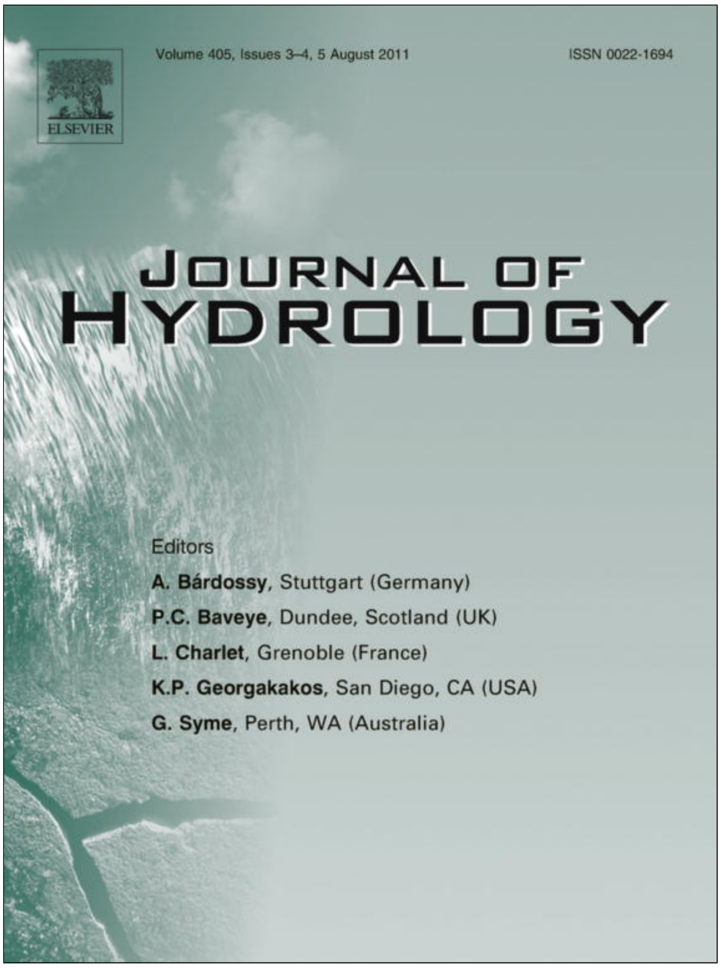
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Flashiness of mountain streams in Slovakia and Austria

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SUMMARY

This article evaluates the spatial and temporal changes in streamflow flashiness in 122 mountain catchments in Slovakia and Austria. The flashiness is quantified by the Richards–Baker flashiness index (*FI*), which is the ratio of absolute day-to-day fluctuations of streamflow relative to total flow in a year. The analysis is based on daily streamflow data from the period 1976 to 2005. The results show that the average day-to-day fluctuations of streamflow vary from 6% to 43%, depending on the catchment. The spatial pattern of the *FI* reflects the variations in the main geological units and generally shows a trend of decreasing flashiness with increasing size of the catchment. Statistically significant temporal trends in flashiness are found in 7 Slovak and 22 Austrian catchments. Most of these trends are related to anthropogenic effects, while, in a few catchments, the change in annual flashiness appears to be caused by changes in precipitation seasonality. A multivariate statistical analysis of *FI* indicates negative correlations with catchment area, mean catchment elevation, percents of forest cover, agricultural land and Quaternary geology. Positive correlations are found between *FI* and Tertiary and Calcareous geologies. Extrapolating the regression models beyond the observed range of catchment attributes used in the estimation leads to significant prediction errors. In order to better interpret the *FI* values, a statistically significant relationship was found between the *FI* and the frequency of peak flows exceeding the long-term mean as well as between the *FI* and the 5% quantile of daily streamflow.

1. Introduction

Understanding the temporal dynamics of streamflow is a major goal of catchment hydrology. From a theoretical perspective it can assists in shedding light on the interplay of catchment and stream processes such as snow melt, runoff generation as well as stream aquifer interaction (Derx et al., 2010). From a practical perspective, knowledge of the streamflow dynamics is important for a range of catchment management purposes such as water allocation and land management. There are different methods for quantifying the temporal dynamics of streamflow. These include the slope of the flow duration curve (e.g. Richards, 1989; Robertson and Roerish, 1999; Werkhoven et al., 2008), the time of concentration by relating the maximum annual flood peak and the average daily runoff (Merz and Blöschl, 2003) and the frequency and rapidity of short-term streamflow changes (Baker et al., 2004). The latter can be quantified by the flashiness index (*FI*) proposed by Baker et al. (2004), which is the ratio of absolute daily streamflow fluctuations and the mean flow. It has been recently applied in several studies quantifying the trends in runoff data, streamflow regime classification and investigating relationships between flashiness and catchment attributes. Baker et al. (2004) calculated the *FI* for 515 catchments in the Midwestern USA and reported a positive *FI* correlation with increasing frequency and magnitude of storm events and a negative correlation of *FI* with baseflow and catchment area. De Girolamo et al. (2007) compared runoff regimes in Mediterranean catchments and reported an increase of *FI* over time, meaning that these catchments are getting flashier. A considerable inter-annual variation of the *FI* was found for the intermittent rivers. Dow (2007) analyzed the streamflow regime of nine New Jersey streams and found both decreasing and increasing trends of flashiness for four rivers. The results suggested that they were related to an apparent slowdown in urbanization and to potential changes in wetland agricultural practices. Oueslati et al. (2010) introduced the *FI* in a streamflow regime classification of Mediterranean rivers. They identified six homogenous river classes representing differences in flow intermittency and variability. Deelstra and Iital (2008) used the *FI* to explain nutrient leaching and soil losses in agricultural catchments of Estonia and Norway. Their findings indicated high nutrient losses for high *FI* and low base flow index in Norway, whereas the contrary results were found for the Estonian catchments. The flashiness variability was attributed to the difference in dominant runoff generation processes, surface runoff and

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macropore flow in Norwegian and subsurface flow and large drain spacing in Estonian catchments. Fongers et al. (2007) found the *FI* to decrease with catchment size for 279 catchments in Michigan and argued that the "…timing of tributary flows helps attenuate main channel peak flows, and because soils and land uses tend to become more varied as the watershed size increases." Holko and Kostka (2008) added that increasing catchment area generally results in a decrease of catchment precipitation and increased contributions of groundwater from alluvia which contribute to dampening the runoff response. They found good correlations between physiographic catchment attributes and the *FI* for selected small mountain catchments in Slovakia. The *FI* was well correlated with catchment slope, percentage of agricultural (especially arable) land and forest.

The above studies showed that the *FI* is a simple characteristic that can be useful in hydrological regionalization and serve as an indication of the changes in the hydrological regime. The objective of this paper is to evaluate the spatial and temporal variability of streamflow flashiness and assess its usefulness for mountain catchments in Central Europe. We used data from 122 catchments in Slovakia and Austria. The specific aims of the paper include:

(a) Estimation and inter-regional comparison of the *FI* using observed daily streamflow data from the period 1976 to 2005,
(b) Identification of temporal trends in the *FI* and the analysis of their spatial variability,
(c) Assessment of the predictive power of physiographic catchment attributes for estimating the *FI* in ungauged catchments.

