TRANSBOUNDARY ASSESSMENT OF THE EFFECT OF CLIMATE CHANGE ON RIVER MEUSE: FLOOD WAVE SELECTION FOR HYDRAULIC MODELLING FROM AMPSIN (B) TO MAASEIK (NL)

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Abstract

This paper addresses high resolution inundation modelling in a transboundary context. In particular, flood wave propagation and inundation characteristics are simulated over a stretch of almost 100 km of river Meuse across the Belgian-Dutch border, using 2D fully dynamic modelling. This transboundary hydraulic simulation requires inflow hydrographs to be prescribed as upstream boundary conditions. However, existing procedures for generating flood wave hydrographs differ between the concerned regions. Therefore, we review the main characteristics of the existing regional procedures and compare the resulting synthetic hydrographs. Besides, transnational hydrological scenarios have been developed to investigate the impact of climate change on flood risk along river Meuse in both countries.

Introduction

The basin of river Meuse has a surface of 35,000 km², covering parts of France, Belgium, The Netherlands, Germany as well as a small portion of Luxembourg (Figure 1). River Meuse is a rain-fed river with limited groundwater storage capacity to buffer precipitations. As a result, its discharge fluctuates considerably with seasons: e.g., measured flow rates in Liege range between 20 m³/s during low flow periods and 3000 m³/s in winter 1993.

Since 2002, the countries of the Meuse basin have been cooperating through the International Meuse Commission (IMC) to coordinate the implementation of the Water Framework Directive (2000/60/EC) and, more recently, the EU Floods Directive (2007/60/EC).

In the framework of the on-going AMICE project, a basin-wide coordinated strategy is being developed to cope with hydrological impacts of climate change, including floods and low flows. As this strategy is intended to be truly integrated at the level of the international basin of river Meuse, the modelling tools and methodologies (e.g., hydraulic modelling, impact assessment, risk management) are being harmonized throughout the basin. In this respect, iterative hydraulic calculations have been performed based on exchange of boundary conditions for the whole Meuse and main tributaries.

In this paper, we focus on 2D dynamic modelling of flood wave propagation and inundation characteristics over a stretch of almost 100 km between Ampsin (Belgium) and Masseik (The Netherlands). Inflow hydrographs need to be prescribed as upstream boundary conditions in river Meuse and in the tributary Ourthe (Figure 1). Nonetheless, current methodologies for estimating synthetic hydrographs differ between the three concerned regions (Wallonia, Flanders and The Netherlands). Therefore, we review the main characteristics of the existing procedures and compare the resulting synthetic hydrographs in terms of duration of the rising and recession limbs as well as flood volume.

The subsequent 2D hydraulic simulations are run based on these hydrographs, in order to quantify the potential damping of flood waves between Ampsin and Maaseik. Damping is expected to remain limited due to the relatively narrow shape of the Meuse valley in this area. This should however be confirmed by the simulations.

Hydrographs have also been modified according to a hydrological scenario accepted in both countries to estimate the impact of climate change on inundation hazard throughout the international Meuse basin.

