amice meuse maas

Investing in Opportunities

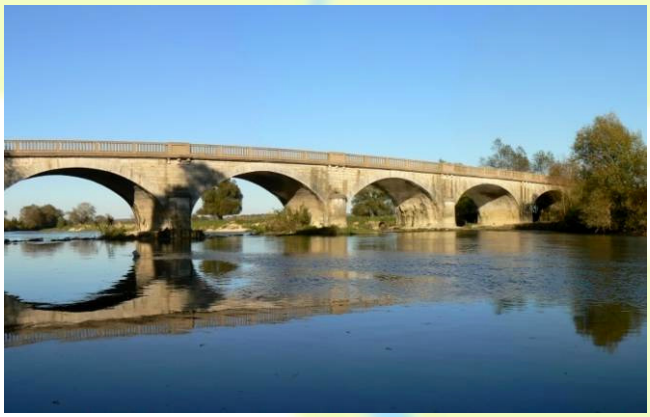
This project has received European Regional Development Funding through INTERREG IV B.

nwe INTERREG IVB

Effects of climate change on river Meuse

Hydraulic modelling from spring to mouth

WP1 report - Action 6




Université de Liège

EPAMA

RÉGION WALONNE

Rijkswaterstaat

flanders HYDRAULICS RESEARCH

RWTH

Deltares Enabling Delta Life

Title	Hydraulic modelling of the Meuse WP1 report – Action 6
Authors	Detrembleur S., Dewals B., Fournier M., Becker B., Guilmin E., Moeskops S., Kufeld M., Archambeau P., de Keizer O., Pontegnie D., Huber N.P., Vanneuville W., Buiteveld H., Schüttrumpf H. and Pirotton M.
Date	2011-03-31
Lead partner	EPAMA
Partners involved	ULg-HACH, EPAMA, RWTH, RWS, FHR
Work package	1
Action	6

AMICE Adaptation of the Meuse to the Impacts of Climate Evolutions
is an INTERREG IVB North West Europe Project (number 074C).
Climate change impacts the Meuse basin creating more floods and more droughts. The river managers and water experts from 4 countries of the basin join forces in this EU-funded transnational project to elaborate an innovative and sustainable adaptation strategy. The project runs lasts from 2009 through 2012. To learn more about the project visit: www.amice-project.eu

The NWE INTERREG IV B Program

The Program funds innovative transnational actions that lead to a better management of natural resources and risks, to the improvement of means of communication and to the reinforcement of communities in North-West Europe.
To learn more about the program visit: www.nweurope.eu

1 Introduction

1.1 Objectives of the AMICE Project

Climate change experts are increasingly pointing out the importance of adaptation to anticipated changes, as opposed to waiting until impacts are irreversible. Consequences of climate change on river basins can be potentially catastrophic. Floods are the main studied hazard, whereas droughts and low-flows are a newer threat, conditioned both by climate change and an increased water demand. Adaptation is necessary if we are to maintain our living standards and remain competitive.

Recently, climate change and its impact on water management have been high on the agenda in the EU: Green Paper, Communication on Water Scarcity and Droughts, Floods Directive (2007/60/EC), Meeting of the Water Directors, etc. The goals are clear, and now is the time to start acting at the basin level.

Despite many uncertainties on the future climatic context, especially on extreme events, climate models are increasingly reliable and the spatial downscaling of climate model outputs has already produced several regional scenarios. According to the precautionary principle, uncertainty about the damage likely to be incurred should not serve as an argument to delay action.

Water managers from four countries of the Meuse basin (France, Belgium, Germany and the Netherlands), have decided to unite forces and knowledge in order to propose an adaptation strategy at the international basin scale.

Each member state has already started developing national adaptation strategies, although they are not easily shared or compared: the climate scenarios are different, the damage costs are evaluated with different methods, the measures enforced by neighbouring countries are not taken into account, etc.

By working together jointly on sharing data and methodologies, it is intended to develop a truly transnational strategic response to the impacts of climate change to the benefit of all the regions covered by the Meuse basin. Transnational cooperation will also facilitate the development of a "basin culture", both between water managers and the population, and increase solidarity.

Therefore, ‘AMICE’ has been set up: Adaptation of the Meuse to the Impacts of Climate Evolutions. The Project receives financial support from the European ‘INTERREG IV B’ Program as well as from the Meuse basin Member States and Regions. It lasts four years (2009-2012) and is coordinated by EPAMA.

The 17 AMICE Partners are:
<u>In France</u>

- EPAMA (Etablissement Public d’Aménagement de la Meuse et ses Affluents), responsible for flood prevention and protection on the French Meuse
- CEGUM (Centre d’Etudes Géographiques de l’Université de Metz), Centre for geographical studies, the University of Metz
- CETMEF (Centre d’Etudes Techniques Maritimes et Fluviales), technical centre for inland and maritime waterways

In Belgium (Wallonia)

- Région Wallonne – GTI (Groupe Transversal Inondations), the cross-disciplinary working-group on floods in the Walloon Region
- HACH - Research group of Hydrology, Applied Hydrodynamics and Hydraulic Engineering, University of Liege.
- Gembloux Agro-Bio Tech, University of Liege, Hydrology and Hydraulic Eng.
- APS (Agence Prévention et Sécurité), the regional agency for overall prevention and security
- Municipality of Hotton

In Belgium (Flanders)

- nv De Scheepvaart, manager of the channels for water transport and drink water production
- Waterbouwkundig Laboratorium, the research center for hydraulic sciences in Antwerp
- Vzw RIOU, association for communication and renaturation

In Germany

- WVER (WasserVerband Eifel-Rur), manager of the Rur tributary
- RWTH Aachen Universität - Lehrstuhlund Institut für Wasserbauund Wasserwirtschaft: the institute of hydraulic engineering and water resources management
- RWTH Aachen Universität - Lehr-und Forschungsgebiet Ingenieurhydrologie: the academic and research department engineering hydrology

In the Netherlands

- Rijkswaterstaat, Ministry of Transport, Public Works and Water Management is involved through two of its departments: Waterdienst and Limburg
- Waterschap Aa en Maas and
- Waterschap Brabantse Delta, water authorities in the Province of Noord-Brabant, water managers of the sub-basins among the 5 of the Meuse basin in the Netherlands.

The aims of AMICE are to:

1. Develop a basin-wide climate adaptation strategy, coordinated transnationally, focused on water discharges and the functions influenced by them. The strategy development will take into account climate scenarios, on-going projects, existing measures and the EU Floods Directive (2007/60/EC), with a particular focus on floods and low-flows.
2. Realize a set of measures against low-flows and floods, profitable for the international basin of the Meuse and that can be transferred to other river basins in Europe.
3. Reinforce and widen the partnership between stakeholders of the Meuse basin, and increase the exchange of knowledge and experience on prevention, preparedness and protection against flood and drought risks.
4. Engage the local population and stakeholders by improving their understanding of climate change, sustainable development, basin functioning, risk consciousness of water hazards and the sense of belonging to a common river basin, across administrative and language borders.

Studies have already been undertaken relating to future climate change, synthesized in 'The impacts of climate change on the discharges of the river Meuse', 2005, International Meuse Commission.

Conclusions have highlighted:

- increased flood frequency in winter, particularly extreme events,
- increases in low-flows, more likely as a result of higher water demand than due to higher air temperatures,
- the need to agree on common scenarios and jointly examine the effect of an improved coordination of water management policies.

The completed Action 3 of the AMICE project has already resulted in basin-wide scenarios on climate change and discharges [1], used as input for the adaptation strategy.

The Project is divided into 5 Work Packages (WP). The present report is part of WP1.

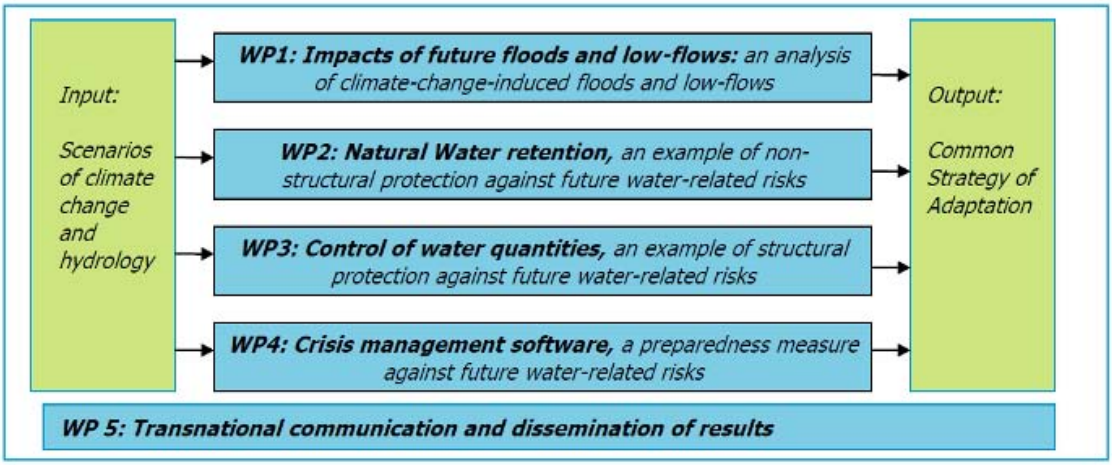


Figure 1-1: AMICE project organization chart.

1.2 Objectives of action 6

Hydraulic modelling is necessary for the identification of future consequences of floods. The inundation characteristics obtained from hydraulic modelling constitute important inputs for the subsequent analysis of socio-economic impacts of floods and the flood risk analysis (Figure 1-2).

Hydraulic models already exist in the countries and regions of the river Meuse. They are run based either on the outputs of rainfall-runoff models or on statistical hydrological data. However, they use neither the discharges nor the water levels computed by the models in the neighbour regions. Therefore, they may be considered as completely decoupled.

Action 6 of the AMICE project is divided into two parts. The objectives of the first part include:

- review the characteristics of the different existing models,
- set up of a modelling methodology enabling to transfer relevant results between the existing models
- run a first transnational hydraulic modelling of river Meuse from its spring to its mouth, accounting for climate change.

The outputs include discharge and water levels of the river Meuse and some tributaries for the agreed scenarios of floods and low-flows (2021-2050 and 2071-2100), which represent essential data for the next steps of the AMICE project.

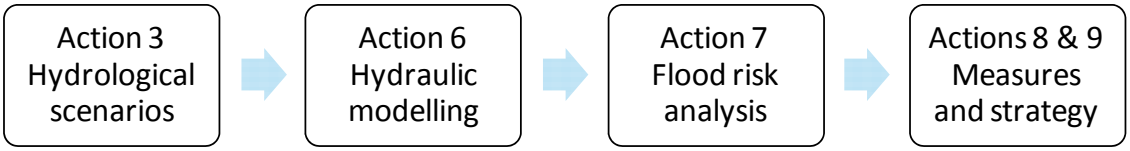


Figure 1-2: Hydraulic modelling is a key component of flood risk analysis and management.

In the second part of action 6, refined modelling will be conducted for the reaches between Ampsin and Maaseik, where hydraulic modelling results are of great importance for the concerned regions, namely Wallonia, Flanders and the Netherlands. Current models appear too heterogeneous and improvements are needed to deliver consistent outputs. In particular, a better insight is needed in the propagation of (extreme) flood waves in the Walloon-Flemish-Dutch border region. Indeed, the largest flood events recorded at this border correspond to about 3000 m^3/s (1926 and 1993), while the design discharge is much larger, at least in the Netherlands. Although based on observed stage-discharge relationships, the refined modelling will also contribute to clarify this discrepancy.

1.3 Position of the advanced report in the elaboration of an adaptation strategy for the Meuse river basin

The Partners involved in the above-mentioned actions achieved a major step that will be used throughout the AMICE project. The hydraulic modelling will not only be used for WP1 but also for some investments in WP2 and WP3, as well as for the definition of the transnational exercise in WP4.

The hydraulic modelling is especially relevant for high flows because damage quantification are based on water levels and, sometimes, flood duration and water velocity. Consequences from low-flows, on the contrary, are discharge-dependant. Low-flows results from AMICE action 3 can directly be used.

Hydraulic modelling is also necessary to draw maps of the future flood extents under the AMICE wet scenario. These maps will help people understand the potential consequences of climate change.

This hydraulic modelling is also a major step in transnational cooperation. The methodology developed by the University of Liege to connect the hydraulic models can be used in future studies for other purposes than AMICE.

2 Presentation of the study area

River Meuse extends over 900 km from Neufchâteau in France, down to Keizersveer in the Netherlands (Figure 2-1). The drainage area (35,000 km²) covers parts of France, Luxembourg, Belgium, Germany and the Netherlands; and has a total population of about 9 million inhabitants.

Since 2002, the five European countries situated in the Meuse basin have been working together in 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).

The river Meuse is classified as a rain-fed river. The catchment has no glacier and limited groundwater storage capacity to buffer precipitations. As a result, the discharge of the river Meuse fluctuates considerably with seasons: e.g. it reached 3000 m³/s in winter 1993 in Liege and may become as low as 20 m³/s during low flow periods.

Figure 2-1: River Meuse extends over about 900km from Neufchâteau in France, down to Keizersveer in the Netherlands [2].

In the last 20 years, major floods took place in 1993 and 1995, while previous major floods date back to winter 1925-1926. In 1993 and 1995, considerable damages were experienced in France, Belgium and the Netherlands. Although the peak discharges were comparable, the flood damage estimates in the Netherlands were significantly lower in 1995 than in 1993, probably as a result of a slight increase in flood warning time and thanks to the flood awareness gained from the 1993 event [3]. This highlights the importance of truly integrated flood risk management at the basin scale, accounting for the non-technical aspects of flood management and flood impact assessment, as well as for upstream and downstream influences of river engineering and water management.

Following de Wit et al. [4], the Meuse basin can be subdivided into three major geological zones, referred to as:

- “Lotharingian Meuse” (southern part),
- “Ardennes Meuse” (central part)
- and the Dutch and Flemish lowlands (northern part).

While the southern and northern parts are characterized by wide floodplains where flood waves are significantly attenuated, in the central part of the Meuse basin, between Charleville-Mézières and Liège, the Meuse is captured in the Ardennes massif, characterized by narrow steep valleys. Consequently, the flood waves in this part of the basin are hardly attenuated as a result of the steep gradients and the relatively narrow cross-sectional shape of the valleys, leading to very low storage capacity in the floodplains. These differences directly influence the selection of the optimal procedure for hydraulic modelling in the different parts of the basin, particularly the choice between dynamic modelling and steady-state approximation.

The hydrological impact of climate change in the Meuse basin has been analyzed in a number of studies, including Booij [5], Tu [6], Leander et al. [7], de Wit et al. [8] and [9]. Here, we simply use the hydrological scenarios agreed upon during action 3 of the AMICE project [1].

3 Common methodology for hydraulic modelling

Hydraulic modelling is necessary for the identification of future consequences of floods. Models already exist in the countries and regions of river Meuse. Presently, each hydraulic model is based either on the outputs of rainfall-runoff models or on statistical hydrological data. The hydraulic models along the Meuse do not use the flow rates or water levels from upstream or downstream models. Therefore, part of action 6 (AC6) of the AMICE project was focused on ensuring the compatibility of these models, which has enabled to perform the first international run of hydraulic models on river Meuse.

Based on a comprehensive synthesis of the main characteristics of available hydraulic data and models throughout the international course of river Meuse, a methodology has been set up for the comparisons, the exchange of outputs, and the hydraulic run itself. While elaborating the methodology, attention has been paid to take benefit as much as possible of existing modelling procedures in each country and region, while fitting in with the timetable of the AMICE project.

3.1 Available data and models: a synthesis

At the beginning of February 2010, a questionnaire was sent to all Partners acting in this part of AC6. It consisted in 11 questions addressing issues such as models available in each country and region, commonly used hydrological variables, reaches covered by hydraulic modelling and considered gauging stations. This section provides a summary of the main results collected, while further details are given in appendix.

For the sake of conciseness, the following abbreviations have been used to refer to involved countries and regions: F (France), W (Wallonia), FL (Flanders), NL (The Netherlands) and GE (Germany).

3.1.1 Available models

For the main river bed, all models solve the Saint-Venant equations (1D) or the shallow water equations (2D). The models used are 1D in F and FL, whereas GE uses a coupled 1D-2D approach and W a full 2D model. In NL, both a 1D and a 2D model are available. The floodplains are represented differently depending on the region: F uses storage cells/compartments, FL uses a combination of cross sections/flood branches and (only to a limited extend) storage cells/compartments, the NL 1D model uses cross sections, while 2D modelling is used in W and GE as well as in the 2D-model in NL. Note that the Dutch results presented in this report are obtained using the 1D model. The Dutch 2D model is applied in the second phase of this AMICE action (Ampsin – Maaseik), and reported separately.

Unsteady simulations are performed in F, FL and NL, using hydrographs as upstream boundary conditions. In contrast, W and GE run steady simulations but a new unsteady model can be run in GE in the framework of AMICE. This difference in modelling approaches is substantiated by differences in the Meuse catchment topography, such as narrow and steep valleys in the Ardennes, compared to wider and flatter floodplains in other parts of the basin. The resulting storage capacity of the floodplains is of course far more limited in the former case compared to the later [10].

Although other friction formulae are also available in several models (W, GE, NL), Manning formula is applied in all of them.

3.1.2 Topographic data

All hydraulic models represent both the main course of the river and the floodplain topography. Types of available topographic data extend from simple cross sections to detailed Digital Elevation Models (DEM) in the floodplains and, to some extent, in the main riverbed.

In brief, following data are used to describe the main river bed:

- F: DEM (resolution: 5x5 m)
- W: sonar bathymetry (resolution: 5x5 m, original data 1x1m)
- FL: cross sections every 100m
- NL: DEM (resolution: 5x5 m)
- GE: cross sections every 100m

On the other hand, the floodplains are described as follows:

- F: DEM (resolution unknown)
- W: laser DEM (resolution: 5x5 m, original data 1x1m)
- FL: laser DEM and photogrammetry (resolution: 5x5m)
- NL: laser DEM (resolution: 50x50 m)
- GE: laser DEM (resolution: 50x50 m, original data 2x2m)

3.1.3 Covered reaches

The course of river Meuse is almost completely covered by existing hydraulic models, from Neufchâteau (upstream end of the French model) down to Keizersveer close to the North sea (downstream end of the Dutch model). The German model is run on river Rur, a tributary flowing into the river Meuse in Roermond.

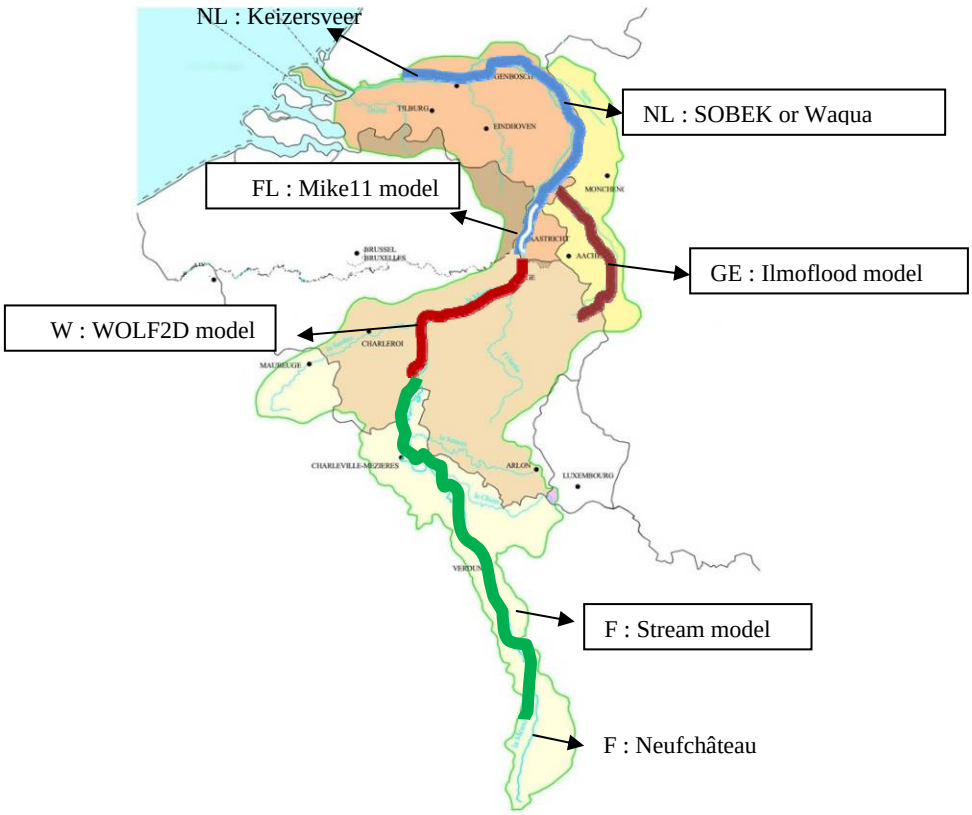


Figure 3-1 : Covered reaches and corresponding hydraulic models.

3.1.4 Hydrological data and statistics

The main gauging stations used to collect time series of flow rates are listed in

Figure 3-2. All stations have recorded historical data extending over a period ranging between 25 and 50 years, except Borgharen where the Meuse discharge has been recorded for 100 years. These time series are the basis for calculating upstream boundary conditions for the hydraulic simulations, either in the form of statistical values or through the shape of the inflow hydrograph when needed.

In AMICE, the discharge for a return period of 100 years, calculated from maximum annual hourly discharges (Q_{100}), was selected as the consensus reference hydrological variable for high flows, as mentioned in meeting reports of action 3 (meeting in Metz on September 3rd 2009) and in the end report of action 3 [1].

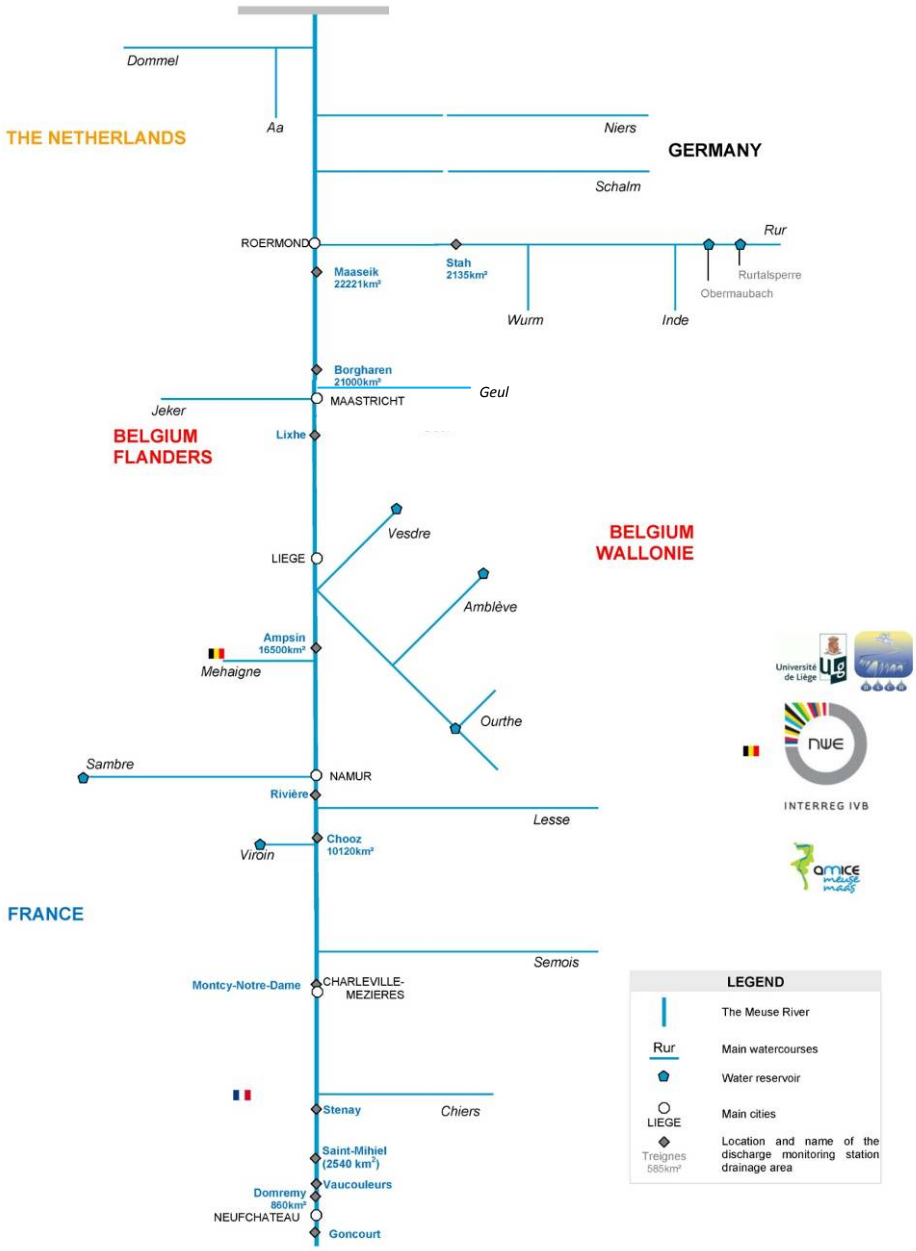


Figure 3-2 : Main gauging stations along river Meuse and Rur.

The Q_{100} value at each border and the shape of the hydrograph prescribed in current unsteady models are summarized below:

- In F, the shape of the hydrograph is based on the 1995 flood. The peak value in Chooz is 1650 m³/s.
- In W, the discharge is steady and it is raised after the 3 main tributaries. Q_{100} value in Chooz is 1645 m³/s, 2005 m³/s between the Lesse and the Sambre, 2328 m³/s between the Sambre and the Ourthe, 3184 m³/s between the Ourthe and Lixhe.
- In NL, the shape of the hydrograph is based on the regression of river stage measurements. The Q_{100} peak value in Lixhe is 3109 m³/s.
- In FL, the hydrograph is bell-shaped. The Q_{100} peak value in Maaseik is 3550 m³/s.

- In GE, steady discharge is assumed and the Q_{100} value in Stah is 176 m³/s.

Hence, measured and statistical discharges at borders are found to differ by no more than 2 to 3 % at Lixhe and less than 1 % at Chooz.

Besides, all models handle inflows from tributaries and, in all of them, water level can be prescribed as a downstream boundary condition using stage-discharge relationships.