This article goes beyond the existing literature in that it strives to identify the main driving factors influencing the spatial and temporal variability in day-to-day streamflow fluctuations in mountain areas. The inter-regional comparison enables us to shed more light on the performance of linear regression relationships for estimating the flashiness in other regions and/or ungauged catchments. We also relate the flashiness to flow characteristics which may be of practical significance for alternative interpretations of streamflow variations.

The article is organized as follows. First we describe the *FI* approach and methods used for the trend assessment and correlation analysis. Next we introduce the study region and streamflow data used in the analysis. The results section examines the spatial and temporal variability in flashiness and compares the performance and predictive accuracy of different linear relationships for the *FI* estimation. Finally, we discuss the results in the context of existing studies and present some concluding remarks and implications for regional hydrological analyses.

2. Methods

Flashiness of streamflow is quantified by the ratio of absolute day-to-day fluctuations of streamflow relative to total flow in a year (Baker et al., 2004):

$$FI_y = \frac{\sum_{i=1}^{n}|q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \qquad (1)$$

where *FI* is the flashiness index, q is the mean daily discharge, i is day, $n = 365$ (366) and y indicates the year of estimation. *FI* is a dimensionless measure which ranges between 0 and 2 (Fongers et al., 2007). Zero represents an absolutely constant flow; increased FI_y values indicate increased flashiness (fluctuations) of streamflow. We first calculated FI_y for each year of the studied time period (1976–2005). Then, the total flashiness of a stream (FI_{avg}) was estimated by averaging the yearly FI_y values. The temporal variability was described by the standard deviation of the FI_y values between years and by the temporal trends in each catchment. The long-term temporal changes of flashiness was examined by trend analysis. The trend analysis is based on the Mann–Kendall test (Kendall, 1975), and the trend significance is tested at the 95% confidence level ($p < 0.05$). Baker et al. (2004) concluded that the flashiness index has low inter-annual variability, thus "making it well suited for detecting gradual changes in flow regimes". The short-term variability of the flashiness was analysed as well by using the seasonal (monthly) flashiness index FI_S. In this case Eq. (1) is modified so that n represents the number of days in the particular month.

The relationship between different catchment attributes and flashiness is investigated for catchments without a significant trend using univariate and multivariate linear regressions. The multivariate regression is based on the set of those three attributes that are associated with the largest multiple correlation coefficient. To diagnose and avoid high inter-correlation of dependent variables (multicollinearity), the variance inflation factor (Hirsch et al., 1992) was examined. If the inflation factor was greater than 10, the set of attributes was rejected and the scheme proceeded to the second best correlation. The rationale of this choice is that a large correlation coefficient may be a good indicator of the

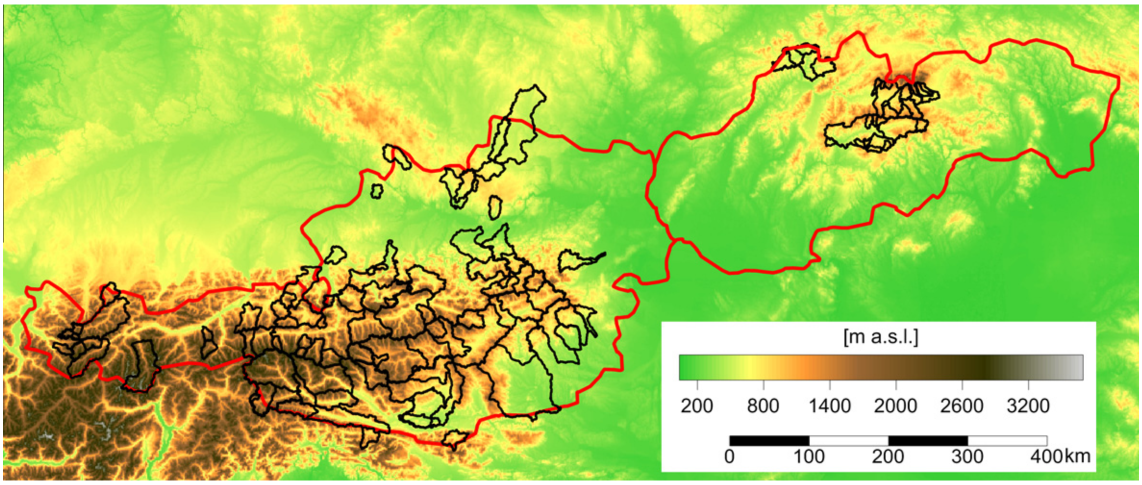

Fig. 1. Topography of the study region (Austria left, Slovakia right) and boundaries (black lines) of the study catchments.

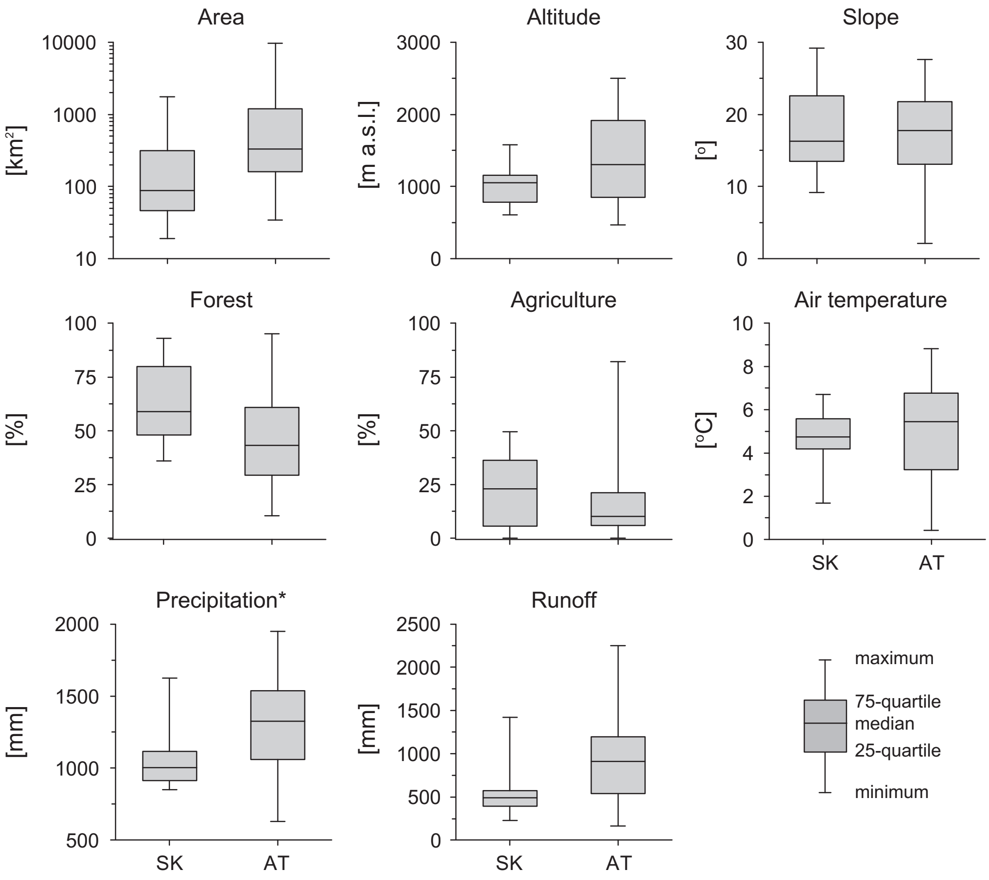

Fig. 2. Variability of physiographic catchment attributes for the Slovak (SK) and Austrian (AT) catchments. Mean annual air temperature, precipitation and runoff were calculated for the period 1976–2005 with the exception of mean annual precipitation for the Slovak catchments which was calculated for 1976–2000 (∗).

