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# Trends in the hydrologic regime of Alpine rivers

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### Accepted Manuscript

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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 timing of occurrence. Statistical trend tests are applied at a local scale (i.e. on a site-by-site 5 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, contrasted trends are found for mixed snowmelt-rainfall regimes in the Southeastern Alps. 11 12 Changes in the timing of snowmelt flows (earlier start and increased duration of the snowmelt season) mostly affect glacial- and snowmelt-dominated regimes. Lastly, glacial regimes show 13 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**

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

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

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

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

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

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

#### 71 **1.3. Objectives**

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

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

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

Data quality has been assessed through a first round of analysis investigating changes 94 95 affecting low, medium and high flows over the whole available period for each gauging station. In particular, step-change tests (Pettitt 1979) were used to highlight suspicious 96 stations. For example a significant step change occurring on the same date for many 97 98 hydrologic indices may be indicative of a measurement inhomogeneity (e.g. due to station relocation, change in the measurement sensor or method, etc.). The results from this first 99 100 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 issues and/or minor direct influences compromise their suitability for low flows. 105

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

<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 whole 20<sup>th</sup> century for variables such as air pressure, temperature or precipitation. Such long 114 series are unfortunately scarcely available for streamflow data: while long series of water 115 116 stages do exist, the same is not true for rating curves that estimate the stage-discharge relationship, thereby reducing the availability of reliable streamflow data. At the time of 117 writing of this paper, 169 time series from the Adaptalp dataset have been made available 118 119 through the Global Runoff Database Center<sup>2</sup>.

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

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

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

<sup>&</sup>lt;sup>2</sup>(GRDC: <u>http://www.bafg.de/GRDC/EN/Home/homepage\_node.html</u>)

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

As seen in Figure 3 pure glacial- and snowmelt-dominated regimes are found in the heart of 140 141 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 February (see Fig. 2). While the highest flows occur during spring and summer. The month 143 144 with the highest flow ranges between April for composite 1 regimes to July for glacial regimes, owing to snow and ice melt and summer precipitation (Birsan et al., 2005). On the 145 146 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 is stored as snowpack, and during the summer due to a combination of earlier snowpack 148 149 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.

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

are combined to create homogeneous hydro-climatic regions, grouping catchments withsimilar 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

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

In order to focus on snowmelt-related streamflow occurring during spring and summer, the 185 186 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 similar filtering was also used by Hodgkins and Dudley (2011) for base flow trend detection. 188 189 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 (Amax) 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", defined as the dates at which 10%, 50% and 90% of the base flow volume is reached. Lastly, 193 the time between the snowmelt "start" and "end" gives an indication on the duration of the 194 snowmelt-induced flows. For these indices, we use the 140 stations that are suitable for high 195 196 flows.

197 **3.1.4.** Calculation time windows

The extraction of all hydrologic indices defined in sections 3.1.1-3.1.3 is not based on calendar years (from 1<sup>st</sup> of January to 31<sup>st</sup> of December) but on selected time windows which depend on the target index and hydrologic regime. Table 1 summarizes the time windows chosen in this study. Time windows are based on the annual regime shown in Figure 2: for high flow indices, the time window starts and ends on the months with the smallest 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 low205 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 window. It is also unable to capture changes associated with two or more dominant flow 211 212 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, even for mixed snowmelt-rainfall regimes where the snowmelt induced runoff is still more 215 important or is fairly equivalent to the runoff produced by autumnal precipitation (Fig. 2). 216 217 Secondly, calculation time windows are specific to the target streamflow index and are centered either on the low or high flow period. Lastly, for high flows the base flow separation 218 219 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

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

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

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

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

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

When applying a statistical test to a large number of series with a 10% error level, a detection 235 236 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 ensuring that these trends are not due to chance? The Bootstrap procedure proposed by 239 240 Douglas et al. (2000), specifically designed to account for the spatial correlation within a dataset, is used for this purpose. Field significance is evaluated for each hydrologic regime, 241 and for the whole dataset. 242

### 243 3.2.3. Regional consistency

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

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

### 257 **4. Results**

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

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

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

hydrologic regime of alpine rivers: low, medium and high flows. An additional analysis based
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, corresponding to a reorganization of the hydrological services. By restricting the analysis to 281 282 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)