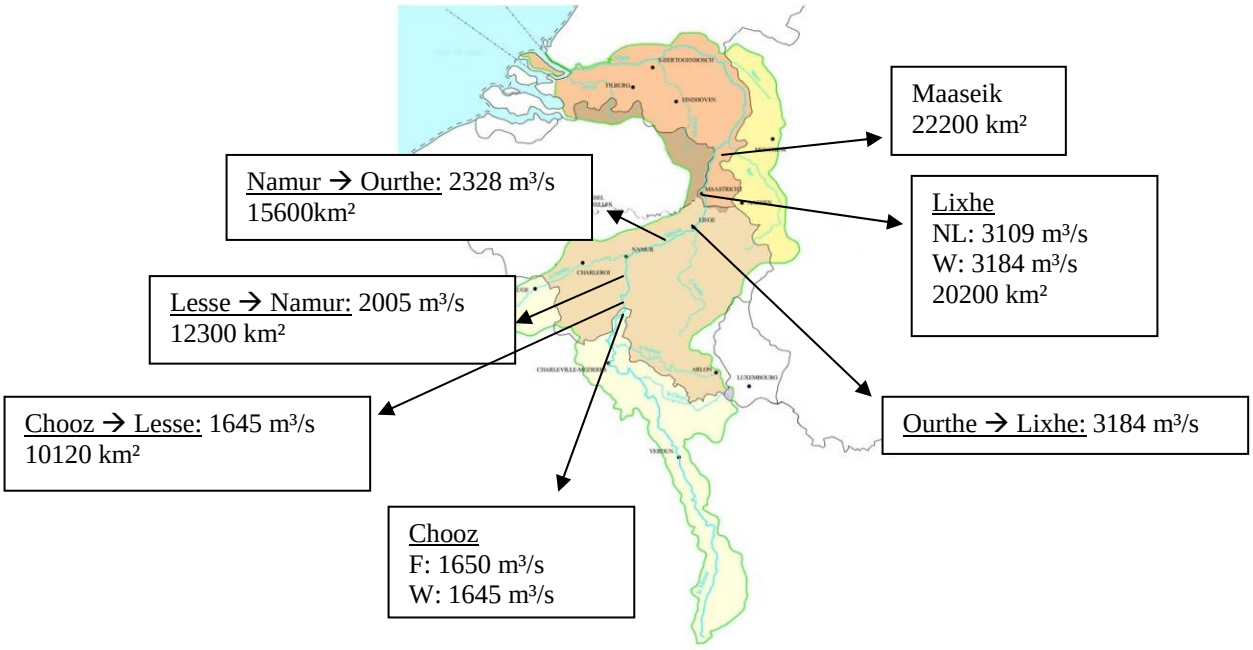


Figure 3-3: Q_{100} discharge and catchment area for each considered reach of the Meuse.

3.2 Common methodology for hydraulic modelling

The questionnaire has shown that existing models cover nearly the whole course of river Meuse from spring to mouth. It has also revealed the numerous similarities between the hydraulic models used in the Meuse catchment, whereas a key difference remains between steady and unsteady modelling approaches. Therefore, a procedure has been defined to combine the existing models, accounting for the need to interconnect data and results from both steady and unsteady models and to ensure continuity of the water levels at borders.

3.2.1 Necessary boundary conditions

The set of mathematical equations solved by the models requires suitable boundary conditions (BC) for the discharges in river Meuse (usually subcritical) to be properly simulated. Discharge is generally prescribed as upstream BC, either in the form of a steady value or as an inflow hydrograph, while water depth or water level is prescribed as downstream BC.

These BC are given by measured data or scenarios at the outer limits of the simulation, i.e. in Neufchâteau (discharge) and at Keizersveer (water level - discharge rating curve). All other BC depend on the results of the other models. As an example the discharge in Chooz for the W model should be given by the discharge computed by the F model. The water level for the F model at Chooz should depend on the water depth computed there by the W model. The same applies at Lixhe for the W and the FL, NL models as well as in Roermond for the NL and GE models.

3.2.2 Steady or unsteady simulations

F, FL and NL models are unsteady and use thus hydrographs as upstream BC, while the W and GE models are run in a steady mode. The common methodology to be followed in AC6 accommodates this difference in modelling procedures. Indeed, both a full steady and a full unsteady simulation would neither be feasible nor provide optimal results in the framework of AMICE.

A fully unsteady simulation procedure would imply that all computational models are linked and run simultaneously in order to transfer continuously the boundary data (water level and discharge) from one model to the next. Such coupling of the models is out of the scope of AC6. In addition, this approach would lead to the following additional drawbacks:

- Unnecessary unsteady modelling in parts of W, where storage capacity of the floodplains is low. As a consequence of this low storage capacity, Figure 3-4 demonstrates for the flood of 2003 that no damping of the hydrograph is produced,
- Difficulty in having the different Partners set up and run their models in parallel to use optimally the available time.

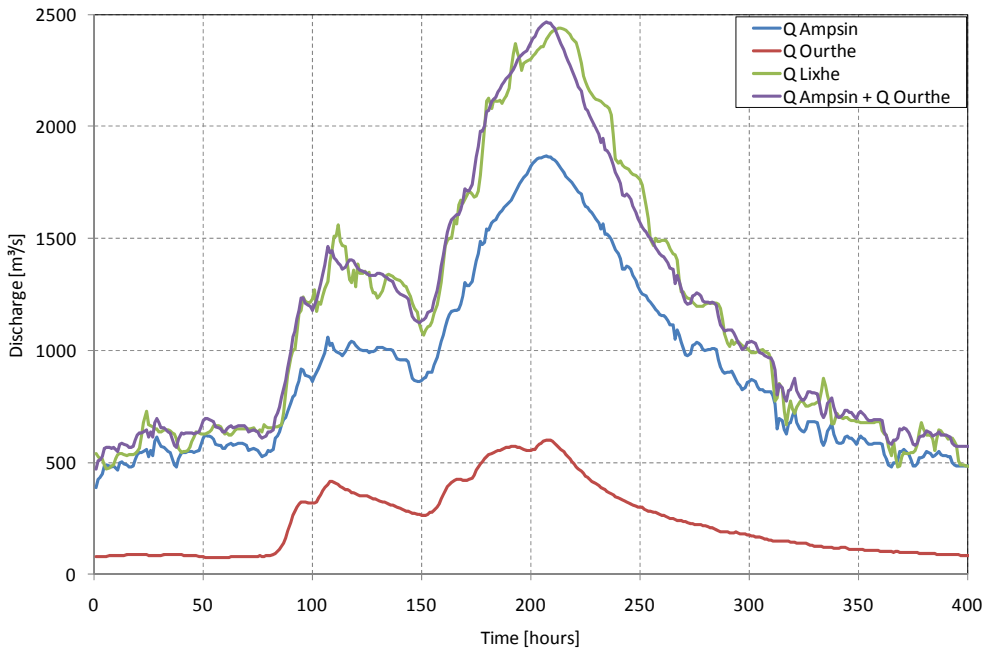


Figure 3-4 : Example of comparison of hydrographs on the downstream part of the Meuse in Wallonia.

Similarly, a full steady approach would not prove satisfactory. It would require inferring discharge values at a number of points along river Meuse and running the models sequentially from downstream towards upstream. The water level in Lixhe would be deduced from the modelling results in NL and FL, and transferred to the W model. Subsequently, the water level computed by the W model would be transferred to the F model at Chooz.

In addition, transient simulations are necessary to represent damping of flood hydrographs in F, FL and NL due to the generally significant storage capacity of floodplains in these regions. As such, a full steady simulation would also lead to sequential runs of the different models (i.e. NL, FL models first, W, GE model next and finally F model), which would prevent an optimal use of available time.

The common modelling procedure combines thus unsteady and steady modelling, depending on existing practice in each region and in accordance with the storage capacity of the floodplains, while enabling parallel (instead of sequential) runs of the models and ensuring reasonable continuity of the results at the borders.

3.2.3 Motivation and overall procedure

A purely sequential run of the hydraulic models in the different regions would lead to a suboptimal use of the time available. The common modelling methodology has been designed to run the models, in a first step, with boundary conditions prescribed from available measured data instead of transferred from one model to the next.

This turns out to be the only feasible approach since hydraulic models for fluvial flow conditions require boundary conditions both at their upstream and their downstream ends. Therefore, running sequentially the models from upstream (spring) towards downstream (mouth) would also fail to satisfactorily transfer the necessary boundary conditions between the different models. Direct coupling of all models was not considered as feasible in AMICE.

Therefore, a two-step procedure has been followed:

- hydraulic models have first been run in each region separately, based on measured data;
- next, consistency of the simulation results at the borders between models has been checked, and, if necessary, a second run of (sub-)models has been undertaken accounting for boundary conditions transferred from the adjacent models.

3.2.4 Handling boundary conditions

3.2.4.1 Downstream

Answers to the questionnaires have revealed that high values of historical discharges are present in the recorded data at the gauging stations (3056 m³/s in Lixhe and 1560 m³/s in Chooz during the flood of 1995) as well as at Roermond (NL), Linne (FL) and Keyserveer (NL). Therefore, only limited extrapolation of the corresponding stage-discharge relationships have been needed to provide the necessary boundary conditions (Figure 3-5).

At the end of the first run of the models, computed water depths have been compared at the borders of the models (see section 4). If substantial differences are observed, a second run of the models has been performed to restore the continuity of the free surface across the borders in the final results. As expected, this re-run has been limited in spatial extent due to the limited distance along which the boundary conditions significantly influence water elevation.

3.2.4.2 Upstream

Peak discharges during Meuse floods usually last several hours. At the borders, the steady discharge value of the W model has thus been assumed equal to the peak value of the corresponding unsteady model (F, FL or NL). The peak discharge from the Rur in Roermond at the boundary of the GE and NL models was taken from the NL model, as this represents the conditions of a flood in the Meuse, whereas the steady value reported in chapter 3.1.4. only takes the Rur into account.

During action 3 (AC3) of the project, Q_{100} (maximum annual hourly discharge of 100-year return period) was selected as the reference variable for high flows in AMICE [1]. As shown in section 3.1.4, a very satisfactory agreement was found on this reference value at the F-W and W-NL borders.

According to the results of AC3, two perturbation factors (for the time horizons 2021-2050 and 2071-2100) based on the transnational climate scenario have been identified. These perturbation factors are noted here respectively PF^{21-50} (+15%) and PF^{71-00} (+30%). Consistently with AC3, Q_{100} has been further used as reference value in AC6 and hydraulic simulations have been conducted for Q_{100} modified by the two perturbations factors PF^{21-50} and PF^{71-00} (Figure 3-6)[1].

In the case of unsteady models (F, FL, NL), the hydrograph reaching the perturbed peak value has been calculated following the current procedure in each region and country for a Q_{100} hydrograph. Similarly, all models vary the discharge to account for the main tributaries, in accordance with present practice in each region and country. Attention has been paid to maintain continuity at the borders (Figure 3-7) in order to deliver continuous inundation maps.

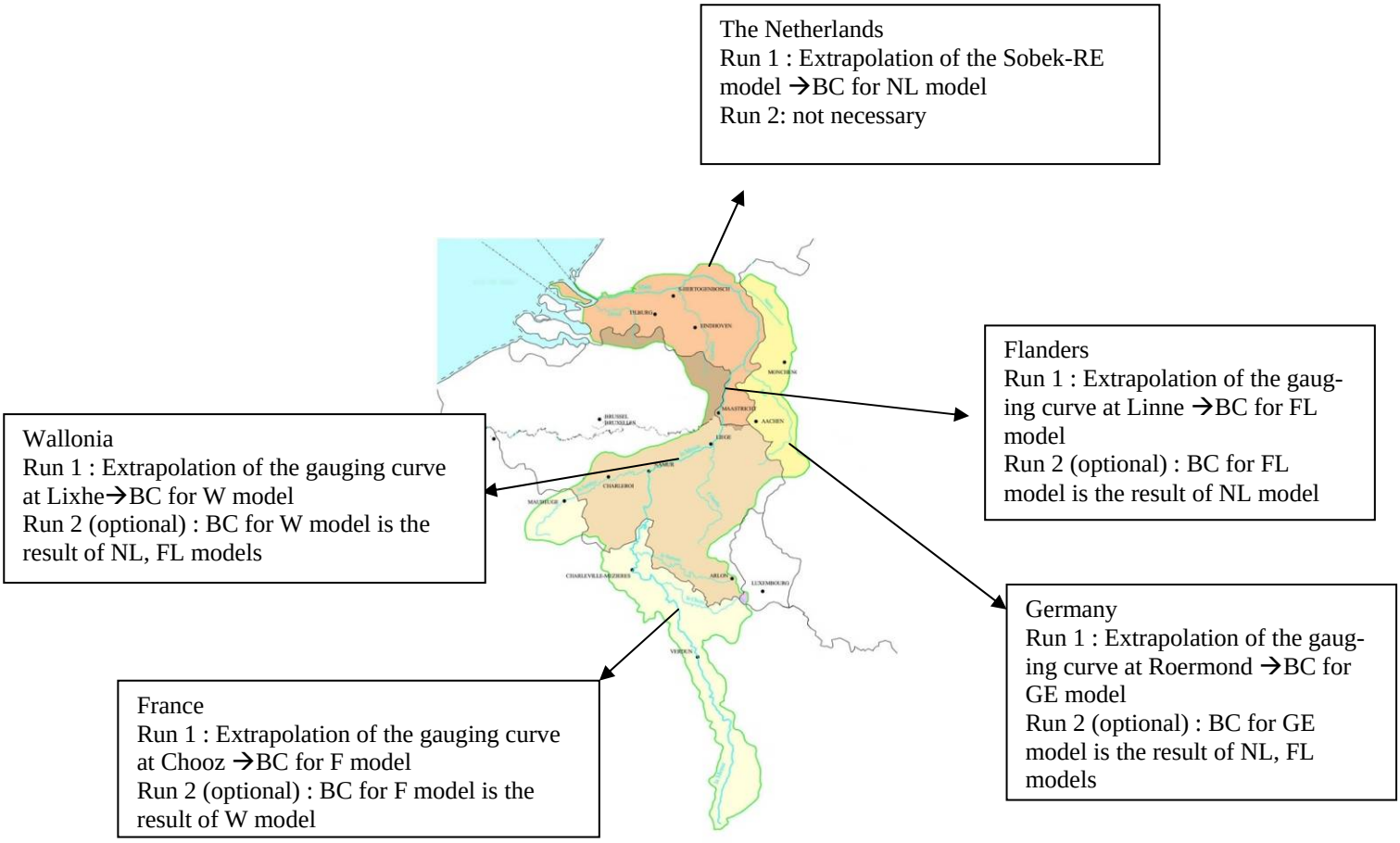
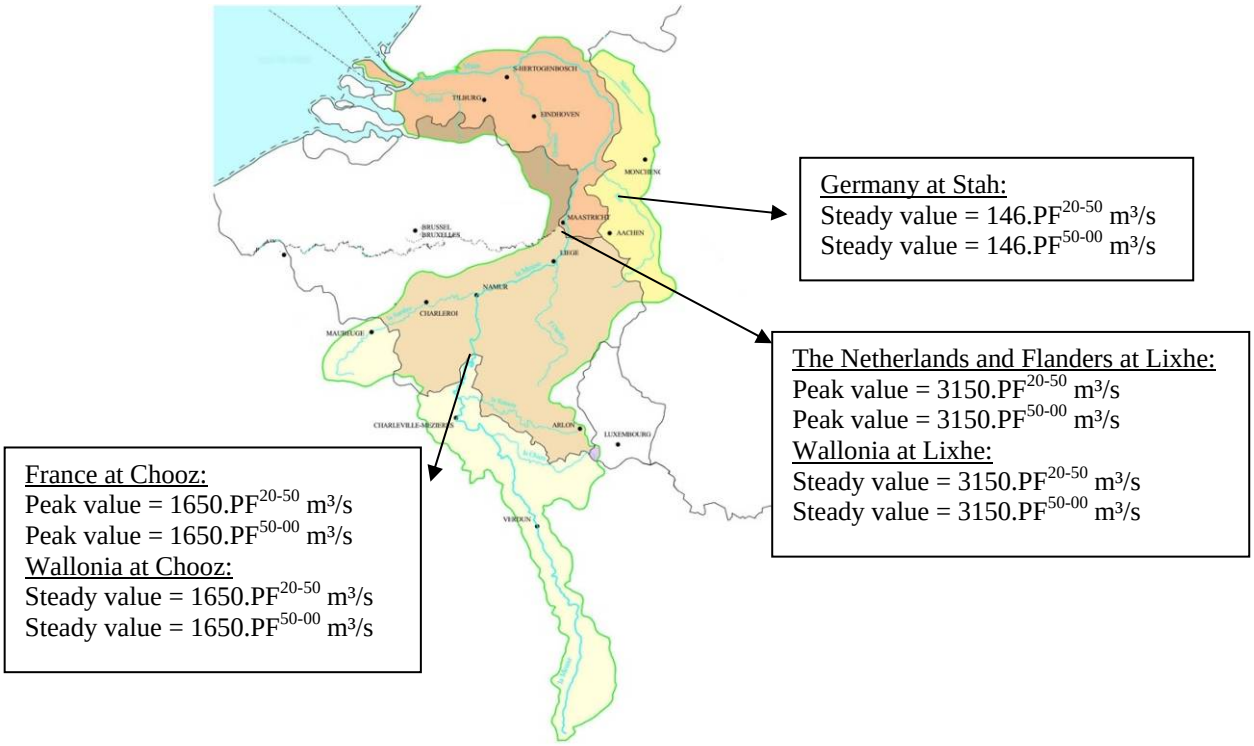


Figure 3-5 : Downstream BC for each model

[1] The Q_{100} discharge at borders is the average of values coming from each country



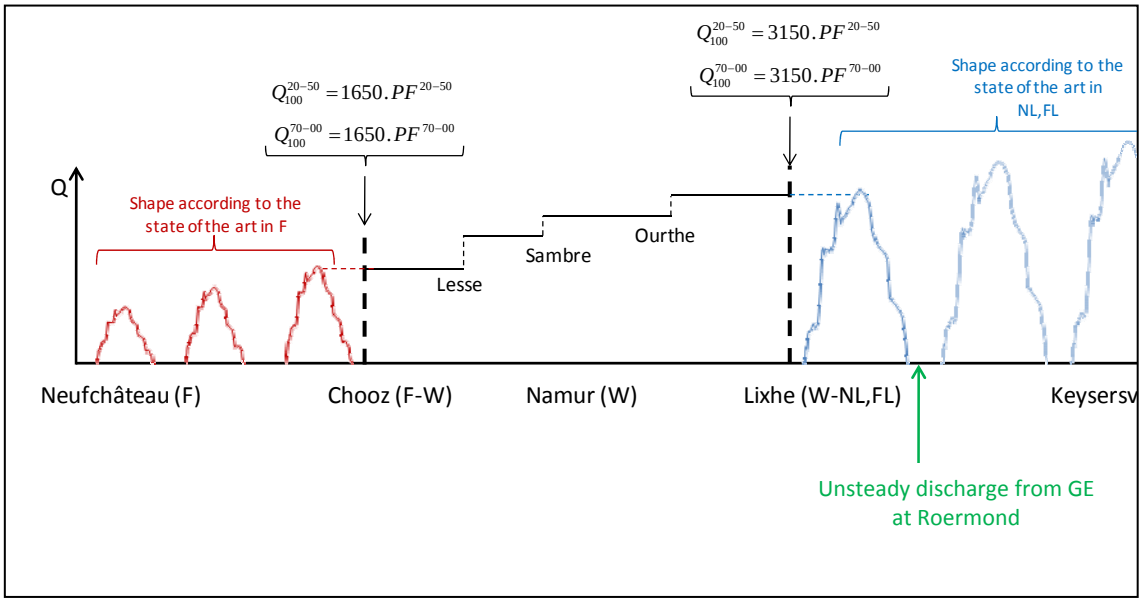


Figure 3-6 : Modified 100-year flood discharge at borders

Figure 3-7 : Sketch for discharge repartition along the Meuse

4 Consistency check at the borders

In line with the defined methodology, a comparison between computed results has been made after the first run of the hydraulic models. The comparison focused on the simulated water levels at the junctions between the models (borders) for the three considered discharges, namely Q_{100}, Q_{100}+15% and Q_{100}+30%.

For unsteady models, the considered water level is the highest one reached during the simulated flood event. No discharge comparison is needed since the methodology ensures their consistency across the borders, at least in terms of peak values.

4.1 Projection systems

Coordinate systems are different in each region. To perform comparisons between results of hydraulic models, the spatial coordinates of comparison points must be converted into a common projection system. Longitude and latitude were chosen as common coordinate system. There are basically three points of comparison located at the borders between countries: Chooz, Lixhe and Roermond. Two additional comparison points have also been included to account for the Flemish model, which covers a part of the Meuse between Borgharen and Linne (Figure 4-1). Results are provided in Table 4-1, with the light orange background identifying the coordinates in the local projection system for each comparison point.

	Chooz - FR		Chooz - W		Lixhe - W		Lixhe - NL		Borgharen - FL - NL		Roermond - GE		Roermond - NL		Linne -FL - NL	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Lambert 1 [m]	777786	277445	777771	277428												
Lambert 72 [m]	182638	95515	182620	95500	243000	160930	242663	161676	243441	174107					258594	207578
Rijksdriehoek [m]					176103	306783	175810	307627	176724	319953	196687	356608	196687	356608	192331	353211
DHDN Gauss Kruger 2											2498735	5673585	2498735	5673585		
Long/Lat [°]	4.826	50.170	4.825	50.170	5.687	50.751	5.682	50.758	5.696	50.870	5.984	51.197	5.984	51.197	5.921	51.168

Table 4-1 : Coordinates conversion for comparison points

Figure 4-1 : Location of comparison points Lixhe and Roermond, as well as the limits of the Flemish model (Borgharen and Linne)

4.2 Reference for elevations

References for elevation measurement also differ between the different countries and all results need to be converted into a common reference system to enable comparisons. The selected common system is the Belgian DNG (or TAW), which is already shared by Wallonia and Flanders.

The DNG elevations are 1.79 meter higher than the French one. This value could be deduced from a topographic survey realized for the Chooz gauging station.

The DNG elevations are 2.32/2.33 meter higher than the Dutch ones (NAP). This value could be deduced from Figure 4-2 and from an Internet reference:

http://nl.wikipedia.org/wiki/Tweede_Algemene_Waterpassing

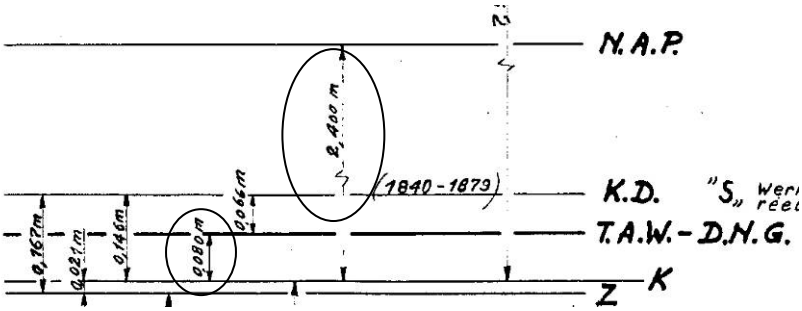


Figure 4-2 : Difference in the reference elevations between Wallonia and the Netherlands.

Finally, the Dutch elevations are 2 cm lower than the German ones.

4.3 Comparison France - Wallonia

At the French-Walloon border, significant differences of up to 1 m were found between the water levels computed at the end of the first run of the hydraulic models (Figure 4-3).

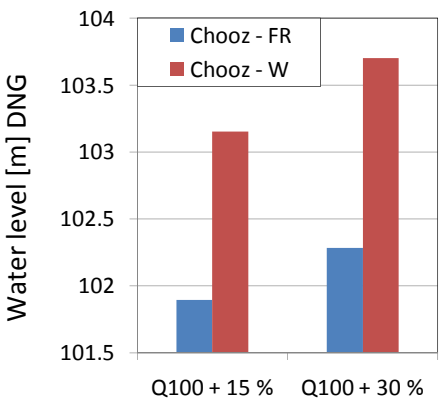


Figure 4-3: Computed water levels [m] in F and W after the first run of the hydraulic models.

Three differences in the models have been identified and contribute to explain this discrepancy:

- The stage-discharge curve used as downstream boundary condition for the French model differs from the computed stage-discharge relationship as simulated by the hydraulic model in Wallonia (Figure 4-4). Although it contributes to reduce the initial gap, changing this boundary condition has however only a limited impact on the water level at the F-W border because the boundary condition used by the F model is located 5 km downstream of the border, such has to reduce the influence of the boundary condition on the computed results in F.
- The bathymetry of the Meuse in the first Walloon reach (Border-Waulsort) needs to be updated regarding the dredging that occurred between 2002 and 2004. This update (bathymetry acquired in 2007) reduces the computed water levels in this reach, as shown in Figure 4-4. In particular, a fairly good agreement between the two models is found for discharges below the highest measured one (1560 m³/s). In addition, the water level by the Walloon model decreases also at the borders by about 40 cm.
- The roughness parameter of the French model in the Walloon part needs to be corrected since it was not calibrated in this reach.

A second run of both models has finally lead to a difference below 10 cm at the border.

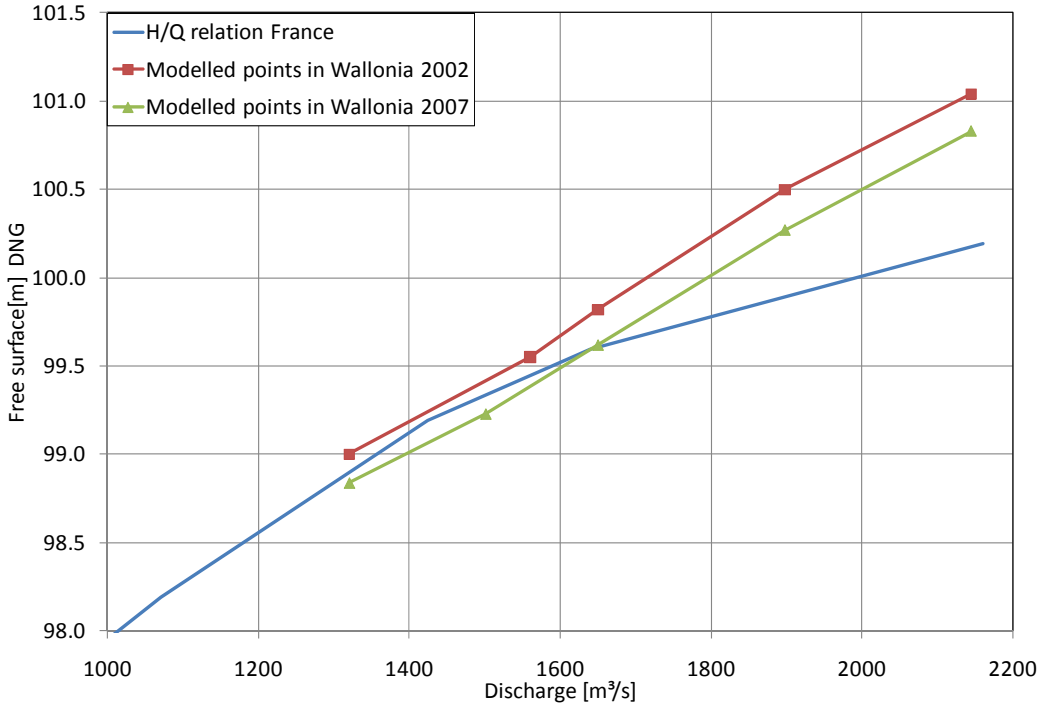


Figure 4-4: Downstream boundary condition of the F model vs modeled levels in W.

