Spatio-temporal variability of behavioral patterns in hydrology in meso-scale basins of the Rhineland Palatinate (1972–2002)

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Abstract Changes in spatio-temporal rainfall patterns have an effect on the hydrological behavior of river basins, the magnitude of the effects depending among others on the physiographic basin characteristics. To assess climate and discharge fluctuations, a visualization tool was developed as a contribution to exploratory data analysis. The tool combined statistical tests of hydro-climatological variables with physiographic basin characteristics. Test results agree with previous studies and suggested a relationship between rainfall, discharge and mean date of the annual maximum discharge on the one the hand and lithology, altitude and west to east positioning of the basins on the other hand. The visualization tool capable of combining the statistical test results with the geologic and topographic configuration of the study area and allowed a reflection on the hydro-climatological as well as spatio-temporal behavior of meso-scale basins by means of exploratory data analysis.

1 Introduction

Numerous studies have been devoted to changes in spatial and temporal rainfall patterns (e.g. Karl and Knight 1998; Osborn et al. 2000; Brunetti et al. 2001; Hisdal et al. 2001), as well as to the link between changes in hydrological behavior and the variability in climate (e.g. Mansell 1997; Pfister et al. 2000; Hisdal et al. 2001). Burn and Elnur (2002) advocate to focus on stream flow variables to study this link, as these variables tend to reflect an integrated response of the basin area as a whole on

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climate variability. Yet, land use change can also be a driving factor behind changes in discharge behavior. However, amplitude and spatial scale at which climate and land use changes are likely to affect the generation of storm runoff are equally difficult to assess (Bronstert et al. 2002). For meso-scale basins, the spatio-temporal variability of atmospheric forcing on runoff generating processes is significant and at the macro-scale, spatial distribution of rainfall or snow melt and the routing of runoff are dominant (Uhlenbrook et al. 2004), where meso- and macro-scale are defined as approximately 10–1,000 km^2 and larger than 1,000 km^2, respectively (Blöschl 1996). A spatio-temporal assessment of the hydro-climatological behavior of meso-scale basins within a macro-scale basin could give insight into their general behavior.

It is common practice to visualize spatial patterns in maps and temporal patterns in graphs. The objective of this paper is to condense maps and graphs into one tool that reflects the relationship between spatio-temporal climate fluctuations, spatio-temporal hydrologic behavior patterns and physiographic basin characteristics of meso-scale basins, located in the Mosel basin and parts of the adjacent Rhine valley. Given the large information content of such a study, the tool will be derived using exploratory data analysis, which is an advanced visual examination of the data and involves using graphs to explore, understand and present data, and is an essential component of any statistical analysis (Kundzewicz and Robson 2004). The tool is used to illustrate the hydro-climatological behavior of macro-scale basins and their sub-basins.

Pfister and Hoffmann (2001) showed that annual and seasonal rainfall patterns in the Grand Duchy of Luxembourg are characterized by a strong negative West-East gradient. An increase in winter rainfall totals and their implication for river discharge were observed since the 1970's and attributed mainly to a significant increase in the occurrence of days with westerly atmospheric circulation types (Mansell 1997; Pfister et al. 2000). Tu et al. (2005) documented the precipitation variability in the Meuse basin with respect to atmospheric circulation. Moreover, Pfister et al. (2004) showed that observed trends over the last 30 years in rainfall characteristics and maximum daily water levels during winter for nine river basins in the Grand-duchy of Luxembourg are closely linked to spatial rainfall patterns and topography. In a case study on winter rainfall regime change in temperate western European areas, Drogue et al. (2006) proved that geographical patterns show a zonal anisotropy of the winter rainfall regime change, hence implying an intensification of horizontal rainfall gradients. They also observed more contrasted westerly winter rainfall amounts in mountainous areas during the post-1979 period following the change point year of atmospheric circulation over northwestern Europe. In comparison to the study of Pfister et al. (2004) the current study area is larger, more heterogeneous and directly situated to the East adjacent to their study area. Hydrologic variables were included in order to investigate the influence of the spatio-temporal variability in rainfall trends on the hydrological behavior patterns of river basins in the area.

Douglas et al. (2000) reviewed diverse studies in the US in which the results of the trend analysis vary widely depending on the spatial scale and location of the study area. In most of these studies the non-parametric Mann-Kendall trend test was used. Burn and Elnur (2002) used this test to detect trends between hydrological and meteorological variables in 248 Canadian basins. Pfister et al. (2004) used Kendall's τ (Capéràa and Van Cutrem 1988) to calculate trends in rainfall structure over the last 50 years for the Grand Duchy of Luxembourg.

However, according to Wijngaard et al. (2003) care must be taken when carrying out a trend analysis on meteorological station series that are prone to anthropogenic effects, i.e. gradual changes due to non-climatic causes. They suggest using different tests to detect in-homogeneities in data series, of which the standard normal homogeneity test (Alexandersson 1986) could be used to detect break point years near the beginning and end of a data series and the Pettitt test (Pettitt 1979) to detect break point years in the middle of a data series (Hawkins 1977). Brunetti et al. (2001) used a sequential form of the Kendall test to detect the approximate time of the occurrence of the trend. In order to prevent the detection of a trend by chance, analyzing hydro-climatological data series with the Kendall test, Douglas et al. (2000) applied an approach based on bootstrapping to detect cross-correlation. However, Pfister et al. (2004) stated in their study that when studying spatial variability of trends, all available measuring stations should be used, even in case of cross-correlation, due to the fact that for each station an observed trend is influenced by climatological and physiographic conditions in the embedded monitored upstream sub-basins.

It is not the intention of this study to present a detailed trend analysis of each individual basin of the study area. The objective of this study is to present a tool that reflects the hydro-climatological behavior of a large area over several decades and results are expected to agree with previous studies in this field. Furthermore, the results of the methodology should be applicable for prediction in ungauged basins.

2 Study area and available data

The study area consists of 70 basins (varying in size between 8 km^2 and 4,011 km^2) located in the upper Mosel basin in the Rhineland Palatinate (Germany) and covers approximately 15,000 km^2 (Fig. 1). The names and numbers of the basins, together with the used physiographic and hydrological characteristics are given in Table 1. Altitudes range from 67 m asl at the lowest point of the Rhine valley to 816 m asl on the Hunsrück mid mountain region. Two successive ridges, both running from southwest to northeast, mark the contours: the Eifel and the Hunsrück; a third mid mountain range lies in the northeastern part of the study area: the Westerwald (Fig. 1).

The study area has a temperate humid climate, influenced by the Atlantic Ocean and transforms from an oceanic temperate climate to a semi-oceanic climate from west to east. Rainfall patterns are under influence of the macro relief. The average annual precipitation ranges from approximately 540 mm in the middle part of the study area (Rhine valley) to approximately 1,100 mm on the higher ridges, with an average annual precipitation of 820 mm for the entire study area. The average annual temperature ranges from 6°C for the higher ridges to 10°C for lower valleys, with an average annual temperature of 8.6°C fort the entire study area.