Figure 5 shows a general increase in lower percentiles Q10 and Q25, with averaged trend 286 287 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 trend magnitudes of 26% and 31%. This increase holds to a lesser extent for snowmelt and 289 composite regimes. The increasing trend is generally consistent at the scale of hydro-climatic 290 291 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)

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

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

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

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

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

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

#### 315 **4.2.1.** Severity

Winter drought severity appears to decrease overall (Fig. 7a-c): volume deficit (a) is indeed significantly decreasing for 25% of stations (Table 2), with a trend magnitude of 39% and drought duration (c) for 26% of stations with a reduction of 21 days on average. Annual 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: drought duration decreases on average by 25 days and volume deficit by 47%. This signal is 325 326 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

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

At-site results do not reveal any generalized change for high flow intensity (Fig. 9a-b). However, glacial regimes show significant trends: both snowmelt volume and annual maximum are significantly increasing for 93% and 47% of the stations (Table 2), with trend 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 earlier, with a small magnitude of 6 days, whereas duration does not significantly increase. 352 On the contrary, snowmelt-glacial, snowmelt 1 to 3 and composite 1 regimes exhibit 353 significant decreasing trends for the snowmelt "start" and "center" indices, with average shifts 354 355 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 the scale of hydro-climatic regions (Fig. 10), the same results are observed particularly for 357 snowmelt 1 to 3 and composite 1 regimes, with a significant increase of the snowmelt 358 359 duration and an earlier onset of the melting season.

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

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

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

significant decreasing trends, whereas higher percentiles are found significantly increasing for 368 snowmelt-rainfall 1 regimes. For low flow indices, snowmelt regimes show a significant trend 369 370 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 decrease and snowmelt duration increases significantly except for two stations. Contrasted 377 changes can be observed for the snowmelt "end" and no clear trend is found for the snowmelt 378 379 annual maximum and volume.

Regarding the influence of the time period, slightly more significant trends are detected over 380 381 the period 1925-2005 than over the two sub-periods: 1925-1964 and 1965-2005 (among which the 1925-1964 period accounts for more significant changes). The detection of 382 383 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 (Fig. 11), but 7 exceptions were found. Among these 7 cases, 5 are not significant overs the 385 386 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).

A particular behavior can be observed for station DE043, with significant increasing trends for almost all percentiles over the period 1925-1964, and even a contradiction in the subperiods trends for the snowmelt annual maximum. However, these changes could not be 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. SCR

#### 5. Discussion 397

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

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 spurious LTP. Quoting Jaruskova (1997): "if the finite part of a time series is observed, it is 414 415 impossible to distinguish between a stationary series with the positive dependence between

the neighbouring observations and a sequence of independent variables with the slowly changing mean". In other words, for a given time series of observations, one can always build a stationary model with complex LTP dependence structure or a simple STP model with some complex non-stationarity that will fit the data equally well. Therefore, this choice has to be made beforehand (using physical considerations if possible), but one should acknowledge that 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 (iii) analysis of consistent regional trends. This threefold strategy helps building confidence in 425 426 the trend detection and highlights general trends at the scale of hydrologic regimes and hydroclimatic regions. Field significant results were found for all major changes observed. 427 428 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 (because trends have to be consistent across the hydro-climatic region to be detected), 430 431 therefore fewer significant trends are found compared with field-significant results at the scale of hydrologic regimes. Nevertheless, trends that are both regionally consistent and field 432 significant are found in 55%, 54% and 42% of the cases for annual percentiles, low flow and 433 high flow indices, respectively (Fig. 6, Fig. 8 and Fig. 10). 434

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

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1. A regionally consistent trend is detected, but field significance is not reached. In this
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and the 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 explanation is that rivers of the same region are impacted differently over time and 446 447 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.

