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Hydrological impacts of climate change at catchment scale: A case study in the Grand-Duchy of Luxembourg

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ABSTRACT

As a consequence of an increase of days with westerly atmospheric fluxes, bringing humid air masses from the Atlantic Ocean to Western Europe, important changes in the annual and seasonal distribution of rainfall have been observed over the past 150 years. Annual rainfall totals observed during the second half of the 19th century were less important than those observed during the second half of the 20th century. Moreover, during the past 50 years winter rainfall totals have significantly increased, while summer rainfall totals have been decreasing. Streamflow observations through the second half of the 20th century have shown a significant increase of winter maximum daily streamflow, in reaction to the winter rainfall increase. The modelling of the streamflow under the 19th century climatological conditions suggests that since then, the number of winter flood days has increased, while the occurrence of summer flood days has decreased. Moreover, high floods appear to have been more frequent in the second half of the 20th century.

KEYWORDS **Alzette river. Climate change. Kendall's tau. HRM hydrological model. Luxembourg.**

INTRODUCTION

Over the past decade several high magnitude floods have been observed throughout Western and Central Europe. The economic losses inherent to these events have been on each occasion tremendous. In the aftermath, land-use changes, as well as climate change have been pinpointed in numerous studies as the main reasons of those extreme hydro-climatological events (Mansell, 1997; Pfister et al., 2000; Robinson et al., 2000; Pfister et al., in press). However, the interactions of the climate system with the hydrological cycle are of such complexity, that the detection of the causes (e.g. climate and/or land use change) that are responsible for changes in the rainfall-runoff relationship is extremely difficult.

Trends in hydrological time series have been linked to changes having affected climatological variables over the past decades (McCabe, 1996; Mansell, 1997; Pfister et al., 2000; Hisdal et al., 2001; de Wit et al., 2001; Burn and Elnur, 2002). As outlined by Kondratyev and Cracknell (1998), the climate system is now clearly recognized as being subject to natural, as well as man-made changes.

Changes in land use, such as forest clear-cutting, agricultural drainage, or urbanization have also been identified as prone to changing the hydrological behaviour of rivers (Cosandey and Robinson, 2000; Robinson et al., 2000).

Most studies on changes in the rainfall-runoff relationship are hampered by the lack of data of relevant spatio-temporal resolution. As outlined by Beven (2001) the extrapolation from those measurements in space and time to other, non-monitored, catchments or into the future in view of the assessment of expected climate and land-use changes can only be achieved through the use of hydrological models.

The Grand-Duchy of Luxembourg has been subject to extreme floodings on several occasions at the beginning of the 1990's. Since then, many research efforts have been put into the investigation of the causes that might have generated these events. For this purpose, a hydro-climatological monitoring network of high spatio-temporal density has been set up in the area, in order to monitor the flood generating processes. Simultaneously, all existing historical hydro-climatological observation series have been analyzed in order to detect any changes in the rainfall-runoff relationship over the last decades.

The present paper first investigates the relationship between historical rainfall-runoff data and atmospheric circulation types in the headwaters of the Sûre river in Luxembourg. This trend analysis is extended to the entire Grand-Duchy of Luxembourg. Finally, a hydrological model is run on a tributary of the Alzette, belonging to the Sûre river network, subject to only little land use changes in the past, in order to detect differences in the rainfall-runoff relationship between the 19th and 20th century.

THE STUDY AREA

The Grand-Duchy of Luxembourg extends over a total surface area of 2,586 km^2 and is located in Western Europe, surrounded by France, Belgium and Germany (Fig. 1). It has a total population of 450000. The river network is almost entirely part of the Sûre river basin (a major tributary of the Mosel river and thus part of the Rhine basin), which has as main tributaries the Alzette, the Wiltz and the Our rivers. The country is divided in two major physiogeographic regions : the Oesling in the North, characterized by schistous substratum and deeply cut V-shaped valleys, and the Gutland in the South, characterized by Mesozoic substratum, with deep valleys cut into the Luxembourg sandstone, alternating with large valleys in the Keuper marls. Altitudes are highest in the Oesling (225 - 559 m a.s.l.) and lowest in the Gutland (140–440 m a.s.l.). Land use is characterized in the Gutland area by agricultural lands, forests, urban areas, as well as most of the industrial infrastructure of the country, while in the Oesling, forests and agricultural lands are dominating.

Historical daily rainfall and temperature observations are available for Luxembourg-city from 1854 to 1884. From 1885 to 1949, only monthly rainfall values are available. Since then, the number of daily rainfall observation sites has been in constant progression and complete daily rainfall data series exist for 13 observation sites, extending from 1954 to 2002 (Fig. 1).

The changes having affected rainfall characteristics were analyzed through the use of the atmospheric circulation classification (Grosswetterlagen), according to Hess and Brezowski (1977). Daily streamgauge recordings have been made since the World War II in over 16 locations. Unfortunately, no reliable rating curves exist for most of these stations and in some cases important changes have been made to the streamgauge locations. Thus, only 7 observation sites were retained for data analysis.

METHODOLOGY

After an initial validation of the historical hydro-climatological data series, they were investigated on any existing positive or negative trends. Since the link between observed changes in the rainfall-runoff relationship had to be restricted to the period 1954-2002, an attempt was also made to reconstruct past rainfall-runoff characteristics in a tributary of the Alzette river for the period 1854-1884. The upstream part (48 km^2) of the Eisch river, one of the major tributaries of the Alzette, has been subject to relatively small changes in land use over the past 150 years and is thus well suited for investigating climate-induced changes in the rainfall-runoff relationship.