The study area is located mainly in the Rhenish Massif and consists largely of schist, siltstone, sandstone and quartzite of Devonian age. The northeastern part is characterized by tectonic dissections of geological strata and displays a heterogeneous geology in comparison to the remainder of the study area. The southeastern part of the study area (Pfalz and Rhine valley) consists of an alternation of sandstone, conglomerates and clay of the *Buntsandstein* and of tertiary sandy, silt deposits and
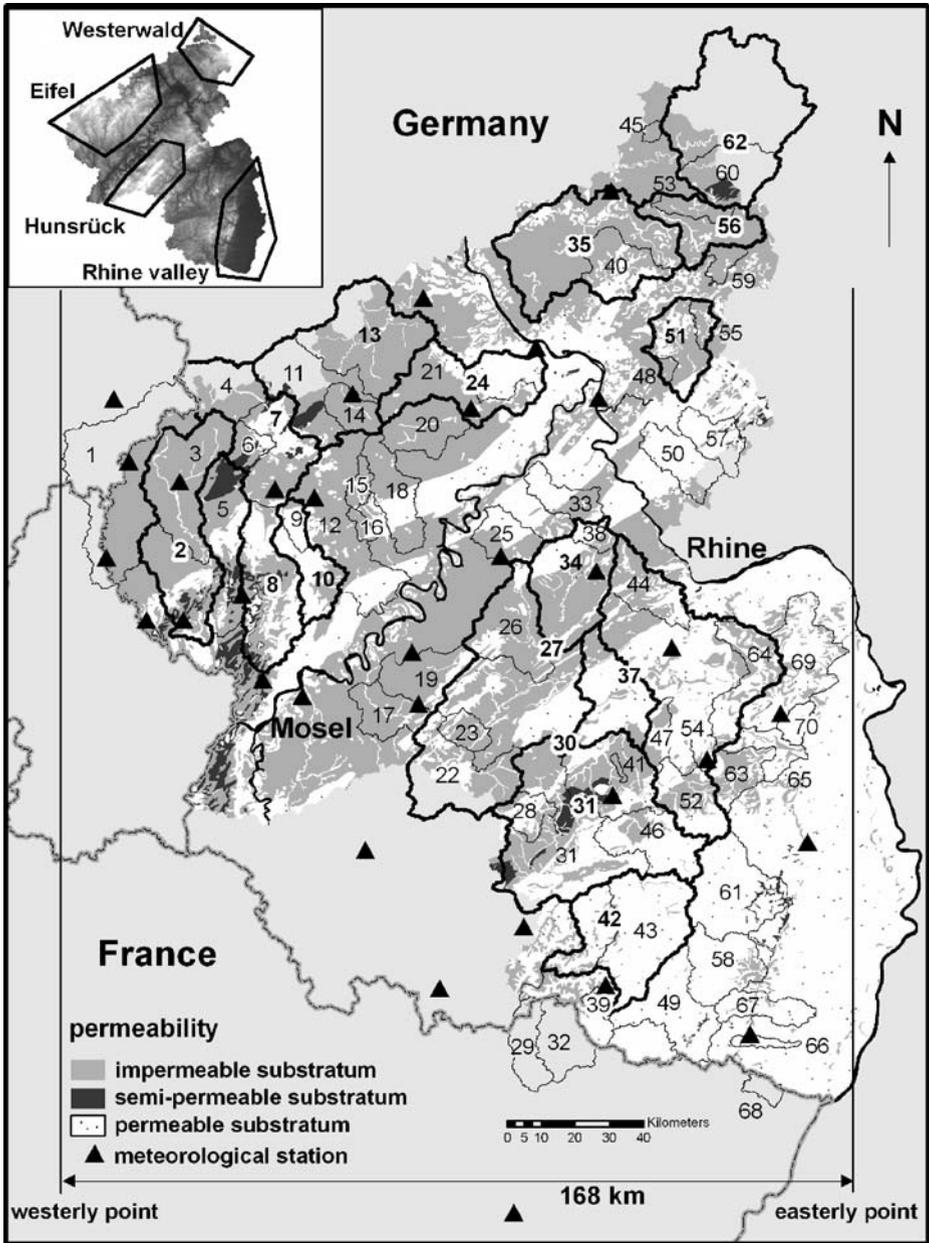
Fig. 1 Study area with numbered basins; basins with sub-basins are indicated with *bold numbers* and *thick basin borders*

quaternary Rhine terraces. The overall land use of the study area is 4% urban area, 28% cropland, 22% grassland and 46% forest. However, land use percentages vary between meso-scale basins.

Table 1 The basins with their respective numbers, size, mean altitude, lithology, mean date of annual maximum discharge (1972–2002), Q_{max}, Q_{mw} and P_{tw}

		Size (km²)	Mean altitude (m)	Impermeable substratum (%)	MDQ$_{max}$ (days after November first)	Q_{max}, mean value (mm/d)	Q_{mw}, mean value (mm/d)	P_{tw}, mean value (mm)
1	Gemünd Our	614	471	–	91	13.91	2.26	460
2	Prümzurlay	577	446	79	79	14.28	2.01	424
3	Echteshausen	326	493	87	87	16.30	2.27	441
4	Jünkerath	176	561	–	89	19.99	2.57	461
5	Alsdorf Oberecken	261	413	54	84	10.99	1.53	415
6	Müllenborn	63	527	54	94	15.15	2.04	470
7	Densborn	472	507	–	90	13.92	2.03	467
8	Kordel	820	420	30	84	10.50	1.67	408
9	Eisenschmit	47	487	20	87	13.08	2.20	458
10	Dreis	188	411	23	82	10.54	1.47	415
11	Müsch	350	469	–	97	10.07	1.30	359
12	Platten	382	405	68	79	12.08	1.50	427
13	Altenahr	748	427	–	116	8.61	1.22	335
14	Kirmutscheid	88	487	–	107	14.73	1.55	359
15	Saxler Mühle	40	486	93	90	13.02	1.88	445
16	Hasborne Mühle	23	398	80	85	19.14	2.17	445
17	Dhron-Talsperre	126	519	76	113	9.35	1.86	331
18	Peltzerhaus	175	382	69	86	12.82	1.54	426
19	Papiermühle	170	488	71	133	8.18	1.46	351
20	Lohbrücke	162	444	–	96	7.61	1.27	271
21	Wernerseck	242	403	57	132	5.75	0.96	267
22	Heimbach_Bhf	318	567	–	93	17.67	2.53	361
23	Kronweiler	65	516	68	92	16.34	2.00	331
24	Nettegut	370	377	42	117	3.83	0.74	260
25	Kloster Engelport	113	336	50	98	8.38	1.16	362

Table 1 (continued)