For glacial regimes, changes are more numerous for lower and medium percentiles than for 453 454 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 total streamflow of their catchment. 460

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

except for the "end" which appears to occur earlier. Similar results were observed by Birsan 464 465 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 for all the regime types except snowmelt-rainfall 2. According to Birsan et al. (2005), 468 increase in winter and spring streamflow is related to changes in temperature rather than 469 470 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 trends found in other mountainous areas of the world. In particular, the trend toward earlier 473 474 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 disappear as the snowmelt influence loses its predominance over other hydrologic flow 476 477 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, snowmelt-rainfall regimes show an overall decrease of all percentiles, particularly in the 481 482 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 increase in temperature is observed in the Alps during the 20<sup>th</sup> century (e.g. Auer *et al.*, 2007), 495 changes in precipitation patterns appear to be more complex. Moreover, empirical 496 497 comparisons between streamflow trends and forcing variables like precipitation and temperature are difficult to interpret and possibly misleading for two main reasons. First, the 498 499 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 by Zampieri et al. (2015), showed that earlier spring streamflow timings are mostly explained 506 507 by the change of precipitation seasonality and its increasing liquid proportion in these large catchments. While the question remains open for smaller alpine catchments, it calls for further 508 509 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:

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#### • Winter droughts:

- Severity tends to decrease for all regimes except snowmelt-rainfall regimes,
  with drought durations decreasing by an average of 25 days over 1961-2005
  and volume deficits decreasing by an average of 47%.
- 521 o 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.
- Mixed snowmelt-rainfall regimes in the Southeastern Alps (mostly Slovenian stations) show an opposite evolution: seasonality seems to be shifted toward later occurrences, for the drought "start", "center" and "end" by 22 days on average. Severity tends to increase for snowmelt-rainfall 1 regimes with a volume deficit increasing by 10%.
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#### Spring and summer high flows:

# • All regimes show a consistent shift toward an earlier start of snowmelt flow, with a trend magnitude of 11 days, along with an increase of 18 days in the duration of the snowmelt season.

Glacial regimes, in particular, show a consistent behavior with a melting
season shifted by a week earlier, and an increase of 29% in the snowmelt
volume and of 21% in the snowmelt induced base flow maximum.

#### • Medium flows:

537 O Glacial regimes show a consistent increase in the annual median flow (*Q50*),
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 are spatially consistent is an indication that they are climate-related rather than the 542 consequence of measurement issues or direct anthropogenic influences. However, whether 543 these evolutions are linked to climate change or to climate decadal variability remains an open 544 545 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, temperatures) and climate variability (e.g. NAO, ENSO) on the evolution of Alpine 547 hydrologic regimes. 548

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- 702

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

- 704 Throughout this appendix, the random variables representing a series of observations are
- noted  $X_1, ..., X_n$ . 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:

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

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

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

with 
$$Var(S) = n(n-1)(2n+5)/18$$

- This statistic asymptotically follows a Gaussian distribution N(0;1) under the H0 hypothesis
  of no trend (Mann, 1945; Kendall, 1975).
- 712 The variance 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:

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

- 714 where  $t_k$  is the number of tied values of extent k.
- In the presence of autocorrelation, the variance is computed as (Hamed and Rao,
  1998):

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

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

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

725 a) Set  $w_m = 0$ .

b) Bootstrap the years used in the original data set, yielding a sample  $(y_1, \ldots, y_n)$ .

727 c) Repeat for 
$$i = 1:p$$

i) Apply the Mann-Kendall test to the series 
$$X_{y_1}^{(i)}, ..., X_{y_n}^{(i)}$$

ii) If the test is significant, increment 
$$w_m$$
,  $w_m := w_m + 1$ 

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

### 734 9.3. Regional consistency test

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

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

$$\tilde{X}_{k}^{(i)} = \phi^{-1} \left( \hat{F}_{i} \left( X_{k}^{(i)} \right) \right)$$
(5)

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

739 site *i*.

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

•  $I_p$  is a vertical vector of size p with all components equal to one. 741

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

745

$$\hat{\boldsymbol{\beta}} = \frac{\boldsymbol{I}_{p}^{T} \left( \tilde{\boldsymbol{X}}^{T} \tilde{\boldsymbol{X}} \right)^{-1} \tilde{\boldsymbol{X}}^{T} \tilde{\boldsymbol{y}}}{\tilde{\boldsymbol{y}}^{T} \tilde{\boldsymbol{y}} \boldsymbol{I}_{p}^{T} \left( \tilde{\boldsymbol{X}}^{T} \tilde{\boldsymbol{X}} \right)^{-1} \boldsymbol{I}_{p}}$$
(6)

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

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

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

- $\hat{\Sigma} = \frac{1}{n} \tilde{X}^T \tilde{X}$ . Under the H0 hypothesis of no trend, the deviance statistics Z in equation (7) 750
- 751 follows a Chi-square distribution with one degree of freedom.
- 752

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755 **Tables** 

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#### 761 Figures

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

Figure 2. The nine hydrologic regimes identified for the AdaptAlp dataset. Thin lines 766 represent the inter-annual monthly streamflow of one particular station (after standardization 767 768 by the inter-annual mean), thick lines represent the within-regime average.