Since the historical rainfall and temperature data sets are split into two distinctive periods, separated by 70 years, a certain amount of statistical tests had to be carried out in order to determine the reliability of the data. As plausibleness criterion, a physical limit for daily rainfall intensities of 100 mm/day was determined by Drogue (2003). In the entire rainfall dataset, ranging from 1854 to 2003, no daily precipitation value exceeded this limit in the study area. A coherence test was also performed on the rainfall and temperature series. This test aimed on the one hand at verifying that there is a good concordance between the observations for a given period, and on the other hand at determining whether this concordance is stable between two observation periods. The 19th and 20th century temperature datasets of Luxembourg-city were first compared to the temperatures observed over the same periods in the closest meteorological stations, Strasbourg (France) and Frankfurt (Germany). The linear relationships between the monthly temperatures of these

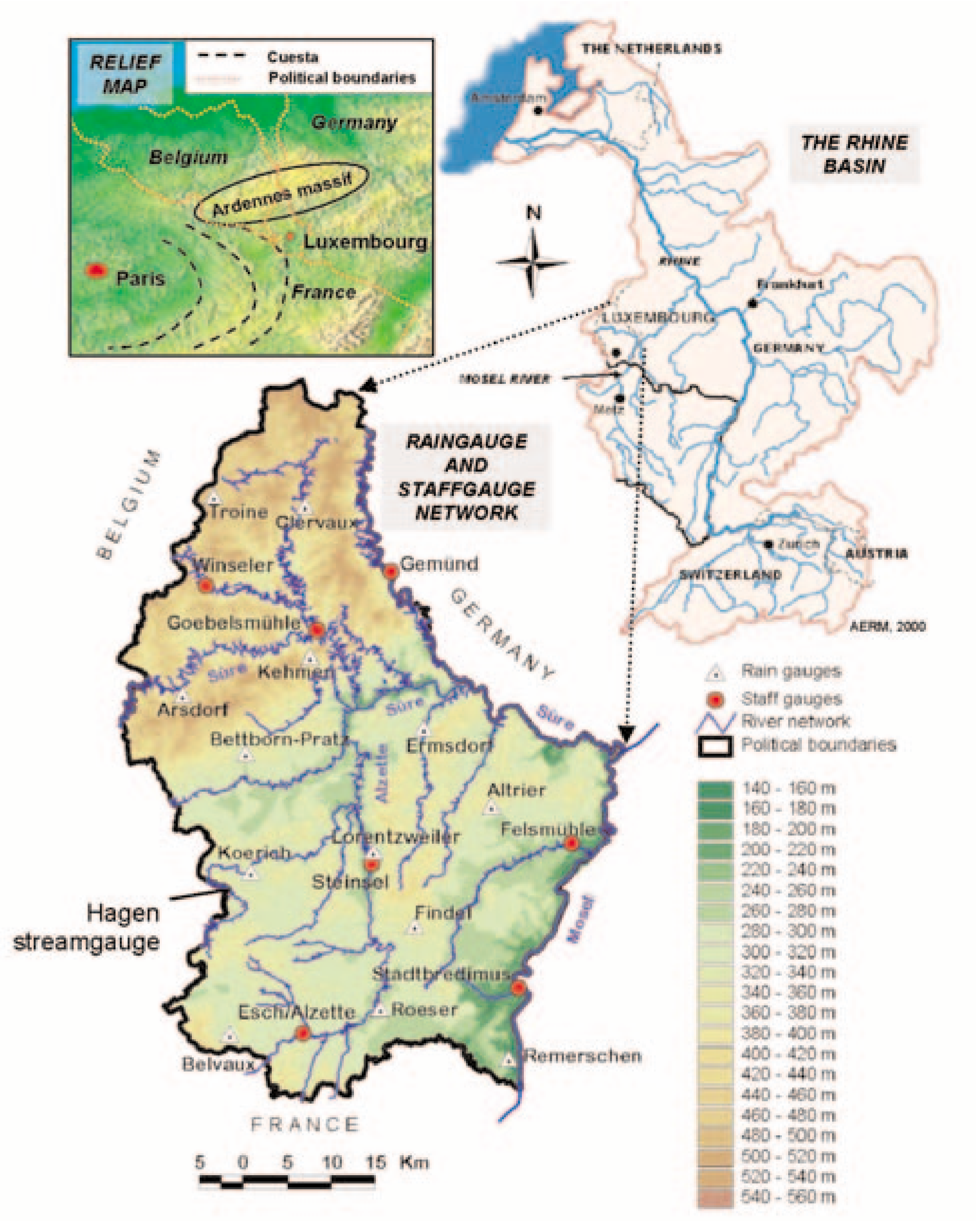

FIGURE 1 **Relief map, Rhine basin map and staffgauge and raingauge network used for the study in the Grand-Duchy of Luxembourg.**

three cities turned out to be equally strong during the two measurement periods and no deviation in the slopes of the correlation graphs could be observed. Double-mass curves between monthly rainfall totals of Luxembourg-city and Trier-Petrisberg (located on the German border of the Mosel river and currently run by the University of Trier - Data downloaded from http://www.wetterzentrale.de), kept the same features over the two observation periods. No deviation in the slopes of the correlation graphs could be observed. Inter-comparison between the streamgauge stations confirmed the reliability of the winter maximum daily water level series.

The non-parametric Kendall test was used for assessing trends in both streamflow and rainfall observation series. The Kendall test is suitable for detecting trends between hydrological and meteorological variables, as shown by Burn and Elnur (2002) for Canadian catchments. Douglas et al. (2000) have shown that a cross-correlation of flow records considerably reduces the effective number of samples available for trend assessment on regional scale. This is of major importance when determining regional trends, since the null hypothesis (of independence) will tend to be rejected more frequently than it should be if cross-correlation is ignored. Nonetheless, in case of an analysis of the spatial variability of trends in streamflow, all available measuring stations should be retained, even in case of cross-correlation, since for each streamgauge station the observed trend is influenced by climatological and physiogeographic conditions in the embedded monitored upstream sub-basins.

