Flood interpretation in case of measurement failure. The Wamme River in 2021.

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ABSTRACT: During the extreme flood events that occurred in Belgium in July 2021, several measuring devices failed before the flow peak. This was the case at Hargimont on the Wamme River, where it appeared difficult to interpret the event a posteriori and to reconstruct reliable time series of water levels and discharges. However, such interpretations are essential to help decision-makers to mitigate similar risks in the future. Most of the time, the measurement failure is clearly visible, and misinterpretation can be easily avoided. However, in some other cases, such as here, measurements seem to be recorded normally, whereas it was not the case because of clogging of a gauge, or displacements of the device. Using a combination of hydrological and hydraulic modelling, it was possible to highlight the erroneous measurement and to propose a corrected hydrograph.

1 THE FLOOD OF JULY 2021

The catastrophic flood event in Belgium and Germany in July 2021 caused a high number of casualties and material damages. Only in the Eastern part of Belgium, 39 people died. The meteorological event was due to a blockage of the weather situation. It was so extreme, and much worse than what had been observed before, that the return period is not yet firmly established and could vary between 100 and 1000 years, depending on the methodology used.

One of the most concerned valleys in the southern part of Belgium was the Lhomme River, a tributary of the Lesse River, which is one of the main tributaries of the Meuse River (Fig. 1).

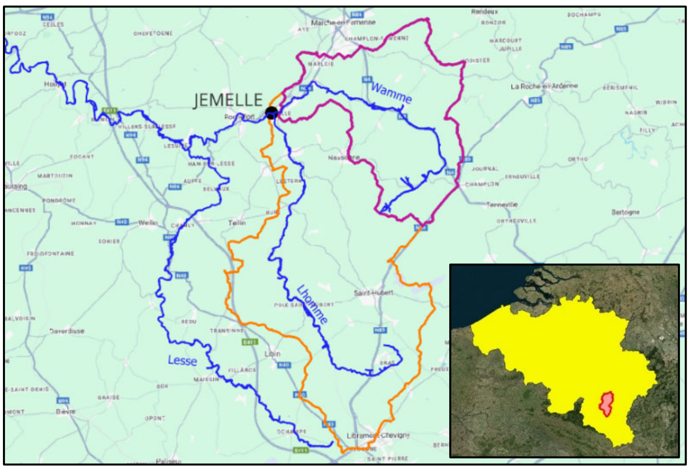

Figure 1. Location of the Lhomme (color orange) and the Wamme (purple) watersheds in Belgium.

Figure 2. City of Jemelle along the Wamme River (OpenSteetMap).
Above: maximum inundation depth (in meters) during the July 2021 flood
Below (detail): maximum inundation depth in centimeters

The city of Jemelle was especially affected by the flood. It is located at the confluence of the Lhomme River and its main tributary, the Wamme River. The area of the watershed of the Lhomme River at Jemelle is 416 km^2, including the 140 km^2 of the Wamme watershed. Figure 2 depicts the flooded area in the lower reach of the Wamme, just before its confluence with the Lhomme. Close to the river, along the “Rue de la Wamme”, the water height reached almost 2 meters, and even houses of the “Avenue de Ninove” were flooded. The figure also shows the tunnel that was built during the 19th century allowing the Wamme to pass below the railway linking Brussels to Luxemburg. A second tunnel further south was built for the road and leads to the “Avenue de Ninove”. In 2021, the Wamme tunnel acted as an obstacle to the flow inducing such a water rise upstream that even the road tunnel was invaded and contributed to a second source of flooding of the “Avenue de Ninove”.

In order to prevent or at least mitigate such catastrophic events in the future, it is essential to understand what happened, because such an extreme event had never been observed before. This requires an accurate estimation of water levels and discharges.

2 RAINFALL AND DISCHARGE MEASUREMENT

2.1 *The measurements during the flood of July 2021*

Accurate measurements are not easy to obtain in case of extreme events. Indeed, many of the measuring devices failed before the flow peak in July 2021. The rain gauge network was not too much affected, in contrast to the hydrometric stations: some of these have been clearly broken by the flood while some others were dysfunctional without it being clearly noticeable. This latter situation is of course the most damaging for a posteriori interpretation.