4.4 Comparison Wallonia -The Netherlands

The difference between the computed water levels at Lixhe is less than 20 cm (Figure 4-5). This result demonstrates that the stage-discharge relation extrapolated at Lixhe by the Walloon model must be slightly corrected in order to fit the Dutch one (Figure 4-6). A second run, based on these corrected values demonstrates that only the first reach between Monsin and Lixhe is affected without any significant impact on the extension of the flooded areas.

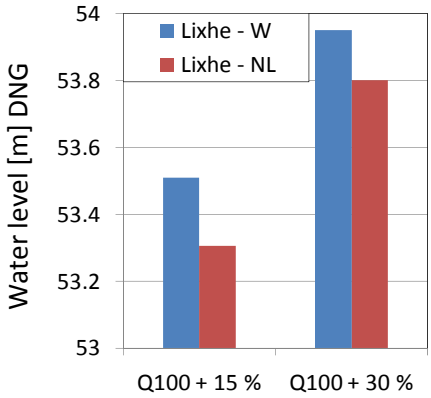


Figure 4-5: Water levels [m] computed at the border between the Netherlands and Wallonia after 1st run.

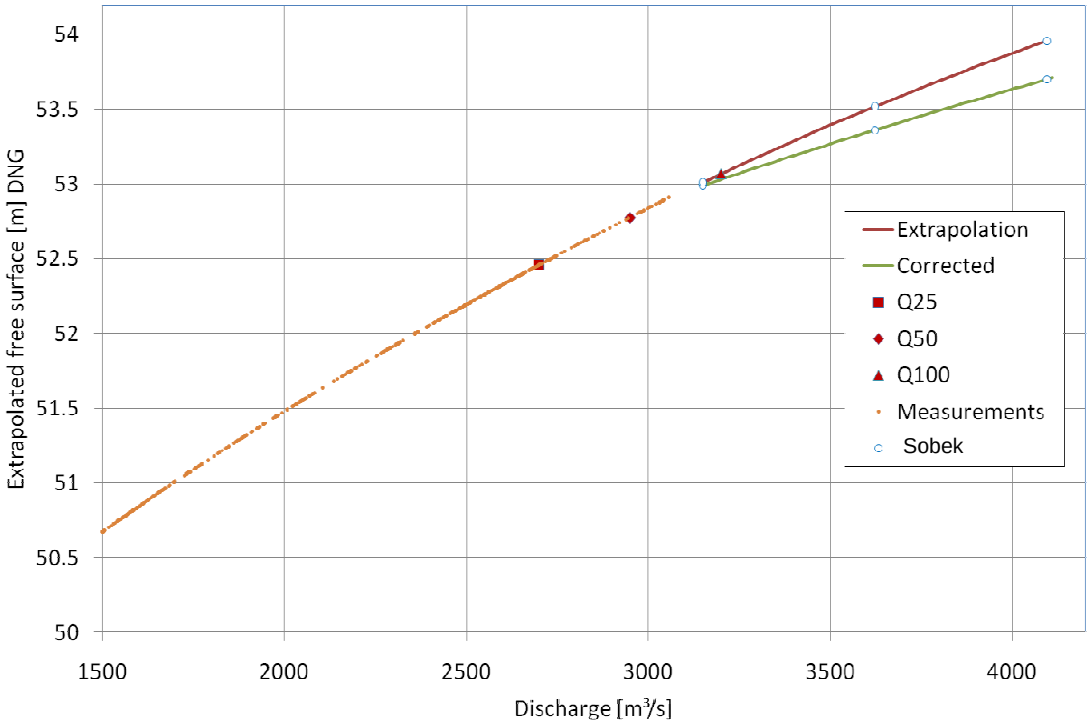


Figure 4-6: Stage-discharge relation at Lixhe compared to the water levels simulated by the Sobek model

4.5 Comparison Flanders - the Netherlands

The stage-discharge relation at Linne is slightly different (~30 cm) from the Dutch model (Figure 4-7). In addition a difference in the peak discharges of both models in Linne (Figure 4-8) appears due to different hydrographs used as upstream boundary conditions in the models (Figure 4-9). A second run has not been undertaken because these inflow hydrographs respect the defined methodology and the water level differences remain small. Finally, some differences appear also in Borgharen due to the differences in the shape of the hydrographs (Figure 4-10). Appendix 8.6 provides additional information on the Flemish hydrograph.

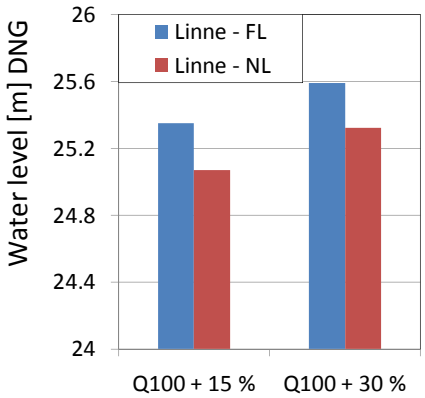


Figure 4-7: Free surface simulated [m] in the Netherlands and Flanders after 1st run at Linne

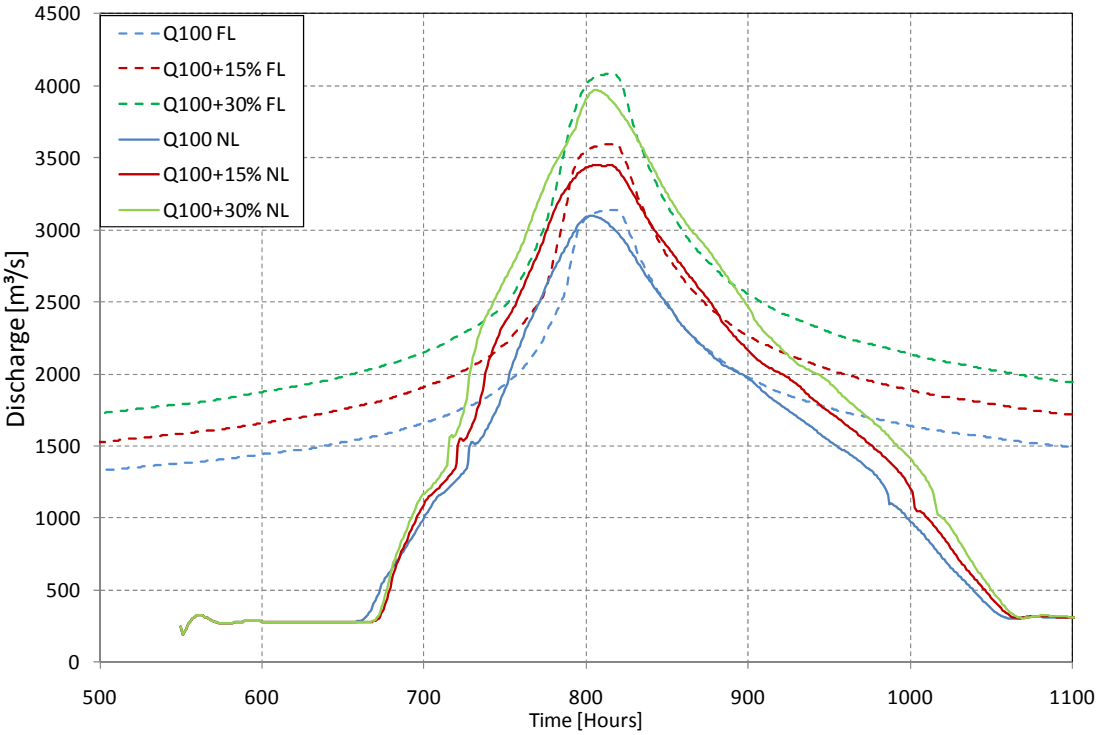


Figure 4-8: Hydrograph in Linne computed by the Dutch and Flanders models

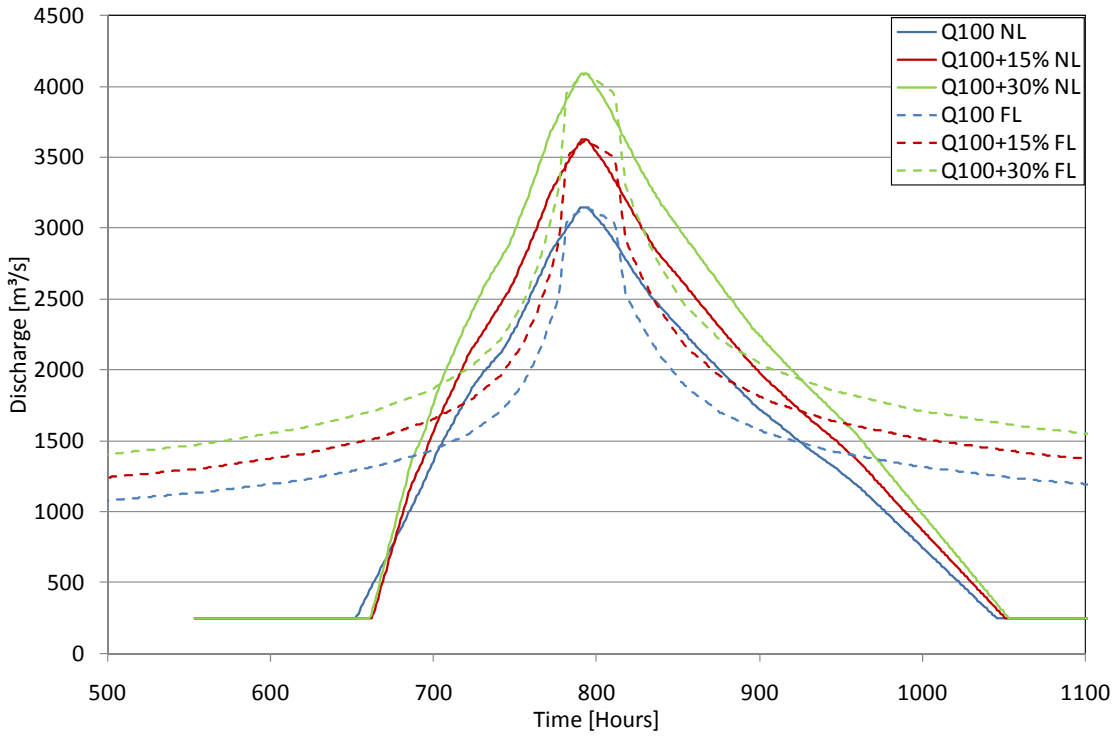


Figure 4-9: Input hydrograph injected in both models

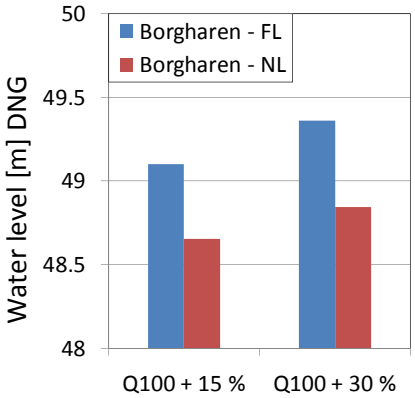


Figure 4-10: Water levels computed [m] by The Netherlands and Flanders after 1st run at Borgharen

4.6 The Netherlands-Germany

The inflow from the Roer into the Meuse at Roermond is determined according to the Dutch scenario generator "afvoergolven" for a HQ100 in the Meuse. The peak discharges determined using this method differs from the peak discharge for a return period of 100 years determined statistically for gauging stations along the Rur [1]. Flooding in the Meuse is caused by high rainfall events in the entire catchment and so the return periods of floods differ for single tributaries and the main river, which is considered by the scenario generator "afvoergolven". The German boundary conditions upstream at the Rur were adjusted as to fit the discharge computed by the scenario generator at Roermond to model the situation in the Rur during a HQ100 in the Meuse. This was done iteratively for the unsteady discharge boundary condi-

tions for the reservoir outflow of Obermaubach (upstream boundary condition) and for the unsteady discharge boundary conditions for the Inde tributary. The hydrograph modelled by the German model of the Rur and the boundary hydrograph used by the Dutch model of the Meuse can be seen in Figure 4-11. The deviation of peak discharge and flood volume is below 5 %. The difference in peak timing is compensated by the use of two separate models for the Rur and the Meuse.

The water level in the Meuse used as the downstream boundary condition in the German model of the Rur was set to the mean water level conditions, as the backwater effects on the city of Roermond cannot be captured by the model at this time. However, by combining the flood extend from the German and the Dutch model the whole extent is still captured.

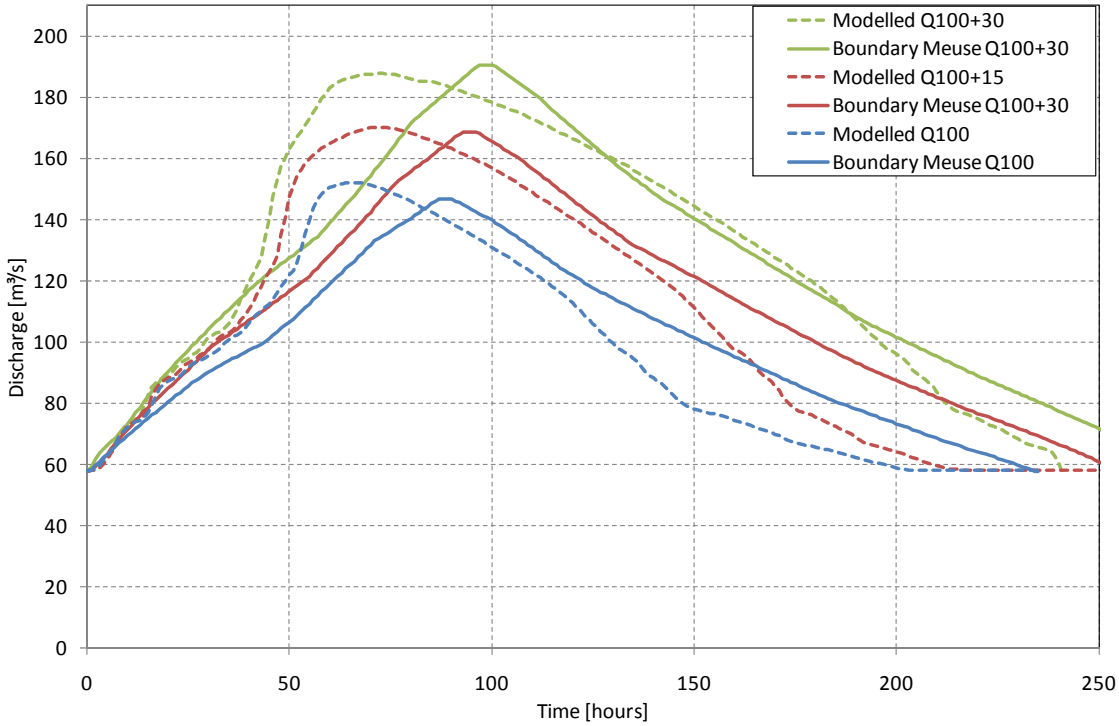


Figure 4-11: Hydrographs in Roermond: Inflow of Dutch model (solid lines) and outflow of German model (dashed lines)

5 Results and analysis

Hydraulic models have been run consistently from spring to mouth of river Meuse. The results are presented and discussed here at two complementary scales:

- **river scale**: impacts of climate change scenarios on discharges, water levels, inundated areas and volume stored in the floodplains are first detailed throughout the river course, from spring to mouth;
- **local scale**: next, detailed impacts on inundation extent and change in water depth are analysed for a limited number of selected hotspots (two per region).

5.1 River scale

Partners have agreed on a number of locations where model results are examined. Two sets of such locations have been defined:

- **points**, such has weirs, gauging stations, borders between regions …, providing a local information on the changes in hydraulic variables in the main course of the river (section 8.3);
- **reaches**, defined mainly between the previously chosen points, and showing a more global picture of trends in hydraulic variables at the reach-scale, or representing other variables such as flooded area or stored volume in the corresponding floodplains (section 8.4).

Depending on the type of result, either points or reaches are used to reveal the effect of climate change on the hydraulic variables of river Meuse. Some results can obviously not be provided by some models, such as hydrographs in a region where the hydraulic model has been run in steady mode because no significant damping of the flood wave can be expected there.

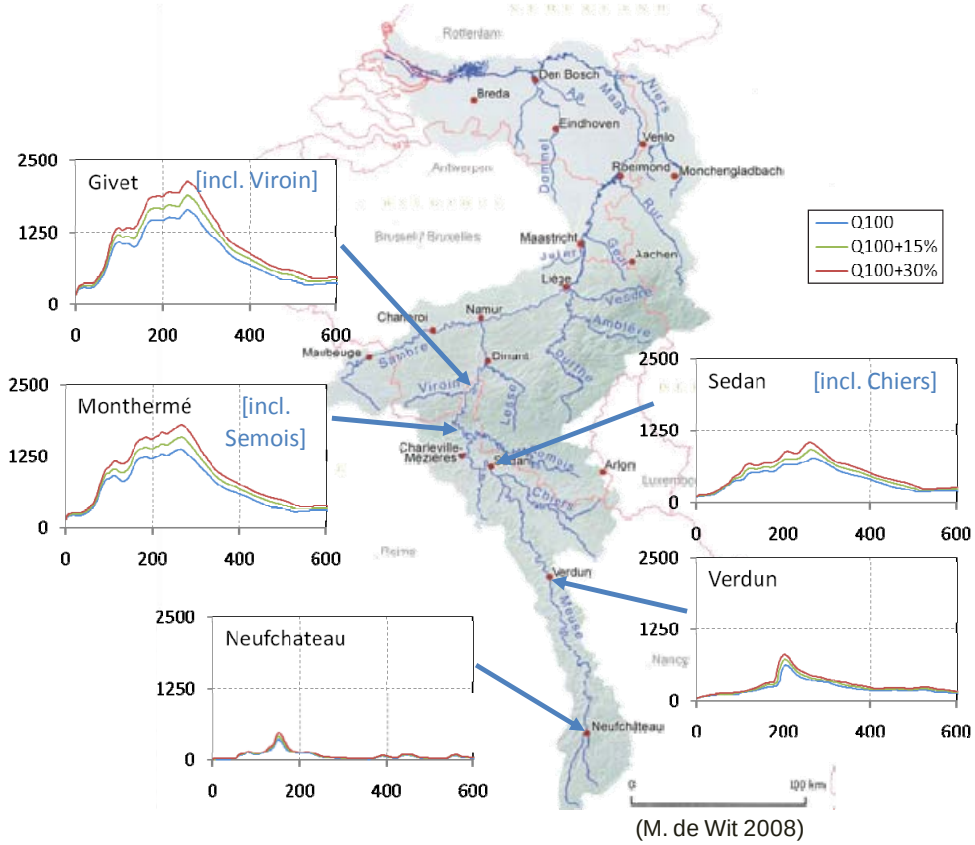
5.1.1 Hydrographs

Hydrographs have been generated by the models from Neufchâteau in France to Keisersveer in the Netherlands, except for the Meuse in Wallonia where the computation was steady state.

The shape of the hydrographs in France is based on reference floods such as 1993 or 1995. As moving further downstream, the peak discharges logically increase and the inputs from the main tributaries can clearly be distinguished (Figure 5-1). This monotonous increase shows that the tributaries have a stronger influence on flood propagation than damping in floodplains or derivation effect. The hydrographs further downstream also get flatter than they are more upstream and cause therefore a longer flood. Detailed charts are available in appendix (section 8.5).

Figure 5-2 shows the flood propagation for Q_{100}+15%, revealing that the propagation time of the peak discharge from Neufchâteau to the French-Belgian border is about 130 hours. Detailed results of flood propagation for all discharges are available in section 8.5.

Between Borgharen and Linne, there are no significant tributaries but damping takes place due to larger flooded areas. Furthermore, the Julianakanaal acts as a bypass. For Q_{100}+15% (Figure 5-3 and Figure 5-4), the damping is found to be about 2 %. The propagation between Borgharen and Linne takes about 20 hours.



(M. de Wit 2008)

Figure 5-1: Hydrograph comparison in France from Neufchâteau to Givet

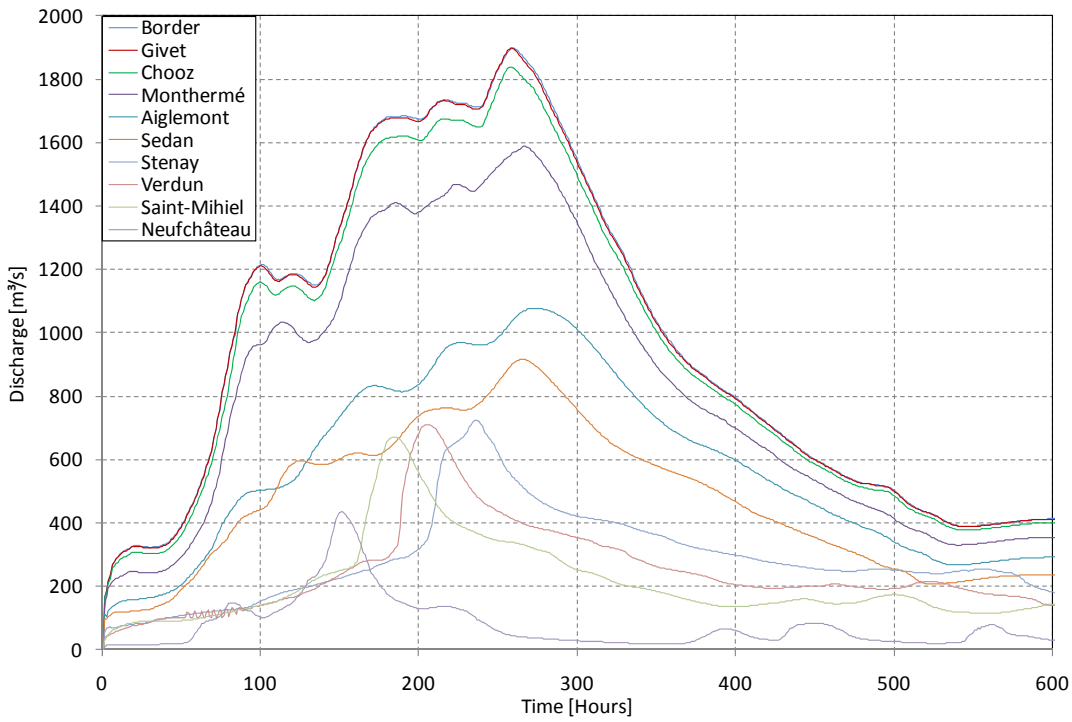


Figure 5-2: Flood propagation comparison in France from Neufchâteau to Givet for Q_{100}+15%

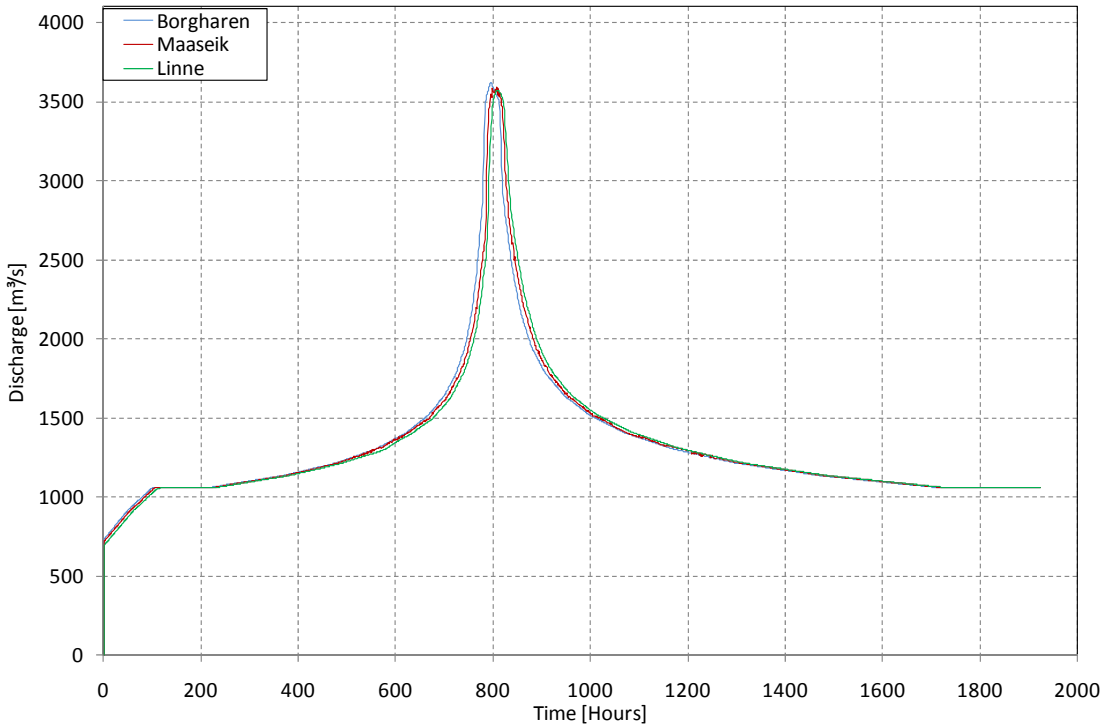


Figure 5-3: Flood propagation comparison in Flanders from Borgharen to Linne for Q_{100}+15%