Trends detected after visual inspection of yearly plots of rainfall and streamflow were investigated by computing Kendall's tau (Capéraà and Van Cutrem, 1988) to test whether rainfall or streamflow values (Y variable) tend to increase in time (X variable).

H_0: $\tau = 0$, no correlation exists between X and Y
H_1: $\tau \neq 0$, X and Y are correlated

To perform the test, Kendall's S has to be calculated first from the X,Y data pairs:

$$S = A - B$$

with A = number of cases where $Y_i < Y_j$, while $i < j$
B = number of cases where $Y_i > Y_j$, while $i < j$

$$\tau = \frac{2S}{n(n-1)}$$

The variable Z, associated with τ normally distributed and of zero mean, has a variance of :

$$\sigma_z^2 = \frac{2(2n+5)}{9n(n-1)}$$

The significance test is based upon the formula :

$$Z_\tau = \tau \sqrt{\frac{9n(n-1)}{2(2n+5)}}$$

The null hypothesis is rejected at significance level α if $|Z_\tau| > z_{\alpha/2}$, with $z_{\alpha/2}$ being the critical value. In the case of a positive trend, the null hypothesis ($\alpha = 0$) 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 case of a statistically significant negative trend ($z_\tau < -z_\alpha$).

The rainfall-runoff characteristics of the Eisch river for the 19th century were reconstructed by using the conceptual hydrological model HRM (Leviandier et al., 1994). The HRM model simulates daily discharge using rainfall and potential evapotranspiration as input (Leviandier et al., 1994; Drogue et al., 2002). It is composed of a non-linear loss and and a non-linear upstream routing sub-model, a unit hydrograph and a groundwater exchange submodel. The lumped version of the HRM model performs a conceptual discretization of a given basin into nested sub-basins, with velocity fitting being the only free parameter, which determines the number of isochronal zones (virtual sub-basins of equal delays routing).

The kth sub-basin is considered to be the kth reservoir, the routing time from the kth sub-basin to the nth sub-basin being n – k time steps. The kth sub-basin has a drainage area of $a_{k/n}$ (isochronal zone). The HRM model is called recursive because the "local" reservoir structure at order k is obtained from the "local" reservoir structure at order k – 1 by a simple transformation (namely, routing + lateral input). The "local" reservoir structure corresponding to the kth sub-basin comprises two functions: a) the "local" production function containing a soil reservoir similar to those of GR3/GR4 (Edijatno et al., 1999). Its level S is determined by net potential evapotranspiration (E_n and further E_s) and the transformation of the net rainfall P_n into P_s (rainfall in soil reservoir) and P_r (rainfall in "local" routing reservoir). Parameter A (mm) represents the maximum storage capacity of the soil reservoir; b) the "local" routing function, including a quadratic reservoir of level R(t) (mm), with outflow following the law:

$$Q_\tau(t) = \frac{R(t)^2}{B + R(t)} \qquad (1)$$

where B (mm) is representative of the storage capacity of the reservoir, though not defined as a maximum storage capacity (which is infinite). The emptying function of the quadratic reservoir includes a groundwater exchange module ECH computed as follows:

$$ECH = d.(k - k_0) \left(1 + = \frac{k - k_0}{k} \cdot \frac{R(t)}{B} \right) \qquad (2)$$

where k_0, fixed in the study to half of n, is the order of a sub-basin for which exchanges are nil, and d (mm) is a parameter. The streamflow $Q_r(t)$ and the groundwater exchanges are added and the sum is weighted by $a_{k/n}$. The resulting streamflow Q_j is routed by the general routing function toward the $(k+1)^{th}$ sub-basin. Finally, the general routing corresponds to a sequence of delayed routings (rather than a cascade of linear reservoirs as in the complete model version). The four free parameters A, B, a_0 (equivalent to $a_{k/n}$ for a first order sub-basin) and d must be fitted to run the HRM model. The parameters are automatically optimized with Rosenbrock's procedure (Rosenbrock, 1960) and due to the significant parsimony of the model, multiple optima (i.e. non-uniqueness; equifinality) are rare (Edijatno et al., 1999).

ANALYSIS OF HISTORICAL HYDRO-CLIMATOLOGICAL DATA

The analysis of monthly rainfall totals over the period 1860-1995 in Luxembourg-city has shown important fluctuations of rainfall (Pfister and Hoffmann, 2001). Around 1885, as well as in the 1940s and the 1970s, the 5-year moving average of annual rainfall only reached 550 and 680 mm respectively, while in the 1900s, 1920s and the 1990s maximum values of 960, 980 and 940 mm were recorded. The maximum annual rainfall totals over the whole study period were observed at the end of the 1980s, with a mean 5-year moving average of 1050 mm. Since then, this average has decreased to less than 800 mm. No general trend could be detected on an annual scale.

The rainfall-runoff relationship in the second half of the 20th century in the Sûre headwaters

Between 1954 and 2002, all 13 pluviometric stations have been subject to comparable variations of winter rainfall. The highest annual rainfall heights were measured in 1967 (1095 mm in Belvaux) and in 1982 (1104 mm in Belvaux). No positive or negative trends were observed on annual totals. The ratio between summer rainfall and winter rainfall, however, indicates a negative trend, with a decrease of 30% between the end of the 1950s and the beginning of the 1990s. Thus, there has been a significant increase of winter rainfall versus a decrease of summer rainfall.

