25	0	8	0	<b>24</b>	0	4	0	8	0	<b>67</b>	0	<b>28</b>	0
Q100	6	13	0	<b>46</b>	20	20	13	13	4	8	6	6	0	9	0	0	17	17	17	11
<i>Low Flow Indices (number of stations)</i>	134		13		5		10		25		18		23		12		9		19	
	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up
Start	6	11	0	8	0	20	0	20	8	16	11	0	<b>17</b>	4	0	0	0	<b>33</b>	0	16
Center	8	7	8	0	20	0	10	0	4	8	17	0	<b>17</b>	0	0	0	0	<b>22</b>	0	<b>26</b>
End	<b>21</b>	4	<b>54</b>	0	<b>40</b>	0	<b>40</b>	0	<b>32</b>	0	17	0	13	0	8	0	0	<b>22</b>	0	<b>21</b>
Amin	4	<b>25</b>	0	<b>54</b>	0	<b>80</b>	0	<b>60</b>	0	12	0	17	9	<b>22</b>	8	8	<b>22</b>	0	5	<b>26</b>
Duration	<b>26</b>	5	<b>54</b>	0	<b>60</b>	0	<b>40</b>	0	<b>28</b>	4	<b>22</b>	0	17	4	17	<b>25</b>	0	11	<b>21</b>	5
Volume Deficit	<b>25</b>	7	<b>62</b>	0	<b>60</b>	0	<b>50</b>	0	<b>20</b>	4	6	0	<b>17</b>	9	17	<b>25</b>	0	<b>22</b>	<b>26</b>	5
<i>High Flow Indices (number of stations)</i>	140		15		7		9		29		19		23		12		8		18	
	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up
Start	<b>49</b>	1	<b>33</b>	0	<b>29</b>	0	<b>44</b>	0	<b>100</b>	0	<b>42</b>	0	<b>26</b>	0	8	8	<b>63</b>	0	<b>50</b>	0
Center	<b>29</b>	0	<b>40</b>	0	<b>71</b>	0	<b>33</b>	0	<b>21</b>	0	<b>37</b>	0	4	0	8	0	<b>38</b>	0	<b>50</b>	0
End	5	<b>16</b>	<b>20</b>	0	0	<b>29</b>	0	<b>33</b>	0	<b>24</b>	0	<b>32</b>	0	9	0	17	13	0	17	6
Amax_baseflow	12	8	0	<b>47</b>	0	0	0	11	3	0	0	5	<b>22</b>	4	<b>33</b>	8	<b>38</b>	0	<b>22</b>	0
Duration	1	<b>49</b>	7	0	0	<b>43</b>	0	<b>89</b>	0	<b>90</b>	0	<b>58</b>	0	<b>57</b>	0	<b>25</b>	0	<b>50</b>	0	6
Volume	11	<b>16</b>	0	<b>93</b>	0	<b>29</b>	11	22	3	3	0	0	13	9	<b>25</b>	8	13	0	<b>33</b>	0