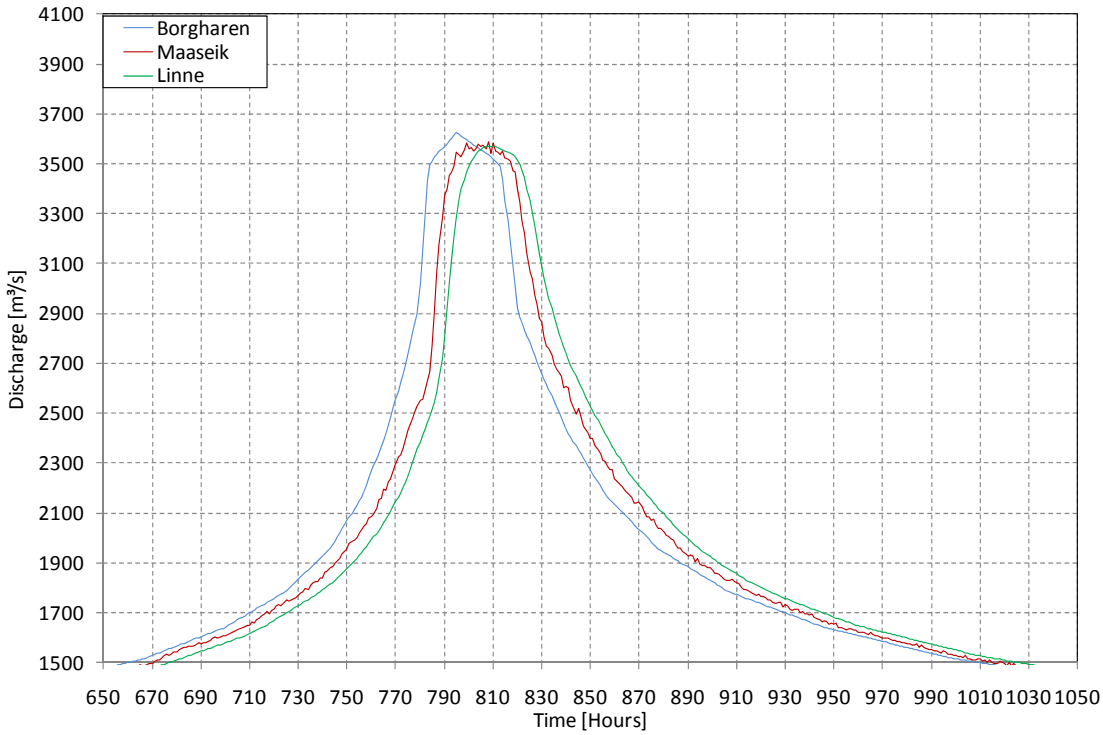


Figure 5-4: Flood propagation comparison in Flanders from Borgharen to Linne for Q_{100}+15%. Zoom on the results of Figure 8-15

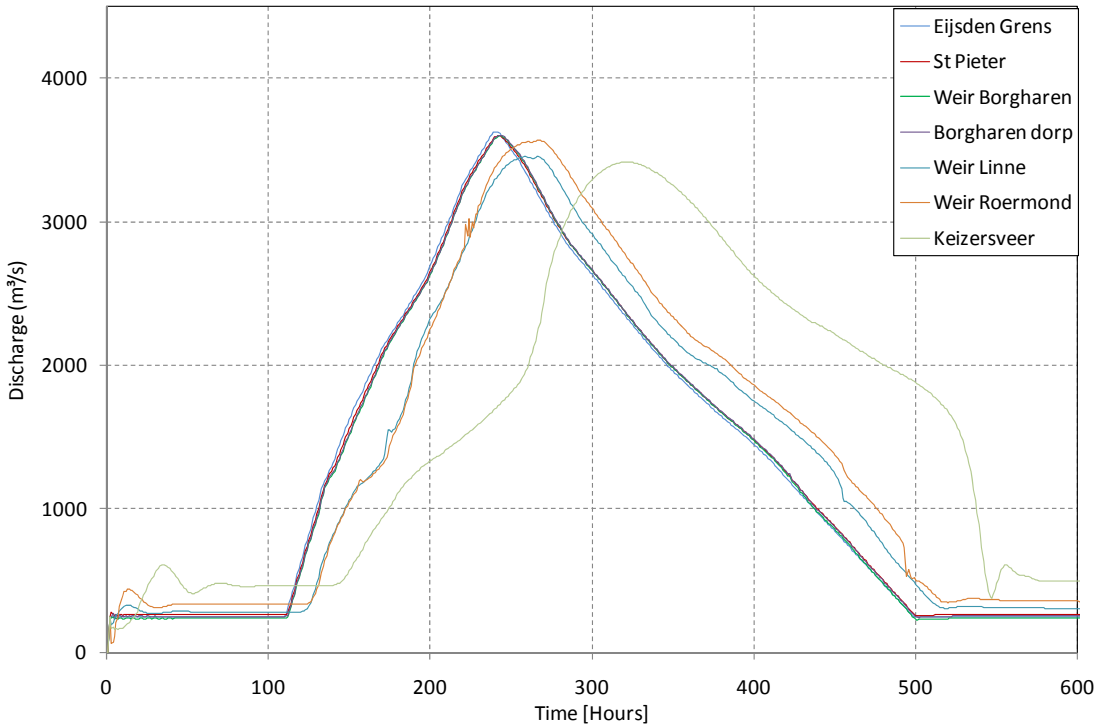


Figure 5-5: Flood propagation comparison in the Netherlands from Eijsden Grens to Keizersveer for Q_{100}+15%

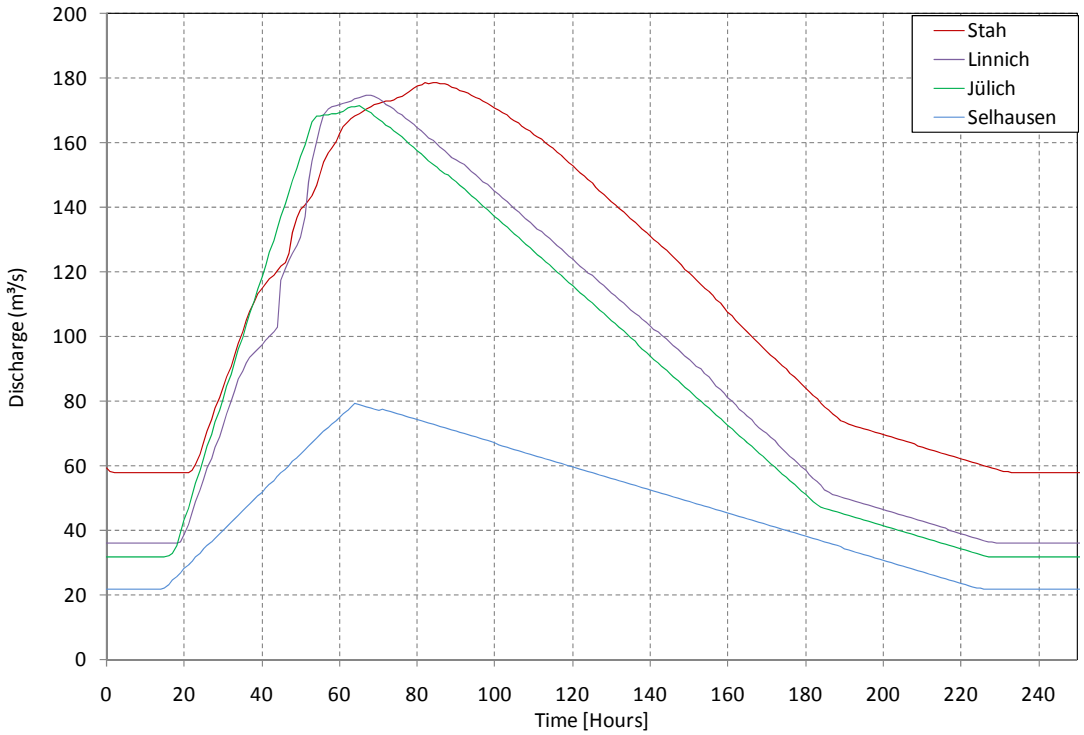


Figure 5-6: Flood propagation comparison in Germany from Selhausen to Stah for Q_{100}+15%

5.1.2 Peak discharges

Based on the previous hydrographs, the values of peak discharge reached can be easily deduced to evaluate the contribution of tributaries and possible damping or derivation effects.

Figure 5-7 shows that the discharge grows gradually from spring to Givet. Second, the discharge grows by steps, corresponding to the major tributaries in Wallonia. Next, the contributions of tributaries are damped between Lixhe and Roermond and finally some more damping occurs downstream due to the large flooded areas in the Netherlands. German results on river Rur are available on Figure 5-8.

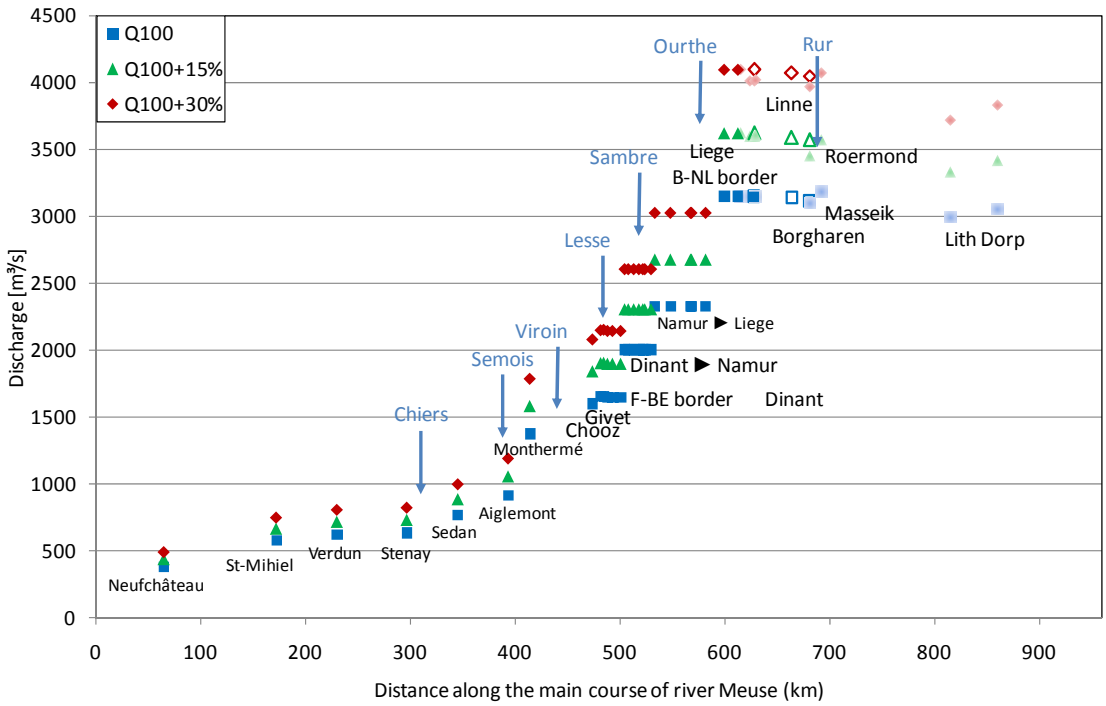


Figure 5-7 : Peak discharge comparison from spring to mouth

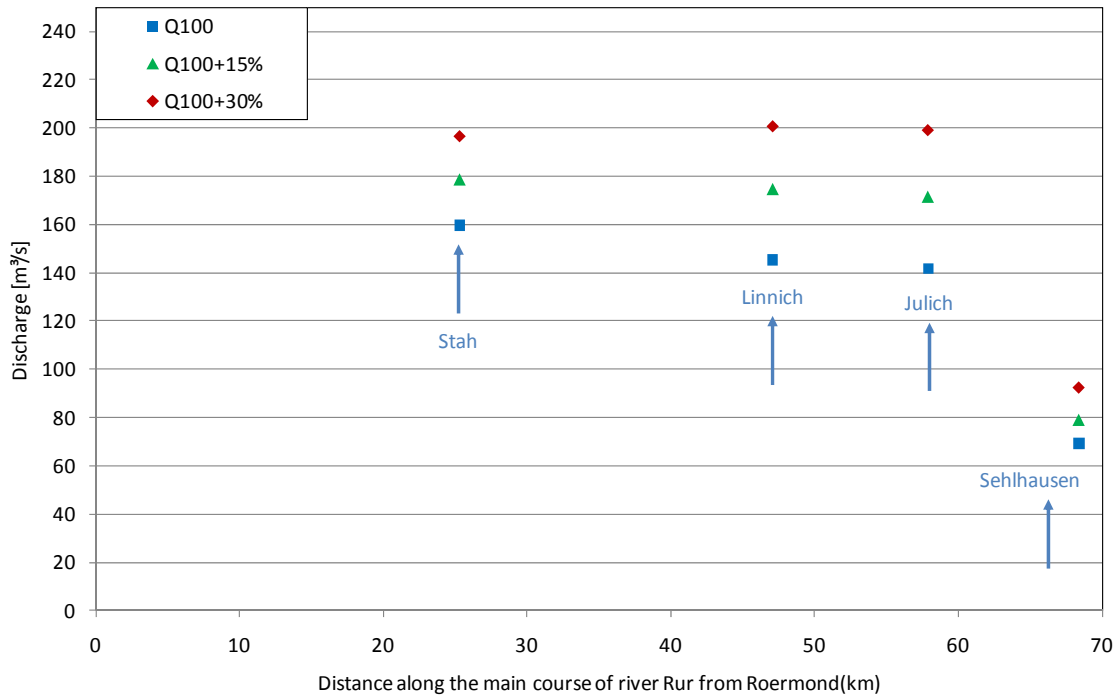


Figure 5-8: Peak discharge comparison on river Rur

5.1.3 Change in water depths

Changes in water depth have been computed for Q_{100}+15% and Q_{100}+30% compared to the reference situation Q_{100}. Values are shown both at each extraction point (Figure 5-9) and along each reach by averaging the corresponding local water depths (Figure 5-10). In both cases, the same trends are found. The bars show the difference between Q_{100} and Q_{100}+15% (blue) or Q_{100}+30% (red).

In Borgharen and Linne, results provided by the Dutch and the Flemish model are found consistent.

Three parts can be distinguished in theses graphs:

- in the **upper part**, upstream of Aiglemont, the mean increases in water depth are respectively +30cm and +50cm;
- in the **lower part** downstream of Monsin, a similar trend is obtained (+30 cm and+70cm);
- in the **central part**, totally different figures are found: variations rise up to 60cm and 130cm respectively.

This separation does not correspond with a change in the models used because the central part extends quite far in the French territory where the unsteady model has been used. In the same way, the steady model extends downstream of Monsin. This suggests that a significant difference is found in the sensitivity of the water levels in river Meuse with respect to increases in discharge. This may be related to the shape of the Meuse valley, which is narrower in the central part of the basin.

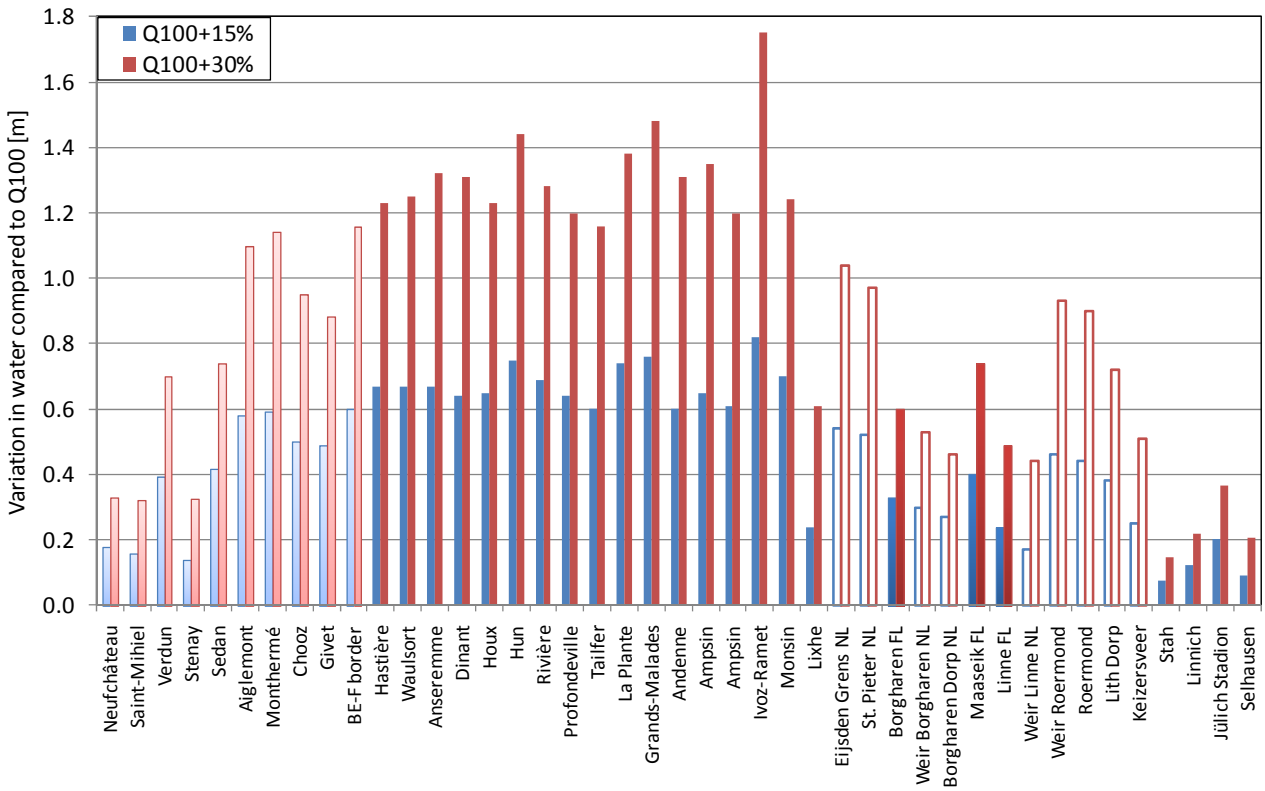


Figure 5-9 : Variation in water depth compared to Q_{100} at extraction points

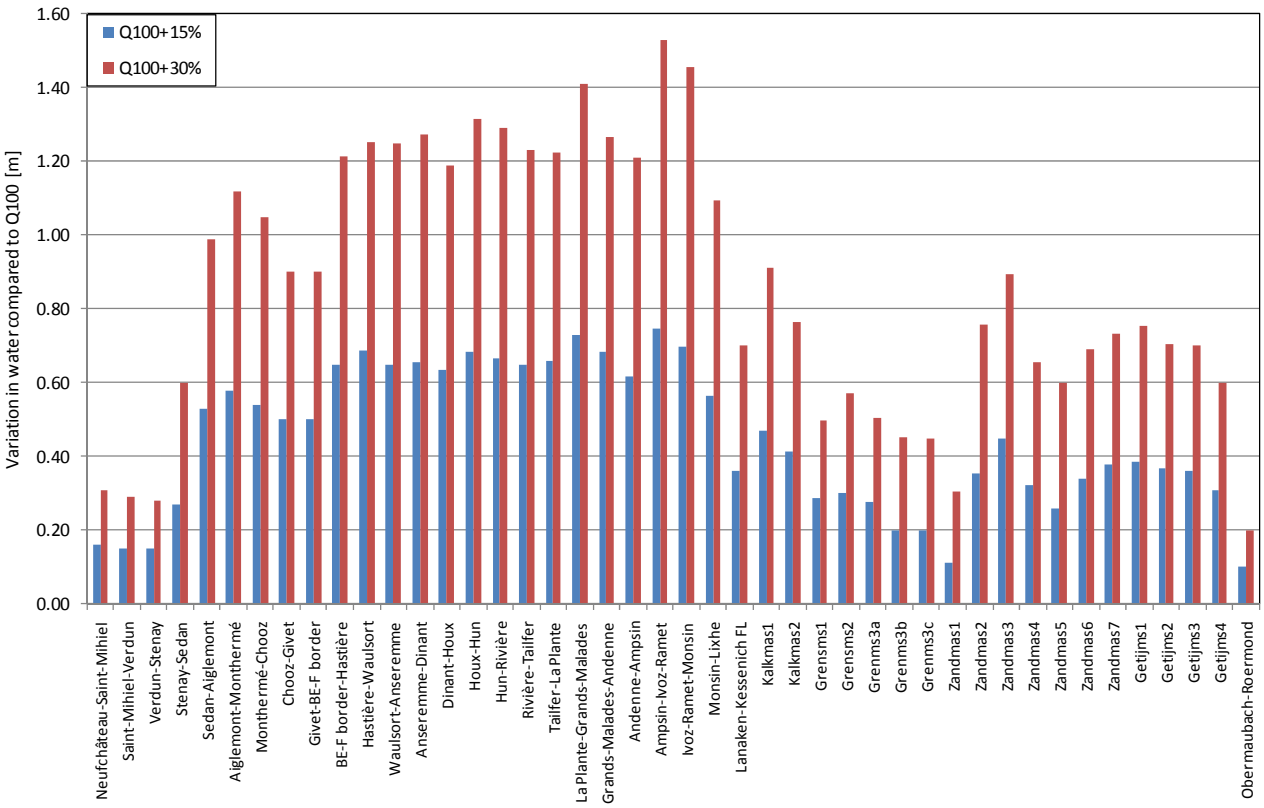


Figure 5-10 : Variation in water depth compared to Q_{100} along each reach

5.1.4 Water levels

Water elevation can be plotted from spring to mouth in a common projection system. Figure 5-11 shows the free surface in the Belgian projection system (DNG). As mentioned in chapter 4, consistency was already checked at borders ensuring a continuous water line. The change in free surface slope downstream of Roermond is due to the smaller bed slope of the Meuse in this area. The slope of the free surface upstream of Roermond is of the order of 4×10^{-4} while it reduces to 1×10^{-4} downstream.

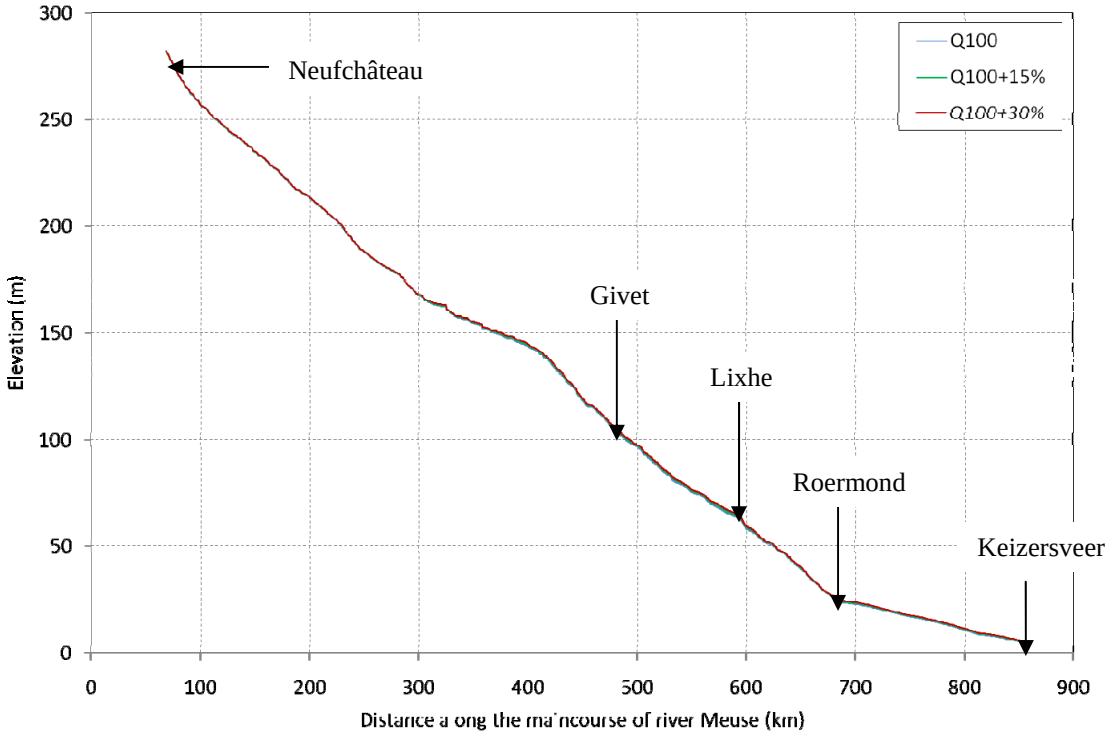


Figure 5-11: Maximum water elevation on the Meuse expressed in DNG referential

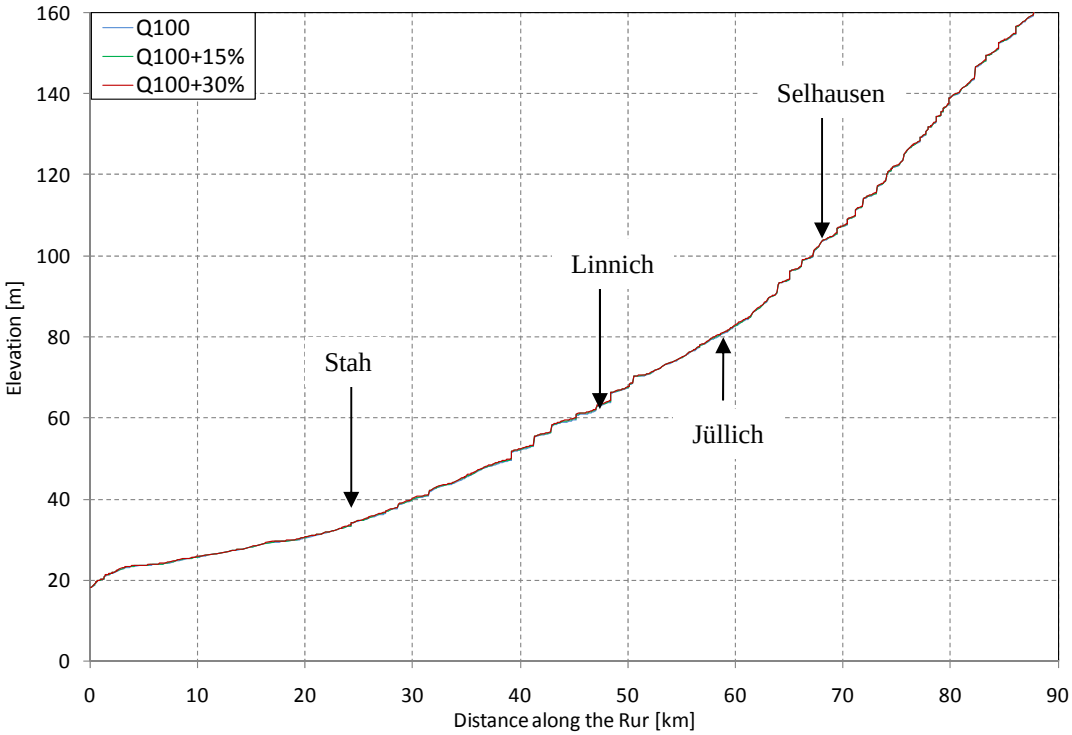


Figure 5-12: Maximum water elevation on the Rur expressed in DNG referential

5.1.5 Changes in flooded area and stored volume in the floodplains

Flooded areas and stored volume are displayed for each reach as their relative contribution to the total increase for Q_{100}+30% in each country. In Wallonia, three reaches are mostly affected by the increase in discharge for Q_{100}+30% (Figure 5-14 and Figure 5-18). They are all three located between Andenne and Monsin. The reach including the industrial area of Liege is the most affected one, since it is found to represent about 35 % of the total increases in flooded area and stored volume for Q_{100}+30%. For Q_{100}+15% the distribution of flooded area is more homogeneous and the two reaches between Ampsin and Ivoz-Ramet are found most sensitive.

