Assessment of the human impact on the temporal variability of stream flow in meso-scale river basins

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INTRODUCTION

Following the obligations of the new European water legislation (EU, 2000) an integrated perspective of the quality status of water resources (surface waters and groundwater) and its predictors in river basins is required for water resources management and river protection. However, in this field, there is a lack of well-established assessment procedures which integrate hydrological criteria.

The biological conditions in river systems are shaped by different abiotic factors (stream flow, velocity, channel structure, water quality and temperature) which are a consequence of the hydrological and ecological conditions in the catchment (DVWK, 1996, Leibundgut, 1996). Because it controls the key habitat conditions, the hydrological variation defines the structure of the biotic diversity within river ecosystems (Richter *et al.*, 1996). In recent years, the particular importance of flow variability for river ecosystems has been demonstrated in a variety of studies (e.g. Poff *et al.*, 1997; Poff and Ward, 1989; Clausen and Biggs 1997, 2000). According to the 'natural flow paradigm', the integrity of the river ecosystems is related to the preservation of the "full natural intra- and inter-annual variation of hydrological regimes" (Poff *et al.*, 1997; Richter *et al.*, 1997). Human activities influence the water balance as well as runoff generation and concentration, and can lead to alterations in stream flow magnitude and variability (e.g. Niehoff *et al.*, 2002; Hawkins, 1990). Therefore, the investigation and assessment of actual and future impacts on stream flow dynamics and the related physical and chemical conditions is a crucial basis for river restoration (Leibundgut and Hildebrand, 1999).

To integrate hydrological aspects in river basin management, assessment procedures which integrate temporal and spatial aspects of water quantity and quality on the catchment scale are needed. In this paper, a methodology for the assessment of human impacts on stream flow variability is presented and its application demonstrated by example results.

STUDY AREAX

The methodology was applied at 71 gauging stations in south-west Germany, representing a nested catchment structure situated in the large river basins of Upper Rhine / Lake Constance, Danube, Neckar and Main (Figure 1). The catchments investigated range in size from a small headwater catchment (15 km²) to the large river basin of the river Neckar at Rockenau (12 674 km²). They are characterised by heterogeneous morphology, geology and land use structure. In the mountainous 'Black Forest' catchments of the upper Rhine tributaries, and the western parts of the Neckar and Danube basins, forestry is the dominant form of land use. All other catchments are more dominated by agriculture and have a smaller share of forestry. In the Neckar river basin significant proportions of the catchment are urbanised. Figure 1 shows the location of the gauging stations and their catchments, which are labelled with an 'index of human pressures' (see next section).

MATERIAL AND METHODS

To combine stream flow variability and human-induced pressures on the hydrological system, the methodology consists of two parts. At the catchment level, all necessary information on the hydrological system (climate, morphology, hydrogeology, soils, land use) and the water management aspects (water abstraction and consumption, water transport, reservoirs and dams, flood protection schemes, urbanisation) are collected. The assessment of human pressures on the aquatic system is carried out by comparing the actual status to the 'potential natural status', defined as the absence of all human activities in the catchment. An '*a priori* estimation' is given in the 'index of human pressures', which is divided into seven classes and combines the assessment results of all the features described above.

At the gauging stations, alterations in stream flow variability are investigated, based on long stream flow records. Different aspects of the temporal behaviour of stream flow are

