

Monitoring of Severe Floods in the Upper Mosel Basin: the Need for a High Spatio-Temporal Density Experimental Network

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Abstract: Hydro-meteorological data of high spatio-temporal resolution have been exploited since the mid-1990s for environmental research in the Grand Duchy of Luxembourg. Examples of ongoing field observations are given in this paper, with a special emphasis on the large hydro-meteorological event of January 2003, which generated severe inundations in the floodplains of the main Luxembourgish tributaries (Alzette and Sûre rivers) of the upper Mosel river. The large rainfall-runoff event of January 2003 was well documented through a single hydro-meteorological database collected *via* dense rain- and stream-gauge networks, set up by three institutions of the Grand-Duchy of Luxembourg (Public Research Center-Gabriel Lippmann, Ministry of Interior and Ministry of Agriculture). Different maps, derived from ground-based measurements of the January 2003 flood, illustrate the relationship between the spatio-temporal distribution of rainfall intensities, runoff contributing areas, as well as the propagation of flood waves in the channel network. Of particular interest is a better estimation of flood peaks related to heavy rainfall intensities, as well as an enhanced understanding of the influence of the geological substrate on the rainfall-runoff relationship with high antecedent saturated conditions. However, monitoring streamflow during such a large event, remains a difficult task owing to the uncertainty related to the rating-curves for high water stages.

Keywords: Ground-based measurements; Large rainfall-runoff event; Flood processes; Grand-Duchy of Luxembourg

1. INTRODUCTION

Since the mid-1970s, the magnitude of oceanic floods during wintertime and the repeated inundations occurring in Western Europe, have caused considerable economic loss and led to an increased social demand for prevention of such extreme rainfall-runoff events. A better understanding of basin hydrology (scale effect, hydrological processes) and flood propagation involved in severe flood occurrence, would benefit from dense experimental networks, both in space and time, as recommended in the PUB (Prediction in Ungaged Basins) initiative [Sivapalan et al., 2003]. Continuous and long-term rainfall-runoff measurements on gauged and representative basins in a given region, are indeed the best way to analyse their hydrological behaviour for various physiographic conditions and therefore to reduce the uncertainty in designing and transposing for example process-oriented rainfall-runoff models. After a brief description of the observation gauges set up in the Grand-Duchy of Luxembourg, hydro-meteorological aspects of the well-documented severe January 2003 flood are presented. This

paper also demonstrates that monitoring severe flood events helps improving rating-curves at gauging stations and in turn, the quality of hydrological series as well as the estimation of hydrological model parameters.

2. DESCRIPTION OF THE EXPERIMENTAL NETWORK

2.1. Meteorological instruments

Since 1947, a set of 12 historical daily manual raingauges, homogeneously distributed throughout the Grand-Duchy (2586 km²), was installed by the Ministry of Agriculture. During the same time, a synoptic station ran in the Luxembourg airport for monitoring other climatic variables. This historical network was completed in the 1990s by a set of real-time automatic meteorological stations collecting precipitation and temperature every minute (Ministry of Interior and Ministry of Agriculture). Twenty-three real-time raingauges, including one Belgian raingauge, were used to document the spatio-

temporal distribution of rainfall during the flood event of January 2003 (Figure 1).

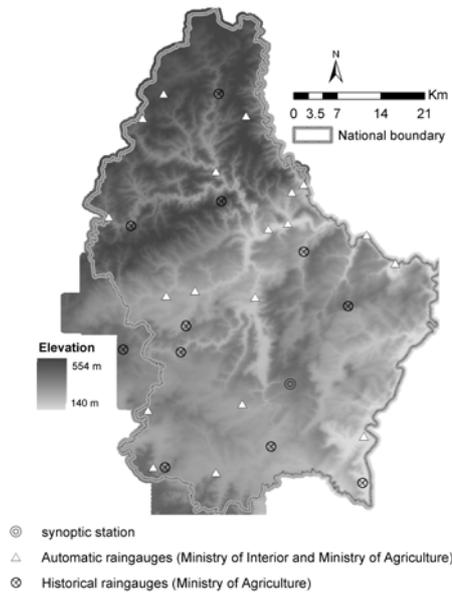


Figure 1. Rain gauge network and relief in the Grand-Duchy of Luxembourg.

