Discrepancies in flood modelling approaches in transboundary river systems: legacy of the past or well-grounded choices?

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Abstract

Flood modelling in transnational rivers requires efficient cross-border collaboration among the riparian countries. Currently, each country/region usually uses a different hydraulic modelling approach, which may hinder the modelling of the entire river. For the sake of accurate and consistent river modelling there is a necessity for the establishment of a framework that fosters international collaborations. This study investigates the current hydraulic modelling approach across the whole length of the River Meuse, the main course of which crosses three North-western European countries. The numerical models used by French, Belgian, and Dutch agencies and authorities were interconnected by exchanging boundary conditions at the borders. At the central part of the river, the Belgian hydraulic model assumed steady flow conditions, while the rest of the river was modelled in unsteady mode. Results for various flood scenarios revealed a distinctive pattern of water depths at the Belgian-Dutch border. To clarify whether this is a bias induced by the change in modelling approach at the border (steady vs. unsteady), we remodelled a stretch of the river across the Belgian-Dutch border using a consistent unsteady modelling approach. The steady and unsteady approaches led to similar patterns across the border, hence discarding the hypothesis of a bias resulting from a change in the employed model. Instead, the pattern in water depths was attributed to a change in the topography of the Meuse Valley, where there is a transition from a narrow steep corridor with limited water storing capacity in Ardennes massif to wide floodplains in the Dutch lowlands. The associated flood damping for the 100-year discharge is less than 1 % in the Ardennes and exceeds 15 % in the Dutch lowlands. It can be inferred that the current differences in regional hydraulic modelling approaches for the River Meuse are generally well-grounded and not just a legacy of the past.

Keywords

Flood · Hydrological extremes · Meuse River · Numerical modelling · Transboundary river

1 Introduction

In Europe, sixty-nine river basins are transboundary (Giordano and Wolf 2002) and cross-border cooperation is thus necessary for conducting consistent flood studies (De Moel et al. 2009, Van Alphen et al. 2009). Following several major flood events and fostered by the EU Flood Directive (2007/60/EC), the number of initiatives for cross-border cooperation in flood management has been growing over the last two decades (De Wit et al. 2007b, Wiering et al. 2010). Although cross-border cooperation faces many challenges (Becker et al. 2007, Van Pelt and Swart 2011, Dore et al. 2012), particularly as it gets closer to actual implementation of joint measures, experience suggests that stakeholders benefit greatly from such cooperation (Wiering and Verwijmeren 2012). Examples of successful cooperation include the joint initiatives taken by the Netherlands and Germany in the Rhine Basin (Middelkoop et al. 2004, Becker et al. 2007, Wiering et al. 2010, Van Pelt and Swart 2011, Wiering and Verwijmeren 2012) and the well-established networks that facilitate flood risk management for River Tweed in the border between England and Scotland (Bracken et al. 2016).

Hydraulic modelling is a key component of flood hazard assessment (Leopardi et al. 2002, Drab and Riha 2010, Wilcox et al. 2016, Paquier et al. 2019). Three levels of transboundary cooperation for flood modelling may be distinguished (Gierk et al. 2014):

1. Information: distinct modelling approaches and data are used in each country, but a high level of transparency enables stakeholders in each country to be aware of the modelling procedures used across the border;
2. Coordination: distinct modelling tools are used in each country, but some level of consistency is ensured across the border by making sure that e.g., topographic data, characteristic flow discharges and water levels agree across the border;
3. Harmonization: consistent modelling procedures are used on both sides of the border.

From a strictly scientific standpoint, it would be ideal to harmonize the various procedures into a single, consistent one covering the whole river course. However, harmonization requires specific international collaboration (Bakker 2009), data sharing (Angelidis et al. 2010, Biancamaria et al. 2011), and may require software developments when model coupling is desired (Fotopoulos et al. 2010). In addition, for some regions, harmonization would lead to using another modelling procedure than the one currently in place and accepted by the respective water authorities, while it is not always necessary to use multidimensional and data intensive modelling (Horritt and Bates 2002, Dimitriadis et al. 2016). In such case, the added value of a harmonized model, may not outweigh the disadvantages.

The alternative approach of coordination of existing models offers several advantages compared to creating a new single model for the whole course of a transnational river:

- no additional efforts for calibration and validation;
- the models incorporate a vast amount of expertise resulting from years/decades of development, maintenance, updates and use in practice;
- they have reached a high level of acceptance by local water authorities.

The aim of this study is to investigate whether differences in flood modelling procedures between neighbouring countries in a transboundary river basin are justified by hydrological or topographic differences across the border. To the best of the authors' knowledge, a similar research question has not been addressed yet in the literature. To tackle this question, we examine the adequacy of the coordinated approach (i.e., combining different modelling procedures) compared to the harmonized approach (i.e., based on a single modelling procedure) in the context of transboundary flood modelling. The transnational River Meuse is used as a case study. Even though each country along the river course has developed its own hydraulic modelling approach, De Wit et al. (2007b) highlight a lack of an overarching view of flood hazard distribution from the spring to the mouth of River Meuse. Existing hydraulic models from three riparian countries (France, Belgium, and the Netherlands) were coordinated with consistent assumptions and data across national borders to evaluate maximum water levels and inundation extents for a 100-year flood and two more extreme scenarios. Intriguing results with large differences in the flow variables were obtained nearby the Belgian-Dutch border, where not only the administration and the modelling approach are different at the two sides of the border, but also the topography changes abruptly. To clarify if the flow differences are owed to the different modelling approaches or to the local topography, we carried out a harmonized modelling approach over a river stretch crossing the Belgian-Dutch.