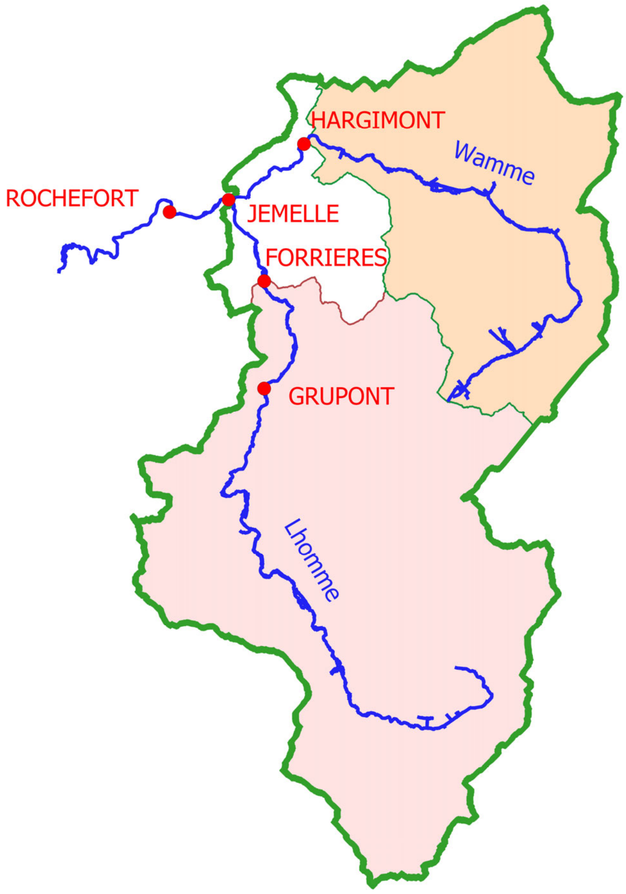

Figure 3. Limnimetric stations and corresponding watersheds along the Lhomme and Wamme rivers.

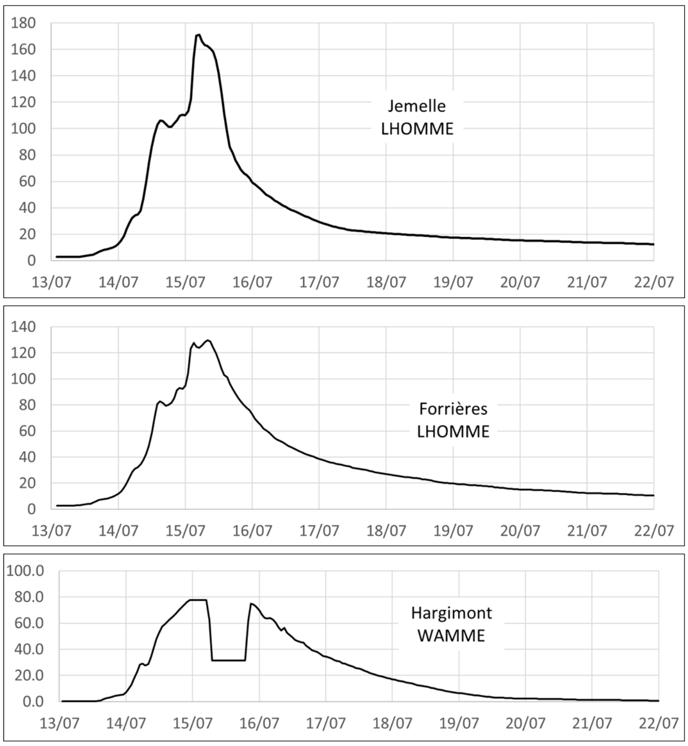

Figure 4. Discharge (m^3/s) of the Lhomme at Jemelle and Forrières and of the Wamme at Hargimont in July 2021.

