RECENT TRENDS IN RAINFALL-RUNOFF CHARACTERISTICS IN THE ALZETTE RIVER BASIN, LUXEMBOURG

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Abstract. The effects of rainfall structure and atmospheric circulation variability on streamflow in the Alzette River basin (Grand Duchy of Luxembourg, Europe) were investigated. Evidence is presented regarding the local-scale sensitivity of the Alzette River basin to large-scale changes in atmospheric circulation. Since the 1950s, there has been a marked increase in the contribution of the westerly component of atmospheric circulation to rainfall. These changes in atmospheric circulation are on a par with an increase in rainfall intensity and duration, which has induced a significant increase in the winter maximum daily storm flow in the Alzette River basin since the 1970s.

1. Introduction

Trends in hydrological time series can be induced by either changes in land use, river regulation, or climatic fluctuations, such as increases or decreases in precipitation and/or temperature. There is now major concern about the possible effects of these factors on streamflow, as there have been several high-magnitude floods since the late 1980s that have caused severe damage in Europe.

In Western Europe, annual rainfall is mainly dependent on eastward-moving Atlantic depressions. Thus, any change in the mean atmospheric circulation pattern, affecting especially the westerly circulation component, has a direct impact on climate and as a result also on rainfall. In the same way, changes in annual or seasonal rainfall are also likely to have an impact on streamflow.

Few studies have examined the relationships between atmospheric circulation and streamflow. Among these, McCabe (1996) clearly identified the relationships between mean winter atmospheric circulation and the temporal and spatial variability in annual streamflow in the western United States. Fluctuations in rainfall structure and pattern were also shown to have an impact on streamflow. Thus, in the contiguous U.S.A., the autumn increase in precipitation is reflected by an increase in streamflow, as reported by Lins and Michaels (1996), for almost all studied regions for the period 1948–1988. In Western Scotland, Mansell (1997) showed an increase in streamflow due to an important increase of winter rainfall coupled to a change in rainfall structure with a higher concentration of periods of

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rain. For a catchment in Greece, Giakoumakis and Baloutsos (1997) pointed out a very clear decreasing trend in rainfall. They have also shown that the fluctuations affecting mean annual streamflow are stronger than those affecting rainfall. Smith and Richman (1993) reported for the state of Illinois (U.S.A.) a shift from a relatively dry climate in the 1950–1967 period towards a wetter climate in the period 1968–1985, causing substantial hydrological changes as well as problems in water resource management. Higher storm flow and an increase in high frequency floods have been clearly related to climatic change by these authors.

On the other hand, Robson et al. (1998) found no evidence of any major impact of climatic change on flood behavior, after having examined peak-over-threshold and annual maxima data from 890 gauging stations in the U.K. Likewise, Nicholls et al. (1996) indicated that no clear evidence of a widespread change in annual streamflow and peak discharge of rivers in the world had been found. Nevertheless, this does not mean that climatic effects can be discarded.

Although some significant trends have been detected on a local scale, their extrapolation to a regional scale remains uncertain. The factors acting on streamflow trends on a basin scale are not necessarily similar to those acting on a regional or continental scale. Furthermore, it is very difficult to detect whether a trend in a hydrologic sequence is significant or whether it is part of an oscillation (Matalas, 1997). In addition to this, anthropogenic influences hamper the detection of the impact of rainfall fluctuations on streamflow.

Located in the middle of Western Europe, the Alzette River basin (Figure 1) is situated between two very different hydroclimatic regions: Northern Europe, with a very wet climate, and Southern Europe, characterized by low annual rainfall. In this study, daily rainfall and streamflow data were used to study the rainfall-runoff relationship in the Alzette catchment over the 1954–1996 period in order to detect the sensitivity of its basin to fluctuations, or even changes, in the climate.

2. Data and Methodology

The Alzette River originates in France, approximately 4 km south of the French-Luxembourg border (Figure 1). Downstream from Esch/Alzette, it heads north for approximately 67.5 km. The catchment surface area is 1072 km^2. At present, the valley accommodates almost 2/3 of the population of Luxembourg as well as an important part of the industrial infrastructure. Natural streamflow of some tributaries of the Alzette River has been severely influenced by mining activities and is only supported by mine water discharge at low flow. Upstream of Esch/Alzette, however, the Alzette River is less influenced by mine water discharge. The geological, topographical, and structural conditions in this part of the catchment have induced stationary mine water discharge (Kang et al., 1992). Most of these mines are now irreversibly flooded and their water level fluctuations are mainly dependent on rainfall supply.