2 Case study

The Meuse Basin has a drainage area of 35,000 km^2. It covers parts of France, Luxembourg, Belgium, Germany, and the Netherlands (Figure 1). The main course of River Meuse extends over 900 km, from the spring in France down to the mouth in the Netherlands, while it crosses Belgium in between. Approximately nine million people live within the Meuse Basin.

As described by De Wit et al. (2007b), the valley shows three distinctive parts, with contrasting topographic characteristics (Figure 1). The uppermost (upstream of the French-Belgian border) and lowermost (downstream of Liege and the Belgian-Dutch border) parts are characterized by relatively wide floodplains, whereas the central part, shaped by the Ardennes massif, is much narrower and has steep side slopes. Consequently, flood waves in the central part of the basin are hardly damped. Another difference is that the tributaries in this central part have steeper gradients than in the other sections of the river (De Wit et al. 2007b).

The River Meuse is a rain- fed river. Mean annual precipitations range between 750 mm in the lower altitudes and around 1200 mm in the Ardennes. The discharge of River Meuse fluctuates considerably with seasons (De Wit et al. 2007b, Wesselink et al. 2009), e.g., in Liege, it reached 3000 m^3/s in winter 1993 while it becomes as low as 20 m^3/s during low flows. After two major floods in 1993 and 1995 (Wind et al. 1999), cross-border initiatives were undertaken to improve flood management on the catchment scale. In the year 2002 the International Meuse Commission (IMC) was founded, which coordinates efforts to fulfil the EU Water Framework Directive (2000/60/EC) and Flood Directive (2007/60/EC). Transboundary modelling efforts started afterwards, with this study being a major example. It was carried out within the EU funded project "AMICE" (Dewals et al. 2013).

3 First coordinated flood modelling of the entire River Meuse

Each country and region in the Meuse Basin has its own procedure for flood modelling. These procedures rely on validated hydraulic models as well as on corresponding datasets and flood scenarios (e.g., based on nationally or regionally defined design discharges). So far, it has not been common practice to have these models linked in such a way that they exchange boundary conditions with the corresponding neighbouring model to ensure a certain level of momentum and mass conservation. Therefore, in an initial effort to come up with intercomparable results over the whole course of River Meuse, the "coordination" of the existing models, was considered.

3.1 Hydraulic models

For the coordinated run of the Meuse River, three hydraulic models were used (summarized in Table S1 in the supplementary material). The models differ in their spatial discretization (1D or 2D) and by the representation of the flow processes in time (steady or unsteady modes), and all use different software implementations:

- Between the upstream end and the French-Belgian border, the hydraulic model STREAM was used (Jacquet et al. 2003). It was developed by the French engineering office BCEOM and it combines a 1D discretization of the mainstream of the river, based on the Saint-Venant equations, with storage cells in the floodplains. A finite volume scheme is used for the numerical resolution, performed in unsteady mode.

- Between the French-Belgian border and the Belgian-Dutch border (Lixhe weir, on the Belgian side of the border), the academic model WOLF was used (Erpicum et al. 2010). It solves the fully dynamic shallow-water equations in 2D based on a finite volume scheme applied on a Cartesian grid of resolution 5 m × 5 m, both for the main riverbed (data from sonar bathymetry) and the floodplains (data from laser altimetry). The model was run in steady mode.
- The 1D model SOBEK-RE, developed by Deltares, was applied between the Belgian-Dutch border (gauging station Eijsden, at the Dutch side of the border) and Keizersveer. The model solves the Saint-Venant equations based on an implicit, finite difference Preissmann scheme. The bathymetry is described by cross-sections with an interval of about 500 m. The cross-sections cover both the main channel and the floodplains.

The three hydraulic models use a discharge boundary condition at the upstream end of the computational domain and a rating curve at the downstream end. All models take into account the inflows from the main tributaries and outflows at the connection with canals (Dewals et al. 2012). The upstream boundary condition takes the form of a constant discharge value in the case of steady simulations (Belgian part), while it is given as a hydrograph for unsteady simulations (French and Dutch parts). All water level results were converted into the Belgian TAW system, whose reference level is 1.79 m and 2.32 m below the reference level of the French and Dutch (NAP) systems, respectively.

3.2 Scenarios

The coordinated flood modelling was performed for three scenarios. The first scenario describes a synthetic event corresponding to a flood with a return interval of once in 100 years. This scenario is referred to hereafter as “scenario Q_{100}”. The two other scenarios are “what if” scenarios, in which the peak discharge of scenario Q_{100} was increased by 15 % and 30 %, respectively. Consequently, these scenarios are referred to as "scenario 1.15 Q_{100}" and "scenario 1.30 Q_{100}".

Scenario Q_{100} was selected as a reference, because the return interval of 100 years is a widely used design criterion and mentioned as such in the EU Flood Directive. The two "what-if" scenarios represent more extreme flood events as requested by the EU Flood Directive. These scenarios are consistent with several studies focusing on the hydrological impacts of climate change in the Meuse Basin (Booij 2005, De Wit et al. 2007a, Leander et al. 2008, Dewals et al. 2013) or in neighbouring basins (Vansteenkiste et al. 2013, De Niel et al. 2019).

In current practice, the "official" values of the peak discharge for a 100-year flood are determined independently by the water authorities in each region. Due to measurement uncertainties and the variability of methods for flood frequency analysis, there are some small differences in the estimated Q_{100} values from each country. These differences are less than 1 % at the French-Belgian border and of the order of 2 % at the Belgian-Dutch border (Table S2 in supplementary material). Given this satisfactory agreement between neighbouring countries, we simply averaged the values across the border, which led to Q_{100} = 1650 m^3/s at the French-Belgian border and Q_{100} = 3115 m^3/s at the Belgian-Dutch border.