In Western Europe, winter rainfall is strongly influenced by the westerly atmospheric fluxes that bring humid air masses from the Atlantic Ocean (McCartney et al., 1996; Pfister et al., 2000). Any change in atmospheric circulation patterns can thus influence the westerly fluxes and rainfall patterns in Western Europe. Hess and Brezowski (1977) have defined 29 atmospheric circulation types that correspond to a mean air pressure distribution that generally persists for several days in Western Europe (zonal, meridian and mixed circulations). Zonal atmospheric circulations are associated with more than 55% of winter rainfall, followed by almost equal contributions of meridian and mixed circulations (approximately 20%). During summer months, mixed atmospheric circulations cause 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. During winter, an overall increase of 200 mm of rainfall due to the westerly component (5-year moving average) was observed between 1954 and 2002 (Fig. 2A). Thus, the contribution of this circulation type to total winter rainfall increased from 15% by the end of the 1950s to 50% at the beginning of

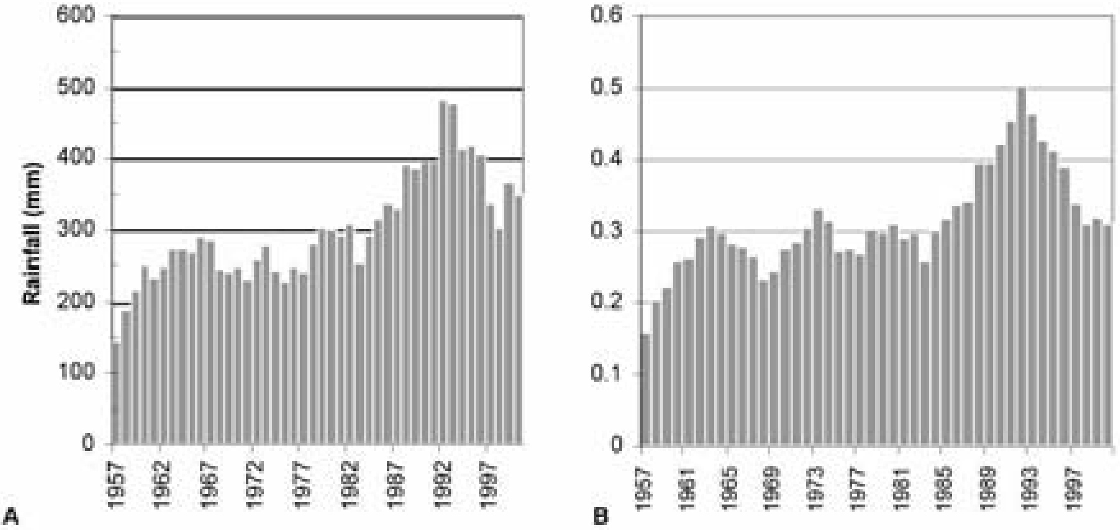

FIGURE 2 **5-year moving average of rainfall (Arsdorf) due to the westerly component (A) and 5-year moving average of the contribution to total rainfall by the westerly component (B) for the 1957-2001 period.**

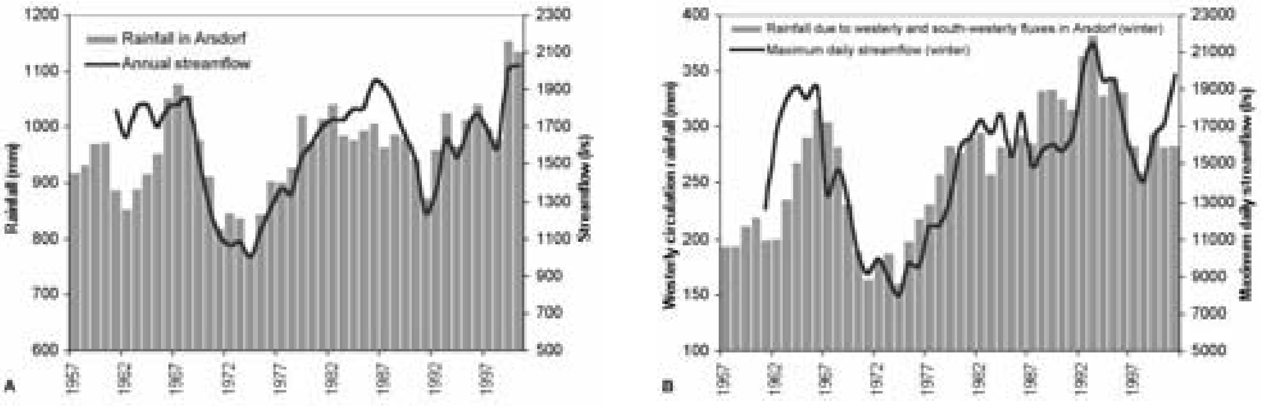

FIGURE 3 **5-year moving average of mean annual streamflow of the Wiltz at Winseler and mean annual rainfall in Arsdorf (1957-2001) (A); 5-year moving average of maximum daily winter streamflow and rainfall due to westerly and south-westerly fluxes in Arsdorf (1957-2002) (B).**

the 1990s (Fig. 2B). Currently, its contribution has dropped to 30%, but still remains well above the values of the 1950s. For the westerly component of zonal atmospheric circulations, the 5-year average of days in winter with rainfall increased from 17 days at the end of the 1950s to 48 days in the mid-1990s. Since then, the 5-year moving average has been stabilizing around 35 days. Winter rainfall variability in the Sûre basin is consequently mainly due to fluctuations in the atmospheric circulation patterns (Pfister et al., 2000).

Regardless of the origin of the atmospheric circulation types that bring more or less rainfall to Western Europe, and also regardless of the maximum daily rainfall intensities, extreme streamflow is always generated by extreme rainfall events. Since the 1980s there is a simultaneous increase in duration and intensity of extreme rainfall events in the Sûre basin (Pfister et al., 2000). Rainfall events longer than 21 days and with daily intensities higher than 50 mm/day appeared on several occasions since the 1980s, while such events had not been observed between 1953 and 1980.