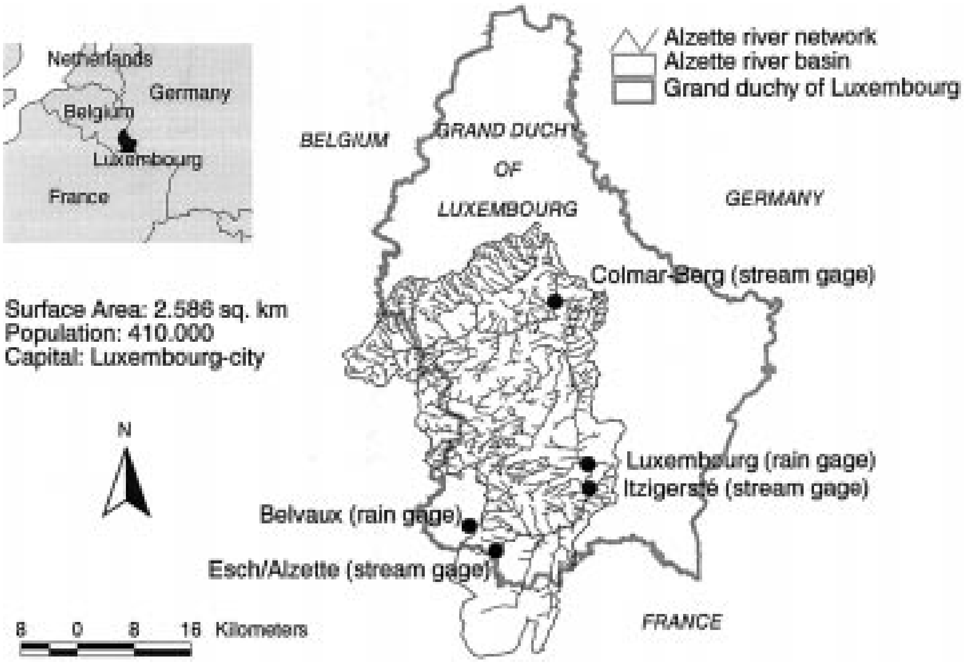

Figure 1. Alzette River basin and observation site locations.

Given these many sources of disturbance for the Alzette River, the hydrological study has been restricted to an area located upstream of Esch/Alzette, covering 21.7 km^2 in a sandstone substratum. Anthropogenic influences are restricted to mine water discharge with an annual mean of 40 l/s. Most of the pumping activities were stopped in April 1985 (M.A.T., 1991). The streamflow characteristics selected for analysis were mainly daily maximum values, little influenced by human activities. River flow data were available in the Esch/Alzette gauging station for the period 1954–1995 (Figure 1). The reliability of the Esch/Alzette records have been tested (data not shown) by comparing two winter maximum flood-level series of the Alzette River basin (Itzigersté and Colmar-Berg, Figure 1).

Monthly rainfall data were obtained from 1854 to 1996 at a meteorological station in Luxembourg city. These data enable the changes in streamflow to be set in a long-term context. Daily rainfall data were analyzed from 1954 to 1996 in the stations of Luxembourg city and Belvaux (Figure 1). Double-mass curves were used to assess the reliability of rainfall data. Annual, winter (October–March), and summer (April–September) rainfalls were determined for Belvaux and Luxembourg city. Mean daily and maximum daily streamflows were determined for Esch/Alzette. The observed changes in streamflow and rainfall patterns were compared to atmospheric circulation patterns, as defined by Hess and Brezowski (1977).

As indicated by Mitosek (1995), linear tests are not appropriate for non-normally distributed variables. The non-parametric Kendall test was thus used for streamflow and rainfall characteristics that were not normally distributed. Trends detected after visual inspection of yearly plots of rainfall and streamflow characteristics were investigated by computing Kendall's tau (Capéraà and Van Cutrem, 1988) to measure the strength of observed trends in both rainfall and streamflow data. Its values can range from –1 to +1, indicating a strong negative (–1) or positive (+1) trend, zero indicating the absence of a trend. The chance that an observed trend occurs was evaluated statistically with a test for significance. In the case of a positive trend, the null hypothesis ($\tau = 0$) is rejected when the auxiliary variable z_τ is greater than the threshold value z_α ($z_\tau > z_\alpha$). z_τ is less than $-z_\alpha$ in cases of a statistically significant negative trend ($z_\tau < -z_\alpha$).

Principal component analysis (PCA) was used to compare the winter maximum daily flow with rainfall characteristics, including predominant atmospheric circulation patterns, rainfall intensity, and average duration of rainfall events. This analytical technique basically allows the reduction of the number of variables and the detection of the structure in the relationships between variables by expressing several variables by a reduced number of factors.