		Size (km^2)	Mean altitude (m)	Impermeable substratum (%)	MDQ$_{max}$ (days after November first)	Q$_{max}$, mean value (mm/d)	Q$_{mw}$, mean value (mm/d)	P$_{tw}$, mean value (mm)
26	Kallenfels	253	488	74	106	8.21	1.20	351
27	Martinstein	1466	490	–	94	12.22	1.58	314
28	Rammelsbach	79	403	43	98	17.42	2.22	339
29	Hornbach	112	332	–	114	8.81	1.61	404
30	Boos	2833	471	50	102	9.51	1.34	321
31	Eschenau	605	397	47	114	9.98	1.43	360
32	Althornbach	428	343	–	123	9.68	1.69	407
33	Burgen 2	106	336	38	146	6.11	0.85	297
34	Kellenbach	361	439	62	113	8.14	1.03	270
35	Friedrichsthal	681	305	–	96	9.62	1.64	424
36	Odenbach-Steinbruch	1092	380	65	117	8.45	1.30	342
37	Grolsheim	4011	449	46	118	8.14	1.15	289
38	Steinbach	46	474	32	131	5.68	0.83	258
39	Eichelsbacher Mühle	28	363	–	133	10.62	1.63	412
40	Seffern	176	333	50	87	8.70	1.59	439
41	Sulzhof	8	318	100	129	9.10	0.96	320
42	Contwig	530	410	10	122	3.90	1.05	404
43	Thaleischweiler	378	417	–	142	2.61	0.88	401
44	Heddesheim	166	395	60	141	5.45	0.75	162
45	Fahren	14	303	–	89	19.65	2.73	462
46	Untersulzbach	217	329	17	157	5.01	1.02	315
47	Obermoschel	62	327	53	124	6.24	0.69	255
48	Niederelbert	16	375	75	106	9.76	1.72	249
49	Bobenthal	252	389	–	150	2.31	0.96	393
50	Schulmühle	146	368	–	132	5.02	0.82	250
51	Weinähr	209	334	–	92	9.46	1.59	249

52	Imsweiler	172	378	34	129	6.18	0.75	261
53	Lützelauer Mühle	58	432	–	101	19.48	2.56	462
54	Gaugrehweiler	42	443	16	137	6.46	0.92	254
55	Kautenmühle	37	329	–	94	10.87	1.53	249
56	Heimborn	217	432	–	97	20.71	2.82	462
57	Kloster Arnstein	113	341	–	111	5.73	0.92	249
58	Siebeldingen	198	381	29	122	3.37	0.86	373
59	Westerburg	43	429	–	99	16.26	1.94	462
60	Alsdorf	197	423	54	105	20.92	2.73	462
61	Neustadt	312	379	0	185	1.68	0.68	267
62	Betzdorf	758	431	–	95	18.98	2.91	462
63	Albisheim	113	422	20	131	4.38	0.58	250
64	Gensingen	197	291	39	169	1.57	0.25	220
65	Monsheim	198	409	26	141	4.03	0.49	238
66	Minfeld	25	283	–	104	4.30	0.40	368
67	Herxheim	105	316	28	126	3.21	0.72	368
68	Salmbacher Passage	36	157	–	122	2.63	1.00	368
69	Stadecken	295	232	22	148	1.19	0.23	213
70	Gundesheim	43	225	2	184	0.46	0.14	212

Daily rainfall values from 54 meteorological stations located throughout the study area were used. For the discharge data 70 gauging stations were available, which supplied mean daily discharge values. Seventeen basins are comprised of two or more sub-basins. No attempt was made to reconstruct natural flow regimes of rivers, which would introduce uncertainty into the discharge series. The record length used for both discharge and rainfall data series runs from November 1st 1972 until December 31st 2002: 30 years in total.

3 Methodology

In order to develop an assessment tool for climate variability and discharge behavior, a three-step approach was applied of which the first two steps are largely based on a study by Burn and Elnur (2002) to detect hydrological trends and variability:

1. Selection of hydro-climatological variables
2. Statistical analysis of the selected variables
3. Visualization of the spatio-temporal behavior of the selected variables

By using all available basins, whether anthropogenic influences impact or not, the hydrological reaction of a larger region will be represented. If anthropogenic effects on basins show clear trends, a detailed study on these trends could indicate to what extent anthropogenic influences are related to discharge variability.

3.1 Selection of hydro-climatological variables

In a study on detecting trends and variability in discharge in Canadian basins, Burn and Elnur (2002) used among others the annual mean flow (Q_{mean}) and annual maximum flow (Q_{max}) of rivers and the date of the annual maximum flow to detect the hydrological response of river basins to climate variability. In addition to Q_{mean} and Q_{max} the mean specific discharge (Q_{mw}) during the winter period (1st of October until 31st of March), total annual rainfall (P_{year}), total rainfall during the winter period (P_{tw}) and antecedent rainfall (P_t) before the maximum annual discharge for $t = 2$ to 7 days (Table 2) were used. The spatial estimations of rainfall depth were performed using Thiessen Polygons. Furthermore, the mean date of annual maximum flow (MDQ_{max}) as proposed by Burn (1997) and the standard deviation of MDQ_{max} (STDEVMDQ$_{max}$) to assess climatological fluctuations (Table 2) were used.

To study fluctuations in climate a classification system derived by Hess and Brezowski (1977) was selected, which describes the specific daily weather situation over Central Europe by looking at the general atmospheric circulation patterns over the whole European continent and the eastern part of the North Atlantic. In this system, the daily weather situation is classified into one of the 29 occurring classes, or so-called *Grosswetterlagen* (GWL). When referred to a specific GWL, a GWLX is mentioned, in which X stands for one of the 29 classes. Due to the fact that a GWL refers a weather situation for a specific day it is possible to link the weather situation directly to hydrological events. The classification system is used to derive a fourth climatological variable, the GWL$_t X$, which relates rainfall to a dominating

Table 2 Hydro-climatologicalal variables with abbreviation and units

Hydro-climatologicalal variable	Abbreviation	Unit
Maximum annual specific discharge	Q_{max}	$L/(TL^2)$
Mean annual specific discharge	Q_{mean}	$L/(TL^2)$
Mean specific discharge during winter period (from 01–11 until 31–03)	Q_{mw}	$L/(TL^2)$
Total annual rainfall	P_{year}	L/T
Total winter rainfall during winter period (from 01–11 until 31–03)	P_{tw}	L/T
Mean date of maximum annual specific discharge	MDQ_{max}	T
Standard deviation of the mean date of maximum annual discharge	$STDEVMDQ_{max}$	T
Total rainfall fallen $t = 2, 3, 4, 5, 6$ and 7 days before date of maximum annual discharge respectively	P_t	L
Ratio between rainfall amounts due to a GWLX and total rainfall amounts during t	R_t	–
Dominating GWLX, based on threshold value $v = 0.5$ of R_t	$GWL_t X$	–

GWLX during an antecedent period t before the annual maximum flow, with $t = 2$ to 7 days. To determine a dominant GWLX in terms of rainfall production the ratio R_t between rainfall amounts due to a GWLX and total rainfall amounts, both occurring during the antecedent period t before Q_{max} (Table 2) was used. Depending on a threshold value of R_t, which in this study was set to 0.5, the dominating GWLX was identified for period t.