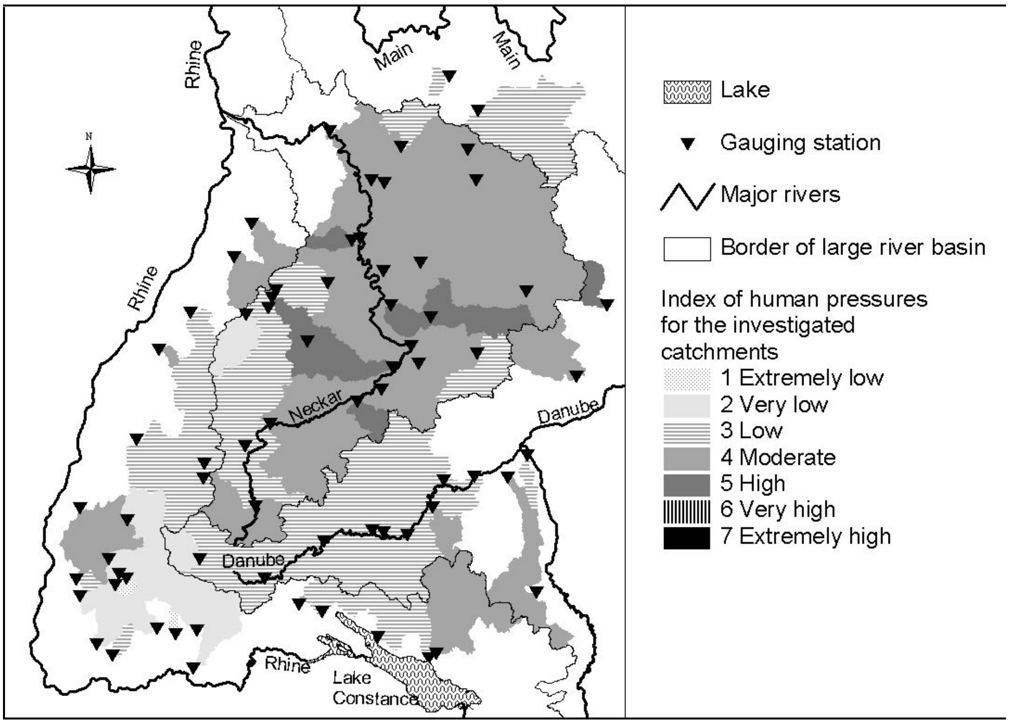

Fig. 1 Location of the gauging stations investigated and the 'index of human pressures' in their catchments

represented by 35 flow variables based on 'Indicators of Hydrological Alteration' (IHA) (Richter *et al*., 1996). These variables were chosen according to their importance for the different functions in the aquatic ecosystems (see Table 1). They are calculated from long time series of daily values and represent different aspects of the annual temporal behaviour of stream flow, including monthly means, aspects of seasonality, magnitudes of extremes, frequency and duration of extremes as well as rise and fall rates (Table 1). Potential hydrological alterations are identified, based on the comparison of an older part of the time series (reference period) in which the human pressure is assumed to be less pronounced with a younger part of the time series (evaluation period). The magnitude of alteration is quantified using the Range of Variability Approach (RVA) (Richter et al. 1997):

$$RVA = \frac{\left(nE_{(inTarget)} / nE_{(all)}\right) - \left(nR_{(inTarget)} / nR_{(all)}\right)}{nR_{(inTarget)} / nR_{(all)}} \qquad (1)$$

where $nE_{(inTarget)}$ is the number of years in the evaluation period with IHA-values within the target (range between 20- and 80-percentile of the reference period), $nE_{(all)}$ the number of all years in the evaluation period, $nR_{(inTarget)}$ the number of years in the reference period with IHA-values within the target (range between 20- und 80-percentile of the reference period) and $nR_{(all)}$ the number of all years in the reference period.

The RVA-values range from –1 to 1 and indicate decrease in variability (positive values), no alteration (values close to zero) and increase in variability or trends (negative values). In the original approach, which was developed to quantify alterations due to single actions (like the building of a dam), the separation of reference and evaluation period is clearly defined by the year in which the action took place. To quantify alterations caused by actions occurring over a period of time, such as water transfer or land use change, the RVA-equation is applied continuously. RVA-values are quantified for all possible years of separation, dividing the complete time series into reference and evaluation periods of different length. To ensure sufficient data for each part of the time series, the minimum length of both reference and evaluation period is 20 years. Using the resulting time series of the RVA-values, possible hydrological alterations can be identified and visualised. The temporal behaviour of the RVA time series indicates whether alterations are occurring promptly, over longer time periods or in a cyclic way. To identify possible climatic effects on hydrological alterations, time series of precipitation (14-day moving averages of daily values of regionalised precipitation for each catchment) are required. After the calculation of time series of IHA-variables and RVA-values, the temporal variability of the precipitation input can be compared with the temporal variability of stream flow. In addition, a trend analysis is carried out to identify long-term changes in the stream flow and precipitation values. For the assessment of hydrological alterations the IHA-series and