3. Data

3.1. RAINFALL DATA

Between 1954 and 1996, the two rain-gauge stations of Belvaux and Luxembourg city had similar fluctuations in rainfall, especially during winter months. The highest annual values were measured in 1967 (1095 mm in Belvaux) and 1982 (1104 mm in Belvaux). No clear positive or negative trend in annual rainfall could be detected by the visual inspection of yearly plots in any of the two rain-gauge stations. However, an increase in winter rainfall and a decrease in summer rainfall were observed, their ratio increasing from 1 to 1.8 between the late 1950s and the early 1990s. Maximum rainfall contribution due to single rain periods (daily rainfall sequences that are not interrupted by one or more days without rainfall) had increased from 200 mm in the 1970s to 450 mm in the early 1990s (Belvaux).

Hess and Brezowski (1977) have defined 29 atmospheric circulation types which correspond to a mean air pressure distribution that generally persists for several days across Europe. They can be arranged in three major categories: zonal, meridian, and mixed circulations. Table I shows the mean annual, summer, and winter rainfall contributions due to these circulation categories for the rain-gauge stations of Belvaux and Luxembourg city.

Zonal atmospheric circulations are associated with more than a 55% winter rainfall, followed by almost equal contributions of meridian and mixed circulations (approximately 20%). During summer months, mixed atmospheric circulations

TABLE I

Mean annual, summer, and winter rainfall contributions by the three major atmospheric circulation categories (zonal, meridian, and mixed) in Belvaux and Luxembourg city (1954–1996)

	Annual		Winter		Summer	
	mm	%	mm	%	mm	%
Belvaux						
Zonal circulation	424.6	45.0	301.2	56.2	123.4	30.2
Meridian circulation	219.7	23.3	116.8	21.8	102.9	25.2
Mixed circulation	299.5	31.7	117.7	22.0	181.8	44.6
Luxembourg city						
Zonal circulation	375.0	44.0	245.8	56.9	129.2	30.8
Meridian circulation	184.5	21.7	81.4	18.8	103.1	24.6
Mixed circulation	292.5	34.3	104.9	24.3	187.6	44.6

comprise more or less 45% of total rainfall, while zonal and meridian circulation contributions vary between 25 and 30%. Amongst the zonal atmospheric circulation types that include northwest- to southwest-oriented airflows, the westerly component has had a growing influence on winter rainfall since the 1970s (Figure 2).

During winter, an overall increase of 230 mm of rainfall due to the westerly component (5-year moving average) was observed between 1954 and 1994. Thus, the contribution of this circulation type to total winter rainfall increased from 20% during the 1950s to more than 50% during the 1990s. For the westerly component of zonal atmospheric circulations, the 5-year average of days with rainfall increased from 15 days at the end of the 1950s to more than 35 days at the beginning of the 1990s. Winter rainfall variability in the Alzette basin is consequently mainly due to fluctuations in the atmospheric circulation patterns.

Ten-year moving averages of monthly rainfall data from 1854 to 1996 in Luxembourg city and daily atmospheric circulation types from 1881 to 1996 are plotted in Figure 3 to detect long-term fluctuations in westerly airflow-rainfall contributions.

The time series plot of annual rainfall shows that there have been several fluctuations in rainfall (Figure 3a). At the end of the 19th century, as well as during the 1960s and 1970s, the 10-year rainfall moving average only reached 560 and 680 mm, respectively, whereas during the 1930s and the early 1990s, maximum values of 880 and 910 mm were observed. Since the mid-1980s, rainfall has been comparatively high. It is important to note that there have been similar fluctuations in both winter and summer rainfall (Figures 3b,c).