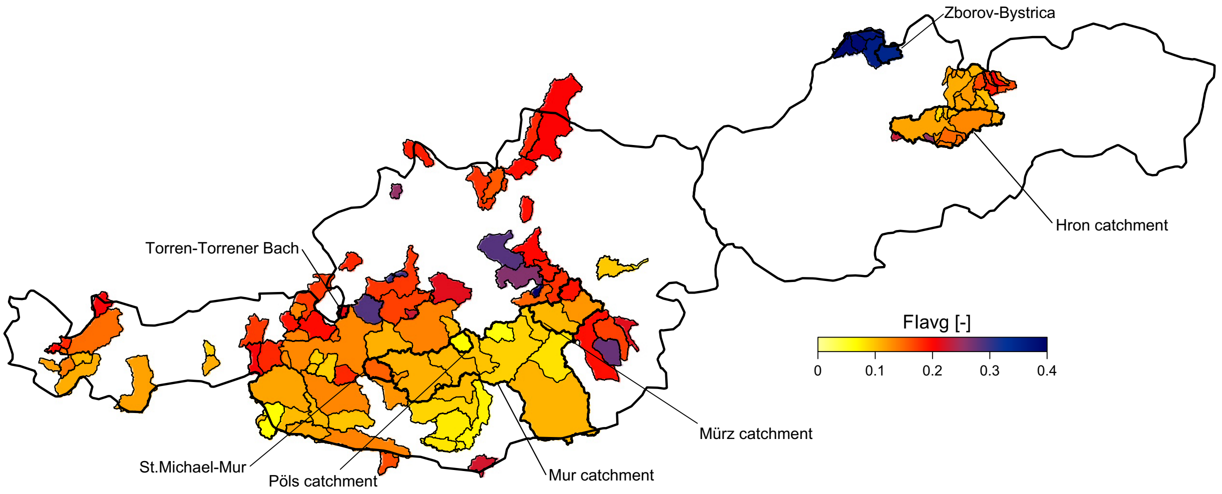

Fig. 3. Spatial variability of the mean annual flashiness index FI_{avg} in the period 1976–2005; the highest FI_{avg} values in Slovakia occur in the flysh catchments (rocks with lower permeability) and in Austria in the Calcareous Alps (karstified rocks).

predictive power of the attributes provided there is no collinearity. The predictive accuracy of catchment attributes for estimating the flashiness index was quantified by jack-knife cross-validation. In this approach, each gauged catchment in turn is treated as ungauged and multivariate linear regression is used to estimate the relationship between the flashiness index (FI_{avg}) and catchment attributes. The differences between the FI_{avg} calculated from observed streamflow data and those estimated from the regression were then evaluated.

3. Data

Daily streamflow data for 91 Austrian and 31 Slovak mountain catchments from the period 1976 to 2005 were used. The location

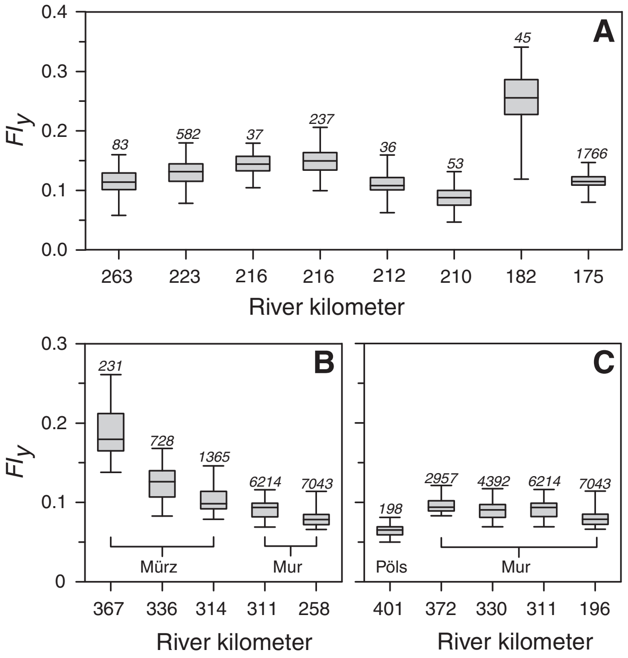

Fig. 4. Change in annual flashiness (FI_y) in large catchments. Panel A shows the FI_y in the Hron catchment. Panels B and C show FI_y in two different parts of the Mur catchment. The horizontal axes show river kilometer (distance to the mouth of the river). Areas (km^2) of the subcatchments are given above the whiskers in italics.

of the selected catchments and the topography of the study region are shown in Fig. 1. Most of the Austrian catchments are situated in the Alps, while most of the Slovak catchments are situated in the highest part of the Western Carpathians. The catchments cover a wide range of different physiographic attributes (Fig. 2). The area ranges between 19 and 9770 km^2 with a median of 320 km^2 and 87.5 km^2 in Austria and Slovakia, respectively. The mean catchment elevation varies between 466 and 2500 m a.s.l. in Austria and between 604 and 1579 m a.s.l. in Slovakia. The Slovak catchments have generally a larger coverage of forest and agriculture land classes. Most of the Austrian catchments (70) are nested, but only eight catchments are nested in Slovakia. Fig. 2 also provides information on the variability of mean annual precipitation, runoff and air temperature in the catchments. The Austrian catchments have generally higher precipitation, runoff and air temperatures than the Slovak ones. The medians of mean annual precipitation in the Austrian and Slovak catchments are about 1300 mm and 1000 mm, respectively. Mean annual runoff is about 800 mm in Austria and 500 mm in Slovakia. The ranges of the basic water balance components in the Austrian catchments are higher than in Slovakia. Skøien et al. (2003) present the spatial and temporal scales of variability of the water balance components in Austria. Snow cover is important in all studied catchments.