The following basin characteristics were selected as drivers of the hydrological variables to analyze interactions with the variables: lithology, relief and basin area. Lithology was expressed in terms of permeability of the substratum and plays an essential role in transforming precipitation into runoff. Since topography plays an additional role in the distribution of rainfall (Drogue et al. 2006; Pfister et al. 2000, 2004) mean and maximum altitude as well as slope areas with an aspect facing south to north in a five-degree step were incorporated. A Principal Component Analysis (PCA) was performed to determine relationships between the physiographic basin characteristics and the hydro-climatological variables.

3.2 Statistical analysis on the selected variables

For each of the selected hydro-climatological variables their autocorrelation was calculated first. Next the SNHT and the non-parametric Pettitt test were applied to detect change-point years in the data series of the hydro-climatological variables (i.e. Q_{max}, Q_{mean}, Q_{mw}, P_{year} and P_{tw}). The level of significance was set to the 1% probability level. When a change-point year occurs, it can indicate either an anthropogenic influence, like the displacement of measurement equipment, or a change in the hydro-climatological regime.

The non-parametric Kendall test as described by Capéràa and Van Cutrem (1988) was applied to the data sets of the above selected hydro-climatological variables to detect possible trends. The record length of the data sets runs from 1972 until 2002 and the level of significance was set to the 5% and 95% probability level with *tau*

values of −1.66 and +1.66, which are commonly used (Burn and Elnur 2002; Pfister et al. 2004). Results of the Kendall test were divided into four classes: a statistically significant trend, either positive or negative and a statistically non-significant trend, either positive or negative, represented by the numbers 2, −2, 1, −1, respectively.

To study a possible relationship between the location of the basins and their hydro-climatological variables and physiographic characteristics Spearman's rank correlation coefficient r_s was calculated for the basins ranked from west to east and north to south. Since westerly fluxes play an important role in the distribution of precipitation amount in the area (Pfister et al. 2004), the west to east representation of the basins was chosen. Furthermore, to investigate changes from west to east for lithology and topography, a grid was projected over the study area (cell width: 5 km, cell length: entire stretch of the study area from south to north) starting at 0 km and ending at 175 km (most westerly and most easterly tip of the study area, respectively). For each of the cells the percentages of permeable substratum, mean altitude, maximum altitude and aspect facing south to north was calculated in a Geographical Information System (GIS). The purpose of the grid is to illustrate changes in physiographic basin characteristics to which the basins are subject to in a west to east direction. In order to combine the trend statistics with space, time and the physiographic characteristics of the basins, a visual representation of the variables with their trends and the basin characteristics was developed.

3.3 Visual representation of the spatio-temporal behavior of the selected variables

To represent the spatio-temporal variability of each variable a so-called variable matrix was derived. The elements of the variable matrix represent the values of hydro-climatological variables. The rows of the matrix represent the winter periods from 2002 back to 1972. The columns represent the position of the basins within the study area ranked from west to east based on the position of their respective gravity center, obtained in a GIS. Consequently, element [1, 1] of the variable matrix represents a value of a variable in the winter of 2001–2002 for the most westerly located basin in the study area and element [30, 70] represents a value of a variable in the winter of 1972–1973 for the most easterly located basin. To visualize this variable matrix, the elements (i.e. the values of the hydro-climatological variables) were classified and each class was represented by a color. To obtain a matrix suited for visualization, the basins were positioned with the same discrete interval to each other, disregarding the actual distance between the gravity centers.

A horizontal line is depicted above the variable matrices indicating the position of the basins ranked from north to south using a Grey scale, where black represents the most northerly and white the most southerly positioned basin. Results of the Kendall test are also depicted above the variable matrices, using the classes defined in Section 3.2. If a change-point year was detected in a time series of a variable according to the SNHT and/or the Pettitt test, this change point year is indicated in the variable matrix. Furthermore, the values of STDEVMDQ$_{max}$ are given on the right hand side of the GWL$_t$X variable matrix only to indicate the spread of the maximum annual flow of the study area. MDQ$_{max}$ is classified and depicted above the Q_{max} variable matrix. A bar underneath the variable matrices indicates where the gravity center of each basin is situated with respect to the most westerly tip of the study area (i.e. 0 km).

4 Results and discussion

The results of the statistical test, the physiographic characteristics and values of the hydro-climatological variables will be visualized using the variable matrices, thus merging space and time. This creates the opportunity to analyze the results with respect to previous studies and it gives insight in how far the methodology is able to represent these results as well as its interpretation potential.

4.1 Statistical analysis

No autocorrelation was found in the hydro-climatological variables. The results of the SNHT, Pettitt-, and Kendall-tests, implemented on the hydrological variables, are given in Table 3. The percentage value indicates the confidence level at which the hypothesis is rejected. The values in Table 3 represent for each hydrological variable the percentages of basins that show a break for the SNHT and Pettitt test. For the Kendall test the percentage of basins with a certain type of trend is given.

According to the SNHT very few basins displayed no homogeneity at the start or end of their data series. The values of the Pettitt test suggested that there were change point years in the hydrological series of winter discharge for a number of basins. Of the 16 basins that make up the 23% of Q_{mw}, 15 had their change-point year in the period from 1990 till 1996 and of those 15, 12 were situated less than 90 km from the most westerly tip of the study area of a total study area width of 168 km. The basins that showed a change-point year for Pt_w (all around 1991–1997) were evenly distributed over the study area. For the Kendall test, most basins displayed a statistically significant positive trend for each hydro-climatological variable (Table 3). Moreover, more basins displayed a statistically positive trend in winter Q means and winter P totals (80% and 86% respectively) compared to annual Q means and annual P totals (71% and 76% respectively). This difference, in combination with the results of the Pettitt test indicated that during the winter

Table 3 Percentage of basins that show a break in the hydrological variables

	Q_{max} (%)	Q_{mean} (%)	Q_{mw} (%)	P_{year} (%)	P_{tw} (%)	P_2 (%)	P_3 (%)	P_4 (%)	P_5 (%)	P_6 (%)	P_7 (%)
SNHT (1%)*	3	4	0	1	1	1	0	0	0	0	0
Pettitt (1%)*	12	6	23	3	13	14	16	11	6	1	3
Kendall (5%)*											
Significant positive (2)	78	71	80	76	86	77	78	76	58	70	76
Non-significant positive (1)	3	6	4	9	3	6	6	10	9	7	4
Non-significant negative (−1)	6	6	6	9	5	6	6	4	14	9	6
Significant negative (−2)	13	17	10	6	6	11	10	10	19	14	14

The percentage values marked with asterisk indicate the confidence levels at which the hypothesis is rejected. Maximum annual discharge (Q_{max}), mean annual discharge (Q_{mean}), mean winter discharge (Q_{mw}), total annual rainfall (P_{year}), total winter rainfall (P_{tw}) and total rainfall fallen 2, 3, 4, 5, 6 and 7 days prior to date of maximum annual discharge, (P_2, P_3, P_4, P_5, P_6, P_7) given in percentages of basins

periods from 1972 until 2002 and especially from 1990 until 1996 a significant increase of rainfall and consequently discharge has occurred in most basins. This agrees with the study of Pfister et al. (2004). During the period from 1990 until 1996 an increase of the North Atlantic Oscillation (NAO$^+$) took place, bringing more wet oceanic air masses to the continent under a westerly circulation regime (GWL2; Pfister et al. 2000). An increase of the NAO$^+$ has been observed during the 1980s as well. Although winter rainfall totals did not differ that much when comparing the two periods, the GWL2 was markedly more dominant in causing high precipitation amounts during 1990–1996 (see later). The difference in values of the Pettitt test between $P_{2,3,4}$ (14%, 16% and 11% respectively) and $P_{5,6,7}$ (6%, 1% and 3% respectively) are caused by smoothing effects of a longer time series.