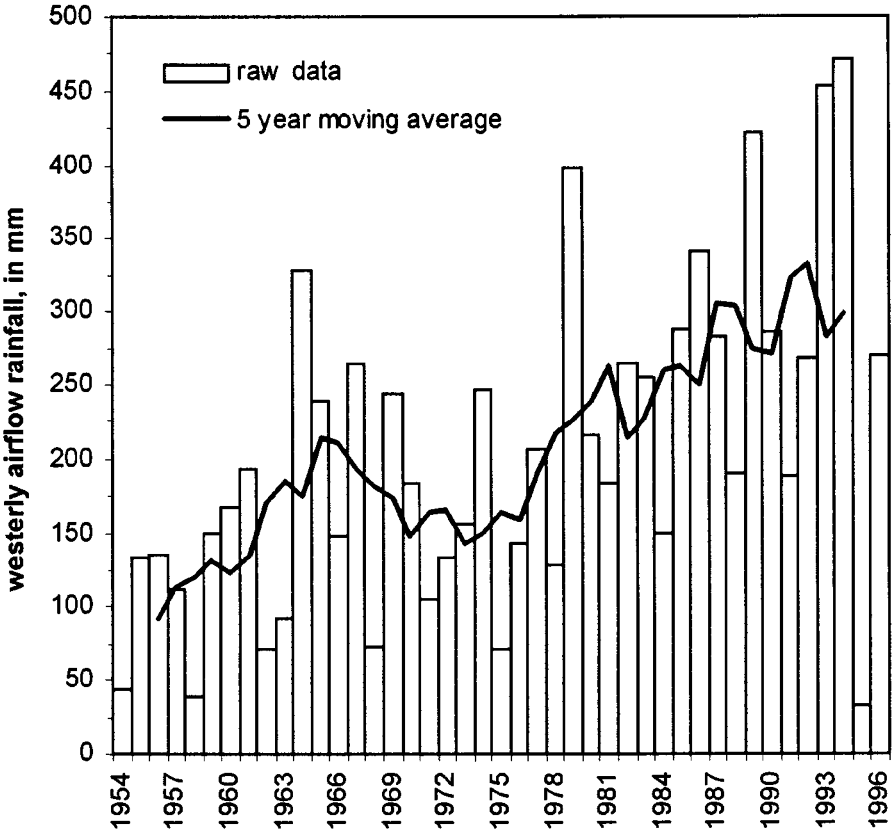

Figure 2. Westerly airflow rainfall in winter between 1956 and 1996 in Belvaux.

Over the last 110 years, the atmospheric circulation pattern has also significantly changed. At the beginning of the 20th century, westerly airflows were more abundant during summer months, whereas since the 1980s, they have been more abundant during winter months (Figures 3d–f).

3.2. STREAMFLOW DATA

The Alzette flow data was analyzed over the 1954–1995 period. For high flows, peak daily mean flow was used as a reasonable surrogate for instantaneous flood magnitudes (Boorman and Sefton, 1997). Alzette streamflow data was smoothed by a 5-year moving average in order to detect any trend or periodicity in the observation series.

Several streamflow fluctuations occurred between 1954 and 1995, with high annual mean flows of approximately 0.6 m^3/s at the end of the 1960s and the early 1980s and low annual mean flows of 0.3 m^3/s during the mid-1970s and the late 1980s, respectively (Figure 4a). These fluctuations were observed during both winter and summer.