3.3 Boundary conditions

To ensure consistency in terms of mass balance and momentum conservation at the borders, the boundary conditions were adjusted iteratively at the shared boundaries, based on the model results from a previous run (details in Table S3 in the supplementary material):

1. Run #1: each model was run standalone based on boundary conditions derived from available observed data, without information transferred from one model to another;
2. Run #2: a second run of the models was undertaken, in which boundary conditions (upstream discharge and downstream water level) were set by transferring results from one model to the adjacent one.

As after the second run the match between discharge and water level between the models at the shared boundary was considered sufficiently accurate, no additional runs were required. A similar method was also applied for loose coupling of groundwater models (Becker et al. 2008).

3.4 Results and discussion of the coordinated approach

Figure 2 shows the peak discharges along the course of the Meuse. Within the uppermost 400 km, the peak discharges increase mildly along the river course. When entering the Ardennes near the border between France and Belgium, peak discharges increase due to the lateral inflow of the tributaries. After the Meuse enters the Netherlands, the peak discharges decrease slightly due to the wave damping effect of the wider floodplains (Figure 1) and the large relict lakes from gravel mining, the so-called “Maasplassen”. Although the Rur tributary contributes significantly to the discharge of the Meuse during low flow conditions (Becker et al. 2018, Bannink et al. 2019), its contribution to peak discharge is small. The plot of the peak discharges along the course of the Meuse reflects the topography of the Meuse Basin (Figure 1) with its moderately hilly shape in France, the steep and narrow valleys in the Ardennes in Belgium, and the lowland areas in the Netherlands.

Figure 2b shows the changes in computed water depths between scenario Q_{100} and scenarios 1.15 Q_{100} and 1.30 Q_{100} along the river. A distinct pattern can be observed, with the mean increase of the water depths, both for 1.15 Q_{100} and 1.30 Q_{100}, in the central part being approximately three times higher than those at the upstream part of the river (until approximately 300 km) and almost two times higher than those at the downstream part (after approximately 620 km).

At the border between France and Belgium there are no discernible differences in the evolution of the peak discharges (Figure 2a) nor in those of water depths (Figure 2b). Particularly for the latter, there is a steep rise of water depths calculated by the French model (from about 350 km from the spring), which is consistent with the predictions of the Belgian model. This agreement is obtained despite the fact that the French model considers unsteady flow while the Belgian one was run in steady mode.

At the border between Belgium and the Netherlands, the flow characteristics of the Meuse change drastically. The flood wave gets damped in the Dutch lowlands (Figure 2) and the water level sensitivity to discharge variation drops substantially (Figure 2b). This sharp transition in the water depth patterns (Figure 2b) coincides with the connection point between the Belgian and the Dutch model. It is not straightforward to infer whether the sharp transition at the connection point should be attributed to different modelling approaches (2D steady simulation for the Belgian part and 1D transient simulation for the Dutch part of the Meuse) or to a local change in topography. Clarifying the respective importance of model and topography influences requires a harmonized modelling approach. The harmonized modelling approach is presented in Section 4.

4 Harmonized flood modelling on a transboundary stretch

To investigate if the rapid change of flow pattern at the Dutch-Belgian border is owed to the different modelling approaches at the two sides of the border or to the characteristics of the valley, a section of the river from Ampsin weir (50 km upstream of the Belgian-Dutch border) until Keizersveer was simulated using 2D model under both steady and unsteady mode.

4.1 Hydraulic models and modelling procedure

For the harmonized approach, both the Belgian and the Dutch models are 2D but they are implemented with different software. Between Ampsin and the Belgian-Dutch border (Lixhe), the academic model WOLF was applied with the same spatial discretization as in the coordinated approach, but in unsteady mode. Between the Belgian-Dutch border (station Eijsden) and Keizersveer, the 2D model WAQUA (Stelling 1984) was used with a curvilinear computational grid, in both steady and unsteady modes. Between Lixhe and Eijsden there is a section of 700 m, which is not covered by any of the available models and was not considered in this study. More information about the modelling tools of the harmonized approach are provided in Table S4 in the supplementary material.

For each scenario, a synthetic design hydrograph was prescribed as boundary condition at the upstream end of the simulation domain (Ampsin weir). This hydrograph was derived from flood frequency analysis of hourly observed flow rates from 1986 to 2010 according to Dewals et al. (2012). For scenario Q_{100}, a synthetic hydrograph corresponding to a return period of 100 years was used. For scenarios 1.15 Q_{100} and 1.30 Q_{100}, the hydrograph of scenario Q_{100} was scaled accordingly. Synthetic flood waves for the main tributaries were generated as well (Dewals et al. 2012). For the steady flow simulations, the peak discharge of the respective flood wave was used as upper boundary condition and the peak discharges of the tributary flood waves were used for lateral inflows.

The model of the Belgian part of the Meuse covers three river reaches, delimited by Ampsin, Ivoz-Ramet, Monsin, and Lixhe weirs. The Dutch part of the Meuse also contains several weirs (Borgharen, Linne, Roermond, Belfeld, Sambeek, Grave, and Lith). In the models, these structures are regulated in accordance with the operation rules of the corresponding structure.