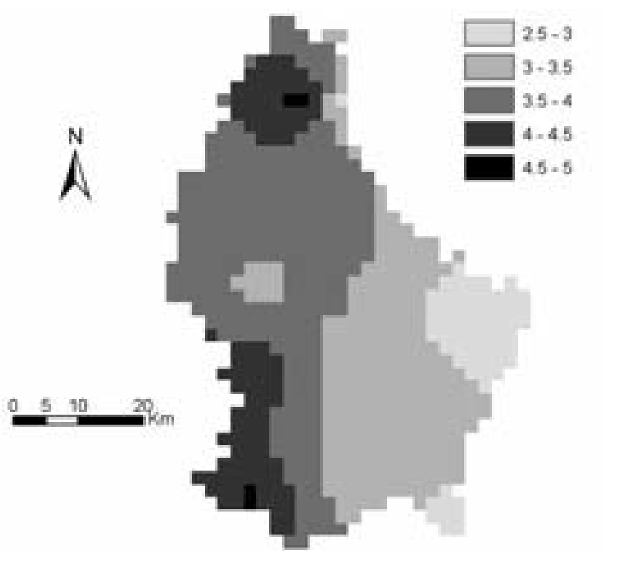

FIGURE 4 **Increase rate of the rainfall due to westerly atmospheric fluxes during winter since 1954.**

Since the beginning of the 1990s, the Sûre and its tributaries have been subject to a large number of heavy floods. As an example, the Wiltz annual streamflow at the Winseler streamgauge station has been studied via a 5-year moving average. Various fluctuations of annual streamflow thus appeared over the last decades, such as high annual streamflow at the end of the 1960s and at the beginning of the 1980s (1900 l/s) and low annual streamflow at the end of the 1970s and at the end of the 1980s (1000 l/s; Fig. 3A). Since the 1980s, the evolution of daily maximum streamflow during winter months is totally different from that observed for mean daily streamflow (Fig. 3B). Between the end of the 1950s and the beginning of the 1970s, maximum daily streamflow was very contrasted, with values ranging from 8000 to 20000 l/s. Since the 1970s, maximum daily streamflow has increased significantly. Maximum daily streamflow values are since then varying between 15000 and 21500 l/s.

Trends in rainfall and streamflow observation series in the Grand-Duchy of Luxembourg

The analysis of the trends in the rainfall-runoff relationship was extended to the Grand-Duchy of Luxembourg, in order to detect a possible spatial variability in the trends.

Positive trends in winter rainfall totals due to westerly atmospheric fluxes revealed to be statistically significant (z_T values ranging from 2.1 to 3.3, with $z_\alpha = 1.66$ at 5% significance level). Moreover, the maximum duration of a single rainfall event during winter also showed a significant positive trend in 12 of 13 raingauge stations (z_T values ranging from 0.39 to 4.34, with $z_\alpha = 1.66$ at 5% significance level).

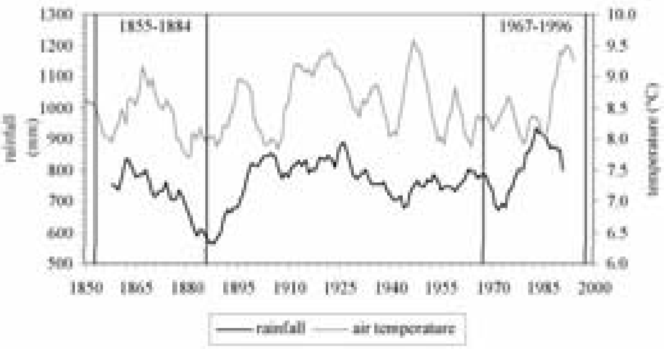

FIGURE 5 **The two hydro-climatological normals in a long-term record context in Luxembourg-city (5-year moving averages of annual rainfall and mean annual air temperature).**

As shown in Fig. 4, the mean annual increase (mm/year) over the past 50 years of rainfall due to westerly atmospheric fluxes varies from 5.0 mm/year in the western part of the Grand-Duchy of Luxembourg to 2.5 mm/year in the eastern part.

Likewise to the positive trends in winter rainfall characteristics, winter maximum daily water levels have been subject to overall positive trends (Fig. 1), with z_T values ranging from 0.81 to 4.48 (with $z_\alpha = 1.66$ at 5% significance level). For most streamgauge stations, a significant positive trend in maximum daily water levels during the winter semester could thus be determined.

Estimated hydrological changes between the 19th and 20th century

Changes observed from historical data

Two climatological normals were used for intercomparison of the past (19th century) and present (2nd half of the 20th century) climate: 1855-1884 (the only daily dataset available for the 19th century) and 1967-1996 (a period considered as having already been subject to ongoing changes in climate). The statistical characteristics of the recent normal were determined with validated data measured at Findel station (Luxembourg airport). Interannual long-term variability in annual rainfall and temperature time series for Luxembourg-city shows different evolution patterns of both variables during the two selected hydro-climatological normals (Fig. 5). No visual trend can be detected for the air temperature series, with nonetheless some alternation of warmer and colder periods. Annual rainfall totals were most of the time comprised between 650 and 850 mm, except for the end of the 19th century (580 mm) and the end of the 20th century (900 mm). The climatological mean temperature is 8.8°C for the twentieth century normal and 8.3°C for the nineteenth century normal. Between these two 30-year periods, no clear trend can be detected. Annual rainfall in the second half of the 20th century has reached a higher level comparatively to the 1890s. Whilst the temperature signals are similar at daily and monthly time steps, the historical temperature series is characterized by the occurrence of colder temperatures than today for most months throughout the year (Figs. 6A and 6B).