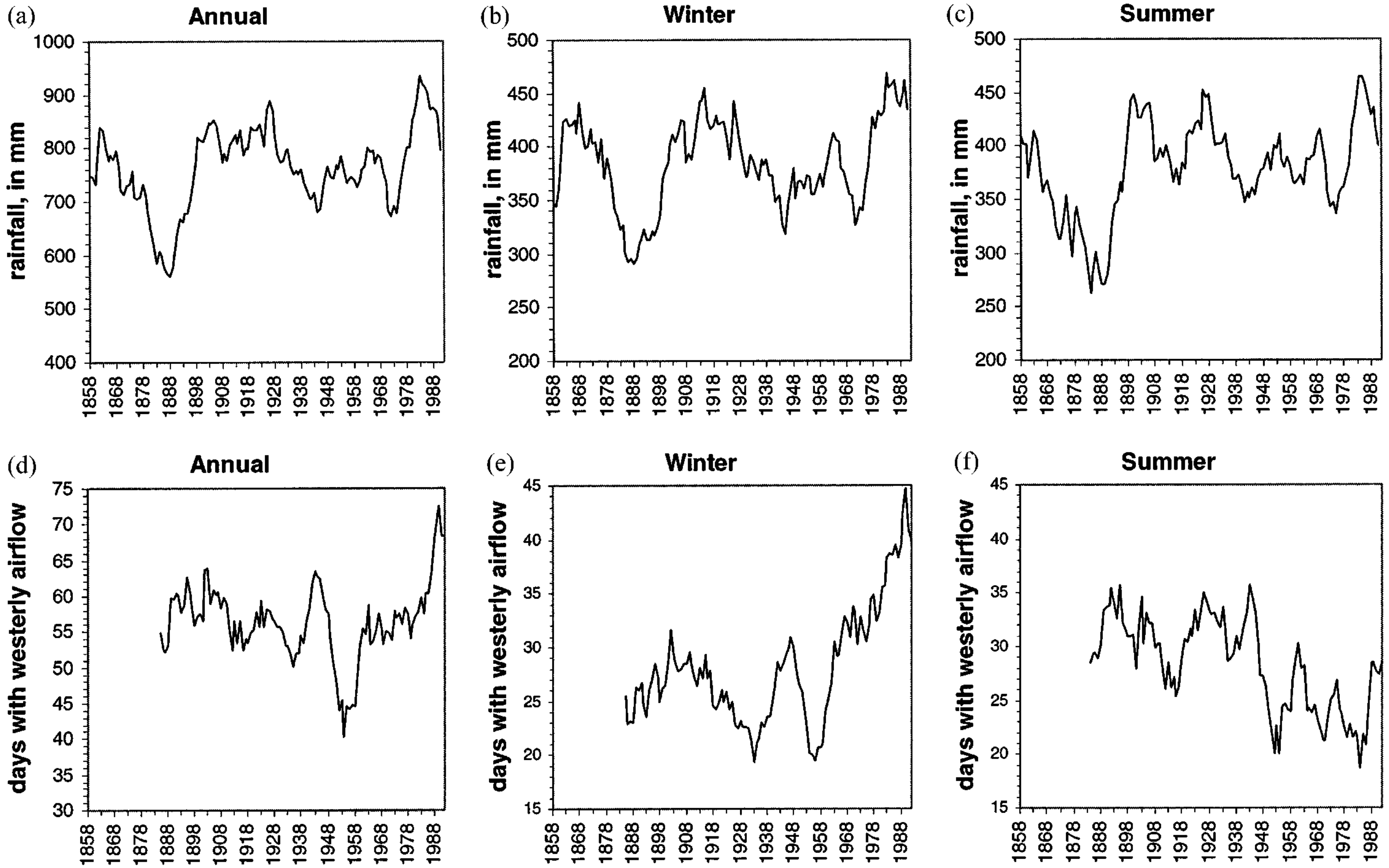

Figure 3. Annual, winter, and summer rainfall in Luxembourg city (1854–1996) and days with westerly airflows (1881–1996) – 10-year moving average.