2.2. Hydrological monitoring

After the devastating floods of December 1993 and January 1995 in the Sûre floodplain, the Ministry of Interior and the Ministry of Agriculture of the Grand-Duchy of Luxembourg decided to equip the main Luxembourgish rivers with automatic gauging stations, except in the eastern part of the country (Figure 2). Since then water levels have been recorded every 15 minutes at numerous points of the channel network drained by the Sûre river. Drainage areas of monitored sub-basins range from 7.3 km² to 3222 km² (Figure 2). The mean basin altitudes range from 295 to 500 m.a.s.l. Some gauged basins are homogeneous from a lithological point of view, with essentially marls or schists, while the other basins are composites with marls, limestone, sandstone and schists (Figure 2).

The geological formations and topography partially condition the land use patterns. Thus, in general, agricultural areas coincide with marls and flat areas and forested areas with sandstones/schists on steep slopes. Most basins can be considered as rural and forested. Due to the important geological heterogeneity of the Alzette river basin (Figure 2), the Public Research Center-Gabriel Lippmann decided at the end of the 1990s, to set up a complementary streamgauge network aiming at sampling outflow data for small tributaries lying on the principal geological formations (limestones, marls,

sandstones, schists). The whole present rainfall-streamgauge network operates continuously since 1997. The data recorded by the public authorities and used to document the January 2003 flood were directly downloaded with the HYDRAS 3.0 software [OTT, 1999], used as a rainfall-runoff database.

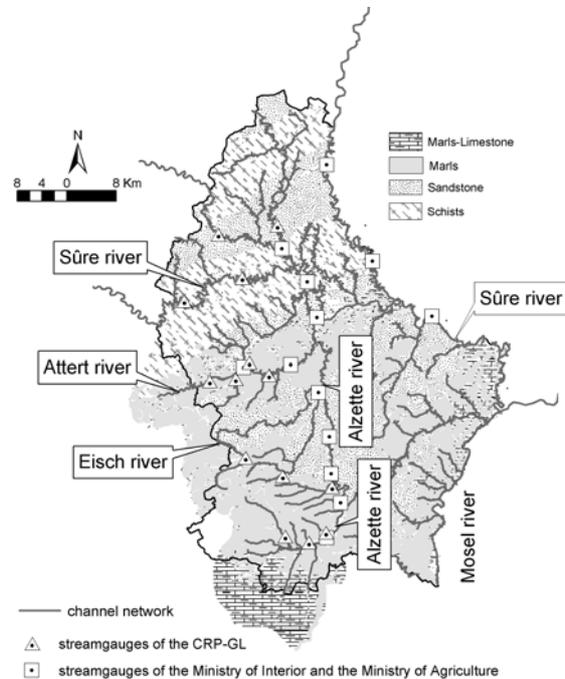


Figure 2. Streamgauge network and geological background in the Grand-Duchy of Luxembourg.

3. PRE-EVENT CONDITIONS OF THE JANUARY 2003 FLOOD OCCURRENCE

3.1 Meteorological records

Rainfall events were unevenly distributed during the first part of winter. October and November had experienced a large surplus of rainfall, between 40 and 70 % above the decennial mean 1990-2000, whereas December was below the decennial mean, between -5 and -30 % [Pfister et al., 2003].

3.2 High saturation level of soils

Due to the abundant rainfall totals occurring during the early winter, soils became saturated. Photographs taken a few days before the large rainfall of January 2003, show evidence of groundwater resurgence in many parts of the Alzette floodplain (Figure 3). The water balance determined for the Alzette at Hesperange (291 km²) rose regularly during autumn and reached 210 mm (near the maximum storage capacity) on

December, 31. At this point, the infiltration rate of soils was considerably reduced.



Figure 3. Groundwater resurgence in the Alzette floodplain upstream of Hesperange on December 29th 2002 (Photograph: Matgen P.)

4. HYDROMETEOROLOGICAL ASPECTS OF THE JANUARY 2003 FLOOD

4.1 The rainfall episode

Synoptic situations prevailing during the January rainfall episode were of Wz type (westerly atmospheric airflows) according to the Grosswetterlagen classification [Hess and Brezowski, 1977]. The rainfall began around mid-day of January 1st. The first of the three intense rainfall events occurred on the evening of January 1st. At that time, 24-hour accumulation was on average around 28 mm with two poles, one in the north and a second one larger, in the central-western part of the country (Figure 4-A). The second intense rainfall sequence took place on January 2nd and affected mostly the western side of the country (Figure 4-B). The latter received an area-average rainfall exceeding 30 mm.