4.2 Spatio-temporal variability

Figures 2, 3 and 4 visualize the values of P_{tw}, Q_{mw} and Q_{max} according to step 3 of the above-described methodology. It should be noted that each value in the variable
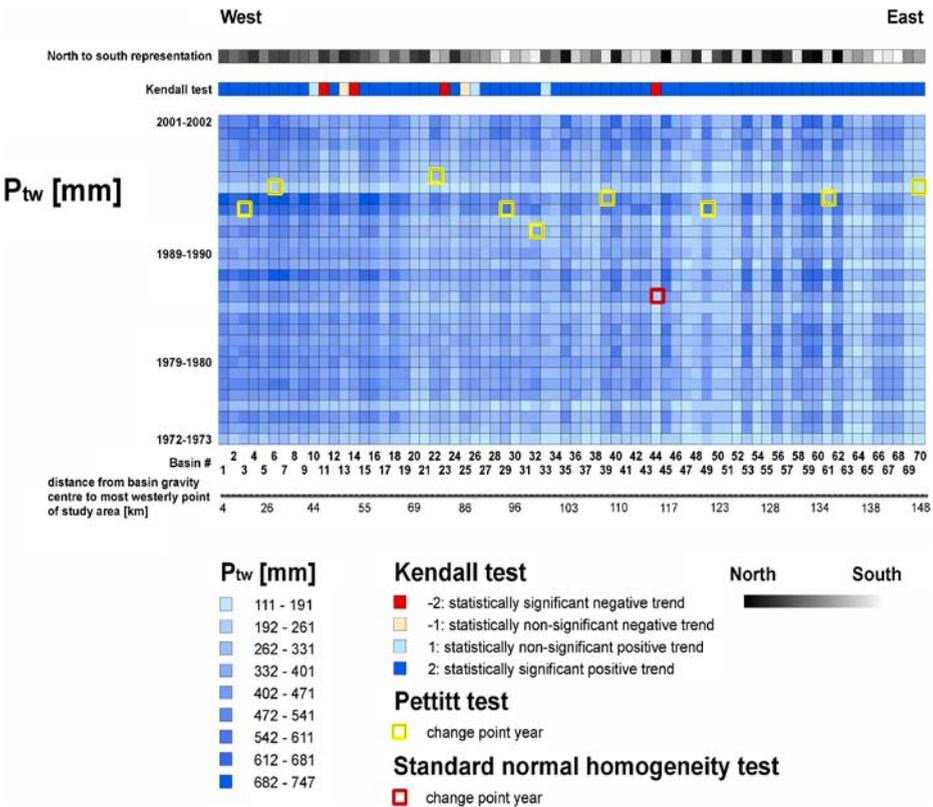
Fig. 2 Visual representation of P_{tw} fallen in the basins of the study area from 1972 to 2002 (basins are grouped from west to east and the numbers correspond to those given in Fig. 1)
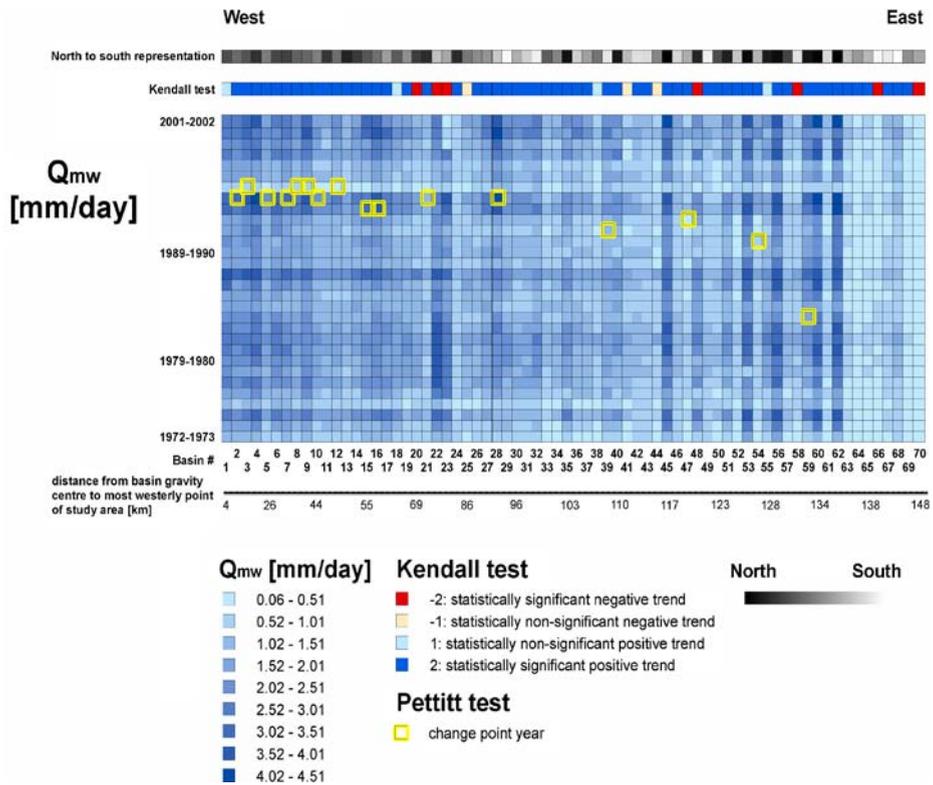
Fig. 3 Visual representation of Q_{mw} of the basins of the study area from 1972 to 2002 (basins are grouped from west to east and the numbers correspond to those given in Fig. 1)

matrix of Q_{max} stands for a single event occurring during a single day. The results of the statistical tests can be depicted consistently in Figs. 2–4.

Since discharge is a result of precipitation, Figs. 3 and 4 have a strong visual resemblance with Fig. 2. The following features have been observed in all three figures:

(1) A gradient of decreasing precipitation as well as discharge from northwest to southeast.

(2) Five basins (basins 53, 56, 59, 60 and 62) showed high values of P_{tw} where the surrounding basins showed lower values of P_{tw} and six basins (basins 45, 53, 56, 59, 60 and 62) showed high values of Q_{mw} and Q_{max} where the surrounding basins showed considerably lower values.