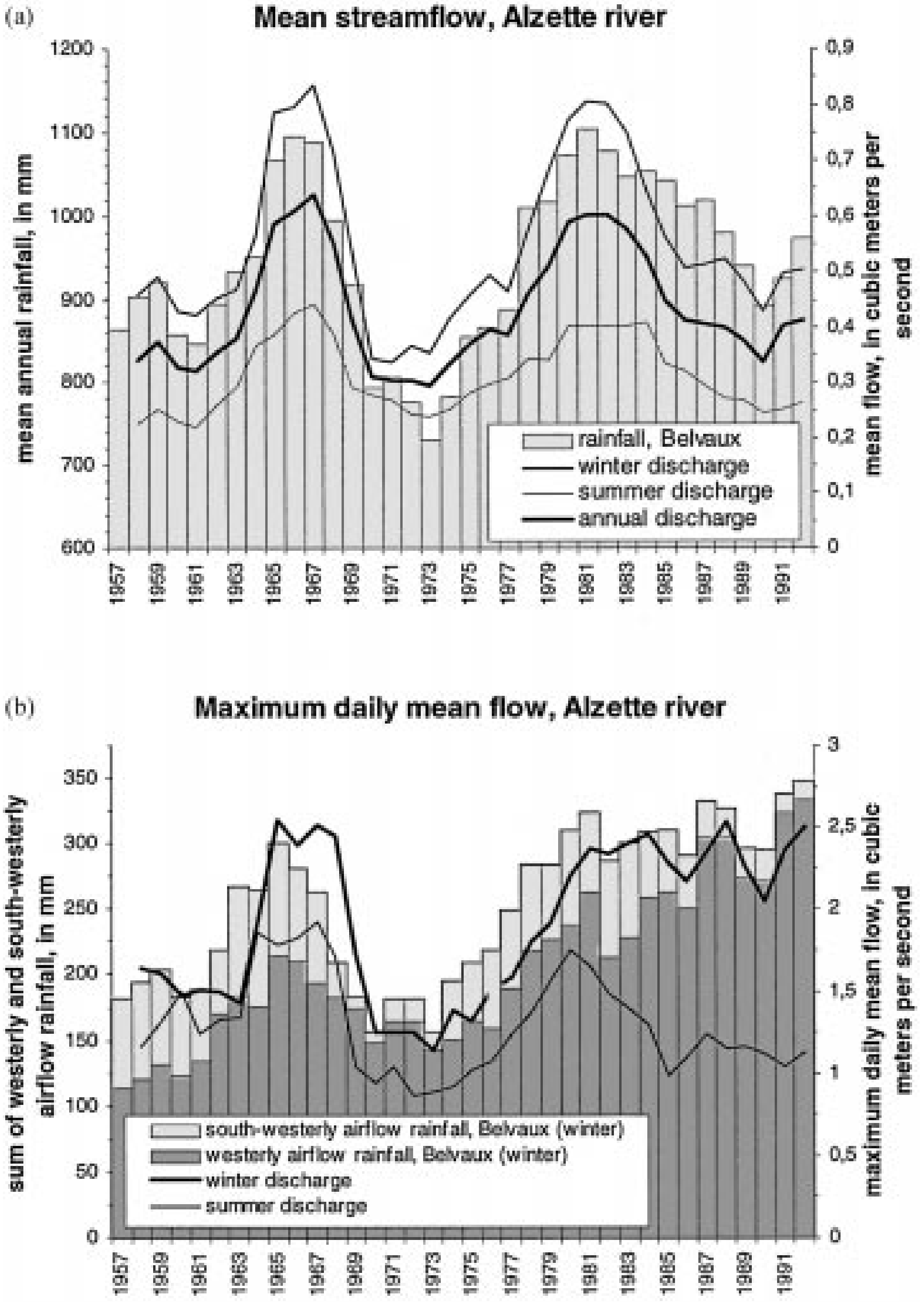

Figure 4. 5-year moving average of mean flow and maximum daily flow of the Alzette River measured at Esch/Alzette (1954–1995) and 5-year moving average of annual rainfall and westerly and southwesterly airflow rainfall in Belvaux (1954–1995).

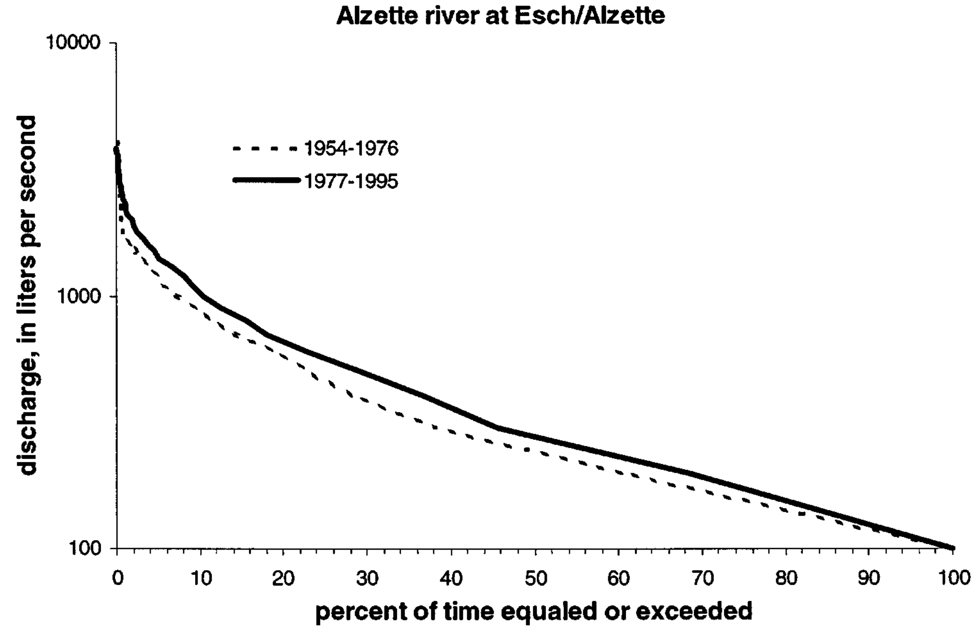

Figure 5. Duration curves for the periods 1954–1976 and 1977–1996.

Since the 1980s, maximum daily mean flow fluctuations have been totally different from the mean streamflow evolution during winter (Figure 4b). Between the late 1950s and the early 1970s, maximum daily mean flow fluctuated greatly, varying from 1.1 to 2.5 m^3/s. Since the 1970s, maximum daily mean flow has increased a lot and has remained between 2 and 2.5 m^3/s. Summer maximum daily mean flow evolved in a similar way to mean streamflow. The flow duration curves indicate that flows with a longer than 40% duration slightly increased between the periods of 1956–1976 and 1977–1995 (Figure 5).The magnitude of flows above 10% duration increased by 7% between the same periods. All these observations clearly indicate a significant change in winter maximum daily mean flow since the 1980s.

3.3. RAINFALL-RUNOFF CHARACTERISTICS

Mean annual streamflow and mean annual rainfall are highly correlated ($r = 0.92$) for the period 1954–1995 (Figure 4a). However, since the 1980s the evolution of winter maximum daily mean flow and winter mean streamflow is no longer parallel (Figures 4a,b).

As seen above, since the 1980s there has also been an increase in the westerly airflow-rainfall contribution to total winter rainfall. The related change in winter rainfall distribution is likely to have had an important impact on Alzette streamflow.