In the Netherlands and Flanders, the reach between Lanaken and Kessenich is the most affected for both time horizons. Downstream, the reaches named "Zandmaas" are affected with an average increase of 10% in the flooded areas and the volume stored.

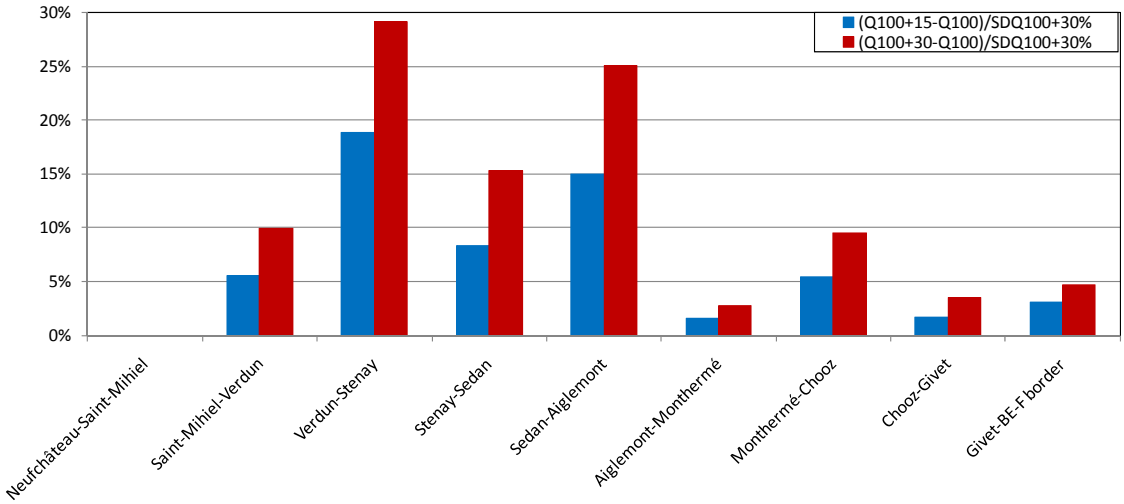


Figure 5-13: Contributions of flooded areas per reach compared to the total increase in flooded area for Q_{100}+30% in France

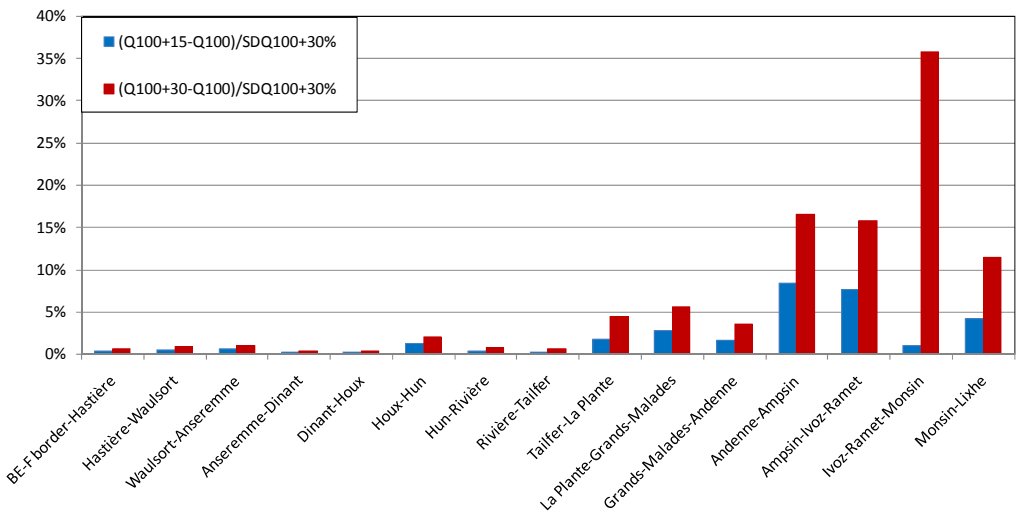


Figure 5-14: Contributions of flooded areas per reach compared to the total increase in flooded are for Q_{100}+30% in Wallonia

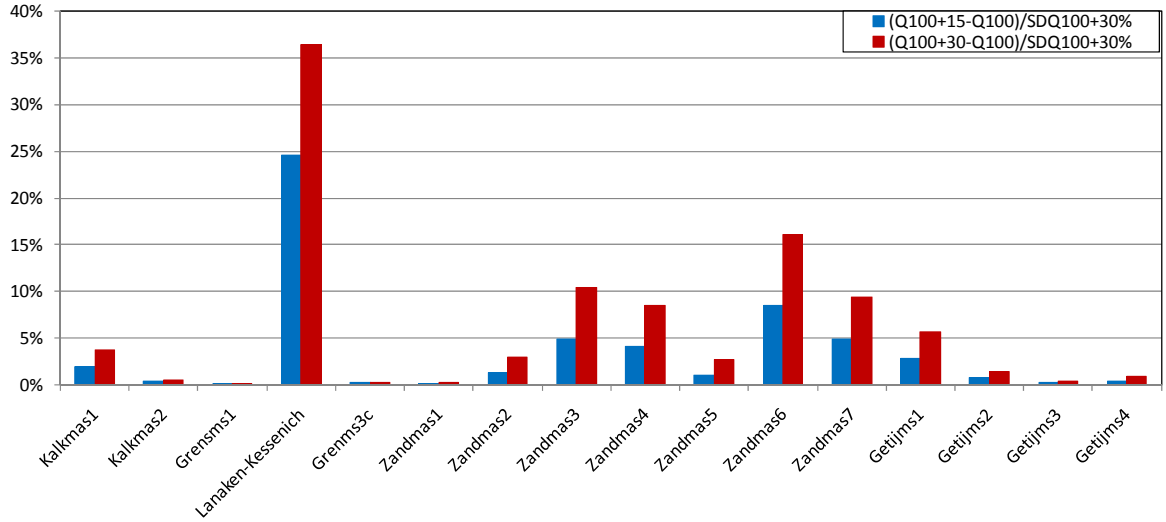


Figure 5-15: Contributions of flooded areas per reach compared to the total increase in flooded area for Q_{100}+30% in the Netherlands and Flanders

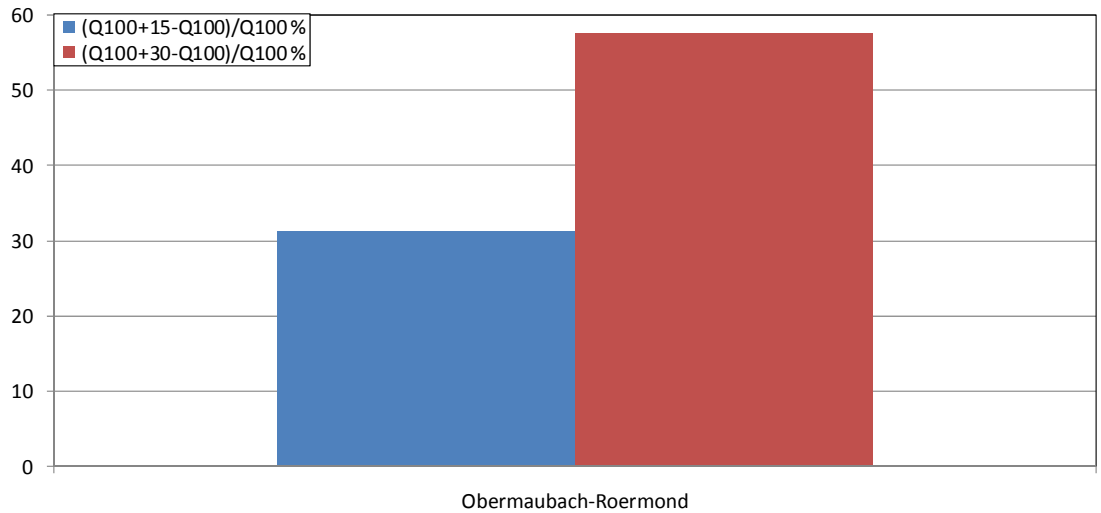


Figure 5-16: Increase in flooded area compared to Q100 for Germany on the Rur

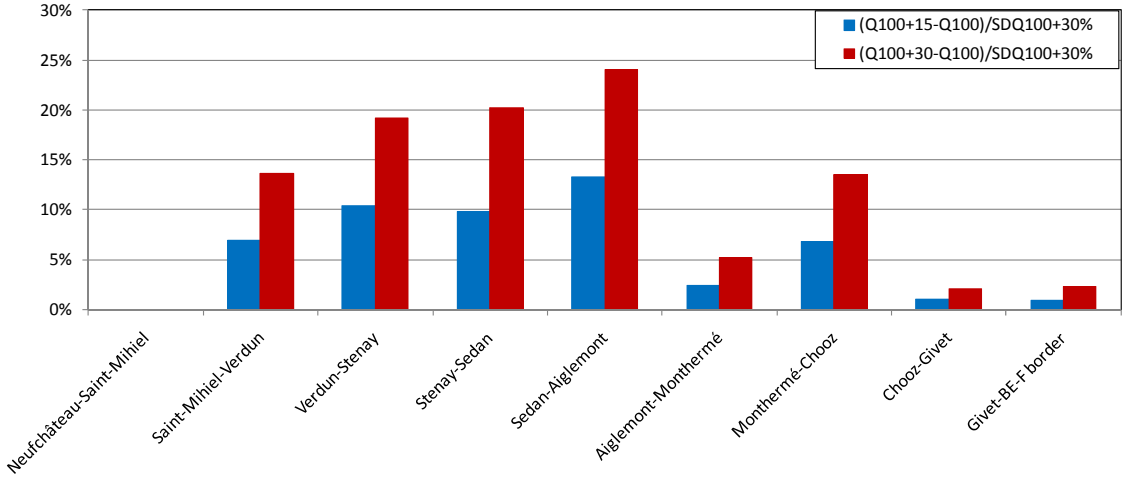


Figure 5-17: Contributions of stored volume per reach compared to the total increase of stored volume at Q_{100}+30% in France.

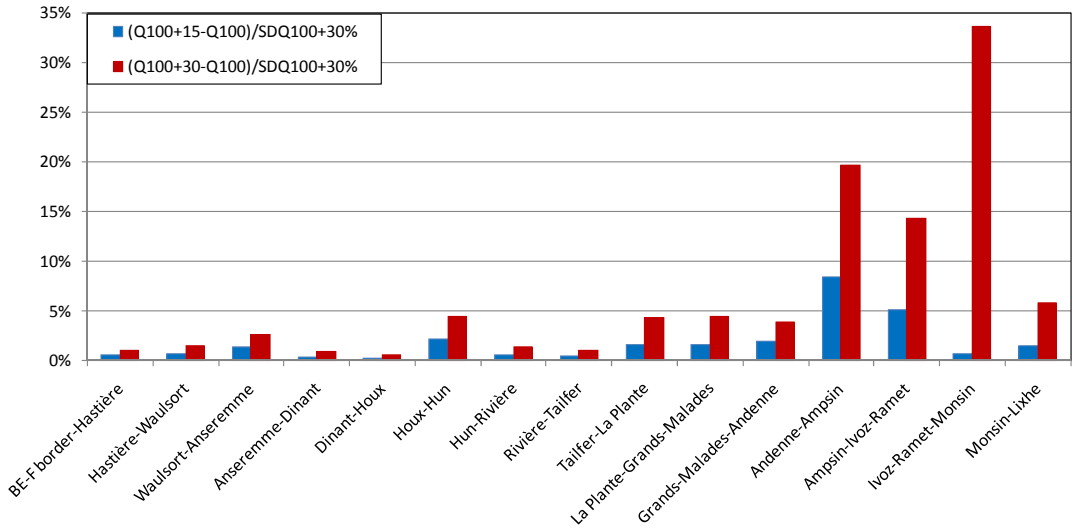


Figure 5-18: Contributions of stored volume per reach compared to the total increase of stored volume at Q_{100}+30% in Wallonia.

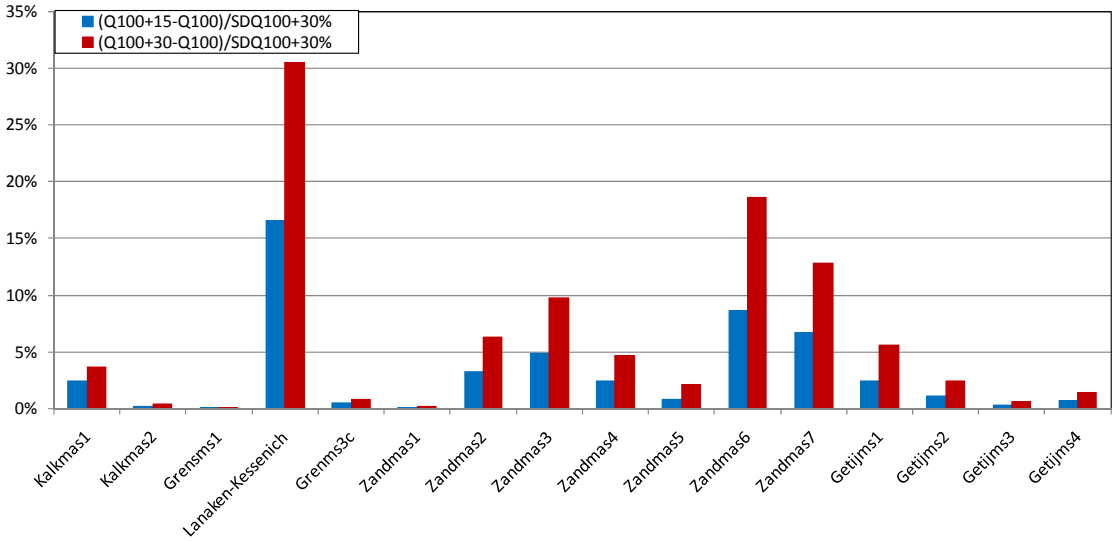


Figure 5-19: Contributions of stored volume per reach compared to the total increase of stored volume at Q_{100}+30% in the Netherlands and Flanders

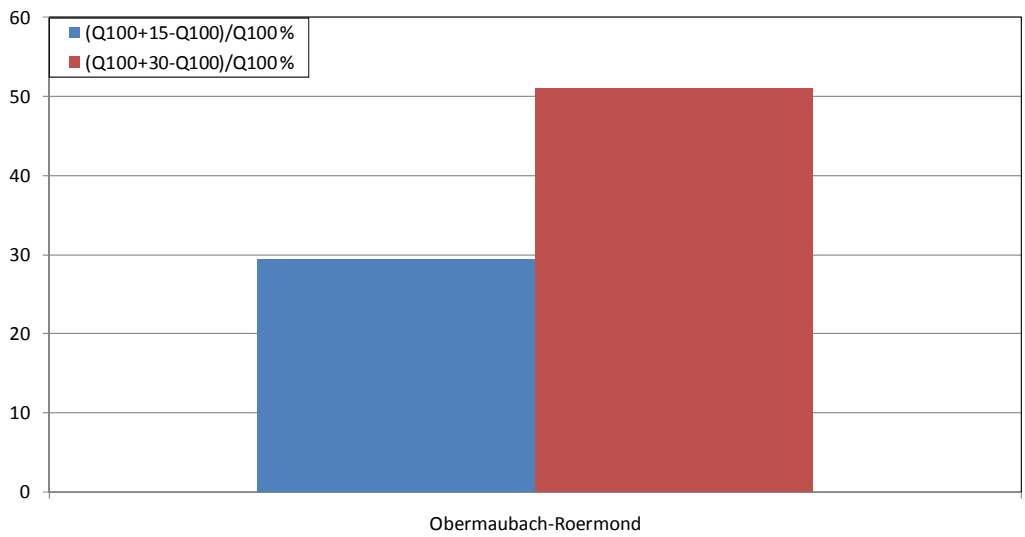


Figure 5-20: Increase in stored volume compared to Q100 for Germany on the Rur

5.2 Selected hotspots

This section focuses on local changes in the hydraulic parameters, particularly inundation extents and water depths, in a number of hot spots selected by the Partners.

5.2.1 France

In France, the sites are located in Verdun, Charlevilles-Mezières and Givet.

Givet is the most upstream harbour of the Meuse where commercial shipping can take place.

The city was severely flooded in 1995. The nearby tributaries Semois and Houille have since then created damages as well. New flood protections have been built to protect the inner city.

They are made of a low fixed wall, on which mobile walls can be erected in less than 48 hours. The harbour can however still be flooded. An automated mobile weir has replaced the old needle weir. The road going to Belgium is regularly under water because of floods. The city could still be flooded under the AMICE wet scenario. The water would enter the city by the downstream part, the harbour, where no flood protection has been created so far.

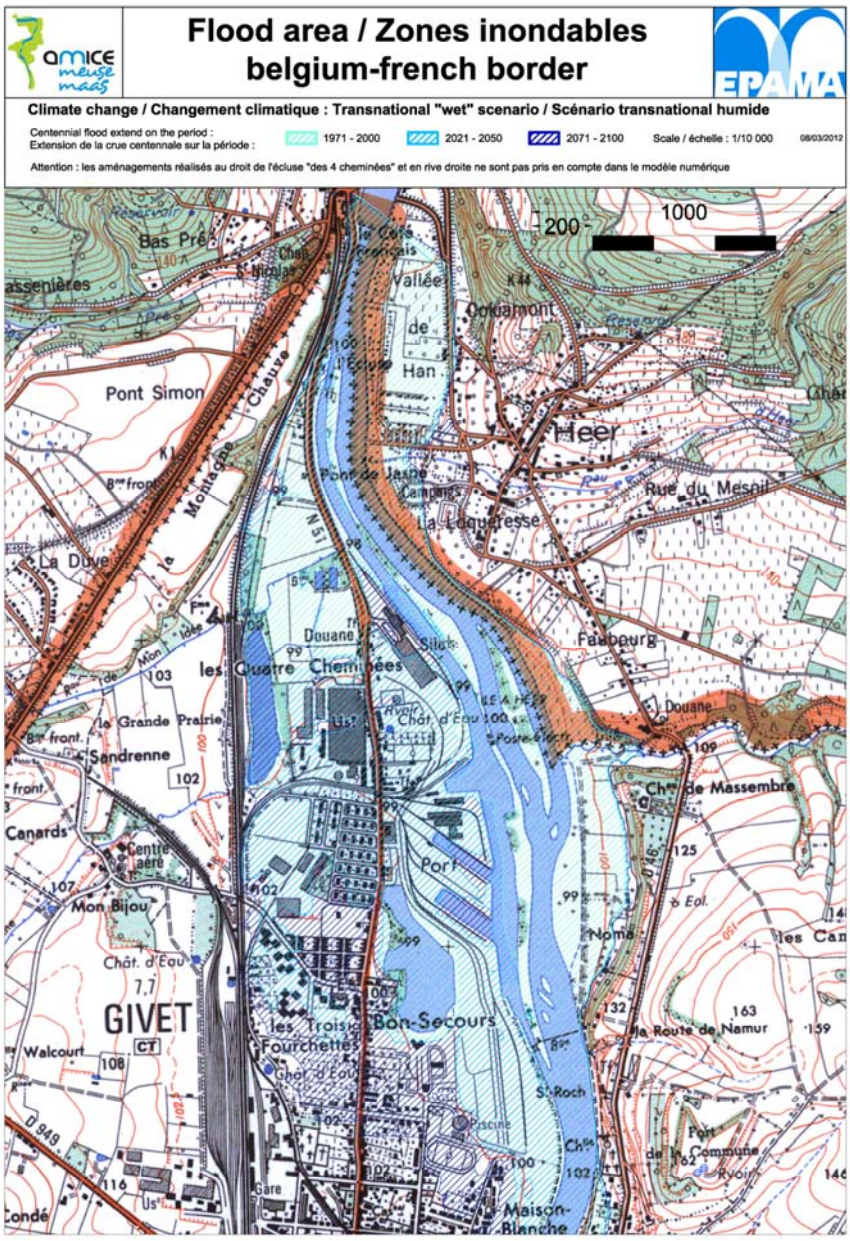


Figure 5-21: Inundation extent for Q_{100}, Q_{100}+15% and Q_{100}+30% in Givet

Charleville-Mézières is the largest town on the French basin as well as the administrative centre of the "Département des Ardennes". New embankments for flood protection have been built after the 1995 flood as well as a short-cut in one of the river meanders (Montcy-Notre-Dame). These flood protections accelerate the flow downstream. In order to prevent increased flooding downstream and in neighbour countries, these protections have been

compensated by a “dynamic flood retention zone” built further upstream of the city, close to Mouzon. The extra flooded area due to climate change is not very large but the potentially impacted assets are important. The “Préfecture” (location of the crisis management centre for the whole Département), the town hall, several major roads and railways, industries and shops.

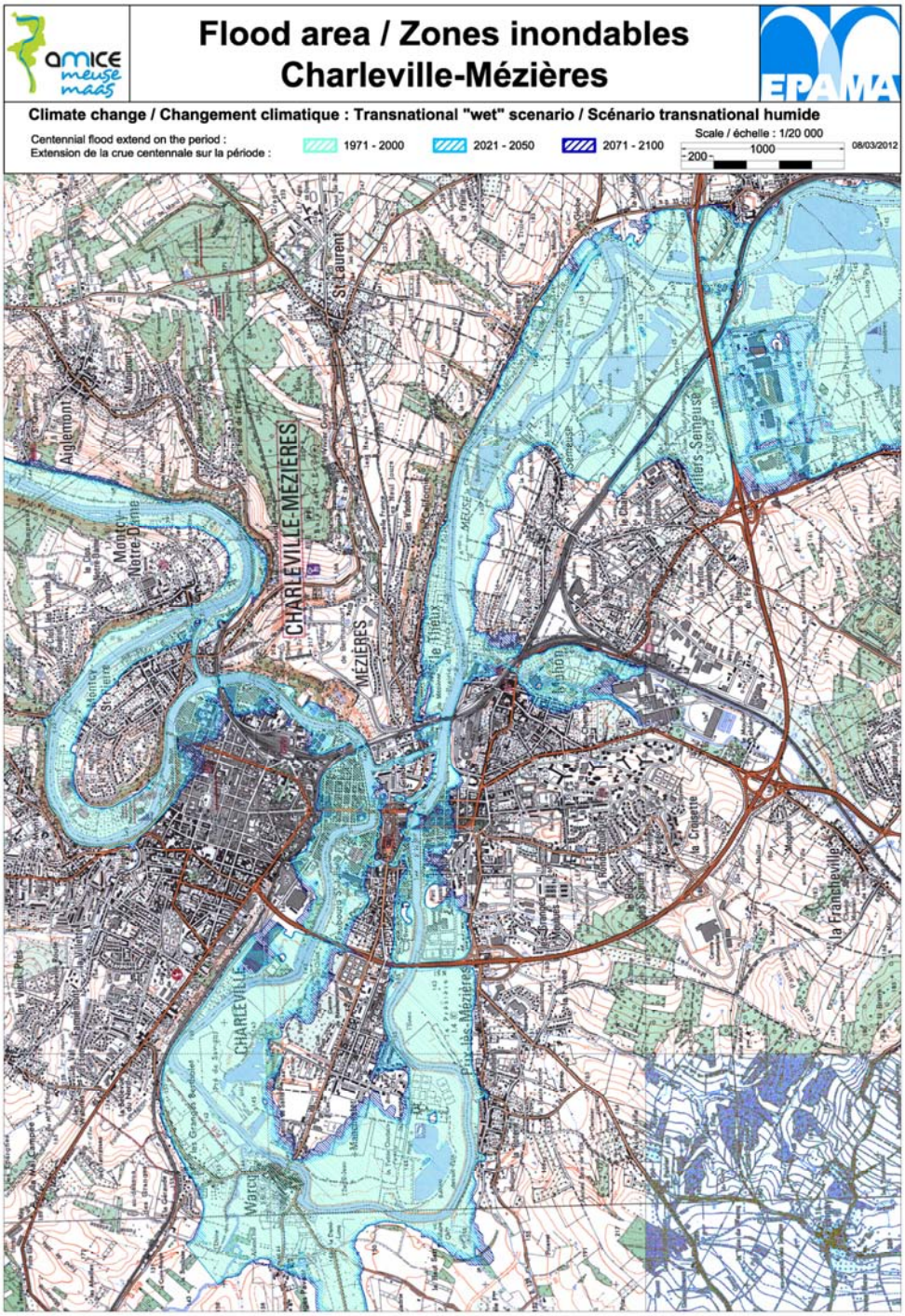


Figure 5-22: Inundation extent for Q_{100}, Q_{100}+15% and Q_{100}+30% in Charlevilles-Mezières

Contrary to the two previous hotspots, there are no protections against floods in Verdun. The impact of climate change is rather limited in terms of flooded area but the water depth would increase from 40 to 60cm by the end of the century.