Figure 3 shows the available hydrometric stations in the concerned region. The measurements of at least three of these stations are required to interpret what happened in the city of Jemelle: the discharge at Jemelle (watershed: 415 km^2) and Forrières (watershed: 247 km^2) on the Lhomme and the discharge at Hargimont (watershed: 129 km^2) on the Wamme. Figure 4 presents the three hydrographs in July 2021.

2.2 *Measurements analysis*

It clearly appears that the discharge at Hargimont, which is the most relevant for the flood description along the Wamme at Jemelle, presents a gap that was curiously replaced by a constant discharge during the failure time. Moreover, this constant discharge proposed by the measurement manager to replace the missing measurements during the peak time is obviously an underestimation of the real maximum discharge.

The water level recorded at the station Hargimont is represented in Figure 5. Two particularities can be observed: a linear rise between July 14 12:00 and July 15 02:00, which probably corresponds to a simple straight line drawn between two measurement points, and a sudden decrease from 2.13 to 1.50 m. Such a decrease, translated in terms of discharge, would mean an instantaneous decrease from 80 to 35 m^3/s, which is physically impossible. The hydrograph of the Wamme at Hargimont is thus clearly not realistic. In fact, it was discovered that the tube containing the measurement device had been moved by the flood, which explains why data were still recorded but with significant errors.

Contrarily to Hargimont, the Forrières hydrograph seems a priori realistic. However, looking at the water level measurements at the bridge just downstream of the hydrometric station (Fig. 6), it can be observed that the maximum water level was very close to the bridge desk, resulting in a high probability of a partial submersion of the bridge affecting the discharge estimation.

Further analyzing the data, it could have been expected that the sum of the discharges of the Lhomme at Forrières and of the Wamme at Hargimont should be lower than the flow rate of the Lhomme at the Jemelle station. Instead, it is just the opposite (Fig 7): the discharge at Jemelle never exceeds the sum of the two discharges measured at the upstream stations.

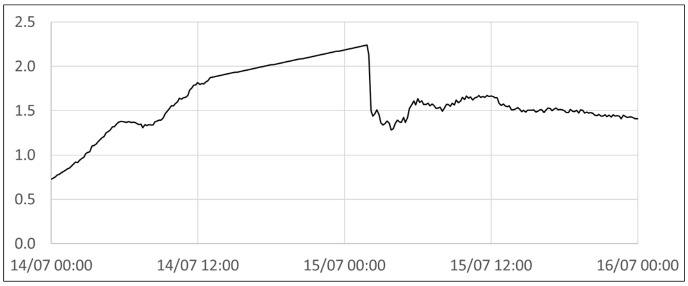

Figure 5. Water level at the station of Hargimont in July 2021 (marks on the limnimetric scale in meters)

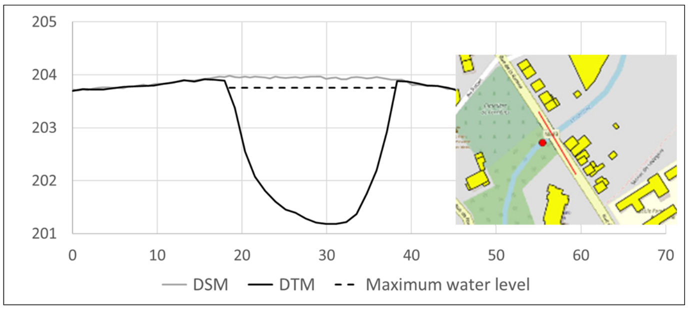

Figure 6. Station Forrières: cross section of the bridge downstream of the measurement device. Sections from Digital Surface and Terrain Models; dotted line: maximum water level observed in July 2021.