TABLE II

Variables characterizing rainfall and maximum daily mean streamflow used for PCA

Variable ID	
	Rainfall contribution due to atmospheric circulation type:
V1	Zonal
V2	Meridian
V3	Mixed
V4	Western
V5	Southwest
	Number of days with rain due to atmospheric circulation type:
V6	Zonal
V7	Meridian
V8	Mixed
V9	Western
V10	Southwest
V11	Maximum daily rainfall
V12	Maximum rainfall due to a single event
V13	Maximum daily mean flow

In addition to this, maximum daily rainfall and maximum contribution by a single rain period can also influence daily maximum streamflow.

The influence of different rainfall characteristics (Table II) on maximum daily mean flow was, therefore, investigated for the 1954–1996 period by using the Principal Component Analysis (PCA). The PCA was restricted to the Belvaux rain-gauge station, because of its proximity to the stream-gauge station of Esch/Alzette. As maximum daily mean flows are mainly observed during winter months, the analysis was restricted to winter. After a scree-test, two vectors were retained for varimax rotation. These two vectors explain 70% of the variance.

The grouping of variables observed after rotation indicated that the impact of meridian (V2, V7) and mixed (V3, V8) circulations on maximum daily mean streamflow (V13) is insignificant (Figure 6). Zonal circulation (V1, V6) appears to act very strongly on maximum daily mean flows. Winter maximum daily rainfall (V11) as well as maximum contribution by a single rainfall period (V12) also appear to be strongly correlated with maximum daily mean flow. These extreme events are closely related to zonal atmospheric circulation. Amongst the zonal circulation pattern, the westerly airflow component (V4, V9), followed by

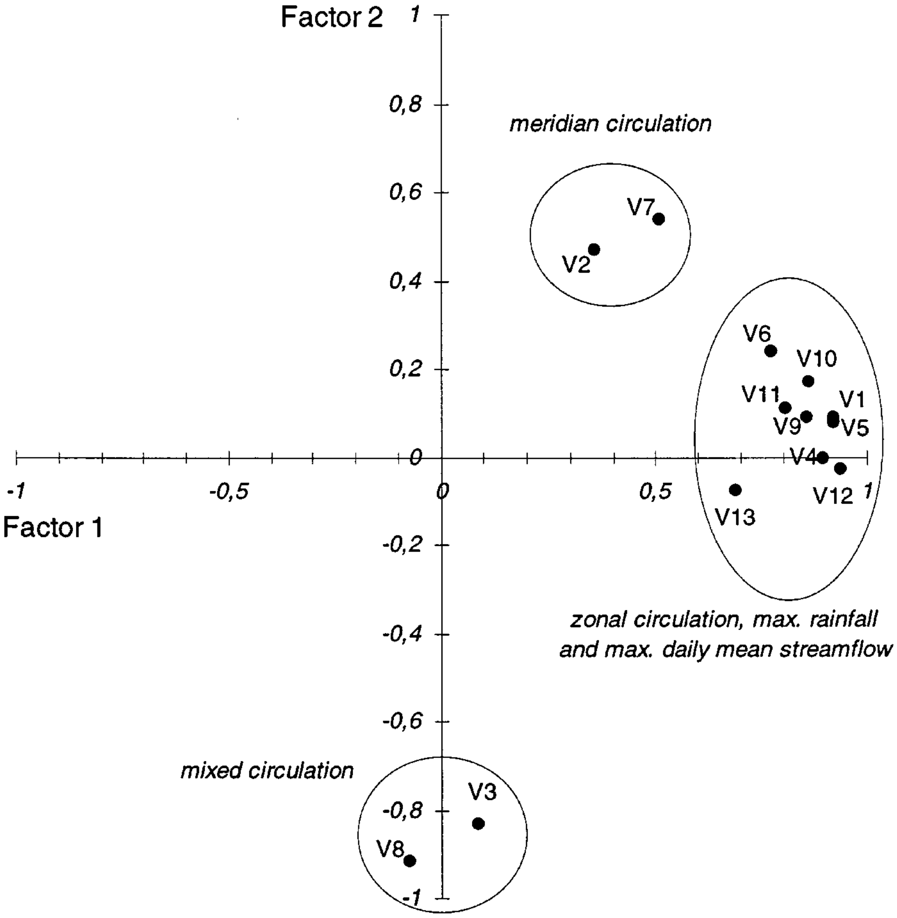

Figure 6. Grouping of variables observed after PCA.

the southwesterly (V5, V10) component, constitutes a major contribution to total winter rainfall.

This PCA has allowed the clear identification of the impact of zonal circulation, especially of the westerly airflow component, on maximum daily mean flow of the Alzette River. Given these results, the evolution of rainfall contributions by westerly and southwesterly airflows and riverflows, was analyzed in detail (Figure 4b). As shown by the correlation coefficient of 0.86, there is a strong correlation between maximum daily mean flow and rainfall contribution due to westerly and southwesterly airflows for the 1954–1996 period.