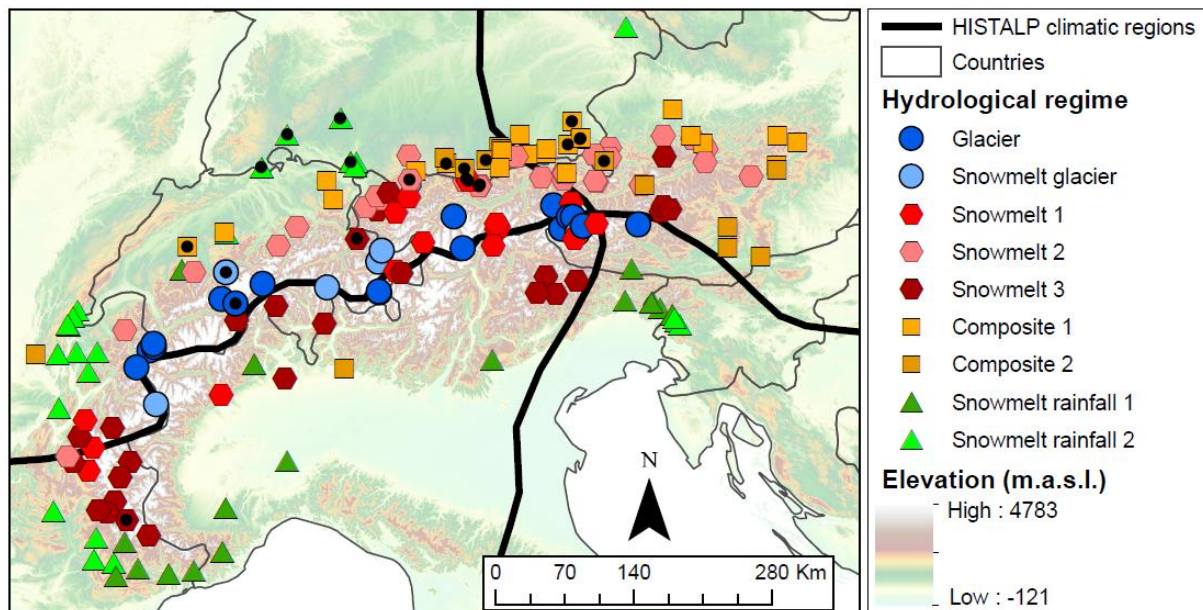


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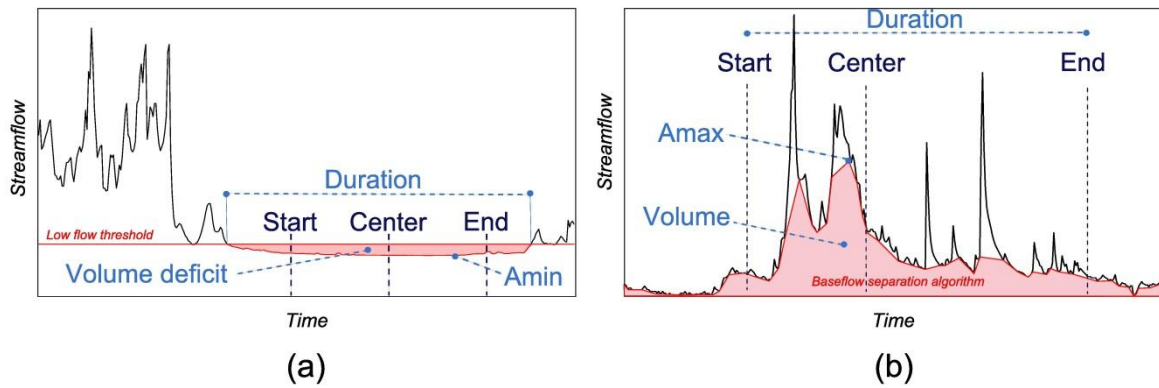


Figure 4. Schematic of streamflow indices: (a) low flows; (b) spring and summer high flows. Timing indices are noted in dark blue, severity indices in light blue.