Finally, a third rainfall cell was identified in the north of the country in the evening of January 2nd (Figure 4-C). Based on historical rainfall series (1954-2003), return periods of 48-hour total rainfall fallen on 01st and 2nd January was calculated for 4 raingauges. The highest return value was obtained for the Koerich rain gauge ($T = 64$ years) located in the central-western part of the Luxembourg, while the lowest value was concentrated in the eastern part ($T = 8.5$ years). Total rainfall in 24h had a moderate return period in the north of the country ($T = 19$ years). Total rainfall amounts during the entire rainfall episode were more abundant in the north and the central part of the Grand-Duchy (around 80 mm) rather than in the extreme south, less affected by the intense rainfall (around 55 mm).

4.2 The variability of hydrological responses

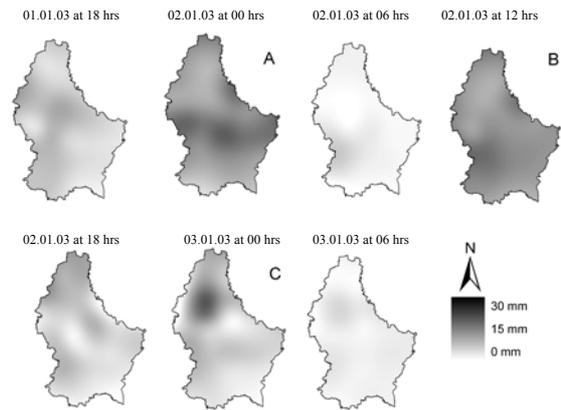


Figure 4. Successive 6-hourly total rainfall maps during the January flood [after Pfister et al., 2003].

The heterogeneous spatio-temporal distribution of rainfall totals during the January 2003 flood led to a wide range of streamflow patterns. Different rainfall-runoff responses corresponding to physiographic representative basins are illustrated in Figure 5.

The structure of observed hydrographs in small mainly rural sub-basins ($7.3\text{--}47.3\text{ km}^2$) located in the central-western part of Luxembourg resembles the time structure of hyetographs. After a quick rising limb, the two main flood peaks (e.g. Figure 5-A) are separated by a recession period corresponding to a sequence without rainfall. Values of specific discharge can reach very high levels (around $700\text{ l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$, Figures 5-A and B) for small basins but rapidly decrease with higher drainage areas (Figure 5-C). On the opposite to this quick reactive hydrological response, probably due to the infiltration excess overland flow and saturation excess on dynamic contributing bottom areas, sub-basins dominated by forested areas and schists (Figures 5-D, E) are characterized by a slow rising limb, without recession during the period with no rainfall.

A unique specific peak discharge of medium magnitude (no more than $400\text{ l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$) occurred after the two first rainfall events (Figure 5-D) or even after the rainfall event (Figures 5-E), depending on the size of the basin. This hydrological behaviour indicates that, runoff generation processes in forested schistose basins were dominated by slow but continuous sub-surface stormflow in thin soils. The lowest water yields ($<250\text{ l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$) were found for a sub-basin where schists and sandstones are present (Figure 5-F). But in this case, the time structure of the hyetograph is well reproduced, probably due the influence of near river saturated zones acting in the deeper alluvial soils developed on sandstones.