(3) Two years (1993–1994 and 1994–1995) of very high P_{tw} and Q_{mw} values for almost the entire study area and a period of high Q_{max} values from 1991–1992 until 1994–1995.

(4) Two years (1975–1976 and 1995–1996) with low P_{tw}, Q_{mw} and Q_{max} values.

(1) The gradient of decreasing precipitation was in agreement with findings of Drogue et al. (2006). Results of the PCA showed that Q_{max} and Q_{mw} of the basins are strongly correlated to the impermeable substratum (correlation coefficients
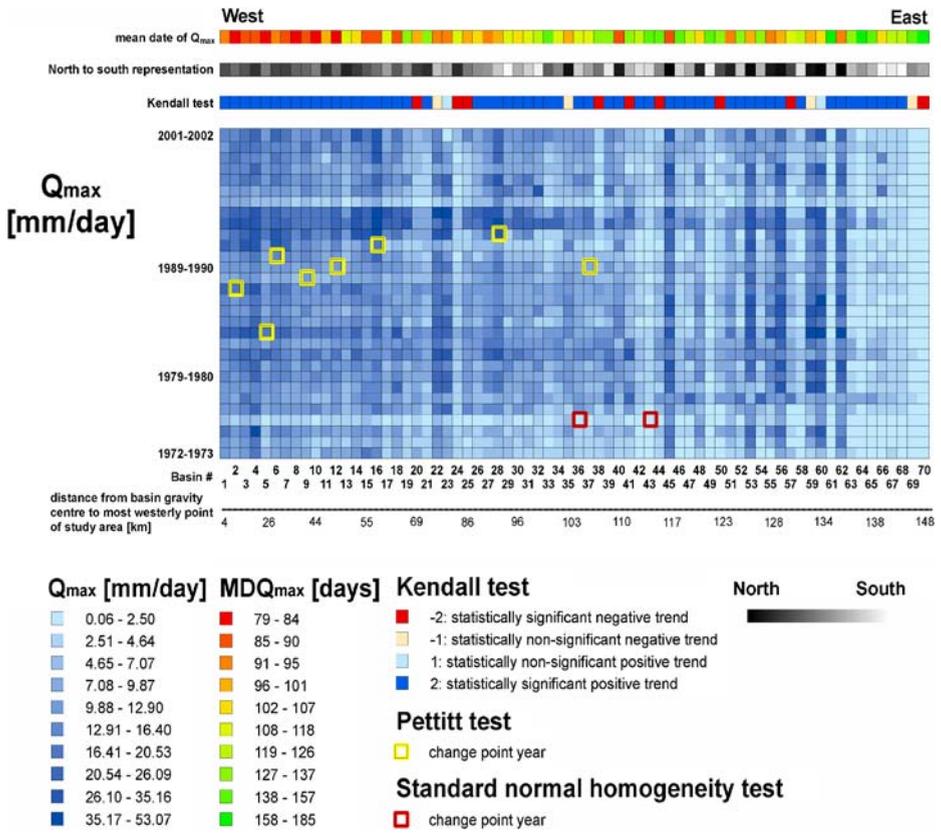
Fig. 4 Visual representation of Q_{max} in the basins of the study area from 1972 to 2002 (basins are grouped from west to east and the numbers correspond to those given in Fig. 1)

between Q_{max}, Q_{mw} and the percentage of impermeable substratum are 0.80 and 0.77, respectively). Mean altitude had a weak correlation with the variables. The basin size and the surface of the slopes facing south to north with a five-degree step had no correlation. The MDQ_{max} was inversely correlated to the variables. The Spearman's r_s statistic confirmed the gradient of Q_{max} and Q_{mw}. Test results are listed in Table 4. Q_{max}, Q_{mw} and altitude had negative correlation coefficients, which indicated a decrease of these values when moving from west to east and from

Table 4 Spearman's rank correlation coefficient r_s between basin ranking and hydro-climatologicalal variables and physiographic characteristics

|	Q_{max}	Q_{mw}	P_{tw}	Area	MDQ_{max}	Mean altitude
All basins from west to east	−0.51	−0.49	−0.41	−0.27	**0.61**	**−0.61**
All basins from north to south	−0.52	−0.47	−0.26	−0.01	**0.50**	−0.22
Basins from west to east without the Westerwald	**−0.78**	**−0.75**	**−0.65**	−0.29	**0.69**	**−0.69**

Significant values are given in bold

north to south, respectively. MDQ_{max} had a positive correlation, which indicated that the date of the maximum annual flow occurred later in winter when moving from west to east and from north to south. In Fig. 5 the results of the GIS calculation of the raster projection are illustrated. A gradual decrease of the mean and maximum altitude and a gradual increase of the permeable substratum occur when moving from west to east. The slope with an aspect facing south to north does not show such a change. Regarding slopes with aspects that face southwest to northwest and slopes with aspects facing west to north, the results did not differ from the pattern observed in Fig. 5 for south–north slopes. The above-described results presume a relation between position, physiographic characteristics and reaction of the basins to climate variability.

Since over the last decades the increase in winter rainfall is to a large extent supposed to be attributable to an increase in westerly atmospheric circulations (Pfister et al. 2000) and since topography is influencing precipitation (Drogue et al. 2006; Pfister et al. 2000, 2004), the Figs. 2–4 depict these findings quite well. The gradient in precipitation and discharge could be endorsed to orographic effects imposed by the two successive Eifel and Hunsrück ranges, running more or less from southwest to northeast. Basins belonging to the former range show higher values for precipitation and discharge than basins belonging to the latter. The remaining basins, except the aforementioned six (see point 2), are situated in the Rhine and Mosel valleys and are on the leeward side of the ranges, hence displaying lower values of precipitation and discharge.

(2) The basins with markedly higher precipitation and discharge than their neighboring basins (based on the west to east projection) were the most northeasterly positioned basins of the study area and belong to the Westerwald, where discharge values were as high as the most westerly situated basins of the study area (basins 1