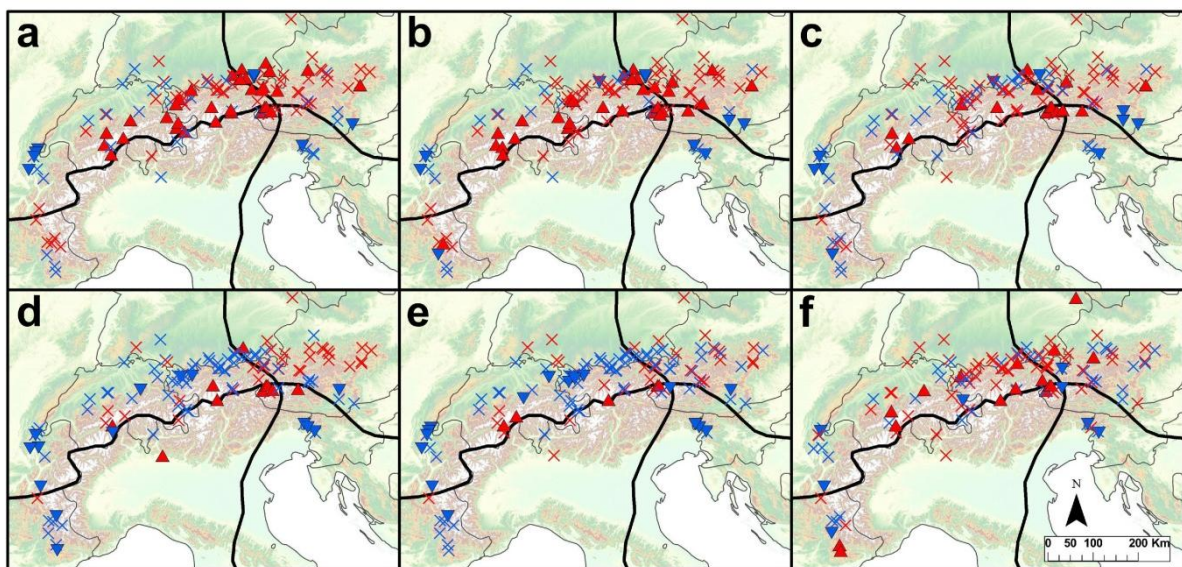
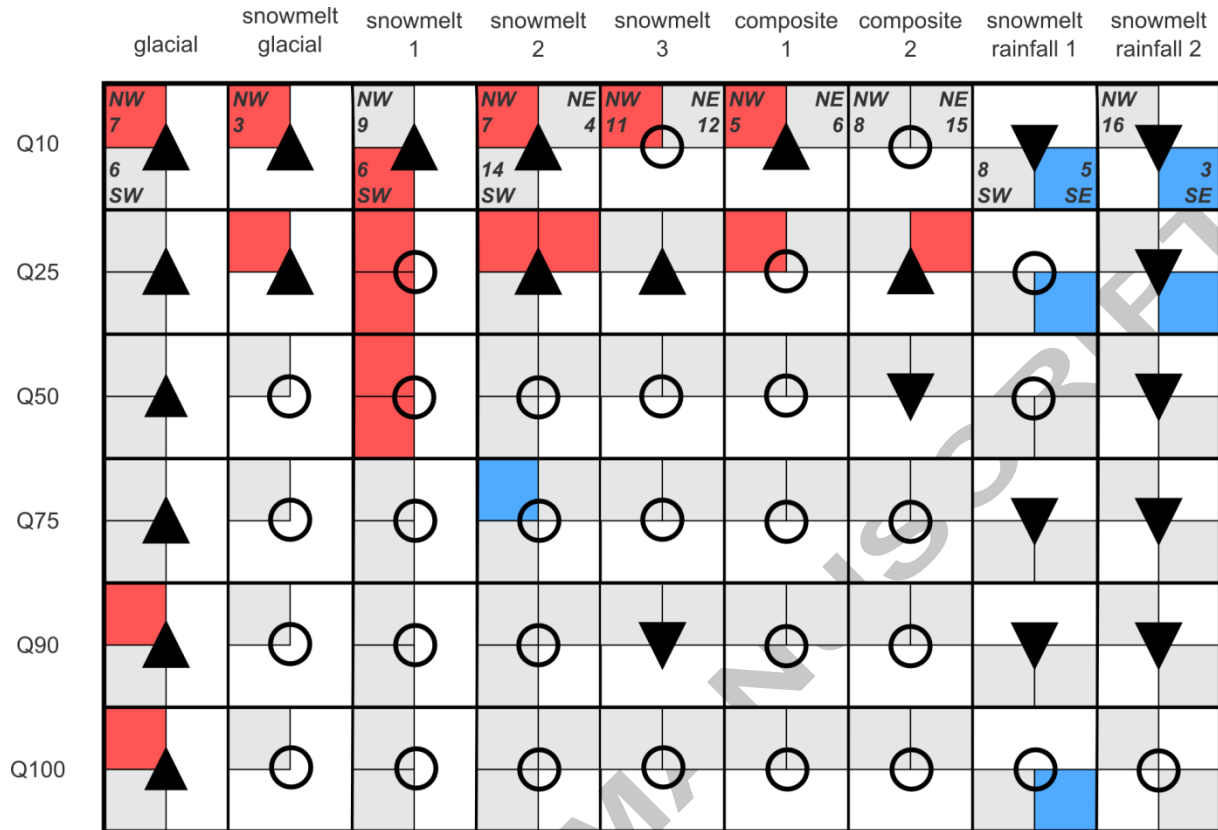