The harmonized modelling starts with a model run of the Belgian part of the Meuse. Next, the computed outflow hydrograph at Lixhe weir was prescribed as inflow boundary condition for the model of the Dutch part of the Meuse. A second run to adjust boundary conditions was not necessary, because the model boundary is formed by a weir, which means that the water level at the upstream end of the Dutch model does not affect the water level nor discharge in the Belgian model.

4.2 Results and discussion of the harmonized approach

Flood damping

Figure 3a compares the peak discharges computed in unsteady mode to the discharges computed with steady flow. In the Belgian part of the Meuse, there is a close agreement between steady and unsteady flow approximations, especially for scenarios Q_{100} and 1.15 Q_{100}. Note that the steep rise in the peak discharges close to river chainage 590 km corresponds to the junction of River Meuse with its main tributary, river Ourthe. On the contrary, downstream of river chainage 670 km, in the Dutch part of the Meuse, a substantial difference is found between the computed peak discharges of unsteady flow and the discharges from steady flow simulation.

The damping of the flood waves in the unsteady simulations is assessed here by comparing the peak of a computed hydrograph in unsteady mode to the corresponding steady-state discharge value. Results displayed in Figure 3b highlight that damping of the flood wave is mostly observed in the Dutch part of River Meuse, with lowland areas and local gravel pit relict lakes. A distinct spatial pattern is visible in Figure 3, with flood damping for all scenarios remaining below 5 % upstream of river chainage 680 km (close to Roermond), and a sharp rise in the relative damping of the flood waves downstream of river chainage 680 km. Flood damping in the downstream part of the Meuse exceeds 15 % for scenarios Q_{100} and 1.15 Q_{100}, and reaches 20 % for scenario 1.30 Q_{100}. As shown in Figure 4a, this rise in flood damping at river chainage 680 km coincides with a relatively sudden decrease of the longitudinal slope of the River Meuse. Overall, the results obtained here support the use of a steady state approximation for flood mapping in the Belgian part of the Meuse but not in the Dutch part of the Meuse.

Maximum water levels

Figure 4c shows the effect of a larger flood discharge on the maximum water levels, similarly to Figure 2b for the coordinated approach. In scenario 1.15 Q_{100}, the maximum water levels upstream of the Belgian-Dutch border are generally 0.5 to 0.9 m higher than in scenario Q_{100}, whereas downstream of the Belgian-Dutch border, this difference is around 0.2 m to 0.5 m. In scenario 1.30 Q_{100}, the computed increases in maximum water levels are roughly doubled compared to scenario 1.15 Q_{100}. Note that the water level differences in the near-field upstream of Monsin weir (600 km) and Lixhe weir (614 km) are almost zero, since these dams regulate the upstream level, even for such high flood discharges. The computed increases in water levels tend to be lower in the river sections where flood damping is strong, such as downstream of the Belgian-Dutch border. This is consistent with the results of the coordinated approach (Figure 2b) and can be explained by the morphological characteristics of the Meuse Valley (Section 2).

Figure 4b depicts the difference in computed water levels between the 2D unsteady and steady simulations. The relatively small differences obtained upstream of Roermond are consistent with the limited damping of the flood waves. In scenario 1.30 Q_{100}, the differences in water levels do not exceed 0.20 m upstream of Roermond, while they reach 0.50 m nearby Roermond and almost 1 m further downstream. A similar pattern is observed for the Q_{100} and 1.15 Q_{100} scenarios, but with lower water level differences.

Figure 4c also provides a comparison with the results of the 1D model used in the coordinated approach to model the Dutch part of the Meuse. The agreement between 1D unsteady and 2D unsteady results is mostly satisfactory in terms of water levels, with the differences between these two simulations for 1.30 Q_{100} being notably smaller than the differences between the 2D steady and 2D unsteady simulations.

Flooded areas and volume stored in the floodplains

Figure 5 shows the computed flooded areas and volumes stored in the floodplains between Ampsin and Maaseik. As shown in Figure 5a and c, upstream of the Belgian-Dutch border there are almost no flooded areas for scenario Q_{100}, while the flooded areas for scenario 1.15 Q_{100} remain limited, with the exception of the most upstream reach. For scenarios Q_{100} and 1.15 Q_{100}, the total stored volume between Ampsin and the Belgian-Dutch border is 0.6×10^6 m³ and 2.6×10^6 m³, respectively. These results are consistent with the very weak damping of the flood wave computed for scenarios Q_{100} and 1.15 Q_{100} in the Belgian part (maximum 1 %, as shown in Figure 3b). However, for scenario 1.30 Q_{100}, more widespread flooding occurs in the Belgian part of the Meuse, with the total stored volume reaching a value of 12×10^6 m³. The increased temporary storage for 1.30 Q_{100} is in agreement with the higher computed damping of the flood wave (about 5 %, Figure 3b). This scenario would lead to considerable flooding in urbanized areas such as Liege (Dewals et al. 2013).

Compared to the Belgian part of the Meuse, the flooded areas and stored volumes computed further downstream in the Dutch part are much larger in absolute terms (Figure 5a and c), even though the considered river segments have similar lengths (Figure 1). The total stored volumes between the Belgian-Dutch border and Maaseik are 111×10^6 m³, 129×10^6 m³ and 150×10^6 m³, for the scenarios Q_{100}, 1.15 Q_{100}, and 1.30 Q_{100}, respectively. These higher values are consistent with the wider floodplains that characterize the Meuse Valley in most of the Netherlands and the greater flood damping in this area (Figure 3b). Finally, the relative increases of the flooded areas and volumes when comparing the respective differences between 1.30 Q_{100} to Q_{100}, and the differences between 1.15 Q_{100} to Q_{100} are generally lower downstream of the Belgian-Dutch border than upstream of the border (Figure 5b and d).