Fig. 5 Altitude (mean and maximum), percentage of permeability and percentage of aspect (south to north) of 5 km strips projected across the study area from west to east
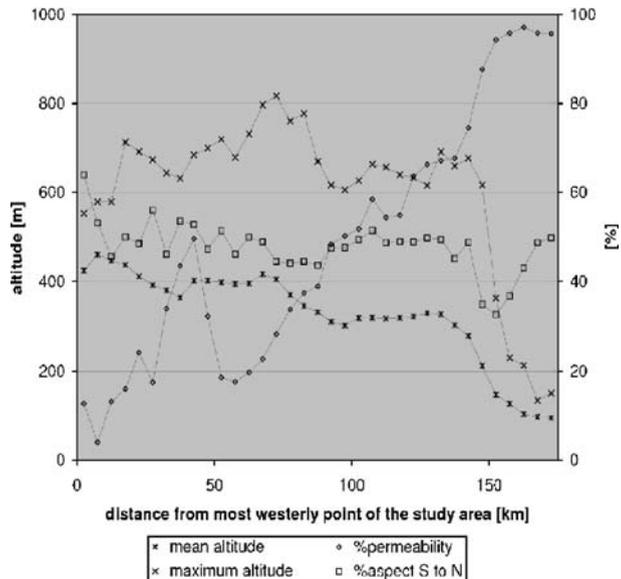
to 21). This is explained by the fact that there is no mountain range of any significance in front of the Westerwald basins to attenuate precipitation amounts, contrary to easterly-located basins. The correlation coefficient of the Spearman's rank test for the west-to-east ranking increased markedly when the Westerwald basins were omitted from the calculation (Table 4). It also explains the anomaly in Figs. 2–4 caused by the Westerwald basins. Basin 45 had a considerably higher Q_{mw} and Q_{max} than its neighboring basins, but the values for P_{tw} were more or less the same. A high percentage of impermeable substratum of the basin explains this, as it induces higher values of discharge.

(3) The two winters of increased P_{tw} and Q_{mw} values and the period (1991–1995) of increased Q_{max} occurred at exactly the same time as the increase of the NAO$^+$ (Pfister et al. 2000). However, the 1991–1995 period provided a more pronounced Q_{max} than for the two years of increased Q_{mw}. Since the difference is probably linked with the GWL during this period, it may only be investigated and explained using a more detailed rainfall data than that available in this study.

(4) The two winters displaying low values of the hydro-climatological variables were 1975–1976 and 1995–1996. These low values are related to the fact that both summer and winter of 1975–1976 were extremely dry as well as the winter of 1995–1996. The winters were dominated by cold dry air masses intruding from the North.

Regarding the Kendall test results depicted in the visualization tool, the spatial distribution of the few basins that showed a statistically significant negative trend for P_{tw}, Q_{mw} and Q_{max} did not give an unequivocal result. Compared to P_{tw} and Q_{mw}, only basins with relatively low values for Q_{max} showed a statistically significant negative trend. For these basins, the 1991–1995 period of increased Q_{max} was less pronounced or totally lacking. There were eight basins where this increase Q_{max} was lacking too, but still gave a statistically significant positive result of the test (i.e. basins 43, 49, 58, 61, 64, 66, 67 and 68, Fig. 4). All these basins, except basin 64, are located in the southeastern part of the study area and have a predominantly permeable substratum (Fig. 1). Taking into account the low amounts of rainfall due to the orographic effects in combination with a permeable substratum, these basins have a more gentle discharge regime with a low ratio of mean monthly maximum discharge versus mean monthly minimum discharge (values ranging between 2.2 and 7.2). For the entire study area a minimum value of 2.2, an average value of 15.4 and a maximum of value of 66 of this ratio were calculated. Considering this, either the period from 1993 until 1995 with increased winter rainfall strongly influenced the results of the Kendall test for Q_{max}, or the test was seemingly very sensitive to minor differences in values of Q_{max}.

The results of the Pettitt test gave the impression that a change point did occur between 1993 and 1996 for the Eifel region of the study area. However, the results of the visualization (Figs. 2–4) indicated 2 years of increased P_{tw} and Q_{mw} and two to three years of increased Q_{max}, followed by a year of low values of P_{tw}, Q_{mw} and Q_{max}. Since westerly fluxes hit the Eifel Mountain range first and induce more rainfall and due to the fact that the lithology of the Eifel is dominantly impermeable (meaning that discharge is more susceptible to rainfall fluctuations), the impact of fluctuations in rainfall was more pronounced in this region. Therefore, the outcome of the Pettitt test, especially for Q_{mw}, could be induced by a succession of random events in precipitation (two years of high values followed by a year of low values) as opposed to a change-point year.

The value of MDQ$_{max}$ (the most upper line) in Fig. 4 depicts a gradient from west to east and also from north to south. The basins of the Eifel and the Westerwald had a mean value of MDQ$_{max}$ between 79 and 105 days after November 1 (except basins 13, 21 and 24). The basins with the highest value of the mean date (between 122 and 185 days after November 1) were all situated in the Rhine valley (except basin 66 having a MDQ$_{max}$ of 106 days). The values of MDQ$_{max}$ of the Hunsrück basins were in-between. This difference was attributed to the fact that the more westerly located basins have a combination of impermeable substratum and more winter rainfall, hence triggering the maximum annual flow earlier in the winter season. The more easterly located basins have a more permeable substratum and receive less rainfall, hence needing a longer period to obtain their saturation state and produce the annual Q_{max} (see also the results of Fig. 5 concerning altitude and permeability). Combining the lower values in rainfall and a later occurrence of MDQ$_{max}$ suggested a slightly different climatological regime for these basins compared to the basins of the Eifel and Westerwald. The differences in discharge, lithology and topography suggested a
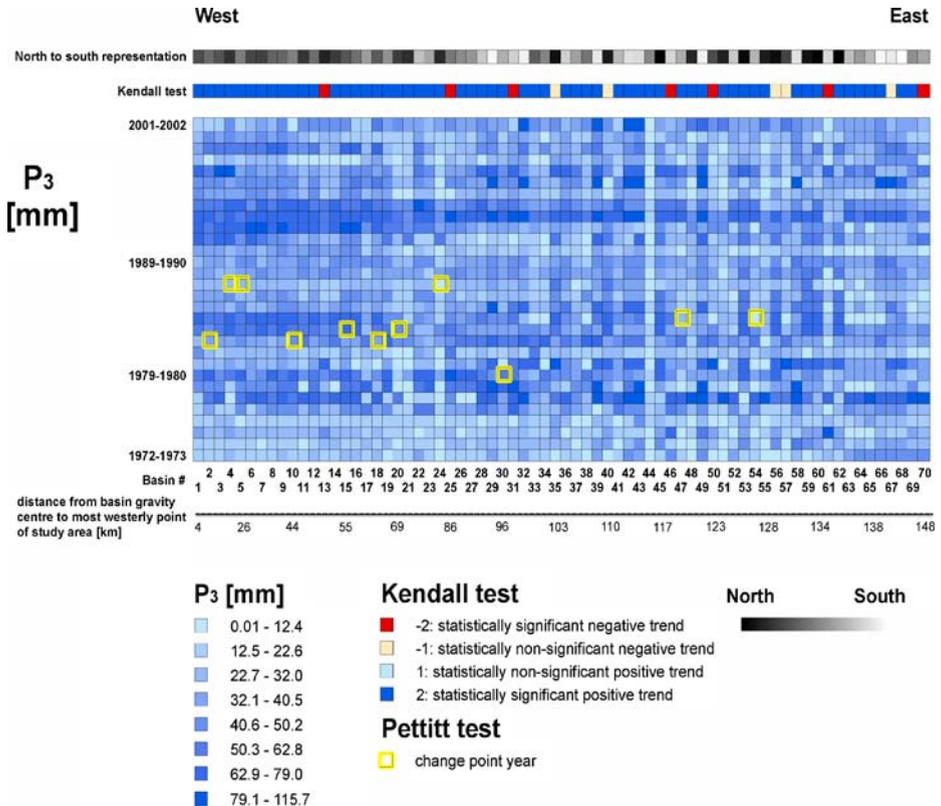

Fig. 6 Visual representation of P_3 (total rainfall fallen 3 days prior to Q_{max}) in the basins of the study area from 1972 to 2002 (basins are grouped from west to east and the numbers correspond to those given in Fig. 1)

slightly different hydrological behavior of these basins in the Rhine valley compared
to the rest of the basins.