769 Figure 3. The four HISTALP climatic regions as defined by Auer et al. (2007): Northwest 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. Grev square = non-significant regional trend, red square = significant 781 upward regional trend, blue square = significant downward regional trend, white square = no station for this climate/regime combination.  $\blacktriangle$  = at-site upward trends are field significant,  $\triangledown$ 782 783 = 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.

Figure 7. Results of at-site trend tests ( $\nabla$  = downward,  $\blacktriangle$  = upward, x = not significant; blue = downward, red = upward) for low flow: (a) volume deficit, (b) annual minimum, (c) drought duration, (d) drought "start", (e) drought "center", (f) drought "end".

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

Figure 9. Results of at-site trend tests ( $\nabla$  = downward,  $\blacktriangle$  = upward, x = not significant; blue = downward, red = upward) for high flow : (a) snowmelt volume, (b) snowmelt annual maximum, (c) snowmelt duration, (d) high flow "start", (e) high flow "center", (f) high flow "end".

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

Hydrologic Regime	Flow duration percentile										
All hydrologic regime types	1 <sup>st</sup> Dec. – 30 <sup>th</sup> Nov.										
	High	Flows	Low Flows								
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.								
	Spring High Flows	Autumn High Flows	Summer Low Flows	Winter Low Flows							
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.							

 Item

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).

	A	II	Gla	cial	Snow glao	/melt cial	Snowr	nelt 1	Snowr	nelt 2	Snowr	nelt 3	Compo	osite	1 Compo	osite 2	Snow rainfa	melt all 1	Snow rainf	melt all 2
Percentile Indices (number of stations)	126		1.	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	25	0	62	0	60	0	38	0	33	0	18	9	22	8	17	33	0	22	0
Q25	8	24	0	62	0	80	0	13	0	21	0	29	13	17	17	25	17	0	22	0
Q50	8	13	0	77	0	20	0	13	0	4	0	6	9	4	25	17	0	0	28	0
Q75	12	10	0	77	0	0	13	0	8	0	18	0	0	4	8	8	67	0	22	0
Q90	15	4	0	38	0	0	25	0	8	0	24	0	4	0	8	0	67	0	28	0
Q100	6	13	0	46	20	20	13	13	4	8	6	6	0	9	0	0	17	17	17	11
Low Flow Indiana														0						
(number of stations)	134 13		3	5	5 10		2	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	17	4	0	0	0	33	0	16
Center	8	7	8	0	20	0	10	0	4	8	17	-0	17	0	0	0	0	22	0	26
End	21	4	54	0	40	0	40	0	32	0	17	0	13	0	8	0	0	22	0	21
Amin	4	25	0	54	0	80	0	60	0	12	0	17	9	22	8	8	22	0	5	26
Duration	26	5	54	0	60	0	40	0	28	4	22	0	17	4	17	25	0	11	21	5
Volume Deficit	25	7	62	0	60	0	50	0	20	4	6	0	17	9	17	25	0	22	26	5
High Flow Indices																				
(number of stations)	14	40	1:	5	7	7	g	2	2	9	1	9	2.	3	1.	2	8	}	10	8
<b>0</b> , <i>i</i>	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up	down	up
Start	49	1	33	0	29	0	44	0	100	0	42	0	26	0	8	8	63	0	50	0
Center	29	0	40	0	/1	0	33	0	21	0	37	0	4	0	8	0	38	0	50	0
End	5	16	20	0	0	29	0	33	0	24	0	32	0	9	0	17	13	0	17	6
Amax_baseflow	12	8	0	47	0	0	0	11	3	0	0	5	22	4	33	8	38	0	22	0
Duration	1	49	7	0	0	43	0	89	0	90	0	58	0	57	0	25	0	50	0	6
Volume	11	16	0	93	0	29	11	22	3	3	0	0	13	9	25	8	13	0	33	0
			6		•															



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**C**CE



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60

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Q75, (e) Q90, (f) Q100.



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= 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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### **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

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