The catchment attributes used in the correlation analyses include: catchment area, mean catchment slope and elevation, percentages of forest cover and agricultural land. Additional data on the mean annual precipitation, snow coverage, rain-to-snow ratio

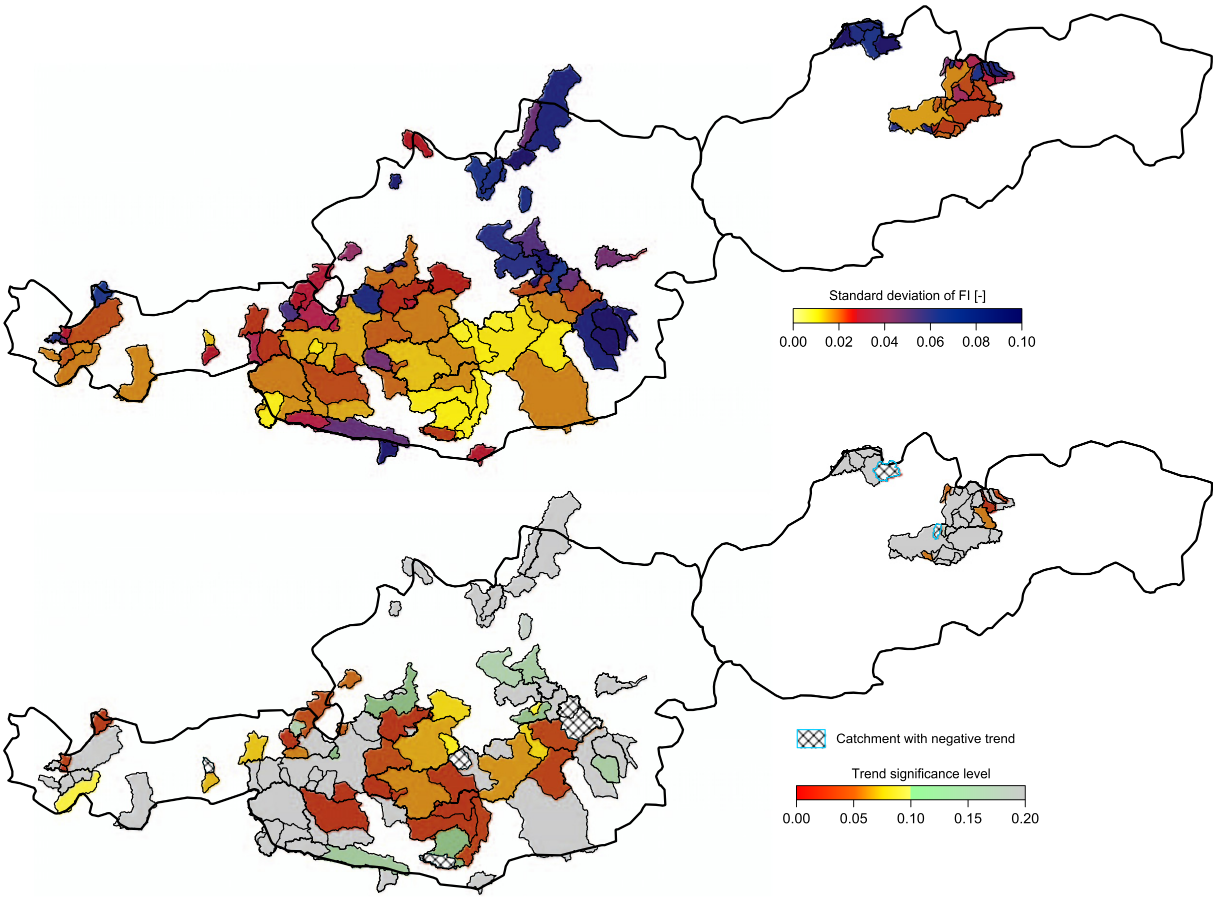

Fig. 5. Temporal variability of flashiness in the period 1976–2005. Top panel shows the standard deviation of the flashiness index (FI_y) between years, bottom panel shows the significance level of the Mann–Kendall trend test. Red color (bottom panel) indicates significant trends at the 5% level ($p < 0.05$) Catchments with negative trends are hatched. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

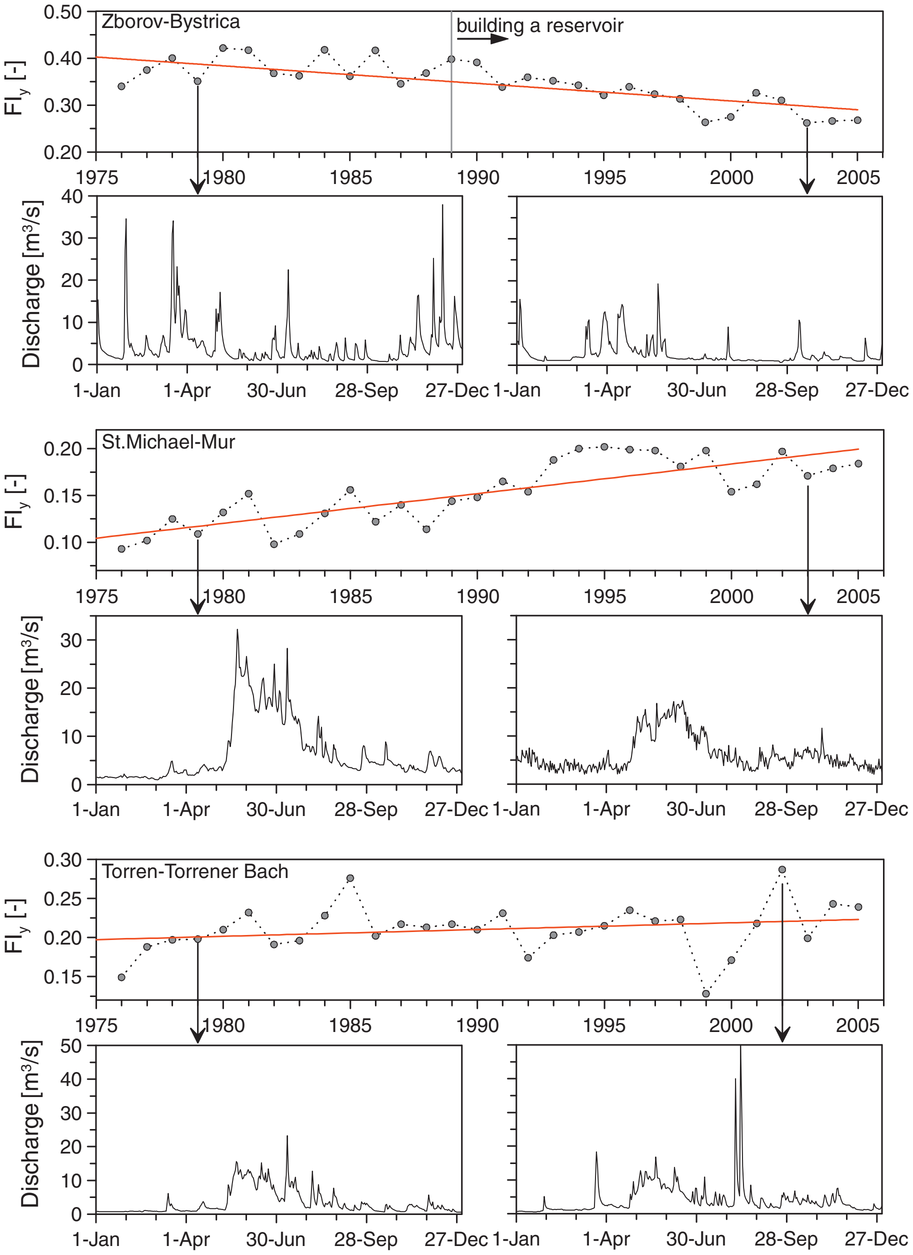

Fig. 6. Example of decreasing (top panel) and increasing (middle and bottom panel) trends of the flashiness index FI_y in the period 1976–2005. Top panel shows Zborov–Bystrica (218 km^2), middle panel shows St. Michael-Mur (289 km^2) and bottom panel shows Torren–Torrener Bach (65 km^2). Observed hydrographs are shown for selected years.

and proportion of geological and soil classes were only available for the Austrian catchments.