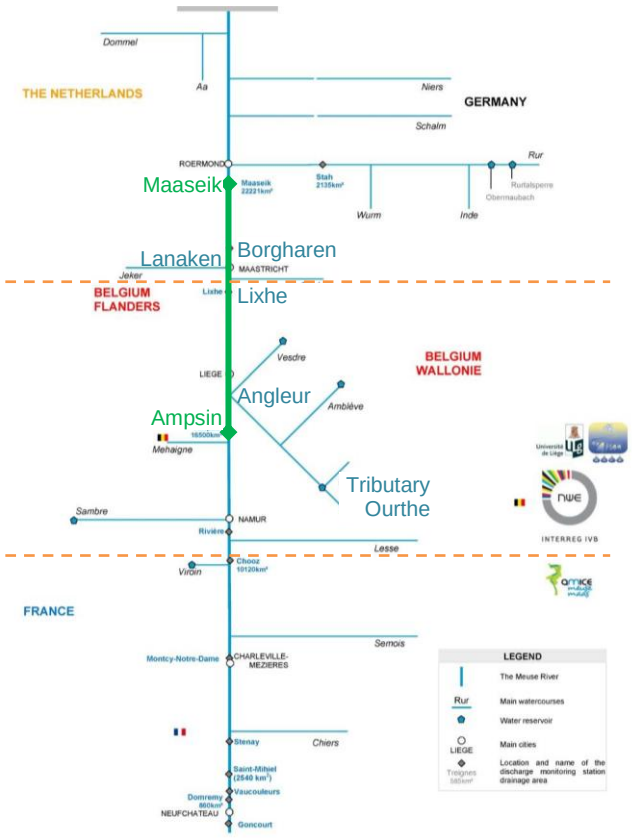

Figure 1: Schematic view of the course of river Meuse and location of the stretch Ampsin (B) - Maaseik (NL).

Existing procedures for generating synthetic hydrographs

Procedures exist in Wallonia, Flanders and the Netherlands to generate synthetic hydrographs as inflow boundary condition for hydraulic modeling (Becker 2011, Blanckaert et al. 2005, Lang and Lavabre 2007, Rijkswaterstaat/RIZA 1999). These procedures differ however by the input data they use and by the underlying methodology. The existing procedures for generating flood waves involve three main steps:

- selection of independent flood events (except in the Flemish methodology),
- statistical analysis of measured flow rates,
- construction of the flood wave hydrograph.

Input data

In Wallonia, data from three gauging stations have been used in the analysis:

- the gauging station "Ampsin" is located at the upstream boundary of the model to be run;
- the gauging station "Angleur" provides data on inflow from river Ourthe, the main tributary of river Meuse between Ampsin and Maaseik;
- data from the gauging station "Lixhe" close to the border with the Netherlands.

In Flanders, time series measured at "Lanaken" gauging station was used and extended based on the correlation with the time series at the gauging stations "Borgharen" and "Maaseik".

In the Netherlands, measurements at the gauging station "Borgharen" were used in the present analysis.

While processing data from the gauging stations "Ampsin" and "Angleur" will deliver the flood wave hydrographs to be prescribed as boundary conditions for the hydraulic modelling, data from the other gauging stations serve here for the sole purpose of comparing the methodologies in the three regions.

Table 1 shows that hourly data have been exploited at the gauging stations in Wallonia from 1986 until present. In contrast, longer time series have been used at the gauging stations in Flanders and the Netherlands, but they are partly based on daily flow rates.

Table 1: Available time series.

	Wallonia	Flanders	The Netherlands
Daily time series used	Not used here	1972 - 1996 (Borgharen)	1911-1981
Hourly time series used	1986-2010	1996 - 2001 (Borgharen) 1989 - 2003 (Lanaken) 1979 - 2003 (Maaseik)	1981 - 2003

Selection of flood events

In the Dutch methodology, the first step in generating flood waves hydrographs consists in selecting independent flood events within the available flow time series. A similar step is needed in the Walloon methodology at the stage of constructing the rising limb of the hydrograph, while the Flemish methodology does not require the identification of individual flood events.

Table 2 compares the number of selected flood events and the selection criteria.

In Wallonia, one single flood event is selected per hydrological year, based on the annual maximum of hourly discharge. The time slot corresponding to a given flood event is assumed to start 300 h before the peak and last until 300 h after the peak.

In the Dutch methodology, all flood events characterized by a peak discharge exceeding 1750 m³/s are selected. The wave is assumed to start when the discharge exceeds a threshold value (1000 m³/s) and to last as long as the discharge remains above this same threshold value.

Two subsequent peak discharges above 1750 m³/s are considered as one single flood wave if the following two conditions are fulfilled:

- the time interval between the two peaks is shorter than 10 days
- and the discharge remains above 1000 m³/s during the time interval in-between the two peaks.