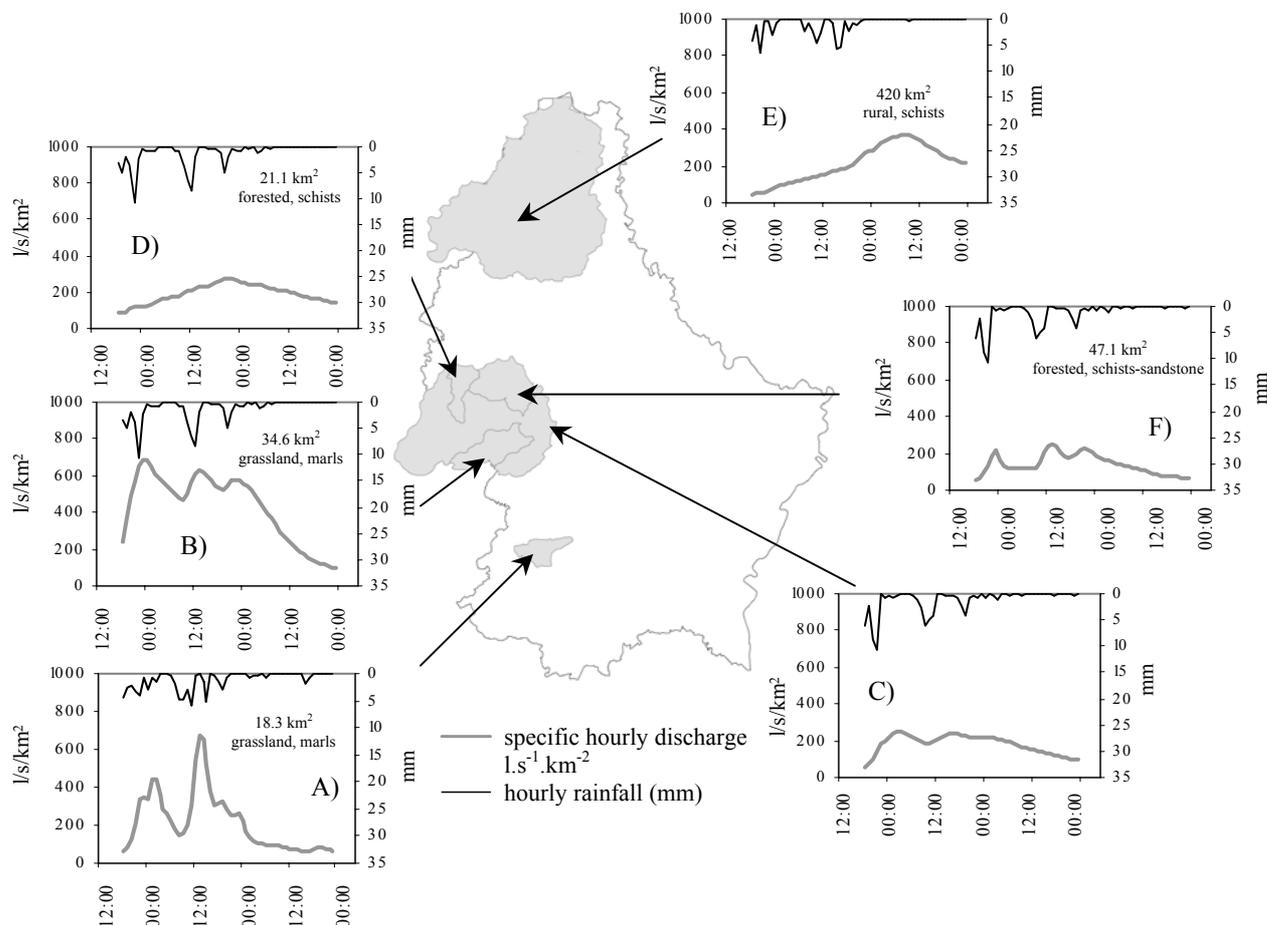


Figure 5. Hourly rainfall-streamflow relationship in some sub-basins during the January 2003 flood.

The downstream evolution of the raw discharge into nested gauging stations illustrated for the Attert and the Alzette basins (see Figure 2 for location), indicate an increase of the magnitude of the peak discharge from upstream to downstream, except for two stations, Reichlange and Useldange. The latter should record higher discharge values due to the contribution of the Roudbaach river (Figure 6-A). This could be the evidence of an incorrect rating curve for high water levels in one of the two stations.

In the Alzette river basin, the presence of an alluvial plain between Livange and Hesperange controls the evolution of the downstream raw discharge values. The alluvial plain acting both by decreasing the magnitude of peak flows and by increasing the time lag of the basin (Figure 6-B).

4.3 Dynamics of the runoff contributing areas

The panel of maps represented in Figure 7 clearly shows that water yields from tributaries of the Alzette river rapidly rose in conjunction with the first major rainfall, mainly concentrated in this area (Figure 7-A). As the specific discharge continued to grow in the Alzette river basin, the second rainfall sequence generated an increase of water yields from the northern tributaries