Table 1. IHA-variables (Assessment and hydrological groups) and their ecological relevance

IHA-variables	*Unit*	*Hydrological groups*	*Ecological relevance*
ASSESSMENT GROUP: MONTHLY VALUES			
Mean monthly values	m³/s(mm)	G1: low flow G2: high flow (winter) G3: high flow (sp./so.)	- Habitat availability (aquatic organisms) - Soil moisture availability (plants) - Availability of food/cover for fur-bearing
mammals supplies for terrestrial	Maxima of monthly values		- G5: 30-90-day-Max., - Reliability of water duration of high pulses animals
Minima of monthly values	-	G4: minima, base flow, G4: minima, base flow, frequency & duration of low pulses	- Access by predators to nesting sites - Influences water temperature, oxygen levels, photosynthesis in water column
ASSESSMENT GROUP: ASPECTS OF SEASONALITY			
Month of maximal value	No.	-	- Compatibility of life cycles of organisms monthly - Predictability/avoidability of stress for
Month of minimal monthly value reproduction	No. Date of annual	-	organisms - Access to spatial habitats during Julian - or to avoid predation
1-day maximum	Date		- Spawning cues for migratory fish
Date of annual 1-day minimum	Julian Date	-	- Evolution of life history strategies, behavioural mechanisms
ASSESSMENT GROUP: MAGNITUDE OF EXTREMES			
Base flow	m³/s(mm)	G4	- Balance of competitive, ruderal, and stress tolerant organisms
Annual minima of 1-day means	m³/s(mm)	G4	- Structuring of aquatic ecosystems (physical habitat conditions)
Annual minima of 3-day means	M³/s(mm)	G4	- Distribution of plant communities in lakes, ponds and floodplains
Annual minima of 7-day means	M³/s(mm)	G4	- Soil moisture stress in plants - Dehydration in animals
Annual minima of 30- day means	M³/s(mm)	G4	- Duration of stress full conditions such as low oxygen and concentrated chemicals in aquatic environments
Annual minima of 90- day means	M³/s(mm)	G4	
Annual maxima of 1-day means	M³/s(mm) frequency of high pulses	G6: 1-7-day maxima,	- Balance of competitive, ruderal, and stress tolerant organisms
Annual maxima of 3-day means	M³/s(mm)	G6	-Structuring of aquatic ecosystems (physical habitat conditions)
Annual maxima of 7-day means	M³/s(mm)	G6	- Distribution of plant communities in lakes, ponds and floodplains
Annual maxima of 30-day means	M³/s(mm)	G5	- Structuring of river channel morphology -Anaerobic stress in plants
Annual maxima of 90-day means sediments	M³/s(mm)	G5	- Duration of high flows for waste disposal, aeration of spawning beds in channel
	ASSESSMENT GROUP: FREQUENCY AND DURATION OF EXTREMES		
Frequency of high pulses	-	G6	- Influence on bed load transport, sediment texture, duration of substrate disturbance
Mean duration of high pulses	Days	G5	-Material exchange between river and floodplain - Soil mineral availability
No. of low pulses	-	G4	-Frequency and magnitude of anaerobic orsoil moisture stress for plants
Mean duration of low pulses	Days	G4	-Availability of floodplain habitats for aquatic organisms - Access to feeding, resting, r eproduction sites for water birds ASSESSMENT
GROUP: RISE AND FALL RATES			
Rise rates	-	G7: rise/fall rates	-Entrapment of organisms on islands, floodplains (rising levels)
Fall rates	-	G7	-Drought stress on plants (falling levels) - Desiccation stress on aquatic organisms

RVA-series of each IHA-variable are obtained as follows:

1. For each IHA-variable of stream flow and precipitation the RVA-value with the maximum absolute value and the corresponding separation year are identified in the RVA-time series. RVA-values < –0.4 and > 0.4 are then extracted as indicators for potential alterations in precipitation or stream flow dynamics.
2. The time series of RVA-values for all IHA-variables of stream flow are analysed in a correlation matrix.
3. The IHA-variables are classified in seven hydrological groups witch are assumed to respond in a similar manner to alterations (see third column in Table 1). For these groups, maximum and mean correlation coefficients are extracted from the correlation matrix. The RVA-values extracted in Step 1 are rejected if mean and maximum correlation coefficients in the group to which the specific IHA-variable belongs are smaller than defined critical limits (see Table 2).
4. For all variables, the trend significance of the corresponding IHA-variables of stream flow and precipitation are compared: if a significant (Mann-Kendall Test: 0.05 %) positive or negative trend is identified for both IHA-time series, the RVA-values (results of Step 3) are classified as climate-induced alterations and excluded from further analysis.
5. The years of separation for which the extracted RVA-values were calculated are compared for stream flow and precipitation. If a RVA-value (result of Step 4) is occurring within a three-year period for both stream flow and precipitation, it is also classified as an climate-induced alteration.
6. The normalized time series of IHA-variables for stream flow and precipitation are compared using a "goodness of fit" criterion (R_{eff}) based on the model efficiency criteria by Nash & Sutcliffe (1970):

$$R_{eff} = \frac{\sum_{i=1}^{n} (IHAq'_{xi} - IHAp_{xi})^2}{\sum_{i=1}^{n} (IHAq_{xi} - \overline{IHAq}_{xi})^2} \quad (2)$$

where R_{eff} is the 'goodness of fit' criteria, $IHAq_{xi}$ is the value of the IHA-variable *x* for stream flow at the year *i*, $IHAp_{xi}$ is the value of the IHA-variable *x* for precipitation at the year *i* and $\overline{IHAq}_{xi}$ is the mean value of the IHA-variable *x* for stream flow.
If the 'goodness of fit' criterion exceeds a critical level which is defined individually for each IHA-variable (levels ranging from 0 to 0.5) a climatic effect is postulated as well and the RVA-value (result of Step 5) is excluded.

If no climatic effects are identified with the procedure described above, the alteration is identified to be induced by human pressures in the catchment. To identify the character and extent of human impact, the alterations are compared with the data on human pressures. In cases of unclear situations (e.g. significant alterations in stream flow dynamics, but no human pressures indicated), additional research has to be carried out.

RESULTS

As a result of the analysis of catchment data, an assessment of different human pressures was achieved for the catchments of all the gauging stations. The 'index of human pressures' (Figure 1) gives an impression of the overall potential for human impacts on the aquatic system. As expected, the index is highest in the Neckar river basin, which is a result of a relatively high population density, significant water transfer and, in some sub-basins, a large number of dams for flood protection. In the sub-basins situated in the Black Forest and in the Danube basin, the index indicates a smaller level of pressures. More detailed information on specific pressures in selected catchments is given in Table 3.

The calculation of alterations in the stream flow records resulted in a dataset of 35 time series of IHA-variables as well as 35 time series of RVA-values for each of the 71 gauging stations. In the first step of the analysis procedure, potential alterations (indicated by a RVA-value > 0.4 or < – 0.4) were extracted for almost every station. After step two and three of the procedure, 70% of the extracted values were rejected

Table 2. Critical limits for mean and maximum correlation in the hydrological groups

IHA-Variables	*Magnitude of absolute RVA-value*	*Limit for mean correlation in the hydrological groups*	*Limit for maximal correlation in the hydrological groups*
Mean monthly values	≤ 0.5	0,8	0,5
	> 0.5	0,8	0
Aspects of seasonality	-	-	-
All other variables	≤ 0.5	0,85	0,3
	> 0.5	0,7	0,25

Table 3. Comparison of pressures in the catchment and impacts on stream flow for selected stations