For determining the characteristics of the flood waves, the daily values are disaggregated to hourly values.

The Dutch methodology requires the estimation of three main characteristics of the flood waves for a number of threshold discharge values:

- time to peak
- duration of the flood wave,
- volume above a threshold.

For compound flood waves, the following rules are applied:

- the time to peak is given as the sum of the time to peak corresponding to the highest peak discharge and the duration of the preceding waves;
- the total duration equals the sum of the durations of the waves above the threshold;
- the volumes are aggregated above the relevant threshold.

Table 2: Criteria for selecting independent flood events.

	Wallonia	Flanders	The Netherlands
Number of selected flood events	24 events (1 per hydrological year)	Not relevant	30 events
Selection criterion	Annual maximum hourly discharge	Not relevant	Peak discharge above 1750 m³/s
Extent in time of flood events	300 h before and after the peak	Not relevant	As long as the discharge remains above 1000 m³/s

Statistical analysis of flood wave characteristics

The main objective of the statistical analysis of flood wave characteristics is to estimate the flood duration at different discharge levels.

The Walloon and Flemish methodologies follow a very similar approach (Table 3), which consists in directly processing the continuous measured time series without prior selection of discrete flood events.

In contrast, the Dutch methodology entirely relies on the processing of the selected individual flood events. It additionally delivers the time to peak of the synthetic hydrograph, whereas the Walloon and Flemish methodology use a different approach to introduce asymmetry in the shape of the synthetic hydrograph, as detailed in the following subsection.

In the Walloon and Flemish methodologies, the considered time series are first transformed into Q_D-t time series, where Q_D stands for the discharge averaged over a duration D. This has been performed for several durations, varying from 1 hour to 480 h (Wallonia) or 1000 h (Flanders). Next, frequency analysis has been executed on each Q_D-t time series, resulting in so-called "QDF" relationships linking the discharge (Q) for a certain return period (T, inverse of the frequency F) to the corresponding duration (D).

In the Dutch methodology, the time to peak and the total duration of the flood wave above a threshold discharge are related to the peak discharge using linear relationships:

$$D = a \; Q_p - Q_d \quad , \tag{1}$$

where

- D = time to peak (h) or total duration (h) above a threshold;
- a = regression coefficient;
- Q_p = peak discharge (m³/s);
- Q_d = threshold discharge (m³/s).

Table 3: Statistical regressions used for flood wave characteristics.

	Wallonia	Flanders	The Netherlands
Extreme value distribution or statistical regression	Weibull Gamma	exponential, Pareto or Weibull	Linear relationships to the difference between peak and threshold discharges
Parameters estimation	Maximum likelihood	Step-wise fitting, starting from a linear regression and partly based on least squares	Least squares
Considered flood wave characteristics	Volume and total duration	Volume and total duration	Volume, time to peak and total duration

For the volume, the following relationship is used:

$$\frac{V}{D} = a \; Q_p - Q_d \quad , \qquad (2)$$

where

- V = volume (m³) above a threshold;
- D = total duration (s) above a threshold;
- a = regression coefficient.

Equation (2) offers the advantage that the regression coefficient gains a straightforward physical meaning: a value below 0.5 corresponds to a flood wave having in average a "convex" shape, and vice-versa for values above 0.5. Values below and above 0.5 are expected, respectively, for low and high threshold discharges.

Using the difference between the peak and the threshold discharges in the linear relationships is substantiated as follows: if the threshold discharge equals the peak discharge, the time to peak, the total duration and the volume are all zero; which is well represented by equations (1) and (2).

Construction of the flood wave hydrograph

Table 4 compares the three existing approaches for constructing the synthetic hydrographs.

Following the Walloon methodology, the construction of the synthetic hydrograph corresponding to a given return period is performed in two steps:

- the rising limb is obtained by averaging rescaled and centred hydrographs corresponding to all selected flood events;
- the recession limb is constructed in such a way to respect the QDF relationships.