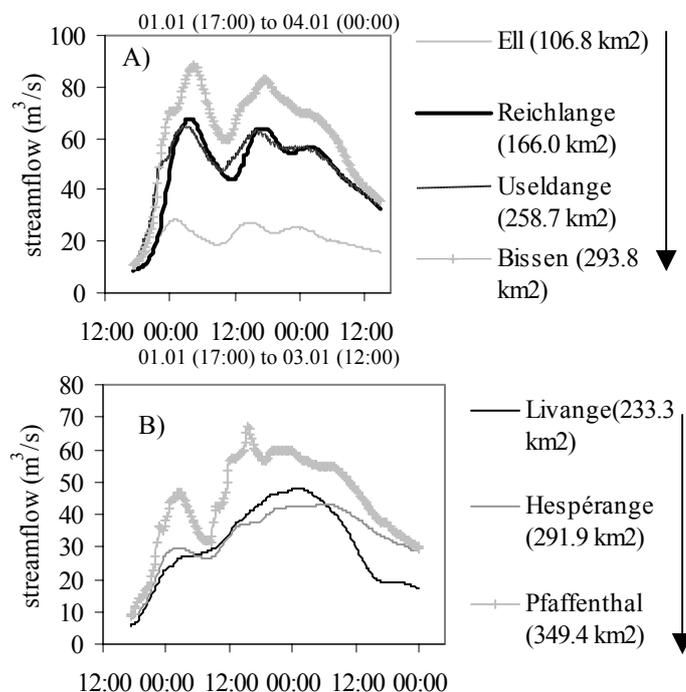


Figure 6. Evolution of the hourly peak discharge downstream to the Attert river (a) and the Alzette river upstream of Luxembourg City (b) during the January 2003 flood.

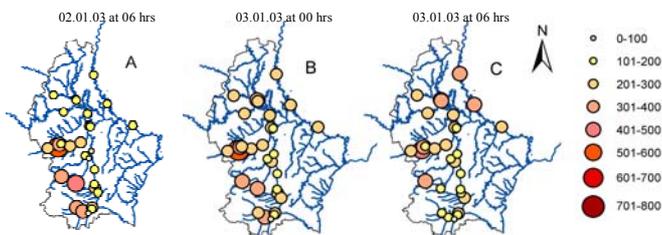


Figure 7. Successive 6-hourly peak water yields (in mm) of gauged sub-basins during the January 2003 flood [after Pfister et al., 2003]

(Figures 7-B, 7 C) with a delay of 12 hours on average compared to the south.

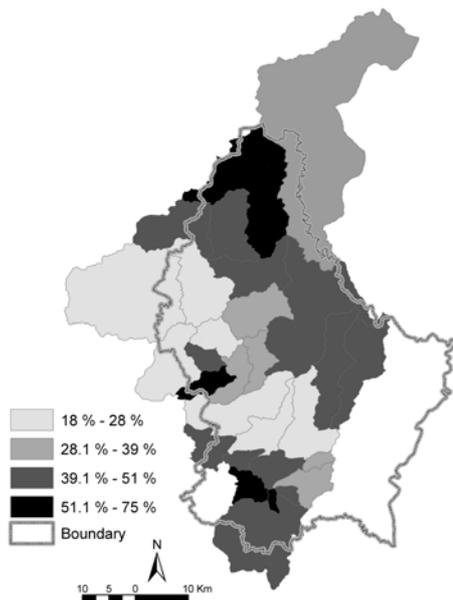


Figure 8. Stormflow coefficient for the different gauged sub-basins during the January flood 2003 [after Pfister et al., 2003].

Apart from the spatial distribution of rainfall, the influence of geological substrate on specific discharge is also clearly perceptible on Figure 8. Highest stormflow coefficients are found for small and medium impervious basins (i.e. dominated by marls and schistose formations) with values up to 40 % and a maximum of 75 % in the north of the country. The influence of the permeable liasic limestone and triassic sandstones led to highest water retention during flood generation.

4.4 Analysis of the flood propagation waves

The time to peak of gauged basins (Figure 9) was strongly contrasted between the north and the south of the country. The southwestern tributaries of the Sûre river reacted generally quickly with times to peak less than 12 hours (Alzette river basin). Those were longer in the northern tributaries of the Sûre river due to a less intense but longer rainfall event in the north of the Grand-Duchy.

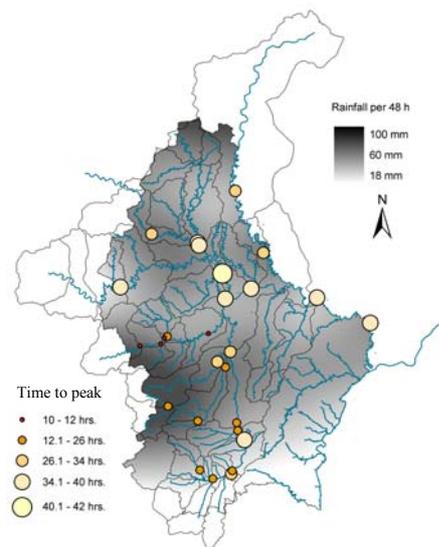


Figure 9. Spatial distribution of the time to peak for the gauged sub-basins of the Sûre river at Bollendorf [after Pfister et al., 2003].