5 Conclusion

Flood risk management is still mostly handled at a national or regional level; however, more international collaboration among riparian countries is encouraged by the EU Flood Directive (2007/60/EC). Transboundary collaboration can be carried out at three levels: *(i)* by only sharing information, *(ii)* with coordinated modelling by ensuring consistent assumptions across the borders, or *(iii)* with a harmonized approach in which fully consistent models are setup across the borders. While the harmonized modelling option is the most consistent one, a coordinated modelling approach offers the benefits of being able to use existing and already calibrated and accepted local/regional models. In this study, we compared the coordinated and harmonized modelling approaches to investigate *(i)* whether the differences in the modelling procedures affect the modelling results and *(ii)* whether they are justified from a technical perspective. As a case study, we considered the River Meuse, the main course of which crosses three north-west

European countries (France, Belgium and the Netherlands). The present study is the first major collaboration effort for transboundary flood modelling in the Meuse Basin.

For the coordinated approach, we applied the existing procedures in the respective countries. Models for the French, the Belgian and the Dutch part of the Meuse were coupled loosely, and the coordinated model run involved both 1D and 2D models as well as steady and unsteady runs. The results of the coordinated modelling showed a sudden change in the flow pattern at the Belgian-Dutch border. To verify whether this sudden change is related to the different modelling approaches, a harmonized modelling of a river stretch of the Meuse across the Belgian-Dutch border was carried out. The harmonized model run used the same modelling approach at both sides of the border, and the results agreed with the results of the coordinated approach. Thus, the sudden change in the flow pattern at the Belgian-Dutch border is not a result of the change in the modelling approach across the border. Instead, it can be explained by a local change of the topographic characteristics of the Meuse Valley, which exhibits narrow and steep corridors in the Belgian part and wide floodplains in the Dutch part.

The harmonized approach based on 2D unsteady modelling confirmed that, in the central part of the Meuse Valley, damping of flood waves does not exceed 1 %, except for the most extreme discharge scenario considered, for which a maximum of 4 % damping was modelled. Consequently, the differences in the computed water levels in steady and unsteady modes remain very low in this part of the valley, which is precisely the region where a steady model was used in the coordinated approach. Conversely, in the Dutch part of the Meuse (lowlands) there is a strong damping of the flood waves and considerable differences are found between the results of steady and unsteady modelling. This stresses the need for the unsteady flood modelling practice in this region, while in the Belgian part of the Meuse unsteady modelling is only required for large discharge peaks exceeding the ones considered in this study. Overall, the present case study indicates that the use of distinct procedures for flood modelling in different parts of the Meuse Basin appears well grounded from a technical perspective and not just a legacy of the past.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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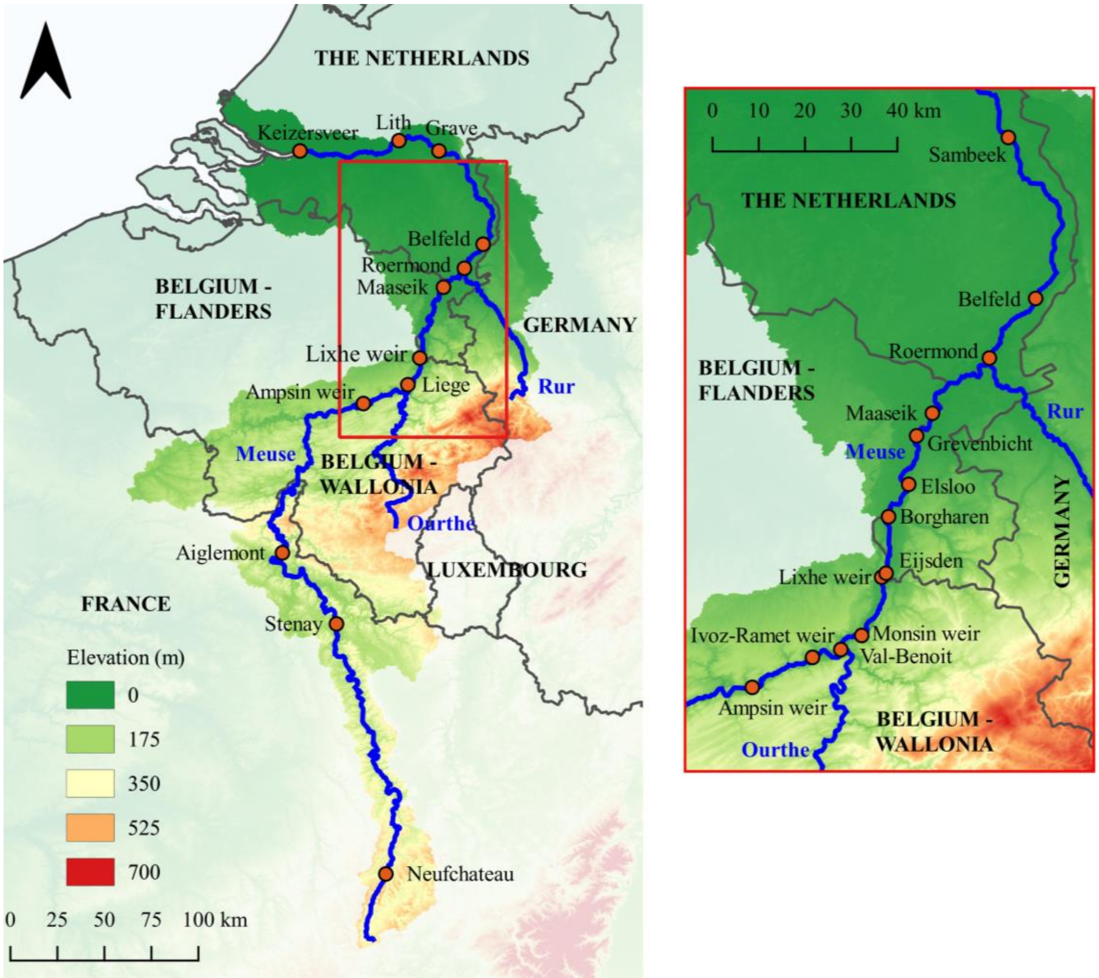