In the Flemish methodology, for each return period, a curve is fitted on the discrete QDF points. As each QDF-curve represents the integrated form of a composite hydrograph, the synthetic hydrograph corresponding to a given return period is simply calculated by differentiation. Eventually, the shape of the hydrographs is made more physically realistic using an asymmetry factor.

In contrast with the two others, the Dutch procedure is executed based on a user-defined peak discharge and not a return period. The durations and volume for different threshold discharges are determined using the regression formulae (1) and (2). The duration of the recession limb is given by the difference between the time to peak and the total duration.

Due to the limited number of observed flood waves with a peak discharge above 2000 m³/s, the shape of the synthetic hydrograph is set using a different method: either based on a rescaling of the 1926 flood wave, or by rescaling all observed flood events before conducting the statistical analysis of flood wave characteristics. The second option was used.

Table 4: Procedure for constructing the synthetic hydrograph.

	Wallonia	Flanders	The Netherlands
Characteristic parameter	Return period	Return period	Peak discharge
Single-return period	Yes	Yes	No
Determination of the characteristics of the synthetic hydrograph	Extrapolation using the fitted extreme value distributions	Differentiation of curves fitted on the discrete QDF points	Extrapolation using the regression formulae (1) and (2)
Shape of the rising limb	Average of rescaling of all selected flood events	Use of an asymmetry factor	Duration defined by specific regression

Results and discussion

Four synthetic hydrographs generated at the border are compared in Figure 2. They refer to HQ_{100}, which was selected as reference hydrological variable throughout the AMICE project (Drogue et al. 2010). The hydrographs have been obtained by combining the input data and methodologies as detailed in Table 5. Three hydrographs correspond to the input data (time series of flow rate) and methodologies of the respective regions. For the purpose of comparison, the measured time series in Wallonia have also been processed with the Dutch flood wave generator. Figure 2 also displays the 1993 flood wave at the border, slightly rescaled to have the peak discharge equal to 3150 m³/s. Obviously, the return period of the 1993 peak flow was very close to 100 years.

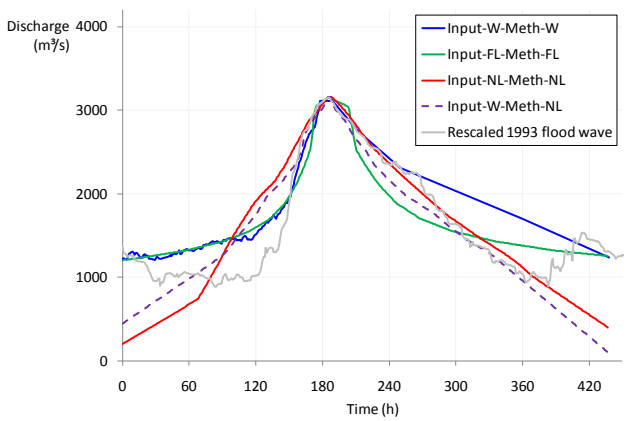

Figure 2: Synthetic hydrographs generated for HQ_{100} at the border.

Table 5: Definition of the synthetic hydrographs generated for HQ_{100} at the border.

Hydrograph ID	Input data	Methodology
Input-W-Meth-W	Wallonia	Wallonia
Input-FL-Meth-FL	Flanders	Flanders
Input-NL-Meth-NL	The Netherlands	The Netherlands
Input-W-Meth-NL	Wallonia	The Netherlands

Our discussion of the shape of the flood waves is deliberately focused on the higher part of the hydrographs (say above 1500 m³/s), which is of primary interest as far as inundation characteristics are concerned (e.g., volume stored in the floodplains) in the reaches between Ampsin and Maaseik.