ID and name of station/river	*Impact on stream flow*	*Maximal/minimal RVA in group*	*Related Pressures*	*Criteria forPressures*
1 Achstetten/Rot	Decrease in variance of monthly means	0.55	Dams and	Several dams for
(264 km²)	Decrease of high flow	0.66	reservoirs	flood protection built
	Decrease of fall rates	084		built in the 60s & 70s
2Trochtelfingen/Eger	Decrease in magnitude in monthly means	0.7	Abstraction	Abstraction in a
(125 km²)	Decrease in high flows	–0.72	of high flows	canalsystem since
	Decrease in frequency of high pulses	0.68		1950s
	Decrease in fall rates	–0.89		
3Friedrichshafen/Rotach	Increase in magnitude of monthly means	–1	Transfer of river	Transfer of water
(129 km²)	and low flow	–1	water	from a neighbouring
	Decrease in frequency and duration of low pulses	–0.97		catchment since 1950s
	Decrease in rise and fall rates	0.55		(not yet confirmed)
4Schafhausen/Würm	Increase in magnitude of monthly means (low flow)	0.53	Influence of	Increasing population
(138 km²)	Increase in low flow	–0.78	urban water	density,
	Increase in frequency of low flow	–0.77	management	water transfer and
	High pulses		land use change	impermeable area
5Pforzheim/Würm	Increase in magnitude of monthly means (low flow)	–0.49	Influence of	Increasing population
	Increase in low flow	0.86	urban water	density, water transfer
	Increase in frequency of Low and High pulses	–0.83	management	and impermeable
			land use change	area
6Abtsgmünd/Lein	Decrease in variance in monthly means	0.63	Dams and	Many dams for flood
(264 km²)	and low flow		reservoirs	protection (built 1955
	Decrease in high flow	–0.91		and 1965)
	Decrease in variance of the frequency of low pulses	0.4		
	Decrease in rise and fall rates	–1		
7Stein / Kocher(1929 km²)	Decrease in variance in monthly means	0.5	Dams and	Several dams for flood
	and low flow	0.4	reservoirs	protection and drinking
	Decrease in the duration of high pulses	–0.49		water supply (built 1955
	Increase in variance in rise rates	–0.5		and 1965)

because the RVA-time series in the hydrological groups were not similar enough (indicated by the mean and maximum correlation coefficients). This high proportion of rejections ensures that the assessment refers only to significant alterations which are confirmed by a similar temporal behaviour of related IHA-variables. In the analysis of potential climatic impacts based on the precipitation data (step four, five and six), again another 35% of the assumed alterations remaining after step three were excluded. These alterations, which were mainly indicated for monthly means, high flow variables and the month of the maximum monthly mean, are consequences of an increase in precipitation during the winter und spring months. In some catchments, a decrease in monthly means and low flow variables due to decreasing precipitation in the summer months was found as well. Some of these climatic impacts have already been identified in previous studies on precipitation and runoff trends for the same region (Sanchez Penzo *et al*., 1998; Luft *et al*., 2002).

The remaining RVA-values indicate alterations which are most probably caused by human pressures in the catchment. In the 'aspects of seasonality' group, almost no human impacts were indicated. In Figure 2 the current maximum of the extracted absolute RVA-values in each of the remaining four assessment groups (monthly means, magnitudes of extremes, frequency and duration of extremes, rise and fall rates) are mapped for the investigated gauging stations. It can be seen that the majority of the stations show no or only small human-induced alterations to stream flow dynamics. However, in some catchments, the human impact is significant. In Figure 2 all stations with higher impacts (RVA mean of all groups > 0.45) are labelled with an ID. Table 3 gives an impression of the relationships between impacts and pressures in these catchments. In the catchments investigated, the human impacts on stream flow resulted from one of four human activities:

- Building of small dams for flood protection: impact on

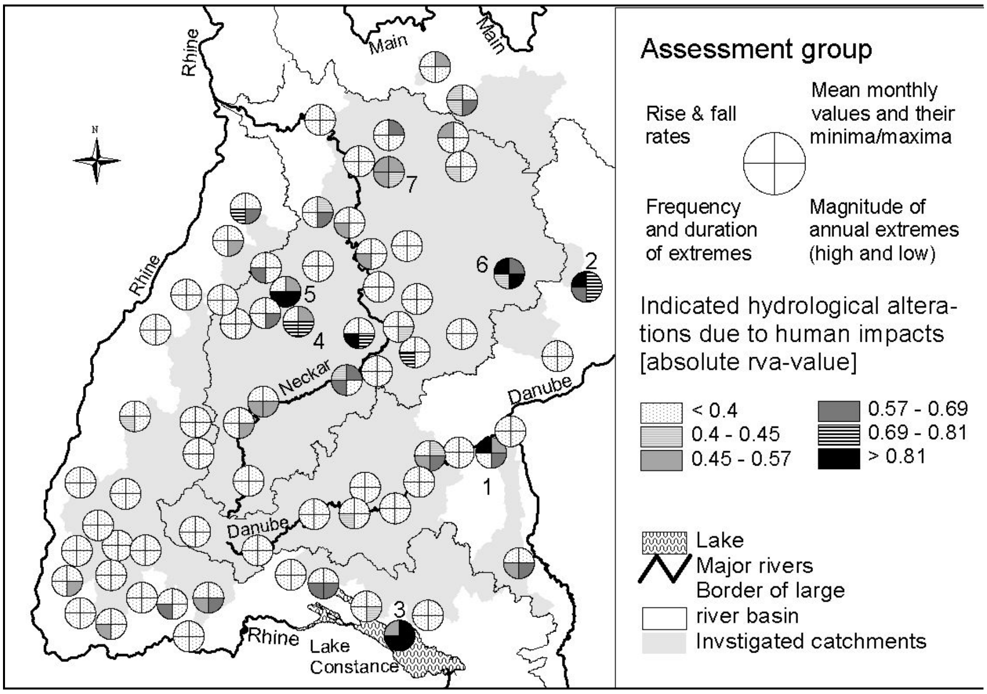

Fig. 2 Overview on results of the assessment of human induced alterations in stream flow variability at the investigated gauging stations

magnitude, frequency and duration of high flows and on rise and fall rates;

- Abstractions of water in the river (for flood protection or other purposes): impact on magnitude of monthly means, the magnitude and frequency and duration of high flows and on rise and fall rates;
- Increasing water transfer for water supply: impact on the magnitude of monthly means and the magnitude, frequency and duration of low flows;
- Increase of impermeable areas: Impact on the magnitude, frequency and duration of high flows.

Figure 3 shows an example of a stream flow variable which indicates a significant alteration in the 246 km² catchment of the river Lein (ID-Nr. 6). No significant alterations are indicated in the time series of the magnitude of 3-day-maxima calculated from the 14 day moving average of precipitation and the resulting RVA-values. In contrast, the same variable calculated for stream flow drops down during the end of the 1950is and remains at a lower level with smaller variability until the present time. This alteration results in negative RVA-values with a minimum for the separation year 1959. It is a result of a flood protection dam-building campaign which took place in the 1950s and 1960s. A detailed description of another example (ID Nr. 5) is given in Eisele *et. al*. (2003b).

CONCLUSIONS

In contrast to existing studies on the biological significance of stream flow indices in natural streams (e.g. Clausen and Biggs, 2000) the focus of the presented methodology lies on the quantification of human-induced alterations in stream flow variability. Referring to the 'natural flow paradigm' (Poff *et al.*, 1997; Richter *et al*., 1997) significant alterations are seen as a limitation on the ecological quality of river systems. Based on the approach of Richter *et al*. (1997), the methodology was extended to the detection of continuous pressures. In the study discussed above, 35 streamflow variables (30 IHA-variables plus five additional variables) have been included, representing all aspects of the hydrological regime. The authors are aware that this selection of variables is only one possible solution which might be replaced by other selections.

From the analysis of the results of the application several important features can be highlighted. It is obvious that most of the identified alterations took place in smaller catchments with areas less than 500 km². The pressures that are listed previously have only a limited impact on the stream flow dynamics of a larger river because their effects are averaged out. For instance, a decrease in flood magnitudes due to small dams in a tributary will have only a small effect on the flood magnitude of a major river if the tributary delivers only small volumes of water, or if the timing of flood peaks is different. Increases in flood peaks due to land use change are usually