4. Results

4.1. Spatial and temporal variability of flashiness

The mean annual flashiness index FI_{avg} in the analyzed catchments varies between 0.06 and 0.43 (Fig. 3). This means that the average day-to-day fluctuations of streamflow vary from 6% to 43%, depending on the catchment. The smallest flashiness indices are observed in relatively small catchments with dominant Austro-alpine Crystalline geology. The largest values are observed in catchments in the flysh formations (alternation of claystones and sandstones) of north-western Slovakia (Fig. 1) and in the Calcareous Alps (mostly karstified rocks, dolomites and limestones) located mostly in the North and South Alps. Overall, the spatial pattern of the FI_{avg} reflects the variations in the main geological units, precipitation and catchment size. The effects of catchment size are illustrated in more detail in Fig. 4. Panel A (Fig. 4) shows the FI_y variability within the Hron subcatchments (Fig. 3). Note that the catchments in panel A are non-nested catchments with the exception of the catchment outlet (river kilometer 175, catchment area 1766 km^2). Although there is a large difference in the FI_y values within the catchment, the flashiness variability (quartile range) at the outlet is lower than that within the catchment. Panels B and C show two cases of nested catchments. Panel B (Fig. 4) shows a typical example of a decrease in flashiness with increasing catchment size. There is a change of the FI_y from 0.19 in the Mürz catchment to less than 0.1 at the outlet of the Mur catchment (Fig. 3). This is because of aggregation effects in the catchment and because

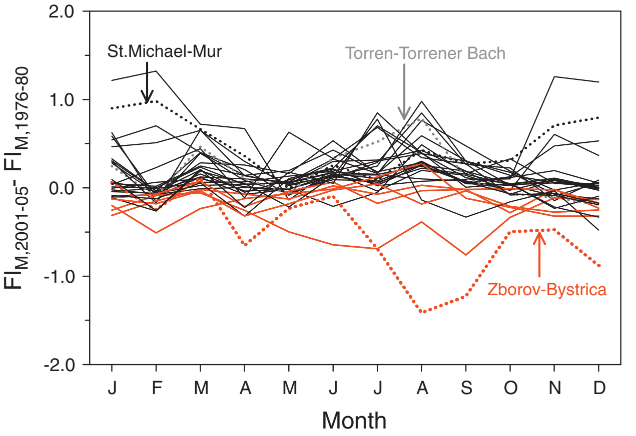

Fig. 7. Change (difference) in mean monthly flashiness index between the periods 2001–2005 and 1976–1980. The lines represent catchments with significantly positive (black, grey) and negative (red) trends, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the headwater catchments have a higher intensity rainfall regime than the lower parts of the catchment. Panel C (Fig. 4) refers to a different branch of the same river system. In contrast to the previous example, flashiness tends to increase from the headwater (Pöls) catchment to the larger catchment. The Pöls catchment has a much lower flashiness than the Mürz catchment because of the lower intensity rainfall regime, higher importance of snow cover and different geology (Crystalline as opposed to Calcareous in the case of the Mürz catchment).

The temporal variability in the flashiness index is evaluated in Fig. 5. The standard deviation of FI_y between years varies between 0.01 and 0.1 (Fig. 5, top panel). The spatial patterns are similar to the variability of the FI_{avg} (Fig. 3), i.e. those catchments that have the largest average flashiness also tend to have the largest standard deviation. The trend analysis indicates statistically significant trends at the confidence level 95% in 7 Slovak and 22 Austrian catchments (Fig. 5, bottom panel). From those, 2 and 4 catchments have a decreasing trend in Slovakia and Austria, respectively, while the others (5 and 18) have increasing trends. We identified the causes of the trends by examining hydroinfrastructure in the catchments as well as the rainfall regime. We found that in 11 catchments the increasing flashiness was related to the construction of hydro power stations and the weekly and daily runoff release patterns in response to energy production demands (Table 1). For four catchments, the trends were related to changes in the water reservoir management. In two instances the operation of release gates caused an increase in flashiness, while in two instances it generated a decrease. In 14 catchments the trends in flashiness could be related to changes in the rainfall regime.

An example of the effect of a water reservoir is presented in Fig. 6 (top panel). A clear decrease in flashiness in the Bystrica–Zborov catchment (area 218 km^2) started after the construction of a water reservoir with a volume of 30 million m^3 in 1989. The Bystrica–Zborov catchment has dominant flysh geology and the reservoir construction had a clear impact on the flow regime in decreasing streamflow peaks and fluctuations.

A typical example of the effect of hydro power stations is shown in Fig. 6 (middle panel), indicating a significant increase of flashiness especially in winter. For a few catchments, the change in annual flashiness is caused by a significant increase in summer fluctuation (Fig. 6, bottom panel). In these catchments, the summer increase in flashiness is typically caused by major flood events and is related to a particular change in extreme rainfall and flood seasonalities. In the case of Fig. 6 bottom, it is the August 2002 flood which was quite extreme. Fig. 7 evaluates the change in seasonal (mean monthly) flashiness between two periods (2001–2005 and 1976–1980). The assessment indicates that the recent increases in mean annual flashiness appear to be caused mainly by increases in the flashiness in the winter and summer months. The winter increases are caused by construction of hydropower stations, which have a strong impact especially on winter streamflow regime (river freezing, winter low flows). The increase of summer fluctuations is also caused by the hydropower constructions. Additionally, it is also affected by a few extreme rainfall-runoff events. In order to shed more light on factors causing the change in mean annual flashiness, a more detailed assessment and comparison of intra-annual variability of hydrologic and climate characteristics was performed in Fig. 8. It shows the monthly variations of mean monthly air temperature, precipitation, runoff and monthly flashiness in catchments with increased winter (top panel) and summer (bottom panel) flashiness. The increase in winter fluctuations in the St. Michael-Mur catchment (Figs. 6–8) shows the effects of hydropower operation. The construction of hydropower stations in 1984 and 1991 is reflected in an increase of streamflow fluctuations in winter and it reduces the effects of small flashiness due to river freezing. This example also shows the effects of individual events on the annual flashiness change. Heavy rain in August 2002 caused a significant increase in mean monthly flashiness, which resulted in one of the largest FI_y in the period 1976–2005 in this catchment (Fig. 6, middle panel). The same effects are shown also for the Torren–Torrener Bach catchment (Fig. 8, bottom panel). This catchment has dominant calcareous geology and is characterized by large FI_y variability. High monthly precipitation values, e.g. in August 1985 or 2002, have an important impact on the FI_y (Fig. 6, bottom panel). The high value of FI_y in 2002 (and consequently the trend for the whole study period 1976–2005) was mainly due to two extreme flood events and does not seem to represent a systematic change in land or water resources management of the catchments.