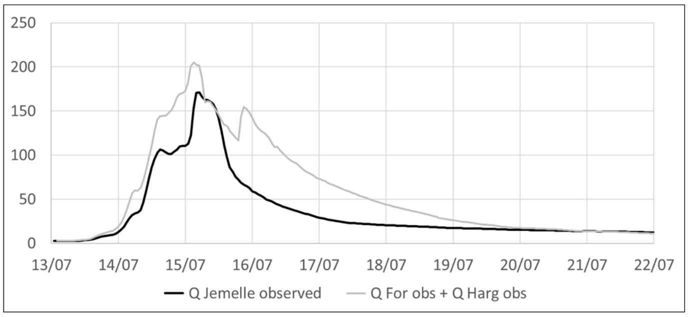

Figure 7. Discharge of the Lhomme at Jemelle compared to the sum of the upstream discharges.

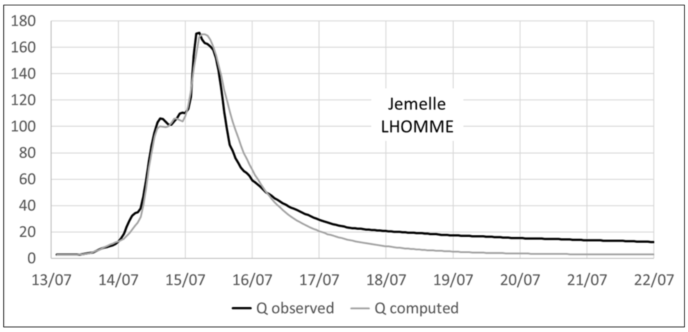

Figure 8. Station of Jemelle: computed (ATHYS model) vs. observed discharge (m^3/s).

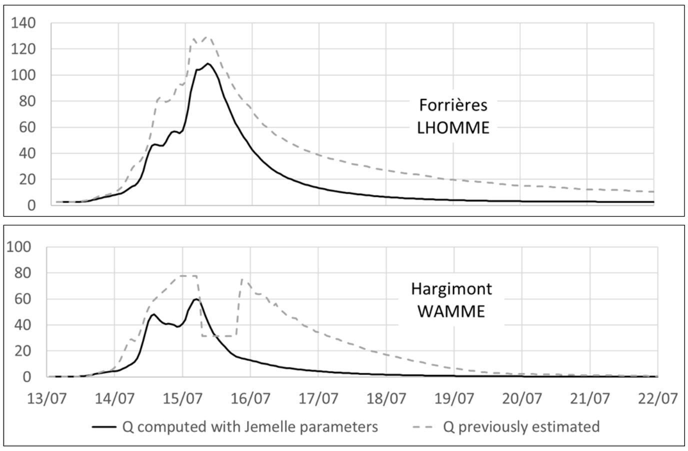

Figure 9. Restored hydrographs (m^3/s) at Forrières and Hargimont using the model calibrated at Jemelle.

Table 1. Volume (in 10^3 m^3) flown at the hydrometric stations.

Station:	Forrières	Hargimont	Forrières + Hargimont	Jemelle
Volume July 13-16	18,904	12,911	31,815	20,344
Volume July-August 2021	46,000	21,797	67,797	48,771

This observation is confirmed by considering the volumes of water either during the mid-July event or during a longer period (Table 1). A volume loss could possibly be explained by karstic phenomena diverting a part of the flow, but such an explanation does not hold anymore for a long period of time.

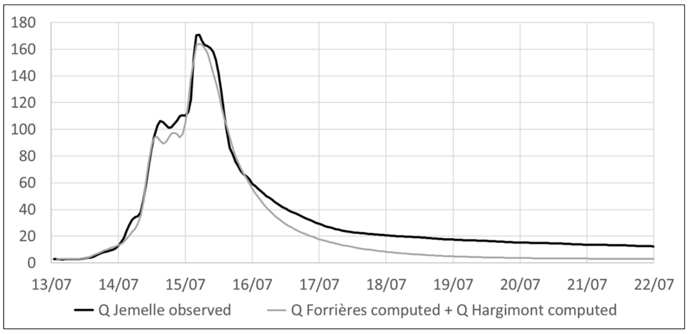

Figure 10. Discharge (m^3/s) of the Lhomme at Jemelle compared to the sum of the computed discharges of the Lhomme at Forrières and the Wamme at Hargimont.