Figure 5. Results of at-site trend tests ( $\nabla$  = downward,  $\blacktriangle$  = upward,  $\times$  = not significant; blue = downward, red = upward) for percentile indices: (a) Q10, (b) Q25, (c) Q50, (d) Q75, (e) Q90, (f) Q100.



**Figure 6. Results of the regional test for percentile indices. Rows represent percentile indices, columns represent hydrologic regimes. Each regime is divided into four squares representing the four HISTALP climatic regions (NW, SW, SE and NE), thereby representing hydro-climatic regions. Grey square = non-significant regional trend, red square = significant upward regional trend, blue square = significant downward regional trend, white square = no station for this climate/regime combination. ▲ = at-site upward trends are field significant, ▼ = at-site downward trends are field significant, ○ = at-site trends are not field significant. The number of stations available for each hydro-climatic region is listed in the first row.**

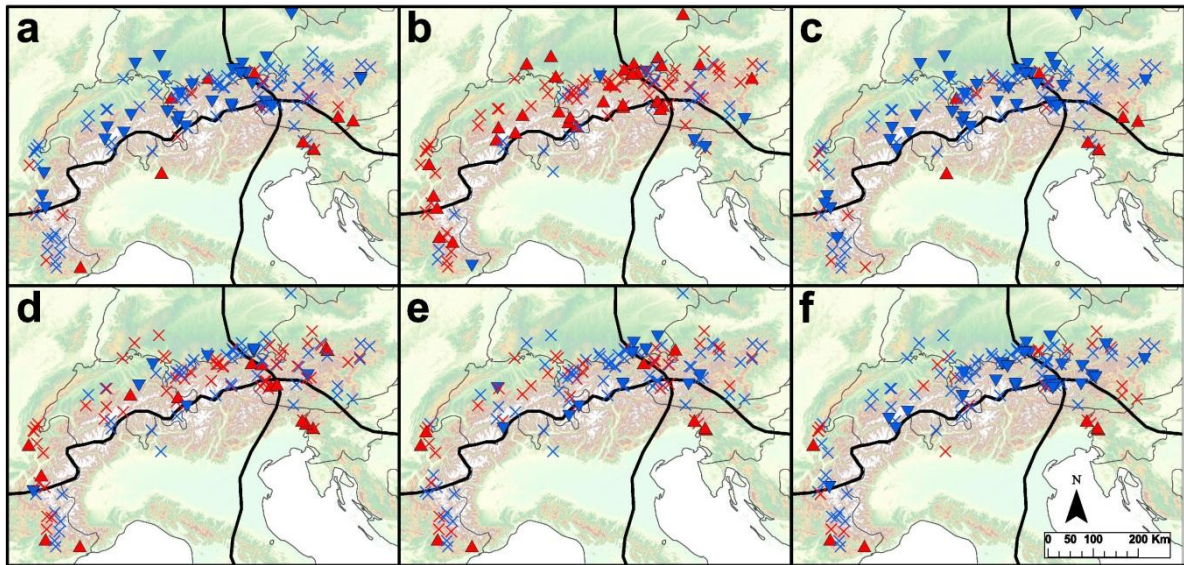


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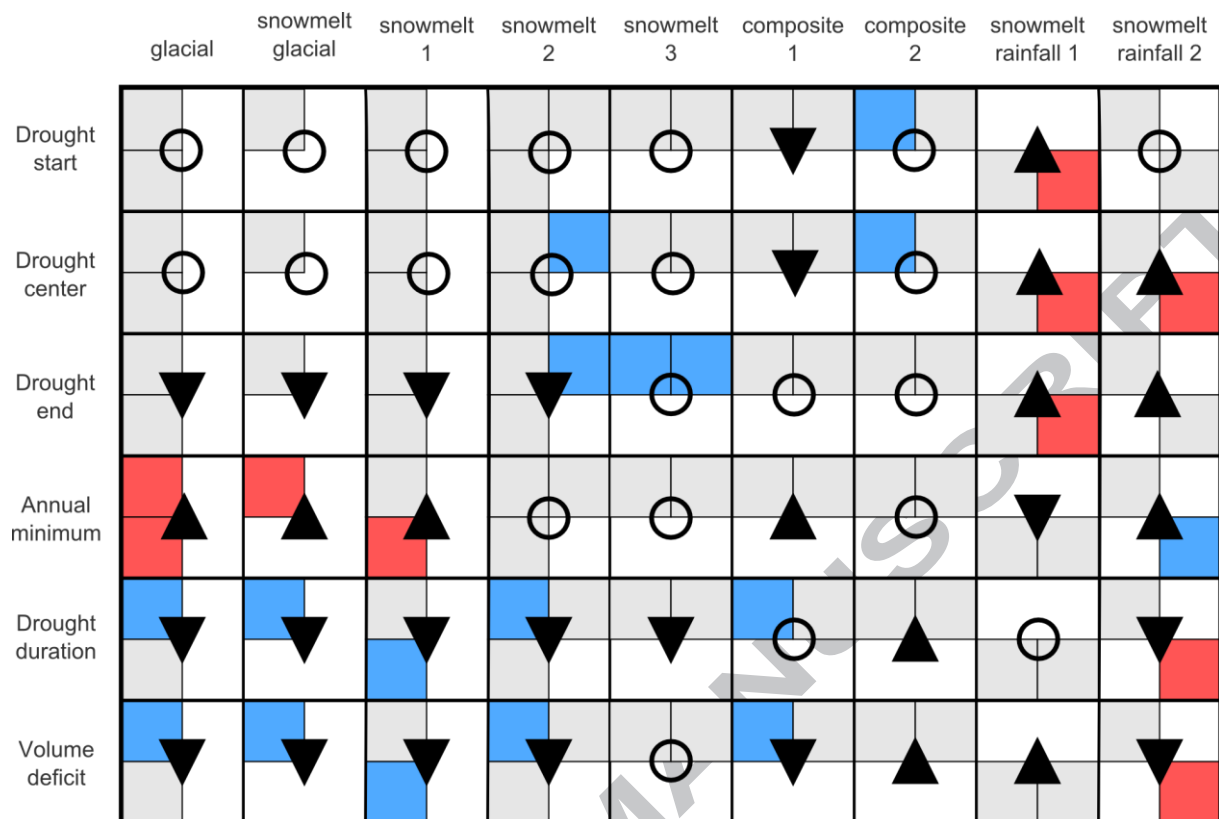


Figure 8. Same as Figure 6 for low flows.