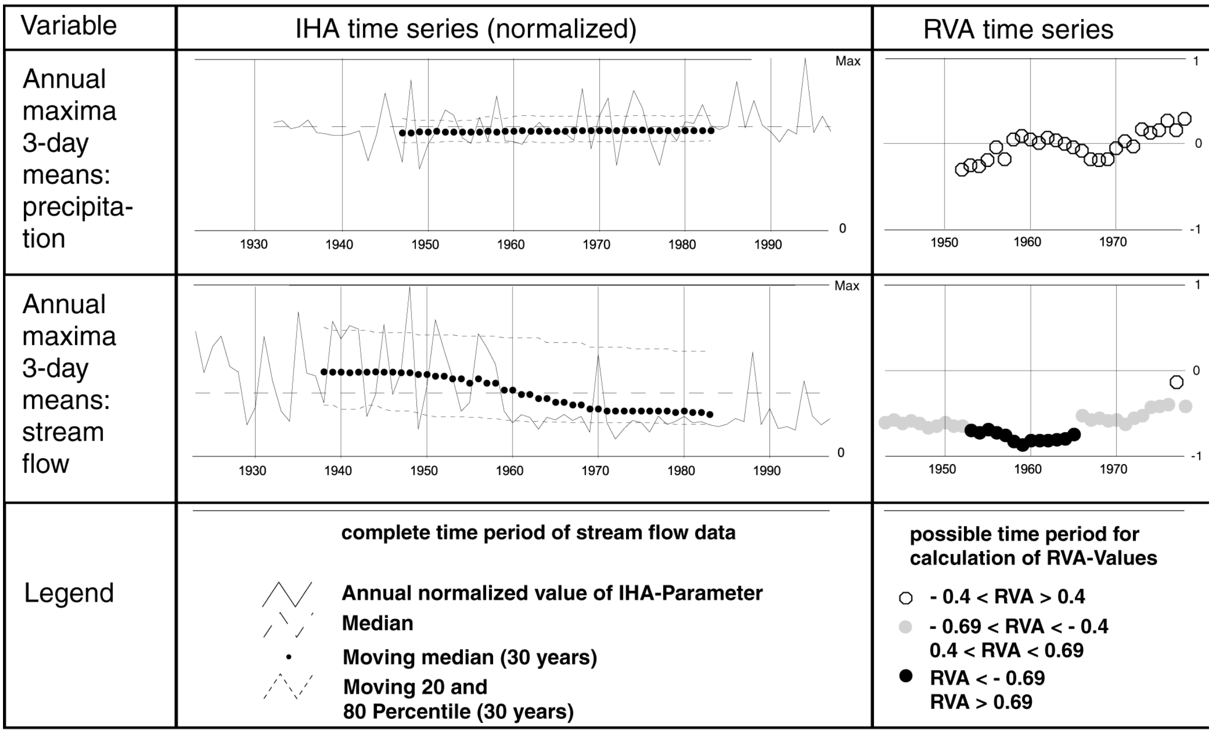

Fig. 3 Time series of the IHA-variable 'annual maxima 3-day means' and the resulting RVA-values for both precipitation (14-day moving average) and stream flow at the station Abtsgmünd of the river Lein.

limited to smaller catchments as well because at larger scales the distribution of precipitation and the process of runoff concentration becomes much more important (Uhlenbrook and Leibundgut, 1997; Niehoff *et al.*, 1992). In the region investigated, only small alterations in the 'aspects of seasonality' group were detected, and these were mostly identified as results of climatic impacts. The human activities present in this region seem to have a very small impact on the timing of hydrological extremes, but a larger impact on their magnitude, frequency and duration. There are, however, other cases which were not presented here, in which human activities have significant impacts on the seasonality. This is for example true in alpine catchments in which large volumes of water are stored by large dams for electricity production.

The assessment of stream flow variability was achieved based on long stream flow time series (60 to 90 years). Therefore, only alterations resulting from actions in recent decades (mainly in the 1950s to 1970s) are identified. For an assessment referring to the 'fully natural' stream flow dynamics scenario, simulations of the 'potential natural status' using water balance models are needed. The possibility of a coupling of the assessment with such models should therefore be a subject of future research. The assessment presented in this paper, which included 71 gauging stations covering a large region, indicates that operational applications are feasible. The methodology will therefore be an essential part of the expert system 'Hydrological quality' which is currently being developed and which will enable a standardised hydrological assessment of meso-scale river basins. With the inclusion of this hydrological approach into the catalogue of existing river assessment procedures (eg. biological, morphological and chemical assessment), a more holistic approach to river protection might be achieved.

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