The increase of warmer air masses driven by westerly airflows, especially significant in December-January-February, and the cloudiness conditions observed in northwestern Europe in summer since WWII could explain this observation. Warmer conditions than today could be found in historical temperature series for February, April and June for which the influence of westerly atmospheric circulation on the temperature regime is less pronounced in the recent temperature series.

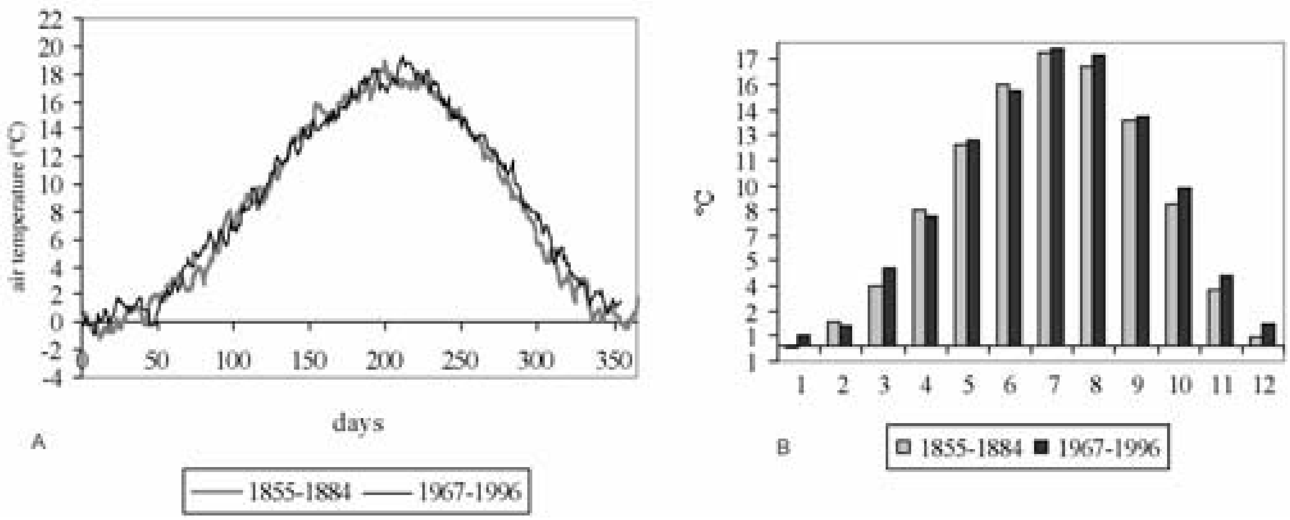

FIGURE 6 **Courses of mean interannual daily temperature (A) and of mean monthly temperature (B) for the past and the recent climatological normals in Luxembourg-city.**

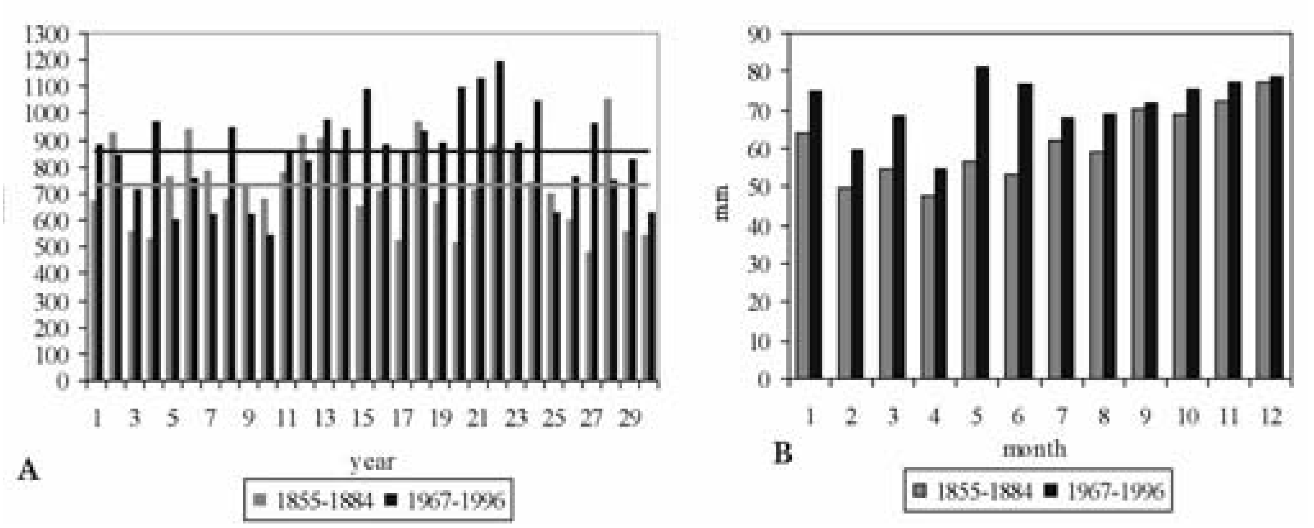

FIGURE 7 | **Annual (A) and monthly (B) rainfall distribution for the past and the recent climatological normals in Luxembourg-city.**

Analysis of rainfall totals and variability is of highest interest in a hydrological perspective, since it is the first order factor in streamflow generation for temperate oceanic catchments. Different rainfall variables were investigated for the two hydro-climatological normals (seasonal totals, daily variability, maximum rainfall event). The annual distribution clearly shows that rainfall totals were more important during the second half of the twentieth century (Fig. 7A), due to the influence of enhanced westerly airflows (see above). Annual totals can reach up to 1200 mm for recent observations, but do not exceed 1050 mm in historical series. The 30-year mean is 730 mm for the historical rainfall series and 855 mm for the recent rainfall series. As monthly temperature was lower during the 19th century period, the snowfall measurement deficit is likely to occur more frequently in the historical rainfall series than in the 20th century normal.