4.3 Climatological fluctuations

In Figs. 6 and 7 the visualizations of the total rainfall, fallen 3 days (P_3) prior to
Q_{max} and the visualization of GWL_3X are given. Only the differences of these
matrices with P_7 and GWL_7X are shown to provide an assessment of the influence
of antecedent rainfall on Q_{max}. The variable matrices of the other antecedent rainfall
periods and dominating GWL_tX, gave similar results.

The visualized patterns of P_{tw} in Fig. 2 and of P_3 in Fig. 6 showed no clear
resemblance. The mean value of the correlation coefficient between P_{tw} and P_3 for
the basins over the 30 years was 0.35, which indicated only very low correlation. The
difference in rainfall quantities between P_3 and P_7 is on average 65% per basin per
year. This means that of all the rainfall fallen 7 days prior the of Q_{max}, 65% falls
during the 3 days before Q_{max} and as a result causing a rather abrupt occurrence of
Q_{max} in the study area. For the annual 1, 5 and 10 maximum events of the basins,
67%, 63% and 57%, respectively could be attributed to a GWL_32. Furthermore, on
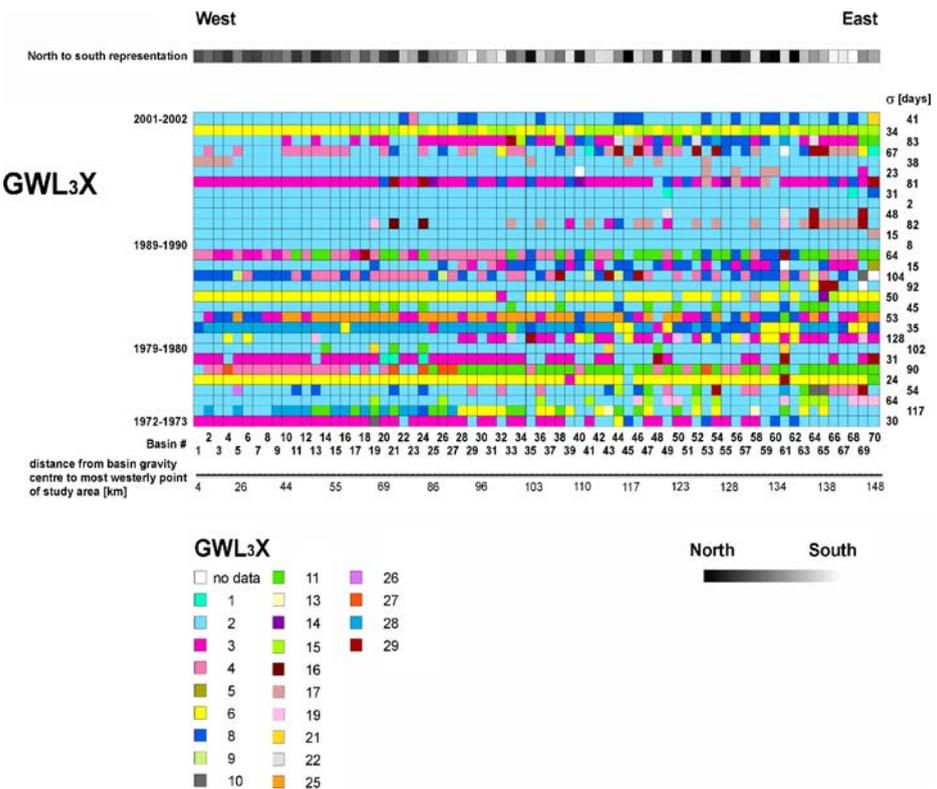average, 14% of the days during summer have a GWL2 against 20% of the days

Fig. 7 Visual representation of GWL_3X in the basins of the study area from 1972 to 2002 (basins
are grouped from west to east and the numbers correspond to those given in Fig. 1)

during winter. When looking at Fig. 7, the influence of GWL_32 on Q_{max} is apparent. For the total study period, in half of the basins Q_{max} were induced by the GWL_32. The same holds for the GWL_72. Moving from west to east over the study area, the influence of the westerly circulation patterns diminishes, as clearly seen in higher variation of GWL_3X ratios in Fig. 7.

The two lowest values of $STDEVMDQ_{max}$ were 2 and 8 days. They occurred in the periods of 1993–1994 and 1989–1990, respectively. In both periods for all basins Q_{max} was induced by GWL_32 (Fig. 6). When evaluating the GWL_7X, all Q_{max} were GWL_72 induced except for basin 62, which had a GWL_717. This meant that a rainfall event caused by a westerly flux is capable of producing the annual maximum discharge in the entire study period, implying furthermore that the rivers in all the basins reached their peak during the same event.

5 Conclusion

The objective of this study was to present a tool that incorporates results of statistical tests, hydro-climatological time series and physiographic basin characteristics by means of exploratory data analysis. The results of the statistical tests were in agreement with existing literature on the topic and could be depicted very well in the visualization tool. The results of the PCA and of the raster analysis suggested a relationship between rainfall, discharge and mean date of the annual maximum discharge on the one hand and the lithology, the altitude and the west to east positioning of a basin on the other hand. The tool reflected this as well. The geological configuration of the study area is such that the basins with the highest percentage of impermeable substratum receive also the highest amount of precipitation and vice versa, which is clearly reflected in the outcome of the Spearman's rank test and was illustrated in the matrix. The values of the mean date of the annual maximum discharge, which are closer to the start of the winter season for the westerly basins than for the easterly basins were also reflected in the matrix and could be explained by the geological and spatial distribution of the basins. The GWL2 played an important role in generating Q_{max} during the study period and was of major importance for triggering flood events. Furthermore, rainfall induced Q_{max} in a majority of the cases in 3 days but is prone to fluctuations in climate. Spearman's rank correlation coefficient r_s gave significant negative results for Q_{max}, Q_{mw} and mean altitude and a significant positive result for MDQ_{max}. The visual representations of Q_{max} and Q_{mw} were in agreement with the test results.

It was possible to use a visualization matrix in combination with trend and correlation analyses to increase our understanding of the spatio-temporal hydro-climatological behavior of a macro-scale area comprised of 70 meso-scale basins. Furthermore, the methodology could be suitable as an initial approach for predictions in ungauged basins. The application of the methodology to other regions for hydro-climatological analysis will be investigated further.

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