The Walloon and Flemish hydrographs are found very close to the rising limb of the rescaled 1993 flood wave. The Walloon hydrograph also follows closely the recession limb of the re-scaled 1993 flood for discharges higher than about 2250 m³/s. In contrast, the Flemish synthetic hydrograph deviates from the rescaled 1993 flood wave due to a faster decrease in discharge compared to the observations; such as the Walloon synthetic hydrograph for discharges below 2250 m³/s.

The Dutch synthetic hydrograph agrees very well with the recession limb of the 1993 flood, but it shows a much higher time to peak than the observed event. The same is observed for the synthetic hydrograph obtained by combining the time series measured in Wallonia with the Dutch wave generator.

There is no objective reason for having the synthetic hydrograph following the 1993 flood wave. Nonetheless, since the return period of the 1993 flood was close to 100 year, it provides a valuable guidance for evaluating the realism of the synthetic hydrographs.

The volumes of the flood waves above different threshold discharges have been computed. As can be seen in Figure 3, the Walloon flood wave carries the highest volume, at least as far as threshold discharges below about 2000 m³/s are concerned, while the Flemish flood wave carries the lowest volume for the same range of threshold discharges.

A logarithmic view of the same results reveals however that for higher threshold discharges (2000 - 3000 m³/s), the flood waves based on Walloon data lead to a lower volume than the Dutch one. This is also confirmed in Figure 4, which displays the volume of the flood wave above threshold discharges compared to the corresponding volumes in the rescaled 1993 flood wave.

The higher range of discharge is of course of primary interest and relevance as regards volume stored in the floodplains and possible damping of the wave. Selecting a "sharp" flood wave, leading to lower volume for high threshold discharges, would also lead to the most challenging conditions for assessing the validity of a steady state approach.

It should also be noted that the Dutch wave generator does not apply "as it" for analyzing data from river Ourthe due to too high threshold values of discharge "hard coded" in the algorithm.

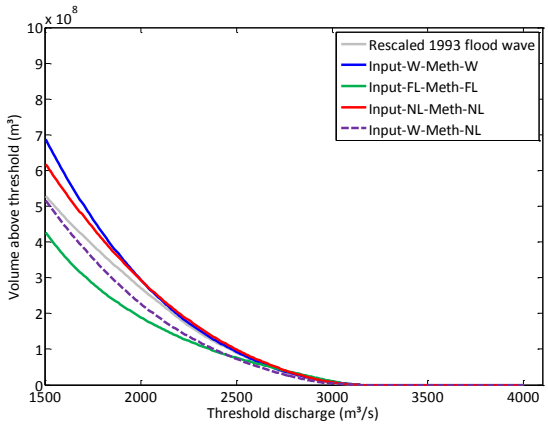

Figure 3: Volume of the synthetic hydrographs above different threshold discharges.

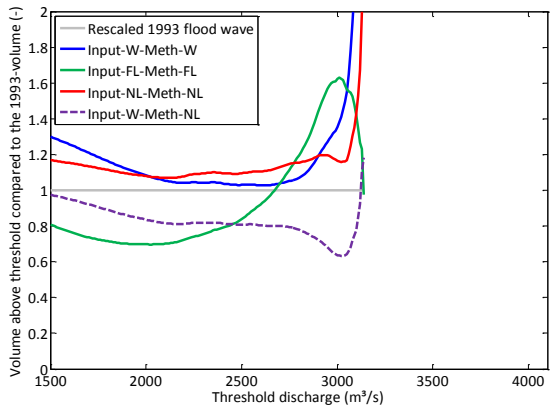

Figure 4: Volume of the synthetic hydrographs above threshold discharges compared to the corresponding volume of the rescaled 1993 flood wave.

Hydrological impact of climate change

The sensitivity of the inundation characteristics with respect to hydrological scenarios accounting for climate change will be assessed. To this end, the hydraulic simulations will be repeated with inflow boundary conditions given by synthetic hydrographs rescaled following the hydrological scenarios developed in the AMICE project (Drogue et al. 2010):

- increase by 15% of the peak discharge for the time horizon 2021-2050;
- increase by 30% of the peak discharge for the time horizon 2021-2050.