Winter rainfall totals can therefore be slightly underestimated for the 19th century. Monthly distribution of the 20th century rainfall totals (Fig. 7B) is bimodal (high totals centred in May-June and December-January, low totals centred in February-April and July-August), whereas a unimodal distribution is characteristic of historical rainfall totals (high totals centred in winter and low totals centred in spring and summer). For both normals, the driest month is April, while May and December are the

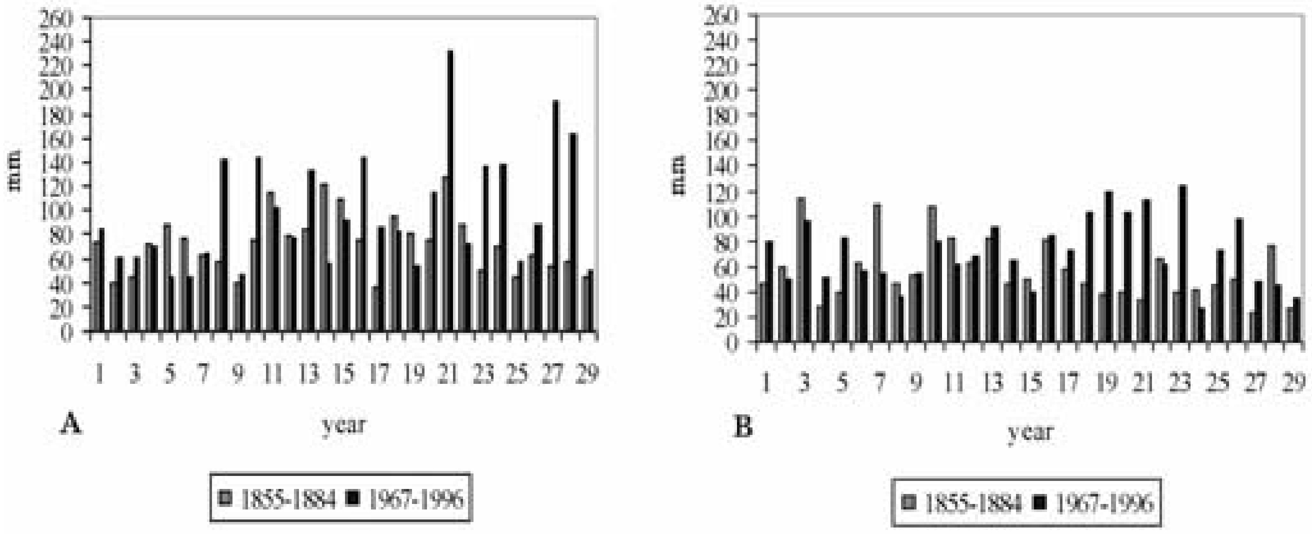

FIGURE 8 | **Distribution of maximum rainfall due to a single event in winter (A) and summer (B) for the past and the recent climatological normals in Luxembourg-city.**

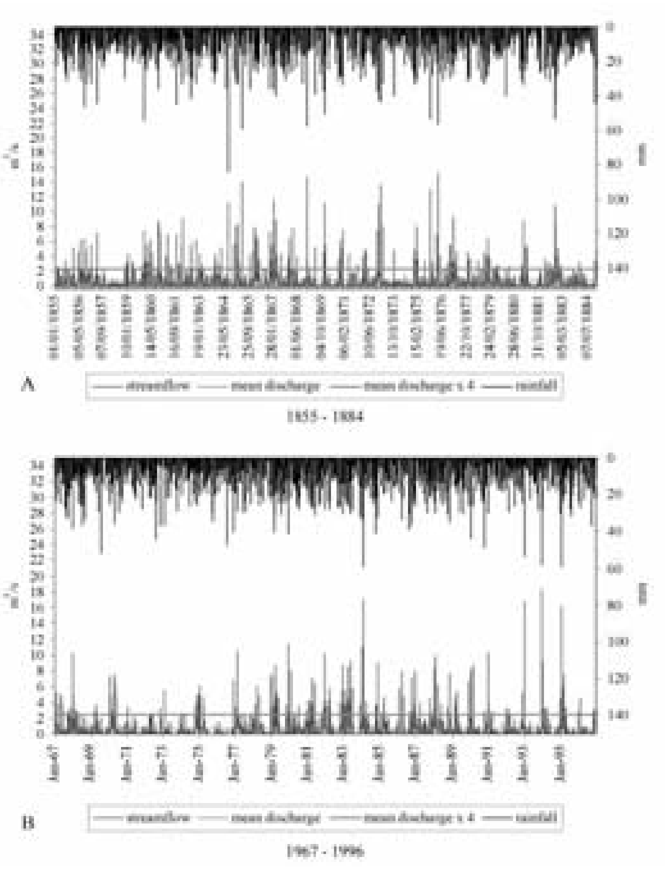

FIGURE 9 **Rainfall-runoff series for the two hydroclimatological normals.**

wettest months respectively for historical and recent observation series.

The seasonal variation of maximum single rainfall events (rainfall occurs during consecutive days with rainfall intensity > 0.1 mm) shows the occurrence in winter of massive rainfall events during the second half of the 1967-1996 normal, totalizing in certain cases more than 200 mm during a single event of a few days (Fig. 8A). Such rainfall events were not recorded during the 1855-1884 normal, characterized by a decrease in total rainfall due to a single event. In summer, patterns of maximum rainfall due to a single event clearly show the wetter conditions prevailing in the 20th century normal (Fig. 8B).

As a conclusion, the 1855-1884 normal was characterized by drier conditions (lower interannual mean), minimum rainfall totals in spring, maximum rainfall totals in winter and shorter and less intense rainfall events throughout the year.