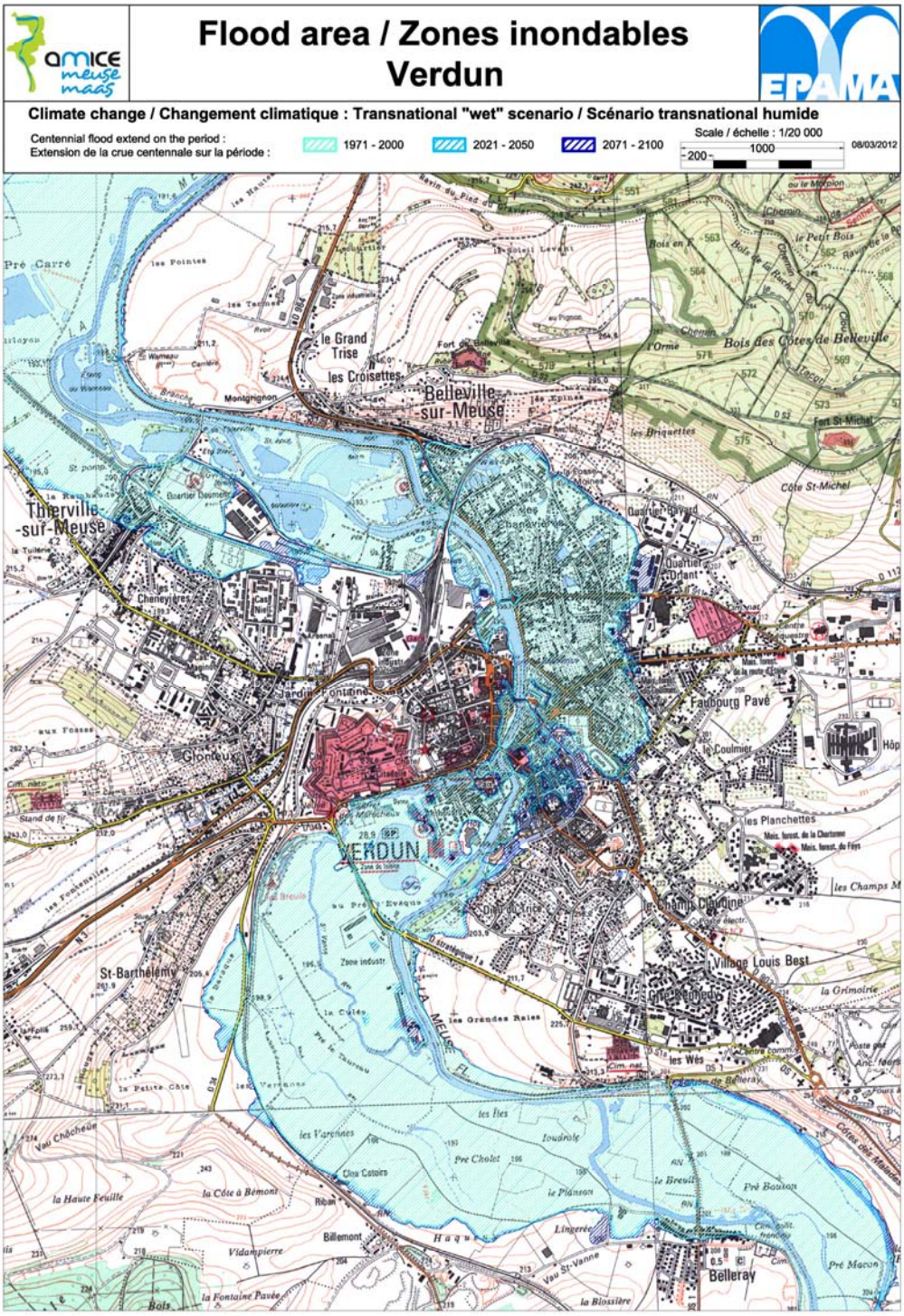


Figure 5-23: Inundation extent for Q_{100}, Q_{100}+15% and Q_{100}+30% in Verdun

5.2.2 Wallonia

In Wallonia, the selected hotspots cover the two most important cities situated along river Meuse. They are located in Namur, close to the junction with river Sambre, and in Liege, close to the junction with river Ourthe.

Figure 5-24 shows the flooded areas in Namur for each modelled discharge, revealing that almost no inundation takes place for a discharge of Q_{100} except on the left bank upstream of the junction with river Sambre. For Q_{100}+15%, the right bank of the Meuse (Jambes) would be partially flooded and for Q_{100}+30% the whole area of Jambes would be flooded as well as the left bank downtown in Namur.

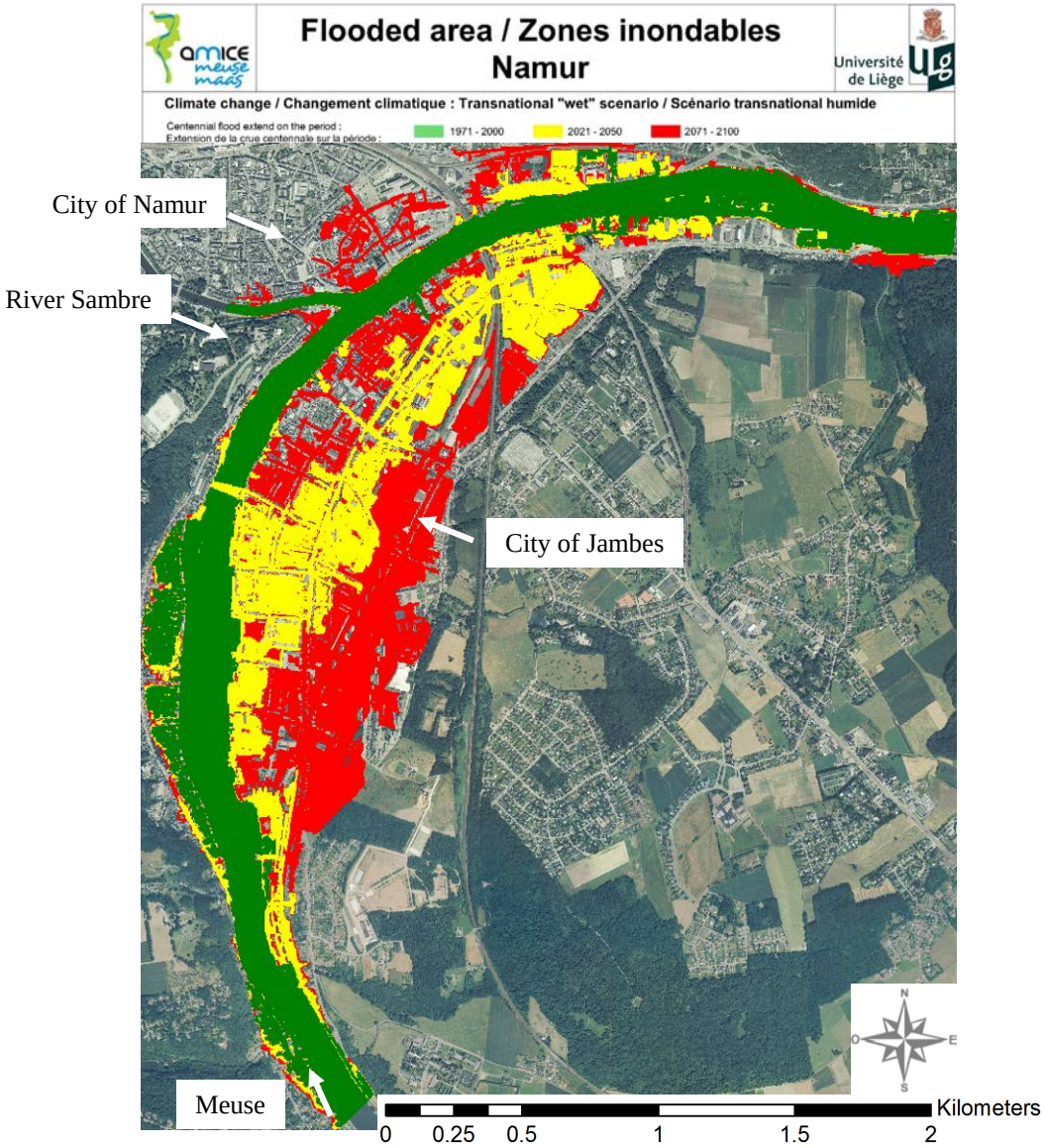


Figure 5-24: Inundation extent for Q_{100} (green), Q_{100}+15% (yellow) and Q_{100}+30% (red) in Namur

The city of Liege would be found to be well protected for discharges up to Q_{100}+15%, except in some parts of limited extent upstream of the city centre (Figure 5-25). In contrast, for the highest considered discharge, large parts of the city would be flooded down to the mobile weir of Monsin, where the water flows back to the main riverbed of the Meuse. The corresponding increase in water depth is represented in Figure 5-26. Globally the water level would rise by up to 1 meter compared to Q_{100} in the entire affected part of the city. An area located close to

Monsin would experience worse conditions (water levels up to 4 meters) due to mining subsidence.

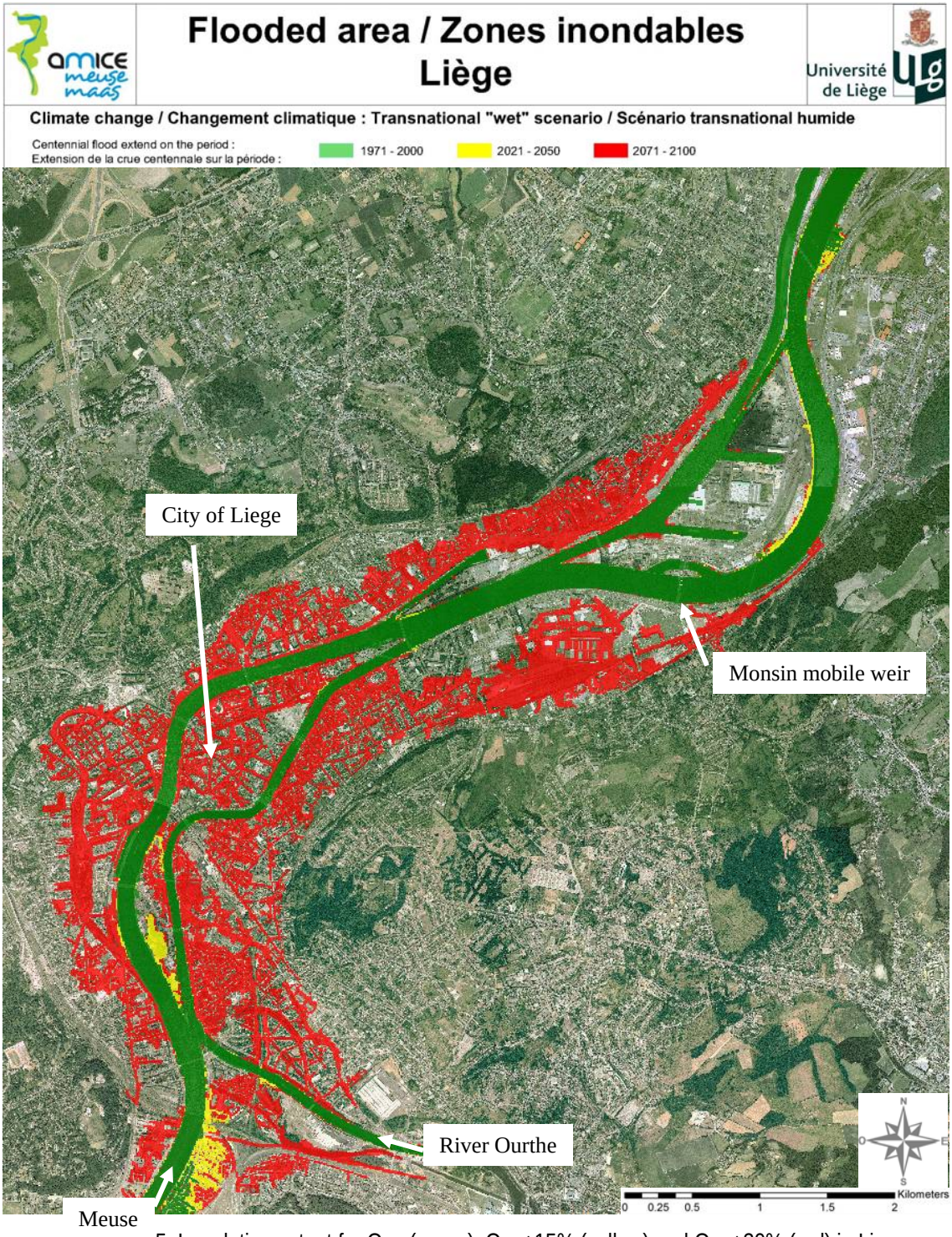


Figure 5-25: Inundation extent for Q_{100} (green), Q_{100}+15% (yellow) and Q_{100}+30% (red) in Liege

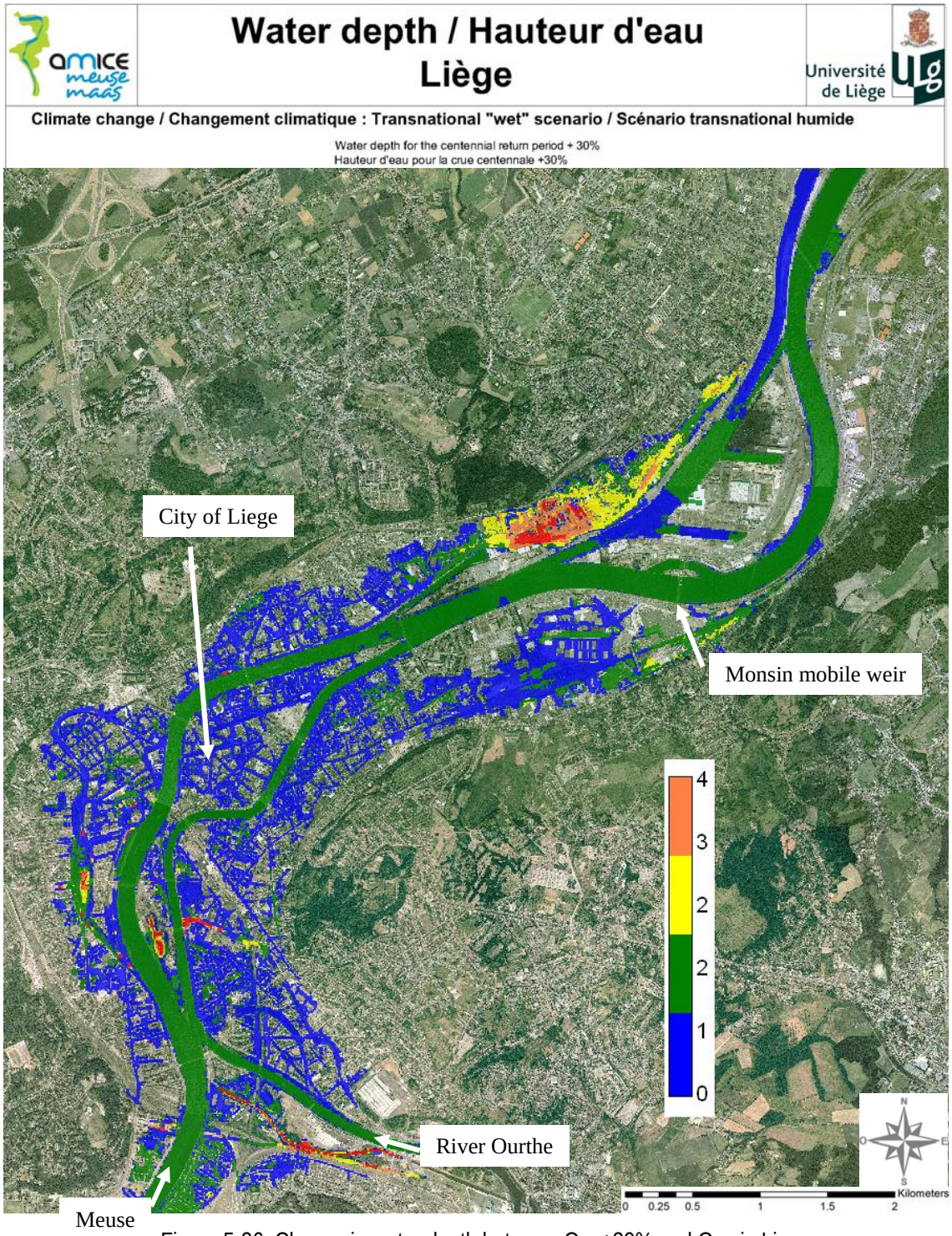


Figure 5-26: Change in water depth between Q_{100}+30% and Q_{100} in Liege

5.2.3 Flanders

The selected hotspot Flanders corresponds to the reach of river Meuse along the Dutch-Flemish border (Figure 5-27).

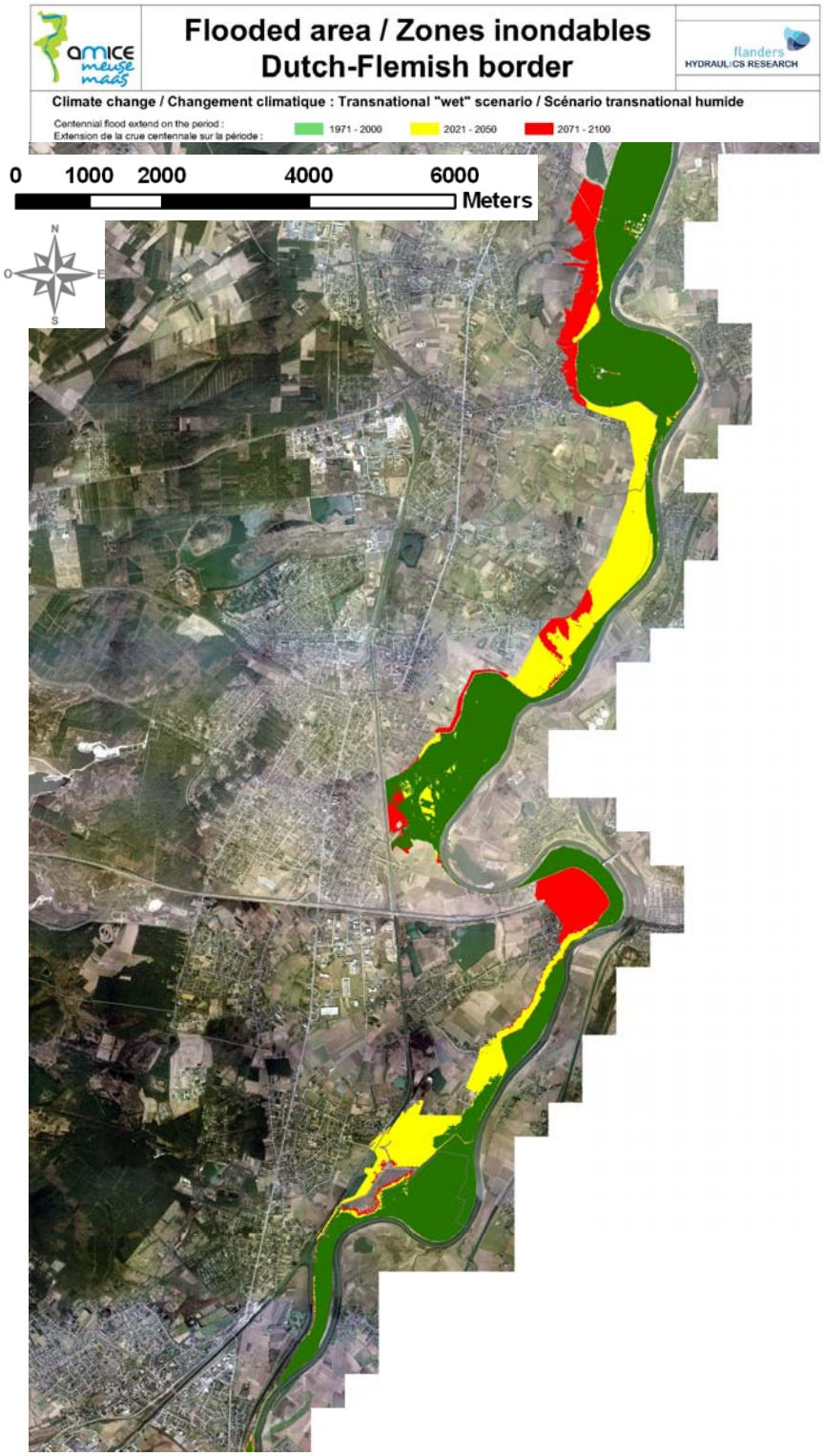


Figure 5-27: Inundation extents for Q_{100} (green), Q_{100}+15% (yellow) and Q_{100}+30% (red) along the reach Lanaken-Kessenich (Grensmaas).

5.2.4 The Netherlands

The Dutch hotspot is a part of the Grensmaas. This hotspot has been selected because this area is modelled by the Flemish partner also. From the comparison it is expected that conclusions for future model updates can be made. The potential flood hazard maps for the scenarios Q_{100} and Q_{100}+30 % are given in Figure 5-28 and Figure 5-29, respectively. Differences in the extent of the inundated areas are minimal, but the water depths in the inundated areas are different in the two scenarios. This is caused by the dike system, which is assumed not to fracture nor overflow in the modelling approach taken (see [11] for details). Flow simulation results (maximum water level) from the one-dimensional Sobek model have been extrapolated and from the resulting surface a digital elevation model has been subtracted. The result is a water depth which is shown in the figures. This method is not mass conservative, because the input water levels do not take into account that water has left the channels for inundation. Hence, by the extrapolating of water levels towards the hinterland additional water is generated virtually. The following characteristics should be considered:

- The inundated area indicated in the potential flood hazard maps will be an overestimation due to this mass balance error.
- The maximum water levels do not occur at all locations on the same time.
- The winterbed of the Meuse has been considered as a boundary for the inundation in order to limit the mass balance error, which might cause an underestimation of the inundated area.
- When extrapolating the water levels, the existence of dikes and flood protection walls is neglected. The potential inundation map can thus be seen as a map that indicates areas that can potentially be inundated in case of a dike break.

Two-dimensional simulations with a model that represents both the river bed and a sufficient part of the hinterland behind the winter bed would be necessary for a more precise analysis. This is, however, beyond the objective of this study, but will be carried out in the second phase of this AMICE action (Ampsin – Maaseik), and will be reported separately.

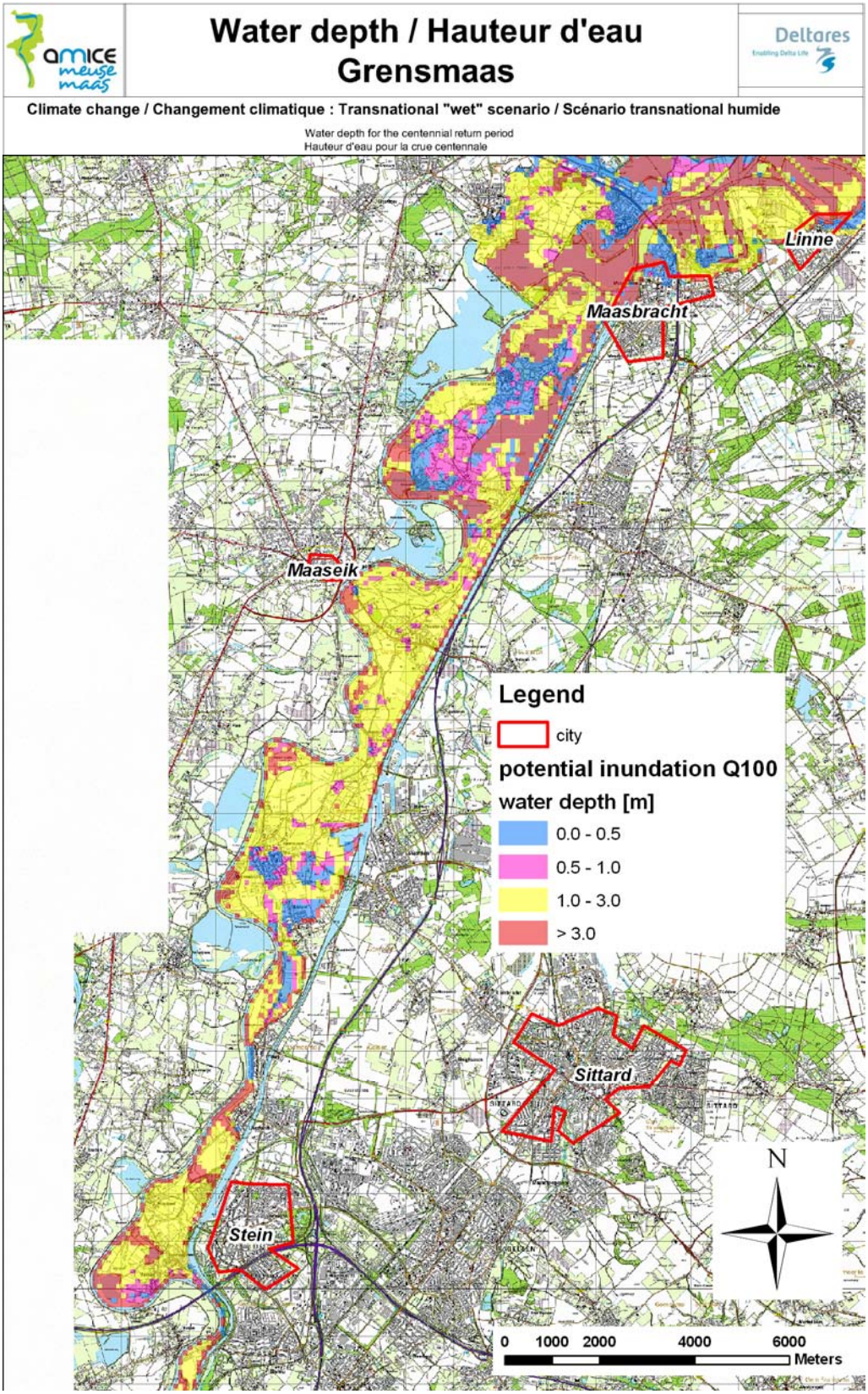


Figure 5-28: Potential flood hazard map „Grensmaas" for the scenario "Q 100"

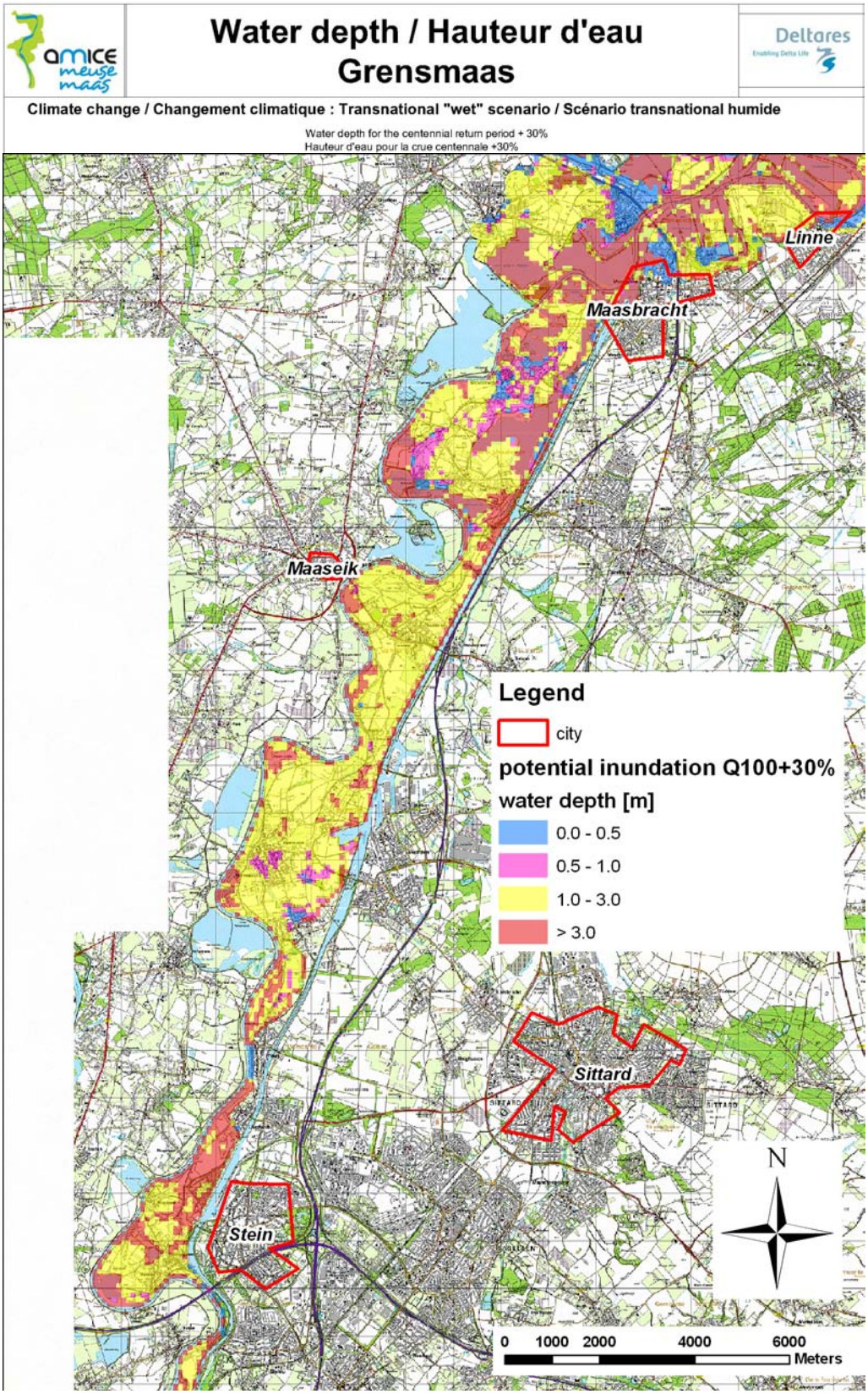


Figure 5-29: Potential flood hazard map „Grensmaas" for scenario "Q 100 + 30 %"

5.2.5 Germany

In Germany, the site is located at the downstream part of the Rur at the border from Germany to the Netherlands near the village Ophoven. Previous floods showed the vulnerability of the site to flooding of the flat river valley. For the climate change scenarios the situation is going to worsen, as can be seen in Figure 5-30.