Figure 1. Meuse river course and catchment topography, national borders, and main weirs (map data obtained from https://www.eea.europa.eu, https://land.copernicus.eu/, http://gaia.geosci.unc.edu/rivers/, EuroGeographics and UN-FAO).

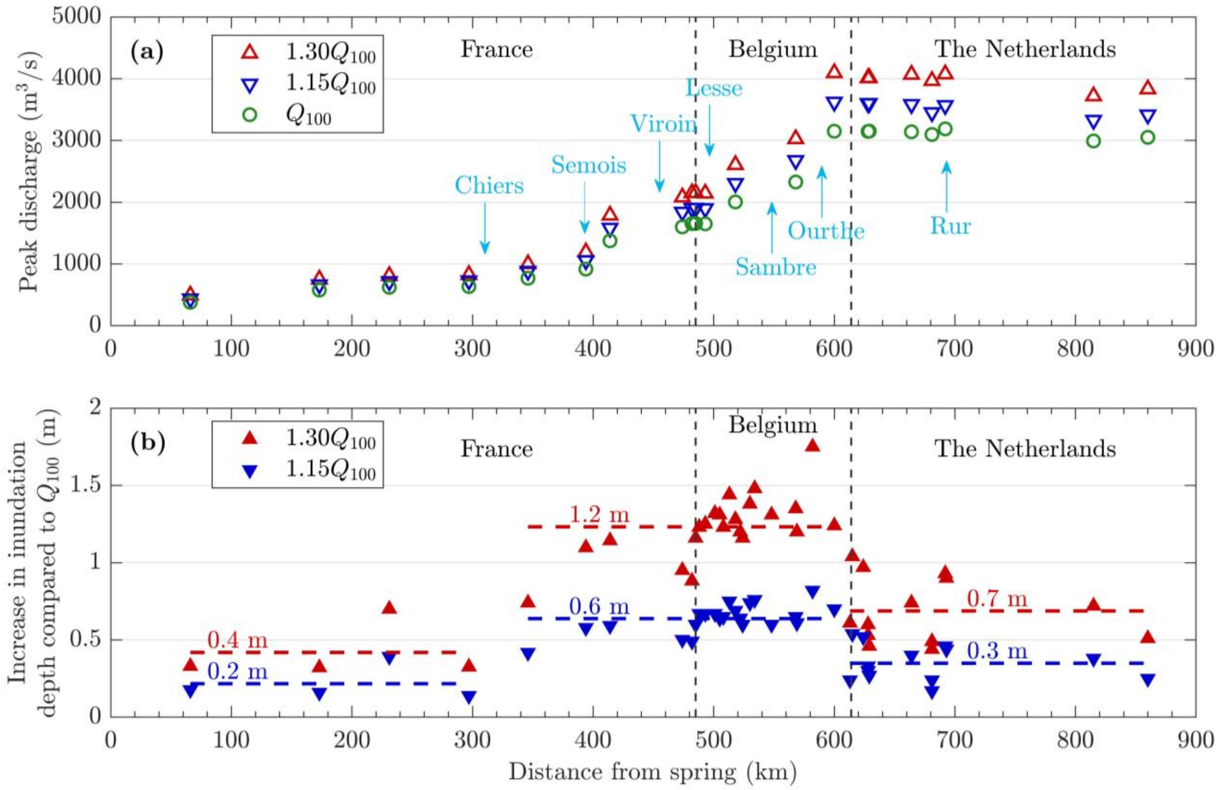

Figure 2. Coordinated modelling (a) peak discharges for scenarios Q_{100}, 1.15 Q_{100}, and 1.30 Q_{100} for the whole length of River Meuse and (b) differences of water depths for scenarios 1.15 Q_{100} and 1.30 Q_{100} with respect to the Q_{100} scenario along River Meuse. The dashed vertical lines denote borders between countries and the arrows in (a) show the location where the tributaries meet River Meuse.

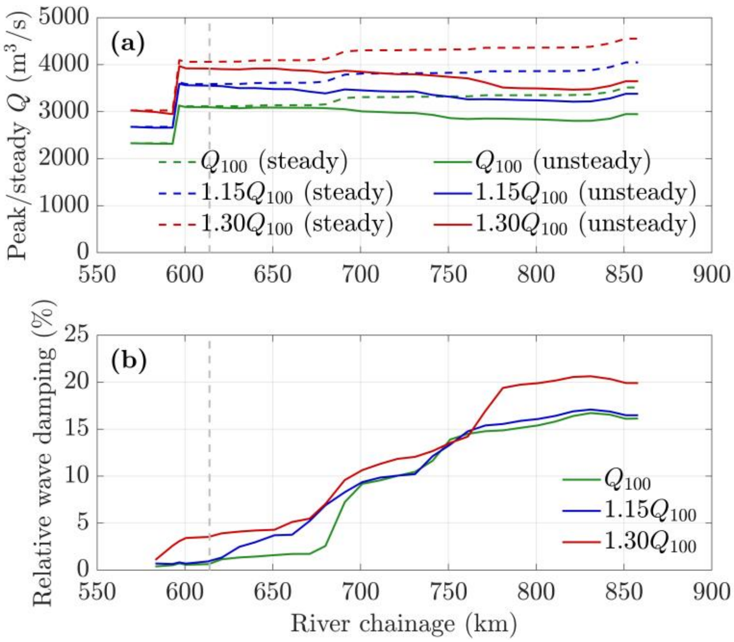

Figure 3. Comparison of (a) peak hydrograph discharge for unsteady flow with steady-state discharge and (b) relative wave damping, for the harmonized approach and the three design discharges. The dashed vertical line denotes the border between Belgium and the Netherlands.