4.2. Relationship between flashiness and physiographic catchment attributes

The relationship between selected catchment attributes and the mean annual flashiness (FI_{avg}) was investigated by univariate and multivariate statistical analysis. In the context of an inter-regional comparison, four different dataset variants were evaluated (Table 2). The variants R_{SK}, R_{AT} and R_{SK+AT} apply the same catchment attributes in order to examine the relationships independently in different regions (R_{SK}-Slovakia and R_{AT}-Austria) or using a merged dataset (R_{SK+AT}). The variant R_{AT+} uses the same attributes as R_{AT} and, additionally, mean annual precipitation, snow coverage, rain-to-snow ratio and proportion of the main geology and soil units, which are available only for the Austrian catchments. All the regressions were estimated only for catchments without a significant flashiness trend.

The results of the univariate linear correlations are presented in Table 3. There are remarkable differences between the datasets. In Slovakia, the strongest correlations are observed between the FI_{avg} and the percentage of agricultural land (0.74) and mean catchment elevation (−0.66). However, we should note that four catchments with the largest percentage of agricultural land are located in the Paleogenous flysh region characterized by the highest flashiness. When these catchments are excluded from the analysis, the correlation between the FI_{avg} and the mean catchment elevation, forest and agriculture percentage decreases to −0.36, −0.42 and 0.59, respectively. For the Austrian and merged datasets (R_{AT}, R_{SK+AT}), the correlations are significantly weaker and practically do not exceed 0.4. It seems that the geology of the region plays an important

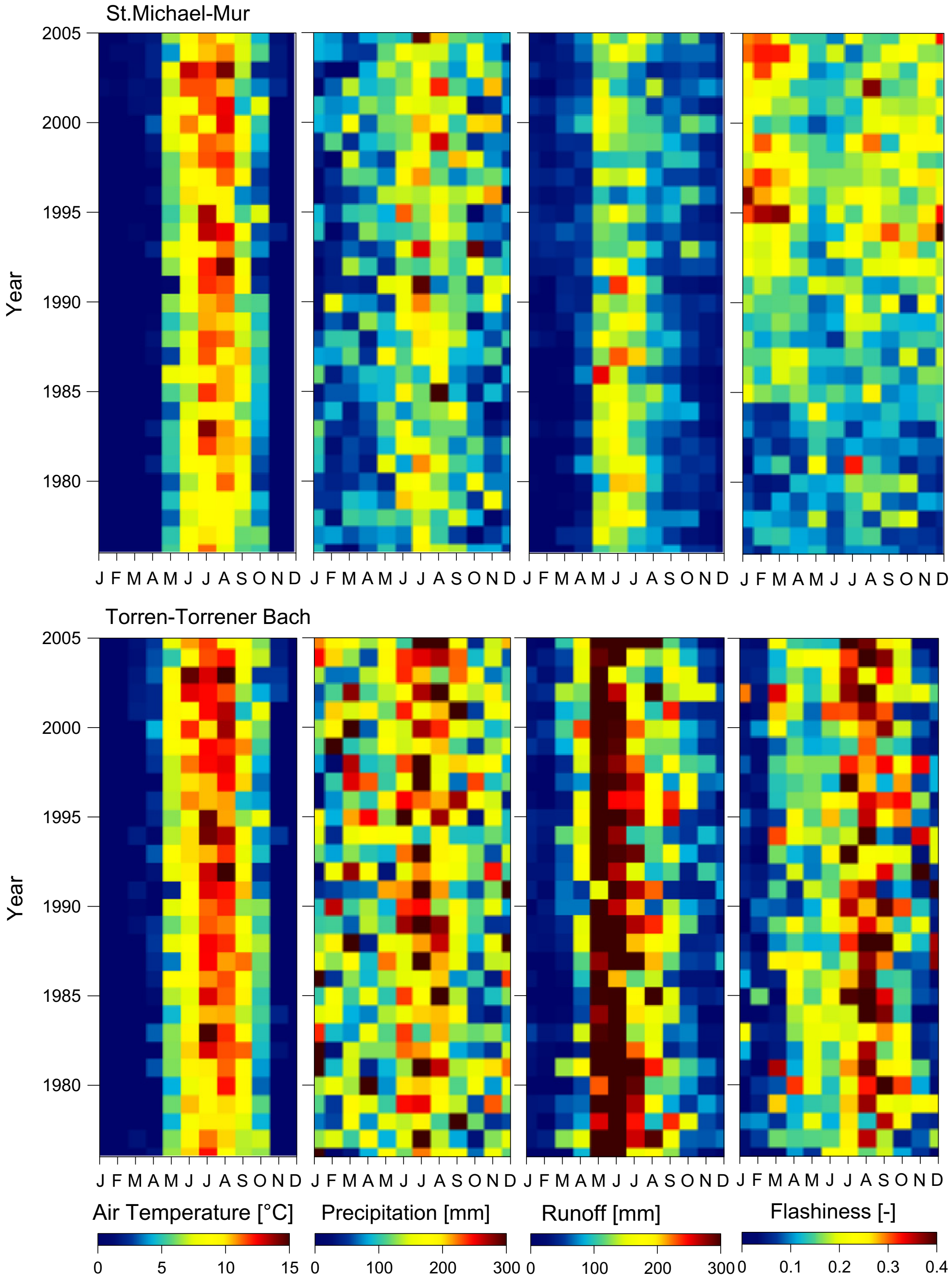

Fig. 8. Monthly variability of climatic characteristics and flashiness index in period 1976–2005 in the St. Michael-Mur (mean elevation 1837 m a.s.l.) and Torren–Torrener Bach (mean elevation 1637 m a.s.l.) catchments.

role in the assessment of flashiness variability. The Austrian catchments have significantly higher geologic diversity and thus, a univariate linear correlation does not capture well the link between flashiness and catchment attributes. When the catchments in the Calcareous Alps were excluded from the analysis (32 out of 76), the univariate correlation between flashiness and the percentage of agricultural land increases to 0.604.

The results of the multivariate statistical analysis are summarized in Table 4. The mean annual flashiness is negatively correlated with the area and mean elevation of the catchments and with the percentages of forest cover, agricultural land and Quaternary geology. A positive correlation is found for the percentage of Tertiary and Calcareous Alps geology. The strongest correlation, 0.79, is found between the mean annual flashiness and catchment area, mean catchment elevation and the percentage of forest in Slovakia. In Austria, the flashiness is best correlated with the catchment area, mean catchment elevation and the percentage of agriculture land and yields a correlation coefficient slightly above 0.53. The correlation coefficient for the merged dataset is similar and slightly exceeds 0.54. Interestingly, accounting for geologic

Table 1
Main causes of trends in flashiness.