The conclusion of the analysis is that the observed discharges must be revised. Fortunately, in contrast to the two upstream stations, the Jemelle station on the Lhomme appeared to be more reliable, mainly because no risk of submergence exists for this station and because no damage was observed on the gauge. The possibility to use this station as a reference station was verified using hydrological modelling.

The ATHYS distributed rainfall-runoff modelling software (Bouvier et al. 1996) was used to check that a realistic relationship could be found between observed rainfalls and observed discharges. This software is based on a production function for each cell and a transfer function from one cell to the other along the steepest slope. The production function is based on the classical SCS model defining an instantaneous runoff coefficient as a function of the cumulative rainfall from the beginning of the event and of the fraction of a soil reservoir representing the infiltration. The lag-and-route transfer function propagates the volume generated in each cell, accounting for a propagation velocity depending on the local slope and for a lag time between the cell and the outlet.

Figure 8 shows the application of the ATHYS model to the station of Jemelle. The parameters of the model were optimized according to a Nash criterion about the discharges. The model appears to be very efficient (Nash criterion = 0.97) with optimized parameters close to the expected ones for this type of watershed (soil reservoir capacity = 152 mm, corresponding to a curve number of 63; mean propagation velocity = 1 m/s).

The hydrological model successfully used at Jemelle was applied to the two upstream stations with the parameters calibrated at Jemelle (Fig. 9). Unsurprisingly, the discharge (mainly the peak discharge) has been seriously reduced, and the unrealistic constant discharge at Hargimont has been replaced by more realistic values.

2.3 *Validation of the process*

In order to validate this methodology, a comparison was made between the sum of the two new hydrographs and the one observed at Jemelle. It was expected that the discharge at Jemelle would be slightly higher than this sum of the two upstream discharges, considering the additional input from the local watershed. Figure 10 shows that it is indeed the case.

3 MODELLING OF THE FLOOD AT JEMELLE AND POSSIBLE MITIGATION

Another way to validate the new hydrograph at Hargimont implies checking that the maximum discharge, decreased from 80 to 60 m^3/s, yields realistic results regarding the road tunnel participation to the inundations at Jemelle. To assess this, a hydrodynamic model focused on the upstream part of the Wamme was constructed as described below and the results were compared to the observations.

3.1 *Hydraulic model of the study area*

A Digital Elevation Model (DEM) of the zone was retrieved from the public service database, with a spatial resolution of one meter. However, as the DEM is acquired using LiDAR technology, the actual bathymetry is not measured and instead the free-surface elevation of the river at the time of the survey is provided. Local corrections are thus necessary and were implemented within the riverbed using available on-site measurements of cross-sections.

Based on the corrected DEM, an unstructured triangular mesh was defined using the open-source tool GMSH (Geuzaine & Remacle 2009), with a refined spatial resolution of 1 m in the riverbed and a coarser resolution of 10 m along the domain boundaries (Fig. 11), leading to a final mesh of 122,000 computational cells.

The inflow discharge was set to 60 m^3/s corresponding to the modified peak discharge of the Wamme river, and as downstream boundary conditions, the water level at the river tunnel outlet was set at 189.14 m, in accordance with local observations of the peak water level. The Manning friction coefficient is considered constant at 0.06 $m^{-1/3}s$ everywhere in the domain, considered as a good approximation when looking at the land use.

The simulation was run using the Watlab simulation tool, which is an open-source Python API developed by the UCLouvain Hydraulics laboratory (https://sites.uclouvain.be/hydraulics-group/watlab/) that was developed based on previous work, e.g. Soares-Frazão & Zech (2008), Van Emelen et al. (2012). This modelling environment includes meshing tools based on GMSH, a bi-dimensional shallow-water equations solver implemented in C++ and parallelized with OpenMP, basic visualization tools and possibilities to export the results into different formats.