The importance of sub-surface flow in flood generation in schistose basins can also explain this delay in the time to peak.

5. THE CHALLENGE FOR REDUCING UNCERTAINTY IN HYDROMETRIC MEASUREMENTS

The above analysis of rainfall-runoff observations has shown the need for dense spatio-temporal experimental networks for the large data set it may provide. The latter is required faced with the large variability of hydrological basin responses and outflow quantities at meso-scale. But this data set may inevitably contain measurement errors and it is well known that performance and optimal parameter estimation of lumped rainfall-runoff model are conditioned by an accurate estimation of input data, especially discharge values [Zin, 2002]. The efficiency of model parameter regionalization is also strongly dependent on the quality of hydrological series, since the estimation of hydrological parameters at ungauged basins is frequently made through relationships between local optimal parameter values and physical basin descriptors e.g. [Drogue et al., 2002]. Different sources of uncertainty in hydrometric data can be analysed : the water stage measurement error, the form of the rating-curves, etc. [Clarke, 1999]. The occurrence of the January 2003 flood was an opportunity to complete the rating-curves of some gauging stations for high water stages. An example of a substantial modification of the terminal form of a rating-curve and therefore derived streamflow values is given in Figure 10 for the Eisch river (47.2 km²). The upper daily peak flow series (Figure 8-A) was determined by selecting all streamflow values exceeding 4 times the average

streamflow for the period 2001-2003. The rating-curve was fitted without the gauging point of the January 2003 flood. The peak flows series in Figure 8-B was obtained according to the same over-threshold method with the new rating curve including the high water stage-discharge point of the January 2003 flood.

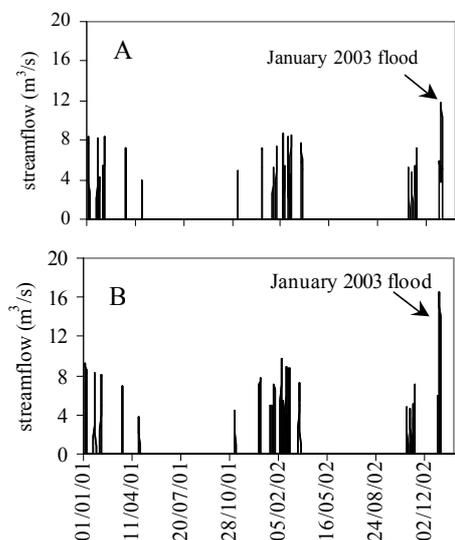


Figure 10. Magnitude of peak flows for the river Eisch at Hagen with the old rating curve (A) and the new rating curve (B) including the measurement point of the January 2003 flood.

A slight increase of medium peak flows magnitude resulted from the new function used to calculate discharge from water stages (Figure 10-B vs Figure 10-A), but the maximum peak flow of the January 2003 flood would have been largely underestimated with the old version of the rating curve. This means that uncertainty related to the form of the water stage-discharge relationship of gauged basins, especially strong in extrapolation, should be included in the analysis between measurement error and parameter estimation before any prediction on ungauged basins. Incorporation of confidence intervals of the regression fit of water stage-discharge relationships in model parameter estimation could help to achieve this objective.

6. CONCLUSIONS

The January 2003 flood affecting part of the upper Mosel basin was the first large meso-scale rainfall-runoff event, which could be monitored with high spatio-temporal resolution rainfall-runoff data in Luxembourg. Dense ground-based measurements were necessary to have a representative image of where the stormflow came from and how it was distributed in space and time according to the rainfall and physical background of gauged basins.

In the future, efforts must be made in order to ensure the maintenance and the reliability of gauging stations, in particular by improving the existing rating-curves. More studies about the effect of measurement errors of observed streamflow data in rainfall-runoff modelling should be realized for reducing the prediction uncertainty in ungauged basins.

7. ACKNOWLEDGEMENTS

The authors wish to thank M. R. Kipgen and F. Wohl (from the Ministry of Interior, Grand-Duchy of Luxembourg) and R. Schoder, C. Wiltgen and D. Buchel (from the Ministry of Agriculture, Grand-Duchy of Luxembourg) for their kind collaboration.

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