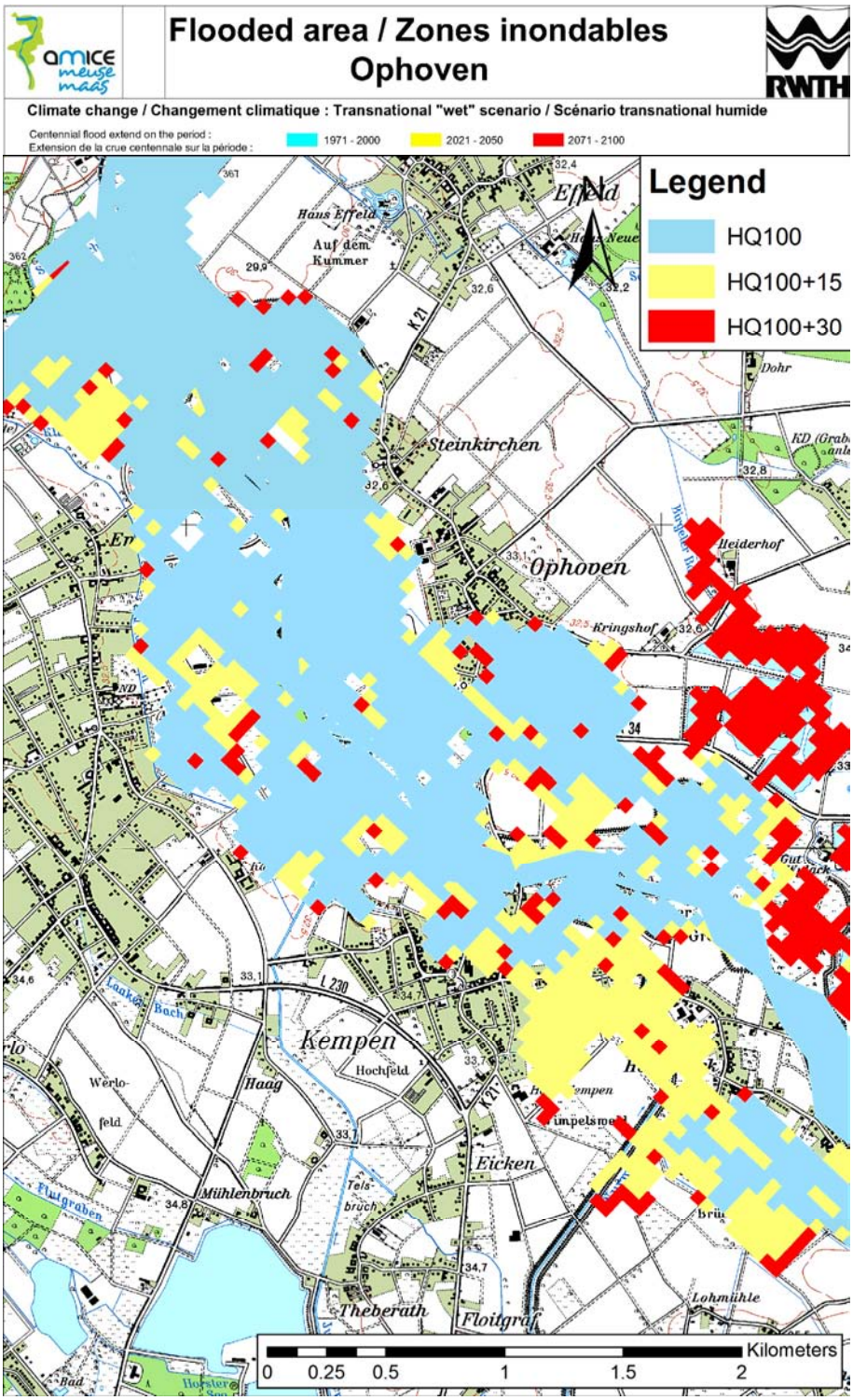


Figure 5-30: Change in flooded area around Ophoven

6 Conclusions and outlook

This report covers hydraulic modelling tasks performed in the context of the AMICE project. These tasks include, first, a harmonization of existing hydraulic modelling procedures and, second, runs of the harmonized hydraulic modelling to clarify the sensitivity of river Meuse with respect to changes in flood peak discharges as a result of climate change.

6.1 Basin-wide harmonized hydrological data and hydraulic models

The AMICE project covers the whole river basin of river Meuse, which extends over parts of France, Belgium, The Netherlands, Germany as well as a small portion of Luxembourg. The goal of the project consists in the development of a basin-wide coordinated strategy to cope with hydrological impacts of climate change, including floods and low flows. As this strategy is intended to be truly integrated at the scale of the international basin of river Meuse, the modelling tools used (e.g., hydraulic modelling, impact assessment, risk management) are also required to be consistent throughout the basin. However, so far, there are as many models and data sets as regions. Each region has developed its own climate scenarios, rainfall-runoff models and hydrological time series as well as its own procedures for hydraulic modelling and risk modelling. This calls definitely for a transnational harmonization effort, which was initiated during Action 3 of the AMICE project and has been pushed further during this Action 6.

Climate and hydrological scenarios as input for hydraulic modeling

The Work Package 1 of the project follows a logical chain, including subsequently results of climate models, rainfall-runoff modelling, hydraulic modelling as well as impact assessment and risk modelling. As far as climate scenarios are concerned, transnational climate scenarios have been derived from the analysis of pre-existing regional climate scenarios. During Action 3 of the project, this work was conducted for two scenarios, namely a wet one and a dry one, and for two time horizons: 2021-2050 and 2071-2100. Similarly, from a number of rainfall runoff modelling distributed throughout the catchment, two hydrological scenarios have been derived for the same time horizons. They have served here to define inflow boundary conditions for hydraulic modelling.

Harmonized hydraulic model

Hydraulic models are available in each region. They are either commercial ones or academic codes. Nevertheless, significant differences between those models have been identified, reflecting differences in the characteristics of the basin, including:

- in terms of spatial representation, the model range from fully one-dimensional, based on cross-sections even in the floodplains (e.g., in France), up to fully two-dimensional description based on laser altimetry and sonar bathymetry (e.g. in Wallonia);
- time description also differs between the models, which are either unsteady or run in steady mode.

Based on a detailed review of existing modelling procedures and on the harmonization work which has been conducted here, a **common modelling methodology for hydraulic modelling** has been developed, which includes the following key aspects:

- Consistency of bathymetry has been ensured across the borders, including latest dredging works; although the original available topographic data in the different regions had not been collected at the same period.
- Regional hydrological time series and statistical analysis have been compared to derive consistent discharge values for a wide range of return periods.

- A coordinated procedure has been elaborated for running the hydraulic models.

Following this newly developed procedure, the hydraulic models from the different regions have been run in parallel but not coupled online. Nonetheless, consistent hydraulic results across the borders have been obtained in just two runs:

- in the first one, necessary boundary conditions have been deduced from extrapolation of measured stage-discharge relationships;
- in the second one, the boundary conditions have been refined if necessary, using the results of the first run of the neighbouring models.

This harmonized hydraulic modelling has enabled to conduct the **first coordinated flow simulation of river Meuse from spring to mouth**. As a next step, a similar harmonization is being developed for impact assessment tools and risk analysis models (Action 7). The harmonization methodology developed here may also be transferred to other river basins.

6.2 First coordinated modelling of river Meuse from spring to mouth

The harmonized hydraulic modelling has been run for the 100-year flood in the base scenario (present situation), as well as for the "wet" hydrological scenario developed in Action 3 of the project. The two aforementioned time horizons are also considered here: 2021-2050 and 2071-2100. The results of hydraulic modelling results have been analysed at two complementary scales, namely the river scale and the local scale (hotspots).

At the river scale, the hydrological impacts of climate change have been evaluated in terms of their effects on hydrograph damping and peak discharges, water levels, extent of inundated areas and volume stored in the floodplains. In particular, the harmonized hydraulic modelling conducted has revealed **a strong spatial pattern in the sensitivity of river stages with respect to changes in flood discharge**: the influence of a similar change in flood discharge is found to be approximately twice stronger in the central part of the basin (between Sedan and Monsin) compared to the upper and lower parts of the basin, respectively upstream of Sedan and downstream of Monsin. This finding is straightforward to explain from the main characteristics of the Meuse basin: both the upper part of the basin and the lower one (including lowlands in The Netherlands) are characterised by relatively wide floodplains with large storage capacity; whereas, in the central part of the basin (Ardennes massif) the river valleys are steeper and narrower, leading to limited storage capacity in the floodplains. As a result, river stages are indeed expected to show a higher sensitivity in the central part of the basin. It was also verified that this abrupt change in the sensitivity of water stages does not coincide with a change in the models used, confirming that this finding is not affected by such kind of numerical artefact.

Analysis of a hotspot in France highlights that, although extra flooded areas due to climate change have been found generally limited in their extent, they may nevertheless lead to serious impacts when key assets are situated within the future flood-prone area (e.g., a town hall in which the crisis management headquarter is located). The hotspots in Wallonia reveal that existing flood defences of the main cities along river Meuse (Namur and Liege) may not be considered as "climate-proof". Indeed, although these cities are basically protected in the base scenario, they would in contrast be exposed to huge flooding as a result of climate change. The common Flemish and Dutch hotspot (stretch of river Meuse along the border) emphasizes the importance of representing accurately protection structures (e.g., dikes) in the hydraulic modelling.

These results constitute valuable inputs for the subsequent impact assessment and risk modelling (Action 7), as well as for the evaluation of adaptation measures (Action 8) and the elaboration of the Meuse adaptation strategy (Action 9).

7 References

[1] Drogue, G., M. Fournier, A. Bauwens, B. H., F. Commeaux, A. Degré, O. De Keizer, S. Detrembleur, B. Dewals, D. François, E. Guilmin, B. Hausmann, F. Hissel, N. Huber, S. Lebaut, B. Losson, M. Kufeld, H. Nacken, M. Pirotton, D. Pontégnie, C. Sohier and W. Vanneuville. *Analysis of climate change, high-flows and low-flows scenarios on the Meuse basin*. 67 p, 2010.

[2] de Wit, M. *Gouttes de pluies, flux de Meuse. Une gestion transnationale de l'eau par temps sec et humide*. 195, 2008.

[3] Wind, H. G., T. M. Nierop, C. J. De Blois and J. L. De Kok. *Analysis of flood damages from the 1993 and 1995 Meuse floods*. Water Resources Research, 35(11). 3459-3465, 1999.

[4] de Wit, M. J. M., H. A. Peeters, P. H. Gastaud, P. Dewil, K. Maeghe and J. Baumgart. *Floods in the Meuse basin: event descriptions and an international view on ongoing measures*. Intl. J. River Basin Management, 5(4). 279-292, 2007.

[5] Booij, M. J. *Impact of climate change on river flooding assessed with different spatial model resolutions*. Journal of Hydrology, 303(1-4). 176-198, 2005.

[6] Tu, M. *Assessment of the effect of climate variability and land use change on the hydrology of the meuse river basin*. 2006.

[7] Leander, R., T. A. Buishand, B. J. J. M. v. d. Hurk and M. J. M. d. Wit. *Estimated changes in flood quantiles of the river Meuse from resampling of regional climate model output*. Journal of Hydrology, 351(3-4). 331-343, 2008.

[8] de Wit, M. J. M., B. Van den Hurk, P. M. M. Warmerdam, P. J. J. F. Torfs, E. Roulin and W. P. A. v. Deursen. *Impact of climate change on low-flows in the river Meuse*. Climatic Change, 82(3). 351?372, 2007.

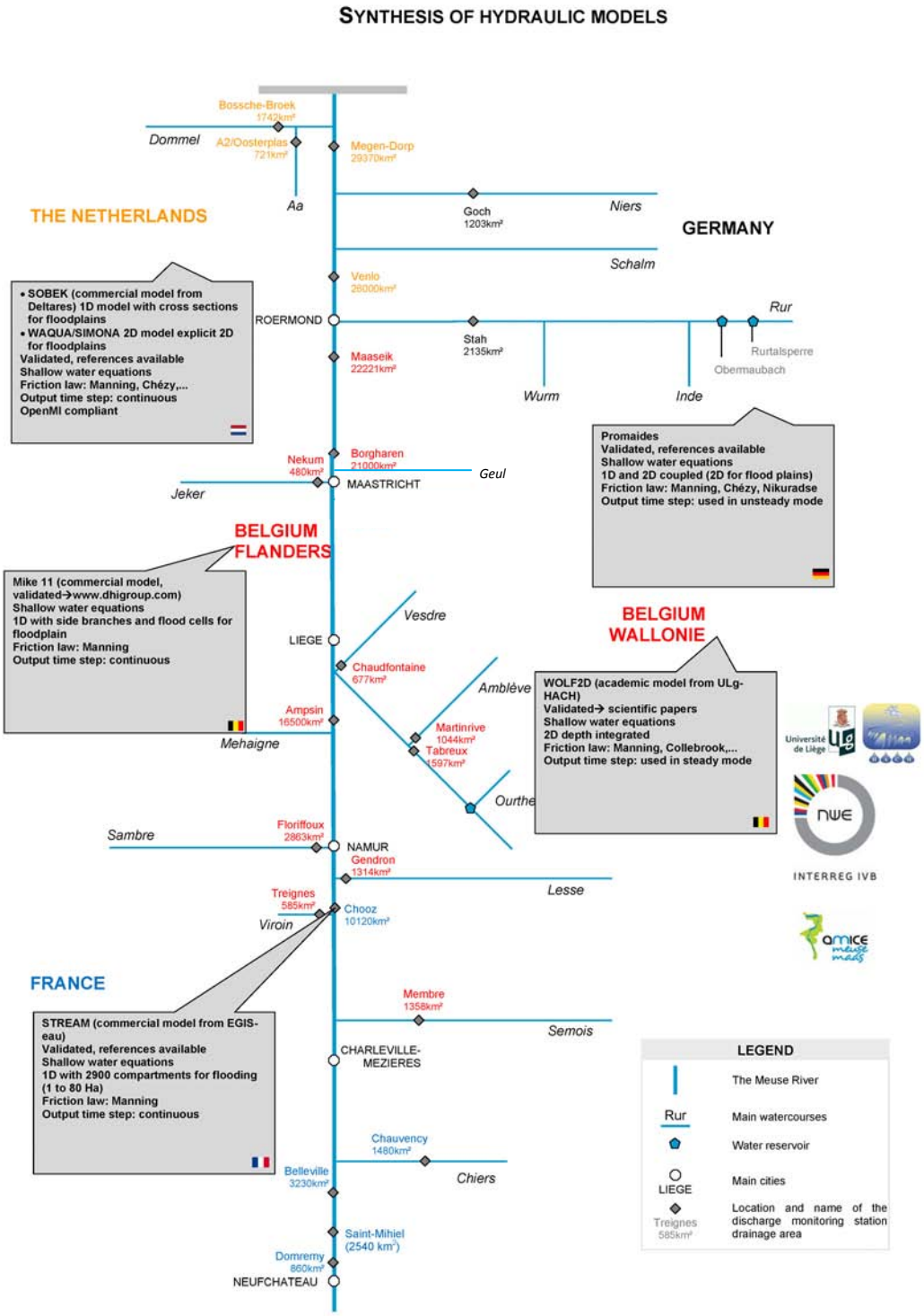
[9] Bauwens, A., C. Sohier and A. Degré. *Hydrological response to climate change in the Lesse and the Vesdre catchments: contribution of a physically based model (Wallonia, Belgium)*. Hydrol. Earth Syst. Sci., 15. 1745-1756, 2011.

[10] Wit, M. J. M. d., H. A. Peeters, P. H. Gastaud, P. Dewil, K. Maeghe and J. Baumgart. *Floods in the Meuse basin: event descriptions and an international view on ongoing measures*. Intl. J. River Basin Management, 5(4). 279-292, 2007.

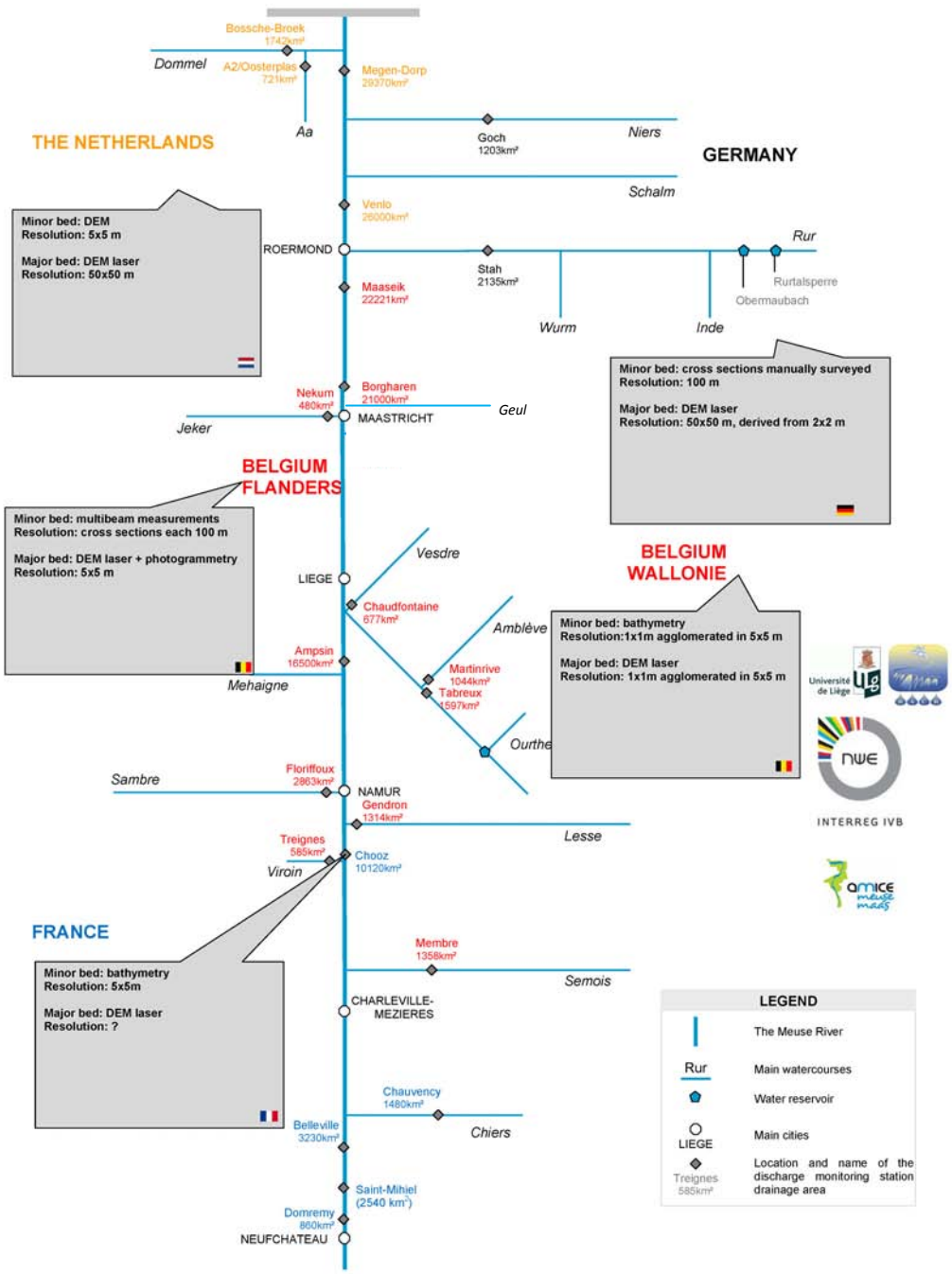
[11] Becker, B., C. Sprengers and T. Ochterbeck. *AMICE: Action 6. Hydraulic Sobek-model for the Dutch part of the Meuse. Deltares memo 1201007-000-ZWS-0014, version 11, 2011-05-02*. 2011.

8 Appendices

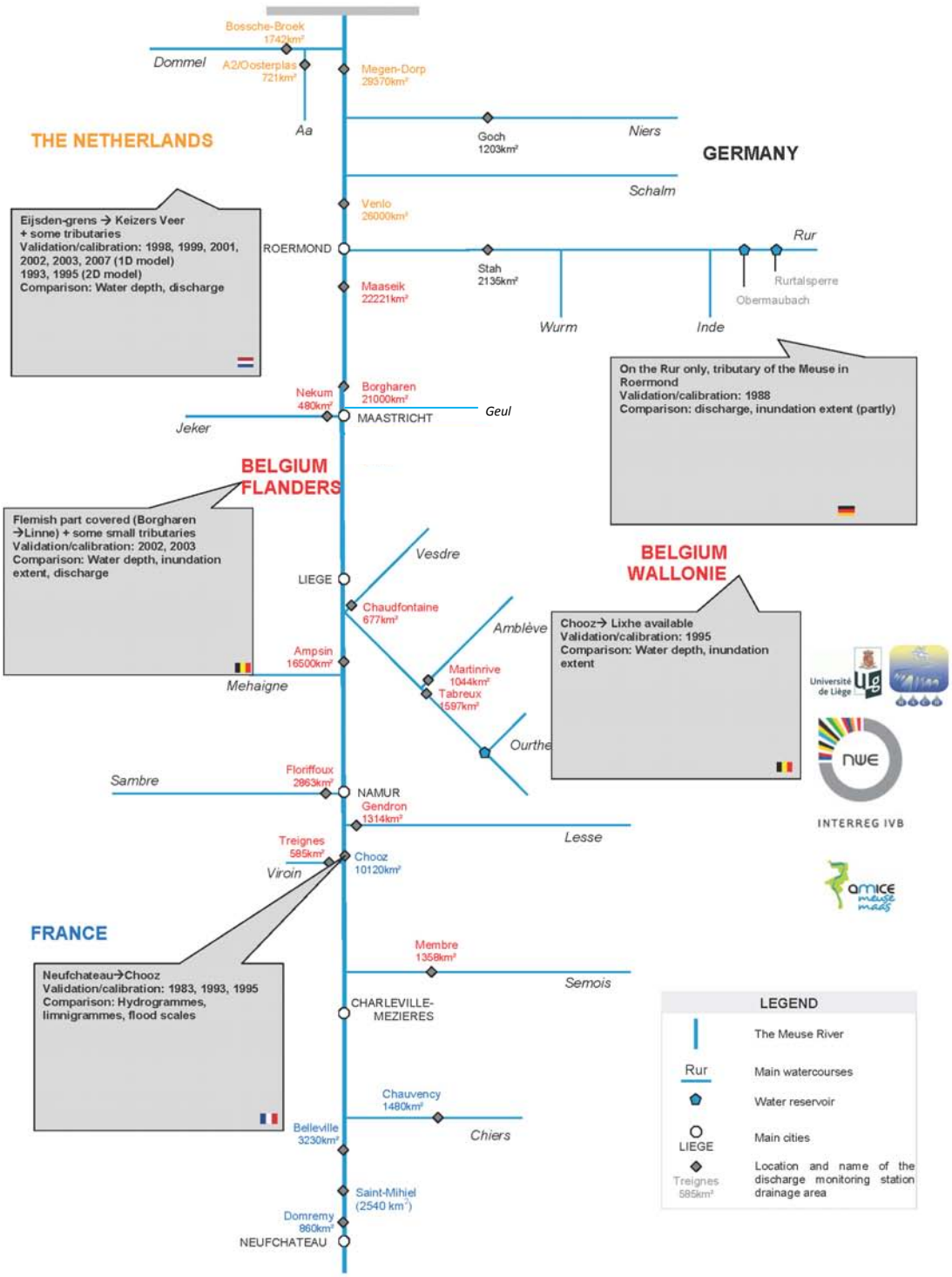
8.1 Synthetic maps elaborated from the questionnaires (common methodology).