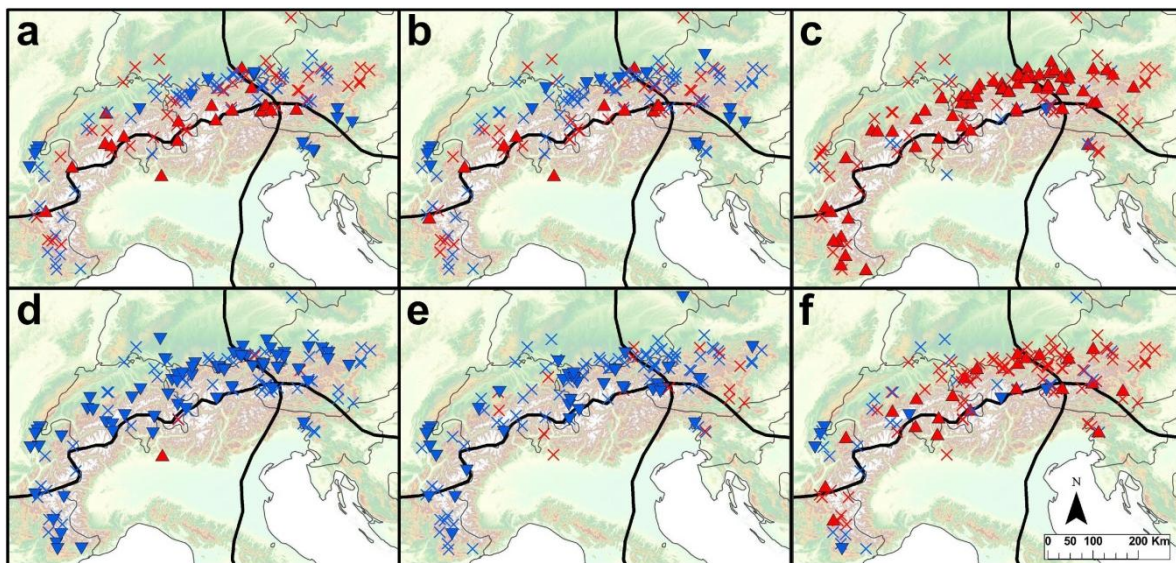


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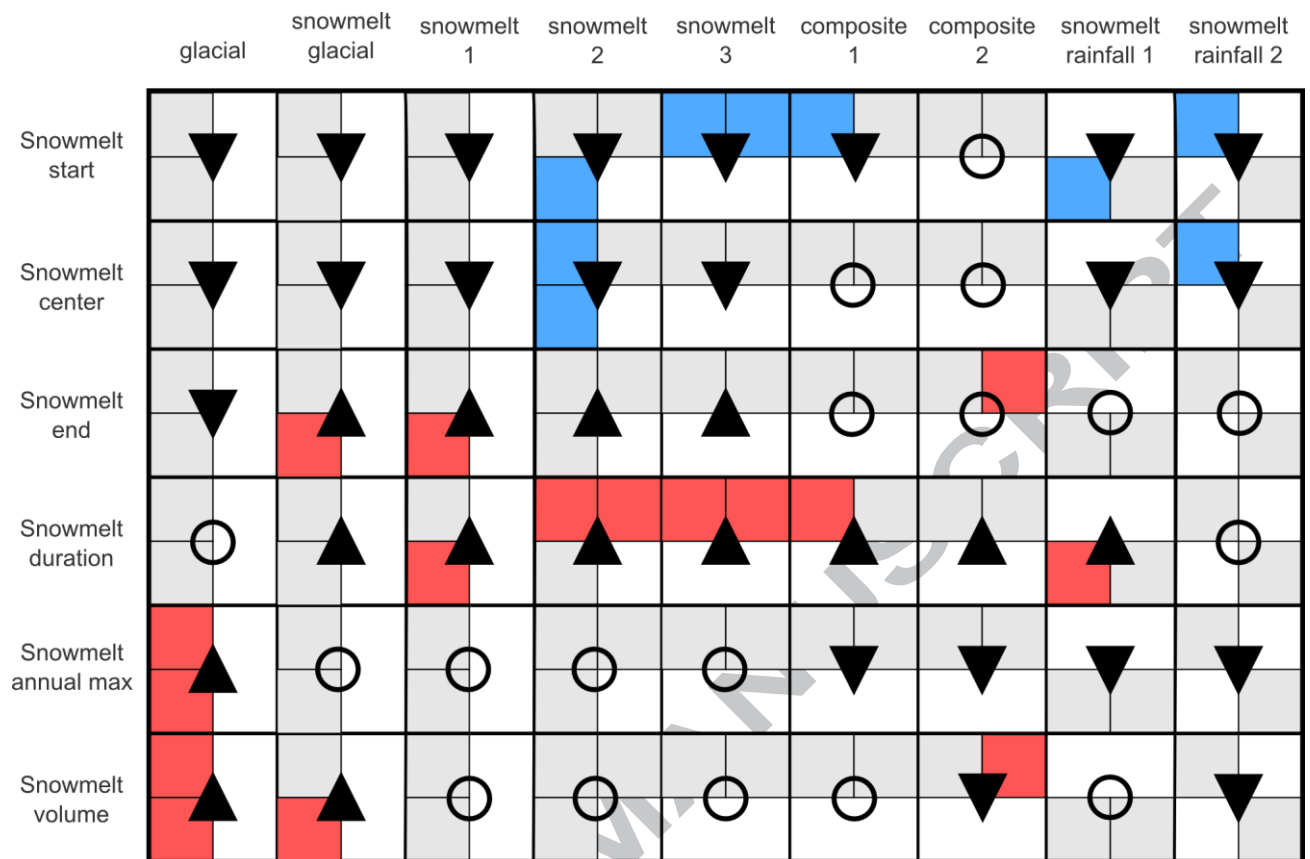
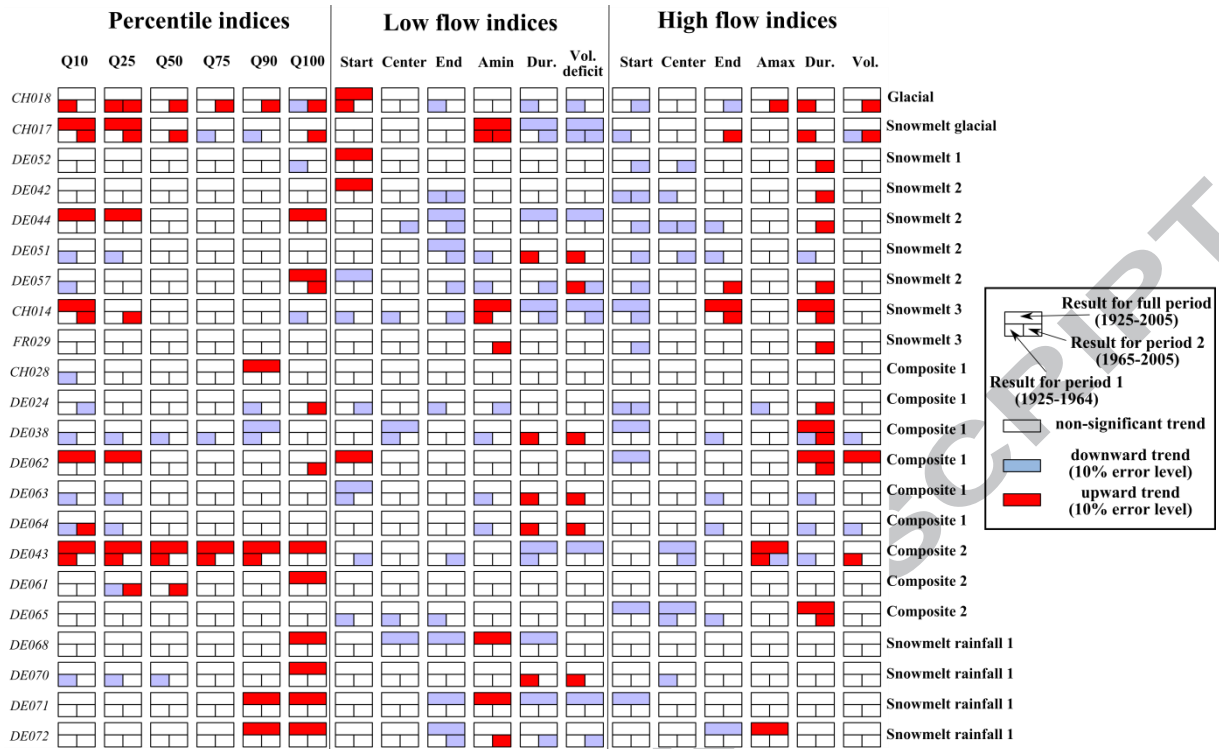


Figure 10. Same as Figure 6 for high flows.





**Figure 11. Stability of detected trends for 22 long series over the period 1925-1965 and over two distinct sub-periods: 1925-1964, 1965-2005.**

### Highlights

- This paper describes a trend analysis of 177 long streamflow series
- Local and regional tests are applied to low, medium and high flow variables
- Less severe winter droughts for most glacier and snowmelt regimes
- Earlier start and increased duration of the snowmelt season for snowmelt regimes
- Glacier regimes show an increase in both mean and peak flows