Changes in the rainfall-runoff relationship estimated from hydrological modelling

The HRM model was applied to the Eisch catchment to simulate the streamflow regime under the retained past and recent hydroclimatological normals using rainfall and Hamon Potential Evapo-Transpiration (PET) series. The calibration of the HRM model was performed with data obtained at a streamgauge station installed in 1997 on the Eisch river near Hagen and measuring at a 15-minute time-step. The past (HH) as well as the recent (RH) expected rainfall-runoff relationships of the Eisch river for the 30-year period are drawn in Figs. 9A and 9B. Mean interannual discharges are sufficiently close (0.56 m^3/s and 0.61 m^3/s, respectively for HH and RH) to justify the comparison of flood day populations. 536 occurrences of flood days defined as a day with mean discharge exceeding 4 times the mean interannual discharge were identified for HH and 560 for RH. The flood risk is thus more important on average for the recent period, but this remark is no longer valid from a seasonal point of view.

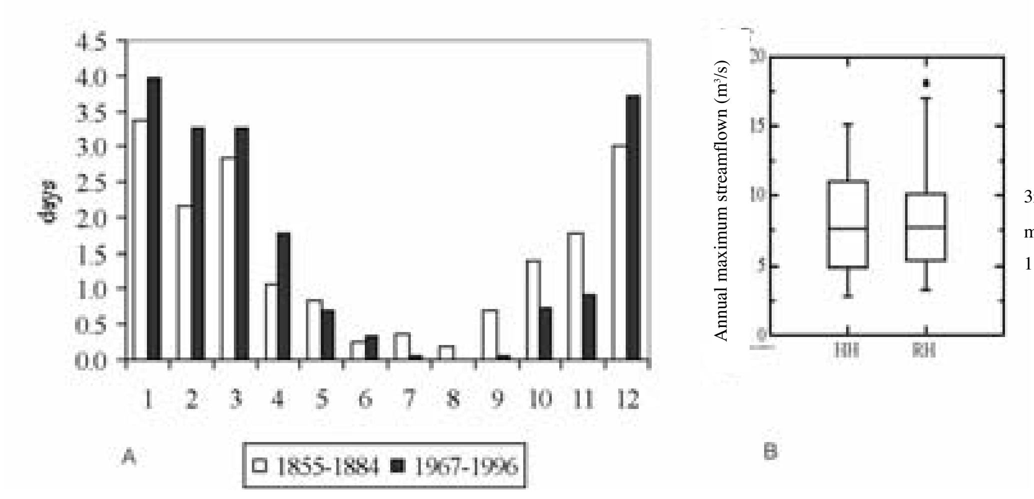

FIGURE 10 **Monthly distribution of the mean number of flood days (A) and annual maximum discharges (B) (30 values).**

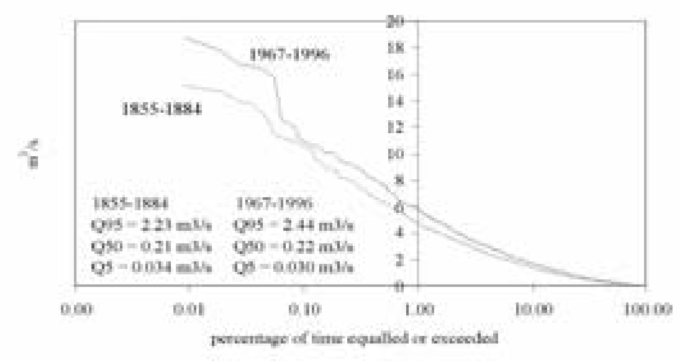

FIGURE 11 **Flow duration curves for past and recent normal hydrographs of the Eisch river at Hagen.**

Massive rainfall events during the recent period generate saturated conditions in the Eisch catchment, therefore producing more direct stormflow. Winter rainfall totals are nonetheless insufficient to maintain such conditions in summer due to greater evaporative conditions, particularly in August where no flood days were recorded for RH against a few occurrences for HH. Note that under globally warmer conditions any increase in rainfall will allow evaporation to reach the potential level more often (Evans and Schreider, 2002) accelerating the water recycling.

Monthly distribution of the mean number of flood days shows that during the annual July-November period, the Eisch river was more subject to high water levels in the second half of the nineteenth century than in the recent period, while it was the opposite in wintertime (Fig. 10A). The box plots of maximum peak flows (Fig. 10B) suggest that the HH and the RH were generally comparable in magnitude for the median and the first quartile, whereas highest peak flow values exceeding 16 m^3/s were simulated in RH series. Inversely, the third quartile of maximum discharge data is higher for HH series, as well as the interquartile range, denoting the greater variability of high water level extremes.

Figure 11 shows that, as a result of colder temperatures, but lower rainfall totals throughout the year, streamflow was lower in the 1855-1884 period, compared to the 1967-1996 period. While median and small percentiles of the flow duration curves are similar for the two normals, deviations are much more pronounced for high discharges, with a greater magnitude of rare floods for the recent period (exceeding 16 m^3/s). This observation simply results from the effect of non-linearity in the simulated rainfall-runoff relationship, according to variable antecedent moisture conditions between the two studied periods.

CONCLUSIONS

In the Grand-Duchy of Luxembourg, climatological observations through the 19th and 20th century have shown a clear trend towards higher winter rainfall totals, as a consequence of changes in the dominating atmospheric circulation patterns. As a result, over the past decades a clear trend towards higher winter maximum water levels has been detected.

The comparison between the reconstructed and observed rainfall-runoff series for a tributary of the Alzette river that has been subject to little changes in land use over the past 150 years has confirmed the above findings by indicating a change of the hydrological regime with a higher number of winter and a lower number of summer flood days in the last decades compared to the second half of the 19th century.

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