Main causing factors	Number of catchments with decreasing trend	Number of catchments with increasing trend
Construction of hydro power station (weekly and daily runoff release patterns in response to energy demand)	0	11
Lake management (operation of release gate)	2	2
Change in seasonality of extreme rainfall and floods	5	9

Table 2
Description of variants used for testing univariate and multivariate regressions between the mean annual flashiness index (FI_{avg}) and physiographic catchment attributes.

Variant	Region	No. of catchments	No. of catchment attributes
R_{SK}	Slovakia	24	6
R_{AT}	Austria	76	6
R_{SK+AT}	Austria and Slovakia	76 + 24	6
R_{AT+}	Austria	76	6 + 15

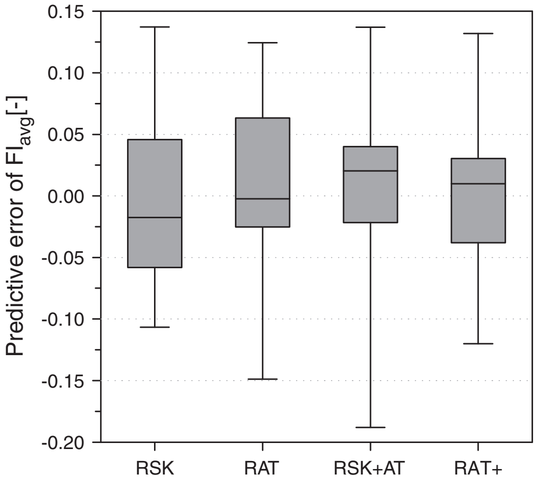

Fig. 9. Box–Whisker plots of FI_{avg} predictive error (estimated minus observed) obtained by jack-knife cross-validation. The whiskers represent the minimum and maximum, the boxes with lines indicate the 25-, 50- and 75 quartiles of the predictive error. R_{SK}, R_{AT}, R_{SK+AT} and R_{AT+} denote different variants of the datasets (Table 2).

attributes in the regression improves the correlation to 0.67. In the extended catchment attributes (R_{AT+}), the best correlation is obtained by using the percentages of Quaternary, Calcareous and Tertiary geological units.

In order to perform a cross validation, the multivariate regression was recalculated by leaving out one of the catchments in turn. For each examined catchment, the mean annual flashiness (FI_{avg}) was estimated by different multivariate regression using the data from other catchments. The statistical evaluation of the predictive errors (estimated flashiness minus observed) is presented in Fig. 9. The Box–Whisker plot in Fig. 9 shows that for more than half of the catchments in each dataset the multivariate regression estimates the flashiness within a range of −0.06 and 0.06. The R_{SK} dataset, has the smallest range. The merged dataset R_{SK+AT} has the smallest quartile range, but the largest range of prediction errors. The median of the prediction errors for the R_{SK+AT} and R_{AT+} datasets is positively biased, which indicates a slight overestimation of the multivariate regressions for the omitted catchments. The physiographic attributes which have the best predictive power in estimation of flashiness in the omitted catchments are practically always the same as the ones found in Table 4. This indicates that the multivariate regressions found are generally stable over the region. Only two exceptions were found. In eight catchments in Austria (R_{AT} dataset) the forest percentage was a better descriptor of the flashiness than catchment area. In three catchments in Slovakia (R_{SK}) the mean slope was a better descriptor than the catchment area.

The performance of the transfer of multivariate regressions to another region is assessed in Fig. 10. The cumulative distribution functions of the FI_{avg} indicate that the multivariate regressions obtained by using data from Austria (R_{AT} and R_{AT+SK}) do not allow to describe the variability of flashiness in Slovakia, as the shapes of the functions are different. There is a remarkable underestimation of the mean annual flashiness in catchments with FI_{avg} larger than

Table 3
Coefficient of correlation between the mean annual flashiness (FI_{avg}) and selected physiographic catchment attributes obtained by different datasets (variants are described in Table 2).

Variant	Area (km^2)	Slope (°)	Altitude (m a.s.l.)	Forest (%)	Agriculture (%)
R_{SK}	0.042	−0.515	−0.665	−0.478	0.740
R_{AT}	−0.270	−0.295	−0.382	0.302	0.183
R_{SK+AT}	−0.214	−0.346	−0.404	0.097	0.332

Table 4
Correlation coefficient and final regression relationships between the mean annual flashiness (FI_{avg}) and selected physiographic attributes (catchment *AREA*, mean catchment *ELEV*ation, the percentage of *FOREST* and *AGRI*Cultural land and the percentage of *QUAR*ternary, *CALC*areous and *TERT*iary geological units). R_{SK}, R_{AT}, R_{SK+AT} and R_{AT+} refer to different variants of applied datasets (Table 2).

Variant	Relationship	Correlation coefficient
R_{SK}	$FI_{avg} = -0.000043AREA - 0.000238 \cdot ELEV - 0.002519 \cdot FOREST + 0.587697$	0.790
R_{AT}	$FI_{avg} = -0.000009 \cdot AREA - 0.000059 \cdot ELEV - 0.000244 \cdot AGRIC + 0.249893$	0.534
R_{SK+AT}	$FI_{avg} = -0.002173 \cdot FOREST - 0.000166 \cdot ELEV - 0.001941 \cdot AGRIC + 0.518974$	0.543
R_{AT+}	$FI_{avg} = -0.003999 \cdot QUAR + 0.000751 \cdot CALC + 0.003090 \cdot TERT + 0.145558$	0.667

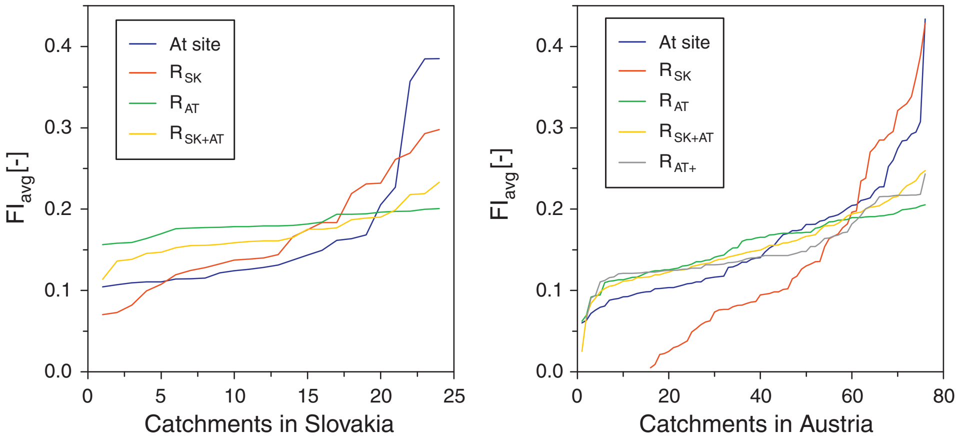

Fig. 10. Cumulative distribution functions of the mean annual flashiness (FI_{avg}) obtained by at site estimation and multivariate linear regression. R_{SK}, R_{AT}, R_{SK+AT} and R_{AT+} denote different variants of the datasets (Table 2).