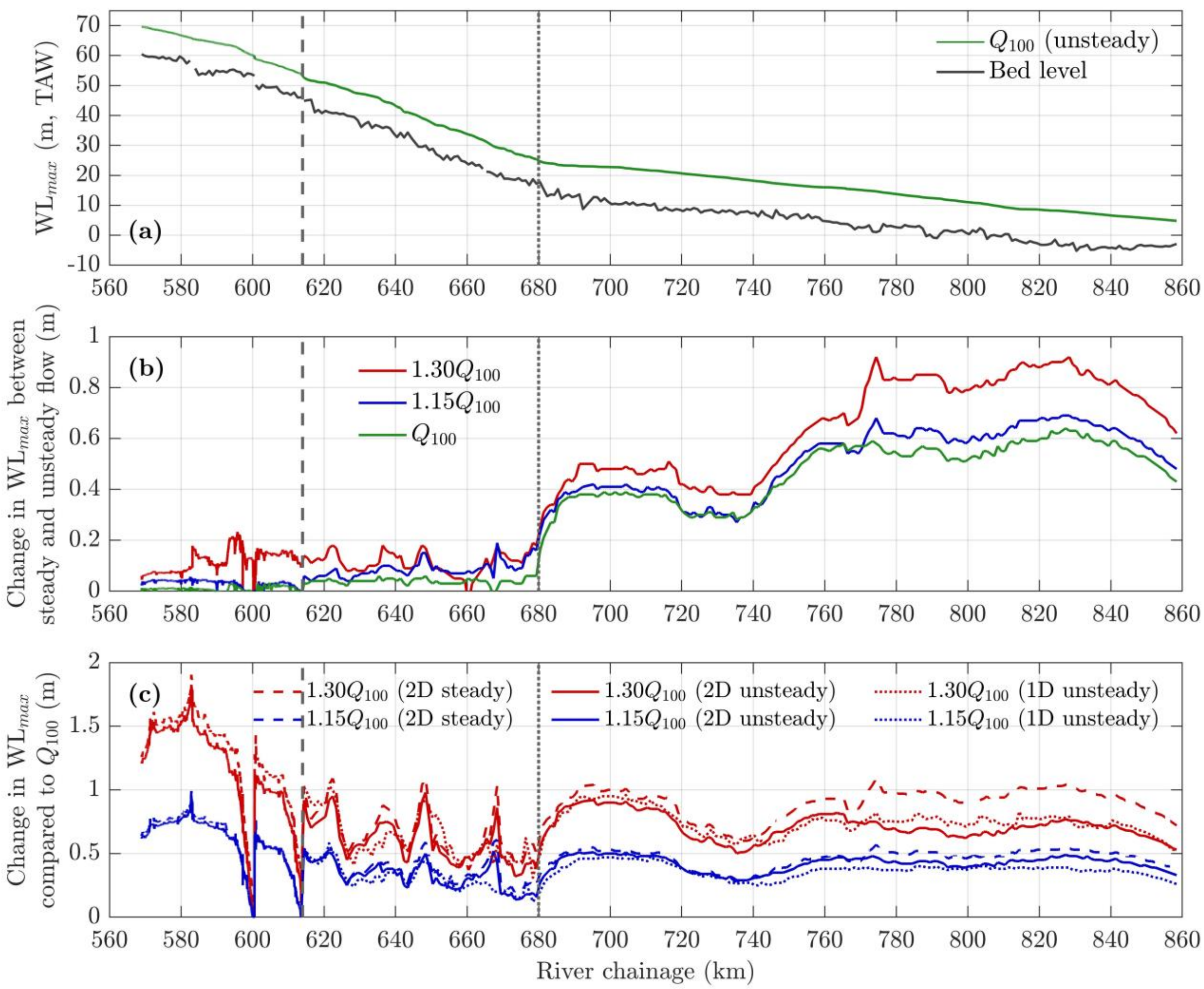

Figure 4. (a) Longitudinal profile of maximum water level (WL$_{max}$) for Q_{100}, (b) comparison of WL$_{max}$ obtained from steady and unsteady simulations, and (c) change in WL$_{max}$ compared to Q_{100} for different numerical simulations with the harmonized approach. The dashed vertical line denotes the border between Belgium and the Netherlands, while the dotted vertical line shows the location of Roermond. Altitudes in (a) are with respect to the Belgian DNG (TAW) reference system.