As an example, Figure 5 shows the rescaled hydrographs for the time horizons 2021-2050.

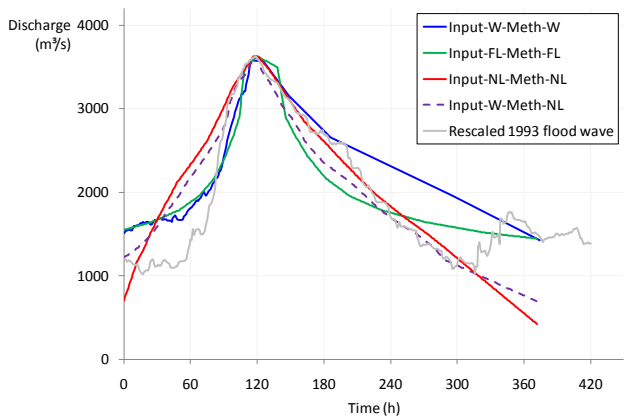

Figure 5: Synthetic hydrographs generated for HQ_{100} at the border following the AMICE hydrological scenario for the time horizon 2021-2050.

Conclusion

Unsteady hydraulic simulations of river Meuse between Ampsin and Maaseik require inflow boundary conditions to be prescribed both in river Meuse (Ampsin) and in river Ourthe (Liège). This implies the selection of synthetic hydrographs describing the inflow flood waves for a 100-year flood in the present climate as well as for the two time horizons considered to investigate the effect of climate change on flood risk along river Meuse.

Flood waves generators are available in the three concerned regions (Wallonia, Flanders and The Netherlands). To support the selection of the inflow flood waves, we have reviewed the main characteristics of the existing flood wave generators and we made a detailed comparison of the hydrographs generated at the Belgian-Dutch border. In this comparison, the focus was set on the duration of the rising limb and the recession limb, as well as on the water volume in the flood wave above relevant threshold discharges.

The analysis has been conducted in light of the main objectives of the study, namely evaluating the potential damping of flood waves between Ampsin and Maaseik and, in turn, assessing the validity of conducting steady state hydraulic simulations to estimate maximum flood levels and extent along river Meuse in this area (as this is the current practice in Wallonia).

The results show that the Walloon flood wave generator leads to a relatively lower volume in the flood wave for high discharge thresholds compared to the other flood generators. Hence, it will provide an upper bound of the possible damping of the wave. It leads also to the most challenging conditions as regards the validity of steady state simulations.

In addition, from a practical point a view, the Walloon flood wave generator is readily available to be applied for river Meuse in Ampsin and river Ourthe in Liege. In contrast, the Dutch generator, for instance, does not apply "as it" for river Ourthe due to a high threshold value hard coded in the algorithm (1250 m³/s, corresponding to the bankfull discharge of river Meuse near the Belgian-Dutch border (Borgharen). Therefore, the unsteady hydraulic simulations will be conducted based on the Walloon flood wave generator.

Detailed 2D inundation modelling will next be performed in the upper part of the stretch Ampsin-Maaseik, using the fully dynamic flow model WOLF 2D entirely developed at the University of Liege. The model is run on a highly accurate DEM resulting from the combination of laser altimetry and, when available, sonar bathymetry. The typical grid spacing for the simulations is kept as low as 5 m, which is definitely fine enough to represent the complex flows occurring at the scale of individual buildings and streets in urbanized floodplains. This way, both the static and dynamic impacts of the flow may be characterized for all affected assets. This approach has been extensively applied since 2003 to issue inundation maps throughout the Walloon region based on detailed 2D flow modelling of over 1,000 km of rivers, for which validation has been systematically conducted (e.g., Ernst et al. 2010, Erpicum et al. 2010, Khuat Duy et al. 2010).

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