Time trends in the streamflow characteristics at Esch/Alzette and rainfall characteristics at Belvaux and Luxembourg city were investigated by computing Kendall's tau. Kendall's tau as well as auxiliary values z_τ and z_α were determined for total rainfall, westerly airflow rainfall, southwesterly airflow rainfall, mean flow, and maximum daily mean flow (Table III).

TABLE III

Selected rainfall and streamflow gauging stations in the Alzette basin, respective mean rainfall and streamflow for the period 1954–1996, z_τ and z_α corresponding to Kendall's tau

	Year				Winter				Summer			
	mm	τ	z_τ	z_α	mm	τ	z_τ	z_α	mm	τ	z_τ	z_α
Total rainfall (1954–1996)												
Belvaux	932	0.12	1.09	1.66	533	*0.16*	1.54	1.66	399	–0.08	–0.70	–1.66
Luxembourg-city	853	0.09	0.81	1.66	433	0.09	0.85	1.66	420	0.01	0.12	1.66
Rainfall due to westerly airflows (1954–1996)												
Belvaux	287	**0.39**	3.61	1.66	208	**0.50**	4.71	1.66	79	0.04	0.34	1.66
Luxembourg-city	252	**0.33**	3.09	1.66	166	**0.37**	3.46	1.66	86	–0.05	0.51	1.66
Rainfall due to south-westerly airflows (1954–1996)												
Belvaux	74	**–0.29**	–2.75	–1.66	55	**–0.24**	–2.20	–1.66	19	0.12	1.09	1.66
Luxembourg-city	65	**–0.24**	–2.20	–1.66	44	**–0.24**	–2.28	–1.66	21	*0.17*	1.60	1.66
	Year				Winter				Summer			
	m^3/s	τ	z_τ	z_α	m^3/s	τ	z_τ	z_α	m^3/s	τ	z_τ	z_α
Mean streamflow (1954–1995)												
Alzette	0.43	0.13	1.15	1.68	0.54	0.14	1.27	1.68	0.31	0.11	1.02	1.68
Maximum daily mean flow (1954–1995)												
Alzette	2.00	**0.30**	2.70	1.68	1.96	**0.33**	2.96	1.68	1.29	–0.001	–0.01	–1.98

Bold: H_o rejected at 5%.
Italic: H_o rejected at 10%.

No significant trend was observed for total annual rainfall, whereas for the westerly airflow contribution the apparent positive trend was found to be highly significant on annual and winter scales (>95% confidence). For the southwesterly airflow, contribution was detected as a decreasing trend on annual and winter scales (>95% confidence). There is no evidence for a significant trend for mean streamflow, while there has been a significant positive trend for maximum daily mean flow on annual and winter scales.

The results of Kendall's test show that positive trends in westerly airflow rainfall as well as in maximum daily flow are statistically significant. Depending on its more or less important interannual fluctuations, southwesterly airflow rainfall has also contributed to the increase in maximum daily mean flow. Thus, during the early 1980s, the heaviest flows were obviously generated by both westerly and southwesterly airflow rainfall (Figure 4b). During the early 1990s, the increase in rainfall contributions due to westerly airflow was sufficient to generate high maximum daily mean flows.

4. Discussion and Conclusion

The growing influence of the westerly atmospheric circulation over the past two decades has led to an increase in winter rainfall due to single rainfall periods. The related change in winter rainfall distribution has an important impact on the Alzette daily maximum streamflow. Similar results were reported by Ghio (1995) and Mansell (1997) for other West European catchments.

Westerly atmospheric circulation is part of a complex energy exchange system between the Atlantic Ocean and the atmosphere. McCartney et al. (1996) reported a decadal fluctuation in these exchanges, influencing the atmospheric circulation. Anomalies of atmospheric circulation patterns have persisted in the North Atlantic since 1989 (Nicholls et al., 1996). They are associated with persistent temperature and rainfall anomalies. Conway et al. (1996) suggest that changes in the relationship between meteorological variables and the atmospheric circulation patterns could be related to changes in the mean trajectory of the atmospheric circulations, as well as to variations of sea surface temperature. On a global scale, the changes in rainfall distribution still remain uncertain (Matalas, 1997). On the one hand, the difficulties of obtaining long and reliable streamflow and rainfall data have led to a concentration of efforts on modeling. On the other hand, given the difficulties in reproducing the high regional sensitivity of flow generation to small changes in rainfall regime, the utilization of historical data rather than global climate models should be preferred (Georgakakos et al., 1998).

While there is no doubt that the factors acting on streamflow trends on a basin scale are not necessarily similar to those acting on a regional or continental scale, it seems obvious that catchments are very sensitive to changes in both rainfall quantities and structure.

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