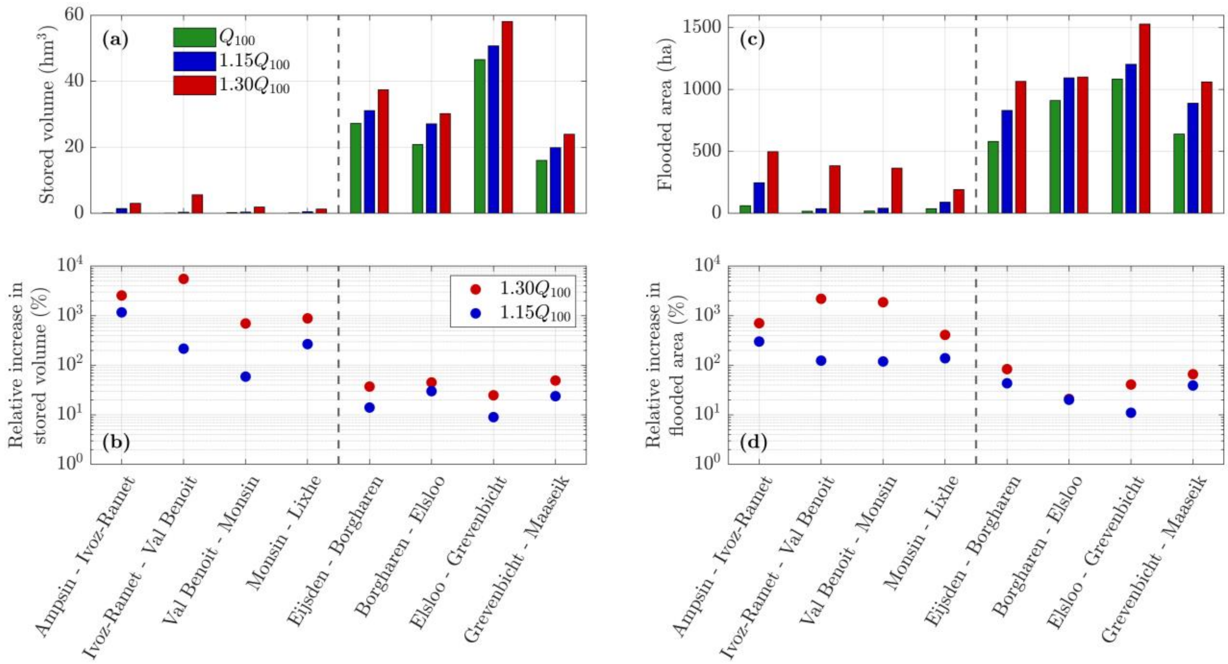

Figure 5. (a) Maximum volumes stored in floodplains, (b) relative increase of stored volumes with respect to Q_{100}, (c) maximum flooded areas, and (d) relative increase of flooded areas with respect to Q_{100}. Computations were done with the harmonized approach. The dashed vertical line denotes the border between Belgium and the Netherlands.

Table S1. Properties of the utilized models for the coordinated approach.

Property	France	Belgium (Wallonia)	The Netherlands
Software	STREAM	WOLF	SOBEK-RE
Software provider	BCEOM	University of Liege, HECE	Deltares
Mathematical background	Saint-Venant equations	Shallow-water equations	Saint-Venant equations
Dimension	1D and 2D	2D	1D
Numerical scheme	Finite volume	Finite volume	Finite difference Preissman scheme
Discretization	1D elements with cross-section and quadratic cells in the floodplains	Quadratic cells	1D elements with cross-section
Steady/Unsteady	Unsteady	Steady	Unsteady
River section	Chalaines to French-Belgian border (Chooz)	French-Belgian border (Chooz) to Belgian-Dutch border (Lixhe)	Belgian-Dutch border (Eijsden) to Keizersveer
Model reference	Jacquet et al. (2003)	Erpicum et al. (2010)	RIZA (2005)

Table S2. Official estimates of peak discharge for a 100-year flood at the French-Belgian border and at the Belgian-Dutch border, and values actually considered in the simulations.

	French-Belgian border	Belgian-Dutch border
Official estimate in France	1650 m^3/s	-
Official estimate in Belgium	1645 m^3/s	3184 m^3/s
Official estimate in the Netherlands	-	3109 m^3/s
Relative difference	0.3 %	2.4 %
Consensus value for scenario Q_{100}	1650 m^3/s	3115 m^3/s
Consensus value for scenario 1.15 Q_{100}	1898 m^3/s	3582 m^3/s
Consensus value for scenario 1.30 Q_{100}	2145 m^3/s	4050 m^3/s

Table S3. Upstream and downstream boundary conditions prescribed in each model for Run #1 and Run #2.

River stretch	Boundary condition	Run #1	Run #2
French part of the Meuse	Upstream	Rescaling of flood waves derived from observations	
	Downstream	Rating curve based on observations at station Chooz	Rating curve based on levels computed by the Belgian model in Run #1
Belgian part of the Meuse	Upstream	Steady discharge derived from observations at the Belgian-French border	Peak discharge computed by the French model
	Downstream	Rating curve based on observations at Lixhe weir	Rating curve based on levels computed by the Dutch model in Run #1
Dutch part of the Meuse	Upstream	Flood wave derived from statistical regression of observations at station Eijsden	-
	Downstream	Rating curve derived from observations at Keizersveer	-

Table S4. Properties of the utilized models for the harmonized approach at the Belgian - Dutch border.

Property	Belgium (Wallonia)	The Netherlands
Software	WOLF	WAQUA
Software provider	University of Liege, HECE	Deltares
Mathematical background	Shallow-water equations	Shallow-water equations
Dimension	2D	2D
Numerical scheme	Finite volume	Composite ADI scheme
Discretization	Quadratic cells	2D curvilinear grid
Steady/Unsteady	Unsteady	Unsteady
River section	Ampsin to Belgian-Dutch border (Lixhe)	Belgian-Dutch border (Eijsden) to Keizersveer
Model reference	Erpicum et al. (2010)	Stelling (1984)

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