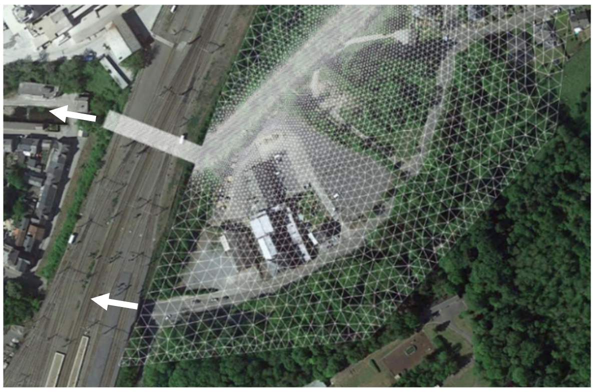

Figure 11: Satellite view depicting the output section of the domain, featuring a triangular mesh refinement of 1 m in the riverbed and 10 m at the domain boundaries.

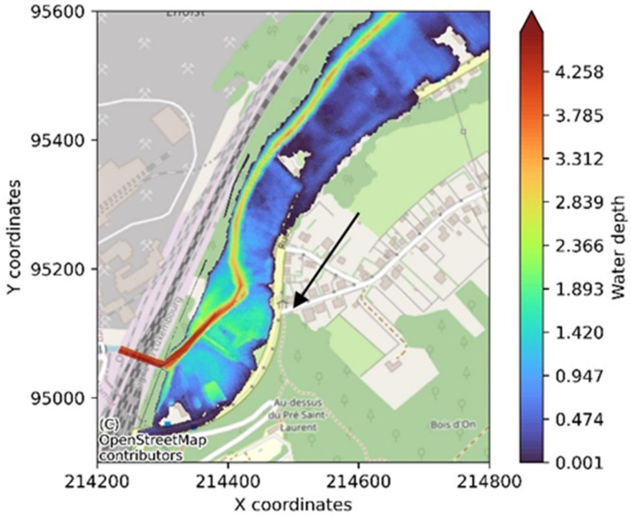

Figure 12. Steady state results of the water depth (m) with a 60 m^3/s inflow. The arrow indicates the flow direction.

3.2 *Simulation results on the Wamme river*

As illustrated in Figure 12, these different boundary conditions led water to flow into the road tunnel and therefore support the theory of a 60 m^3/s maximum discharge in the Wamme. At some point, up to 35 cm of water can be observed in the road tunnel. This confirms that people living between the Rue de la Wamme and the Avenue de Ninove were flooded both from the Wamme river and from an additional flow through the road tunnel.

This hydrodynamic analysis confirms that a maximum discharge of 60 m^3/s can result in flooding in both the road and river tunnels. This supports the validity of the reconstructed hydrograph presented in Figure 9.

Moreover, it shows that this discharge level represents a limit beyond which any increase in discharge would lead to more severe and potentially catastrophic floods.

4 CONCLUSION

The catastrophic flood event in Belgium and Germany in July 2021 caused a high number of casualties and material damage. Only in the Eastern part of Belgium, 39 people died. Such an exceptional event deserves to be understood, if only to improve mitigation and prevention measures. But this understanding requires a good knowledge of what happened and thus accurate measurements of rainfall and discharges.

However, many measurements devices were destroyed by the flood, thus depriving modelers and decision-makers of valuable information. An additional difficulty is that some device failures were clearly visible while others were not.

An in-depth analysis of the observed hydrographs and of the consistency between neighboring results allowed to estimate the level of confidence of the available data. Then, hydrological modelling calibrated from trusted measurement stations has been extended to questionable stations.

In a second step, a hydrodynamic model was created to perform further analysis and validate the conclusions of the hydrological model. The hydrodynamic simulations were run using the open-source software Watlab and led to the same conclusions as the hydrological model.

Such an approach mixing observations and modelling thus appears as an appropriate solution to get insight into extreme events with problematic measurements.

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