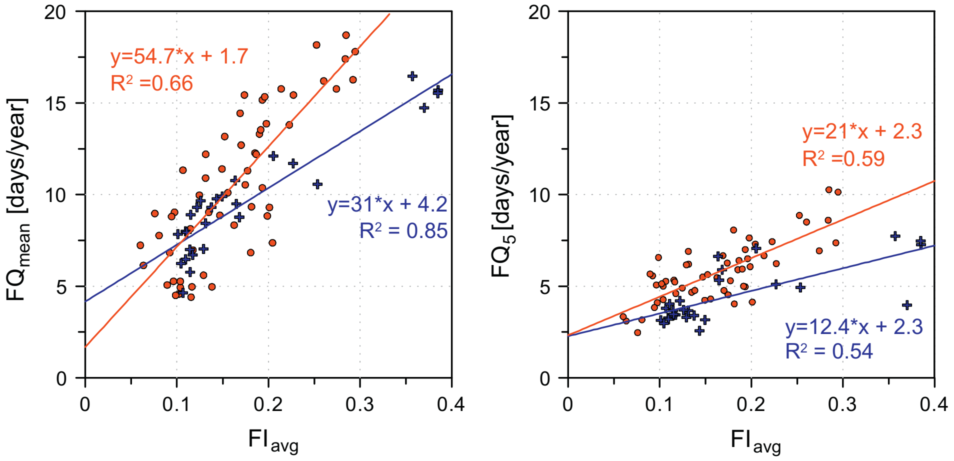

Fig. 11. Relationships between the flashiness index FI_{avg} and the frequency of daily peak flows exceeding mean annual flow (Q_{mean}) and flood quantile Q_5 in a year. Red circles and blue crosses represent the catchments in Austria and Slovakia, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.15. The transfer of the R_{SK} regression to Austria resulted in negative flashiness values for large Austrian catchments and in a significant overestimation of FI_{avg} in catchments with lower catchment elevation. In both cases, the variability in physiographic attributes in the Austrian dataset is larger than in the Slovak dataset. This result clearly indicates that the inter-regional transfer of regression models has only a limited predictive power.

The Baker flashiness index is a simple and robust indicator of the daily streamflow fluctuations. It is often used as a relative criterion for comparing streamflow fluctuations between catchments. Larger values indicate higher flashiness and vice versa. However, it is difficult to directly interpret particular flashiness indices with respect to other hydrologic characteristics. Fig. 11 shows the relationships between the flashiness and the frequency of peak flows exceeding long-term mean daily flow (Q_{mean}) and the 5% daily streamflow quantile (Q_5) in the period 1976–2005. We found that both relationships are statistically significant, but different in the two regions. The scatter plot in the left panel indicates the relationship between flashiness and mean daily peak flow frequency. The linear regression explains more than 66% and 85% of the variability for the catchments in Austria and Slovakia, respectively. Linear regressions between the flashiness and the frequency of peak flows exceeding the 5% flow quantile (right panel) explain 59% and 54% of the variance between examined variables for the Austrian and Slovak catchments, respectively.

5. Discussion and conclusions

The main objective of the study was to investigate the spatial and temporal variability in flashiness of selected mountain streams in Slovakia and Austria. The assessment of the spatial variability showed that the flashiness index varies between 0.06 and 0.43, which significantly smaller than the ranges 0.03–1.32 and 0.006–1.009 calculated for the catchments in the Midwestern states of the USA by Baker et al. (2004), Fongers et al. (2007), respectively. The mean values of flashiness indices for the Slovak and Austrian catchments without trends were 0.18 and 0.15, respectively. The inter-annual variability was characterized by the standard deviation of FI_y. Its mean value in both Slovak and Austrian catchments was 0.03. Over the Alps, the spatial pattern of the flashiness is related to the main geologic units and partly reflects the tendency of decreasing flashiness with increasing size of the catchment. The regions with large and small flashiness values coincide with spatial patterns obtained by Merz and Blöschl (2003), who estimated the flashiness as the ratio of the maximum annual flood peak and the average daily runoff on the day the flood peak occurred. The highest mean values of the flashiness index in Slovakia are also clearly related to catchment geology. However, the data show that the region with the highest flashiness was not hit by any flash flood in the last decade (Gaume et al., 2007). This means that the flashy behavior of hydrological response does not necessarily imply higher occurrence of flash floods compared to other regions.

In this study, we have identified significant trends of FI_y in 29 catchments. Most of the trends were found in catchments affected by human interventions, e.g. by building a water reservoir or operation of hydropower stations (Table 1). The study of Dow (2007) explained the negative trends by the slowdown in urbanization along with changes in wetland agricultural practices. Similarly, Baker et al. (2004) attributed the trend in streamflow fluctuations to changes in land use and in land management practices. They noted that the "Changes in amounts and intensity of rainfall cannot account for the geographical pattern of changes in stream flashiness." In contrast, our investigations showed that most of the positive increases of streamflow fluctuations were caused by the operation of hydropower stations in Austria, which significantly increased streamflow fluctuations especially in winter. In some catchments the changes in annual flashiness appear to be mainly caused by change in monthly precipitation totals, which indicates that trends in the flashiness index does not necessarily imply anthropogenic effects on the flow regime. As it is shown in Parajka et al. (2009) the variability of the date of occurrence of annual precipitation maxima in the Alps has increased in the last two decades. In further studies, more detailed analyses are needed to examine the effect of the variability of climate variables on the seasonal change in daily streamflow fluctuations.

The regionalization of the flashiness index for catchments without a temporal trend indicated that a multivariate regression can describe the main spatial pattern of flashiness. Previous studies tested different physiographic attributes to describe the variability in the flashiness index. Dow (2007) reported a significant positive correlation between the index and the areal percentage of artificial water bodies. Deelstra and Iital (2008) and Baker et al. (2004) found a negative correlation with the base flow index, i.e. a larger base flow contribution decreases flashiness. Baker et al. (2004) found a positive correlation with the frequency and magnitude of storm events and negative correlation with catchment size. We also found a negative correlation with mean catchment elevation, but this is likely due to different geological units in catchments of different elevation ranges. Some of the lower elevation catchments consist of flysh which results in flashy response. For the extended data set in Austria, the geological units were indeed the best predictors of flashiness. The negative correlations between flashiness and percentage of forest cover found here are consistent with generally more permeable soils in forest as compared to open land (Jewitt, 2005) leading to a larger portion of subsurface flow and therefore reducing flashiness. The inter-regional transfer of multivariate regression has shown that care should be taken when extrapolating the regression relationship beyond the range of attributes used in the estimation. Our results suggest that such transfer may lead to significant predictive errors, which may have significant implications for the prediction of flashiness at ungauged sites.

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