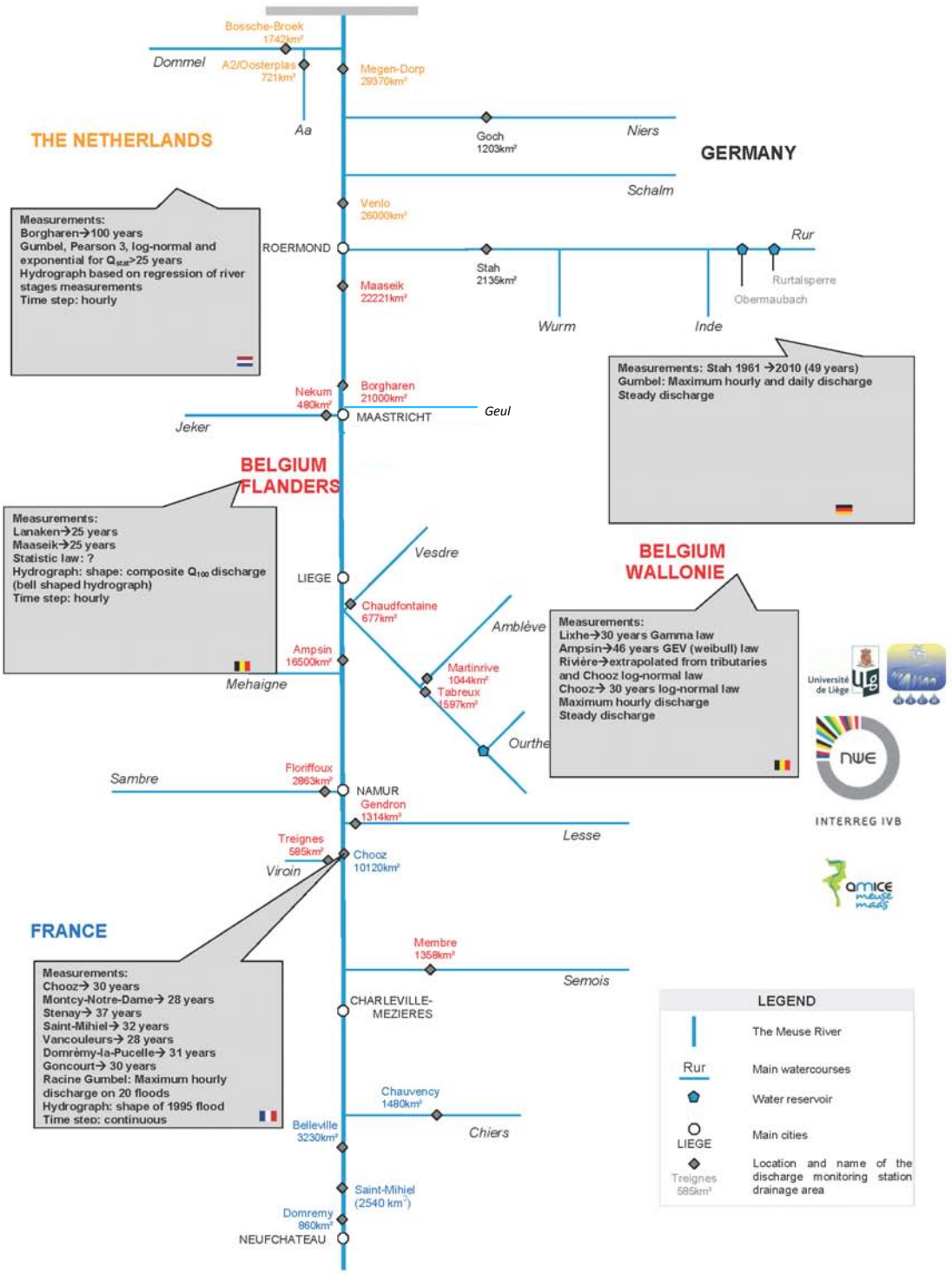
SYNTHESIS OF TOPOGRAPHIC DATA



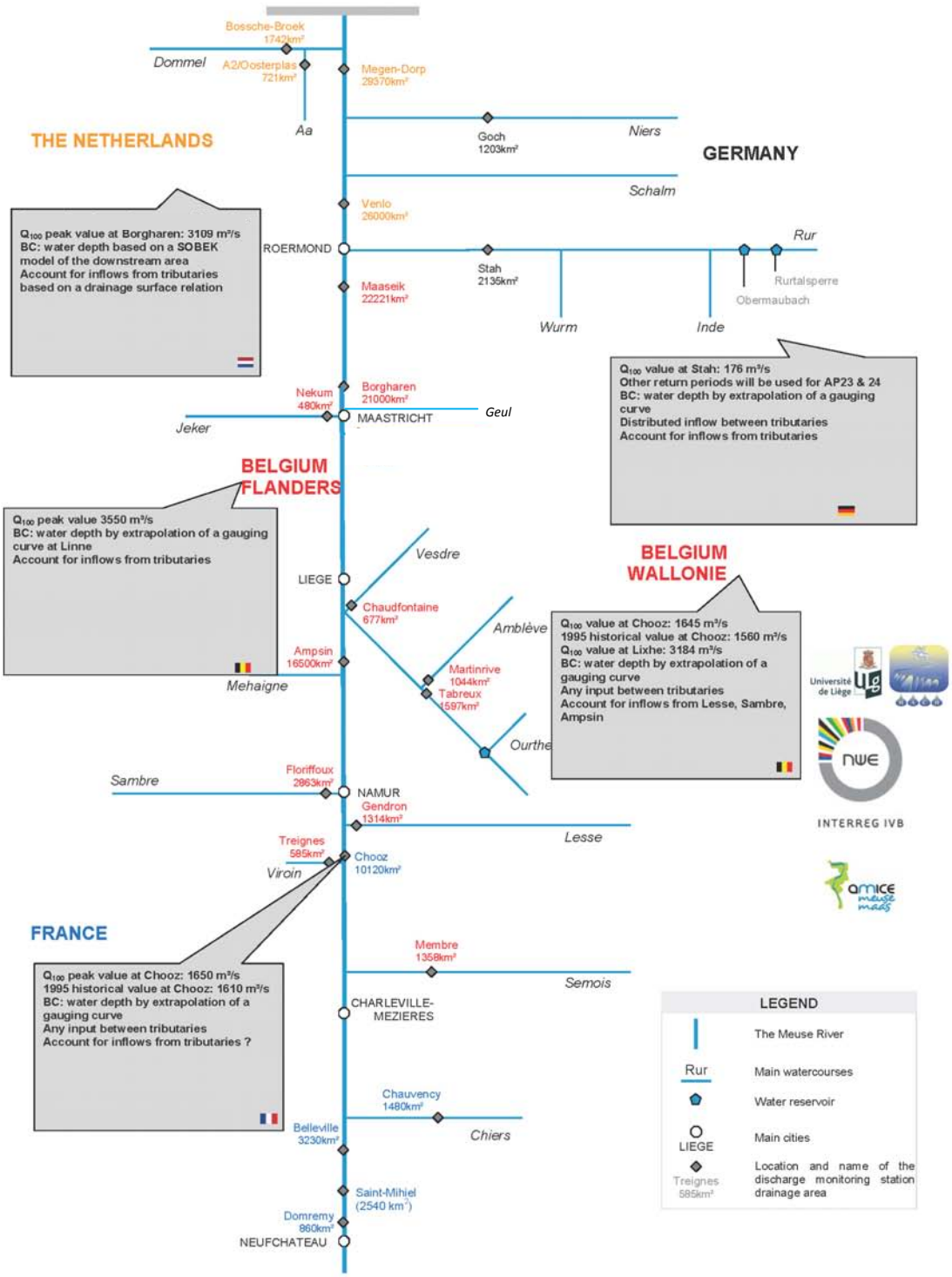
SYNTHESIS OF VALIDATION/CALIBRATION, REACHES COVERED



SYNTHESIS OF MEASUREMENTS, STATISTICAL LAWS



SYNTHESIS Q_{100} VALUES AND BOUNDARY CONDITIONS



8.2 Tabulated detailed description of each model

8.2.1 France

General information	
Model name	STREAM (Simulation en TRansitoire des Ecoulements A surface libre Multidirectionnels)
Version	There is only one version but with regular updates: the last one dates back to 2009 to take into account the flood protection works along the Meuse.
Author/first publication	N/A
Contact person	N/A
Institute	BCEOM
Web site	N/A
General modelling objective	The model is run in unsteady mode.
Domain of applicability (flow regimes, slopes, ...)	The model is dedicated to the study of complex hydraulic phenomena (transfers between the minor bed and flood plain, deltas, flood propagation from upstream to downstream).

Model description	
Model type	The minor bed and the flood plain are represented by storage cells. Each cell has its own: • borders' topography: the profiles of the cells' borders result from the Numerical Terrain Model (NTM) for the flood plain, from the bathymetry for minor bed, and from hydraulic structure surveying when applicable. • hydraulic transfer laws on the borders: friction law or management rules of the hydraulic structures. • internal topography: it is represented by a surface-height (or volume-height) law..
Spatial discretization	The size of each cell depends on the stakes and the complexity of hydraulic phenomena. In rural areas, large cells are sufficient whereas smaller cells are required in urban areas. There are 2900 cells over the French Meuse basin. The mean size of the cells is 15ha (ranging from 1 to 80ha).

Short description of the model detailing mathematical background	The model is based on the Saint-Venant equations and weir formulae.

Model parameters

Distribution of roughness parameter

The Strickler coefficients have the following values:

Location	minimum	mean	maximum
Main riverbed			
Meuse from Chalaines down to confluence with Chiers	25	-	38
Meuse from confluence with Chiers down to Belgium frontier	27	33	36
Chiers	25	29	31
Floodplains			
Meuse from Chalaines down to confluence with Chiers	10	-	23
Meuse from confluence with Chiers down to Belgium frontier	10	13	17
Chiers	15	15	17

Procedure for parameter calibration

The calibration is based on historical floods: April 1983, December 1993 and January 1995. The data comes from flood scales or limnimetric stations in Chalaines, Commercy, Saint-Mihiel, Verdun, Belleville, Stenay, Sedan, Mézières, Montcy-Notre-Dame, Monthermé and Chooz for the Meuse, as well as Carignan for the Chiers. The Strickler coefficients can be modified to represent better the reality.

The model reproduces the observed hydrographs with a deviation of about 2% on the peak discharges. The shape of the hydrogrammes is also correct. The model reproduces the observed water levels with a deviation of about 10 to 15cm in urban areas and about 30cm in rural areas.

Model inputs and outputs

Characteristics of inputs

The input discharges are hydrographs resulting from the rainfall-runoff model AGYR (see previous WP1 report). The downstream boundary condition is a height-discharge relation at the French-Belgium border. This boundary condition appeared not to be right when comparing with the Belgium

	model and was corrected.
List and characteristics of model outputs	In the cells, the output is the water depth. At the borders of the cells, the results are the velocity and discharge.

Examples of previous model applications

STREAM was used for modelling the French Meuse basin in order to understand better the basin's behaviour and to decide on flood protections.

Minimum 5 selected references (research papers / reports)

N/A

8.2.2 Wallonia

General information	
Model name	WOLF
Version	The model is being continuously developed by the HACH research team at ULg. Version used: end 2010.
Author/first publication	Michel Pirotton, Pierre Archambeau, Sébastien Erpicum, Benjamin Dewals, Sylvain Detrembleur
Contact person	Michel Pirotton
Institute	University of Liege, HACH unit
Web site	www.hach.ulg.ac.be
General modelling objective	Free surface and pressurized flows in civil and environmental engineering, including related processes such as sediment / pollutant transport and air entrainment
Domain of applicability (flow regimes, slopes, ...)	The shallow-water model used is dedicated to the study of various complex hydraulic phenomena, including inundation flows in natural and urbanized floodplains, dam break flow, flows on hydraulic structures …

Model description	
Model type	The model solves the shallow water equations on structured grids with turbulence models and sediment or air transport (optional). The model is 2D depth averaged. Topography and roughness are spatially distributed and physically based. All

	flow regimes can be simulated.
Spatial discretization	Cell sizes are customized and case-dependant. In the case of Amice, square cells of 5 × 5 m are used. The topography is based on a DEM with a spatial resolution of 1 × 1 m and a vertical accuracy of 15 cm. Bathymetry is derived from sonar measurements with the same resolution and accuracy. This DEM has been averaged on cells of 5x5 m.
Short description of the model detailing mathematical background	The model is based on the shallow water equations. The equations are solved on a structured grid by the way of a finite volume method. Constant or linear reconstruction are available leading to 1st or 2nd order accuracy in space respectively. Time integration is ensured by Runge-Kutta schemes. The finite volume method ensures an exact mass conservation even if drying and wetting of cells are involved.

Model parameters	
Distribution of roughness parameter	The Strickler coefficients in the main riverbed is continuously distributed from upstream in Chooz (30 $m/s^{1/3}$) to downstream at Lixhe (40 $m/s^{1/3}$). In the floodplains, the coefficient for impervious areas is 50 $m/s^{1/3}$ and 30 $m/s^{1/3}$ for other areas.
Procedure for parameter calibration	The calibration is based on historical floods: December 1993 and January 1995. Reference data come from gauging stations, aerial pictures or watermarks on buildings. The model is run in steady mode corresponding to the value of the discharge to be compared with historical data. The model reproduces the observed water levels with a deviation of no more than 5 to 10 cm.

Model inputs and outputs	
Characteristics of inputs	As boundary conditions for subcritical flow computation, the inputs include a discharge value upstream and a water level downstream. The model also needs a distributed topographic model on a 5x5m grid. The roughness parameter must also be distributed on the same grid.
List and characteristics of model outputs	On each computed cell, water depth and specific discharges in both x and y directions. Time step is variable and can be chosen by the user.

Examples of previous model applications

- inundation mapping in Wallonia based on 2D hydraulic modelling (more than 1000 km of rivers)
- computation of dam break flows
- design of hydraulic structures ...

Minimum 5 selected references (research papers / reports)

Inundation modelling

Dewals, B. J., Detrembleur, S., Archambeau, P., Erpicum, S., Pirotton, M. and Ernst, J. (2011), *Caractérisation micro-échelle du risque d'inondation : modélisation hydraulique détaillée et quantification des impacts socio-économiques*, Houille Blanche-Rev. Int., **In press**.

Khuat Duy, B., Archambeau, P., Dewals, B. J., Erpicum, S. and Pirotton, M. (2010), *River modelling and flood mitigation in a Belgian catchment*, Proc. Inst. Civil. Eng.-Water Manag., **163** (8), 417-423.

Erpicum, S., Dewals, B. J., Archambeau, P., Detrembleur, S. and Pirotton, M. (2010), *Detailed inundation modelling using high resolution DEMs*, Engineering Applications of Computational Fluid Mechanics, **4** (2), 196-208.

Ernst, J., Dewals, B. J., Detrembleur, S., Archambeau, P., Erpicum, S. and Pirotton, M. (2010), *Micro-scale flood risk analysis based on detailed 2D hydraulic modelling and high resolution geographic data*, Nat. Hazards, **55** (2), 181-209.

Detrembleur, S., Dewals, B. J., Archambeau, P., Erpicum, S. and Pirotton, M. (2009), *Modélisation numérique et gestion du risque inondation - Retour d'expérience sur les modèles topographiques à haute résolution*, Techniques - Sciences - Méthodes, 7/8.

Dam- and dike-break flow

Dewals, B. J., Erpicum, S., Detrembleur, S., Archambeau, P. and Pirotton, M. (2011), *Failure of dams arranged in series or in complex*, Natural Hazards, **56** (3), 917-939.

Erpicum, S., Dewals, B. J., Archambeau, P. and Pirotton, M. (2010), *Dam-break flow computation based on an efficient flux-vector splitting*, Journal of Computational and Applied Mathematics, **234** (7), 2143-2151.

Roger, S., Dewals, B. J., Erpicum, S., Schwanenberg, D., Schüttrumpf, H., Köngeter, J. and Pirotton, M. (2009), *Experimental und numerical investigations of dike-break induced flows*, J. Hydraul. Res., **47** (3), 349-359.

Design of hydraulic structures

Dewals, B. J., Kantoush, S. A., Erpicum, S., Pirotton, M. and Schleiss, A. J. (2008), *Experimental and numerical analysis of flow instabilities in rectangular shallow basins*, Environ. Fluid Mech., **8**, 31-54.

Dewals, B. J., Erpicum, S., Archambeau, P., Detrembleur, S. and

Pirotton, M. (2006), *Depth-integrated flow modelling taking into account bottom curvature*, J. Hydraul. Res., **44** (6), 787-795.

Dufresne, M., Dewals, B. J., Erpicum, S., Archambeau, P. and Pirotton, M. (2011), *Numerical investigation of flow patterns in rectangular shallow reservoirs*, Engineering applications of computational fluid dynamics, **5** (2).

8.2.3 Flanders

General information	
Model name	Maasuitgebreid_v6
Version	Version 6 (2010)
Author/first publication	Flanders Hydraulic Research
Contact person	Erika D'Haeseleer: erika.dhaeseleer@mow.vlaanderen.be Wouter Vanneuville: wouter.vanneuville@mow.vlaanderen.be
Institute	Flanders Hydraulic Research
Web site	http://www.watlab.be
General modelling objective	All Examination of effects from infrastructure and nature projects (Levende Grensmaas, Maasdijkenplan, exploitation of gravel pools, etcetera)
Domain of applicability (flow regimes, slopes, ...)	Unsteady flow simulation, 1 Dimensional model

Model description	
Model type	1D, with valleys modelled as separate branches or storage cells (software DHI Mike11)
Spatial discretization	Distance between cross sections for the Meuse (summer bed): 100 m Distance between cross sections for the winter bed (parallel branches with the Meuse): 200 m. Resolution floodplains: 5x5 m
Short description of the model detailing mathematical background	Mike 11 solves the Saint-Venant equations using an implicit finite difference scheme.

Model parameters

Distribution of roughness parameter	Roughness in the main course of the Meuse: 0.032 $m^{-1/3}s$ Roughness in the winter bed of the Meuse: 0.04 $m^{-1/3}s$.
Procedure for parameter calibration	The model is calibrated based on the hydrograph of January 2003 (max. discharge 2548 m^3/s) and validated based on the hydrograph of February 2002 (max. discharge 2327 m^3/s). Calibration was done manually.

Model inputs and outputs	
Characteristics of inputs	Upstream: Q-t relation Downstream: Q-H relation
List and characteristics of model outputs	Water levels and discharges

Examples of previous model applications

N/A

Minimum 5 selected references (research papers / reports)

Bogman, P.; Smets, S.; D'Haeseleer, E.; Van Eerdenbrugh, K.; Mostaert, F. (2010). UITBREIDING MIKE11-MODEL: GEMEENSCHAPPELIJKE MAAS – 2008. Versie 2_0. WL Rapporten, 710_13. Waterbouwkundig Laboratorium & International Marine and Dredging Consultants: Antwerp, Belgium.

Pannemans B., D'Haeseleer E., Van Eerdenburgh K., Mostaert F., 2006, "project: 710/10 Actualisatie Mike11-model Gemeenschappelijke Maas - 2005", WL.

8.2.4 The Netherlands

	Sobek-RE model
General information	
Model name	j10_04 (Sobek-Maas)
Version	J10_04
Author/first publication	Michels, C.; Agtersloot, R.; van der Veen, R.; van der Veen, S.
Contact person	Anke Becker
Institute	Deltares (model maintenance), Rijkswaterstaat (model owner)

Web site	www.deltares.nl
General modelling objective	water management, flood risk management
Domain of applicability (flow regimes, slopes, ...)	low flow and high water (water distribution)

Model description	
Model type	one-dimensional
Spatial discretization	cross section profiles, distance ca. 500 m
Short description of the model detailing mathematical background	Sobek-RE solves the full St.-Venant equations, real time control of structures.

Model parameters	
Distribution of roughness parameter	the model schematisation is distributed into reach segments. For each reach segment a constant value or a value as function of discharge is set.
Procedure for parameter calibration	manual calibration based on historical flood events. Validation with independent datasets.

Model inputs and outputs	
Characteristics of inputs	upstream boundary condition: discharge hydrograph, downstream boundary condition: rating curve (discharge – water level –relation). flow widths and storage widths of the cross-sections are derived from the 2D model described below.
List and characteristics of model outputs	for each output location, water level and discharge for main channel, left flood plain, right floodplain and total discharge are generated. Furthermore, flow width and flow area are generated.

Examples of previous model applications	
	Rijkswaterstaat: model Noordelijk Deltabekken (the Netherlands) Rijkswaterstaat: model Rijn (the Netherlands)

	Rikswaterstaat: model Landelijk Temperatuurmodel (the Netherlands)
	Nederlands Hydrologisch Instrumentarium: Waterverdelingsmodel (the Netherlands)
	Bundesanstalt für Gewässerkunde: model Oberrhein (Germany)
	Bundesanstalt für Gewässerkunde: model Niederrhein (Germany)
	Bundesanstalt für Gewässerkunde: model Rheinnebenflüsse (Germany)
Minimum 5 selected references (research papers / reports)	
Meuse model	Michels, C.; Agtersloot, R.; van der Veen, S.; van der Veen, R. (2010): JAMM 2010 / Jaarlijkse Actualisatie Modellen Maas 2010 / Beschrijving werkzaamheden en resultaten simulaties. Eindrapport. Rura-Arnhem, AHA BV, Acima.
	Becker, B.; Sprengers, C.; Ochterbeck, T. (2011): AMICE: Action 6. Hydraulic Sobek-model for the Dutch part of the Meuse. Deltares Memo 1201007-000-ZWS-0014, version 11, 2011-05-02.
	van Mierlo, T.; van Zetten, J.; Vissers, T. (2008): JAMM2008; Jaarlijkse Actualisatie Modellen Maas 2006, 2007 en 2008. [Report by] Deltares [on behalf of] Waterdienst, projectnummer Q4556.
	van der Veen, R. (2006): Memo*2006-002(A). Rijkswaterstaat. 27-02-2006.
	R. van der Veen, U. Pakes en L. Schutte (2002): Bouw en calibratie SOBEK-Maas : versie 2000.1 t/m 2000 RIZA Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling. Arnhem : RIZA, 2002 Report nr. RIZA 2002.031
Applications	R. van der Veen, U. Pakes, L. Schutte (2002): Bouw en calibratie SOBEK-Rijn : versie 2000.1 t/m 2000. RIZA Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling Lelystad : RIZA, 2002
	Fokkink, R.J. (1995) : SOBEK simulations of estuarine morphology in simple network models; DYNASTAR project, report II. Delft : Delft Hydraulics Laboratory, 1995
	Schwanenberg, D. ; Sloff, C.J. (2005): Set-up of a 1D morpho-

	logical model : River Donau, Straubing-Vilshofen (km 2247,0 - 2329,5) Delft : WL | Delft Hydraulics, 2005. report no. Q3971 prepared for Bundesanstalt für Wasserbau (BAW) Schwanenberg, D.(2005): SOBEK Modellierung fuer Nebenfluesse im Rheingebiet : Teilprojekt 5: SOBEK Modell Main - Pegel Trunstadt bis Pegel Würzburg. Delft : WL | Delft Hydraulics, 2005. report no. Q3281 prepared for Bundesanstalt für Gewässerkunde . Schwanenberg, D.(2004): SOBEK Modellierung fuer Nebenfluesse im Rheingebiet : Teilprojekt 4: SOBEK Modell Lahn - Pegel Giessen bis Lahnmündung. Delft : WL | Delft Hydraulics, 2004. report nr. Q3281 prepared for Bundesanstalt für Gewässerkunde Meißner, D. (2008): Erstellung, Kalibrierung und Validierung des SOBEK-Modells für die Rheinstrecke zwischen den Pegeln Andernach und Lobith im Rahmen des Projekts „Grenzüberschreitende Abstimmung von Hochwasser mindernden Maßnahmen“ der Deutsch-Niederländischen Arbeitsgruppe Hochwasser. Koblenz: Bundesanstalt für Gewässerkunde, 2008. BfG-SAP-Nr.: A39610203226, prepared for Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen
	WAQUA model
General information	
Model name	j10_04 (WAQUA)
Version	1
Author/first publication	The model is updated each year by or under supervision of Deltares. The version used was updated in 2010. The following report describes the latest yearly actualisation (in dutch): JAMM2010, Jaarlijkse Actualisatie Modellen Maas 2010; beschrijving werkzaamheden en resultaten simulaties; eindrapport. Rura-Arnhem, AHA, Acima.
Contact person	Anke Becker
Institute	Deltares
Web site	www.deltares.nl
General modelling objective	Examination of effects due to measures in river or floodplains. WAQUA is used for two-dimensional hydro-dynamic and water quality simulation of well-mixed estuaries, coastal seas and rivers.

Domain of applicability (flow regimes, slopes, ...)	Free surface flow, 2D depth-averaged.
Model description	
Model type	WAQUA is a water movement and water quality simulation system, able to perform two-dimensional computations. The system enables the user to simulate stationary as well as nonstationary flow patterns. The model system solves the shallow water equations. Topography and roughness are spatially distributed and physically based.
Spatial discretization	The computational grid is a curvilinear grid; the size of the grid cells varies between a minimum value of 6 m in the summer bed and maximum value of 175 m in the floodplains.
Short description of the model detailing mathematical background	The numerical method is a composite ADI scheme. At the first half time step, u-velocities and resultant water levels are calculated and also separate v-velocities (explicit). At the second half time step, v-velocities and resultant water levels are calculated together with separate u-velocities (explicit). The method has as properties: - it is symmetrical over the x and y directions, - it attains its highest accuracy over every two half time steps, - it is mass conserving, - it is computationally efficient, - it is suitable not only for time-dependent problems, but also for steady state problems, - it is unconditionally stable. A full account of the numerical method that is used in WAQUA is given in: G. S. Stelling, On the Construction of Computational Methods for Shallow Water Flow, Rijkswaterstaat Communications no 35/1984.
Model parameters	
Distribution of roughness parameter	The roughness of the summer bed is given as a Nikuradse value. In the floodplains, formulations for vegetation, buildings, hedges are applied. All roughnesses are translated into a Chézy value.

Procedure for parameter calibration	The model is calibrated on the peak of the flood of 1995 by the summer bed roughness. The Nikuradse formulation for the alluvial summer bed, which is a function of the water depth, contains the calibration coefficient alpha, which is varied during calibration between measuring stations.

Model inputs and outputs

Characteristics of inputs	As boundary conditions, the inputs include a discharge value upstream and a water level downstream. The model also needs a topographic model on the grid. The roughness parameter must also be distributed on the same grid
List and characteristics of model outputs	For each computed cell, outputs are water depth, water level, flow velocity and specific discharges in both x and y directions. The user can specify for which time steps the output is stored.

Examples of previous model applications

Project Maaswerken: determination of water levels for design conditions

International collaboration between The Netherlands and Germany: Assessment of the impact of inundations on the water levels

Minimum 5 selected references (research papers / reports)

Maaswerken (2003). MER Grensmaas 2003, Achtergrondrapport Rivierkunde.

Ministerie van Verkeer en Waterstaat (2007). Hydraulische Randvoorwaarden primaire waterkeringen; voor de derde toetsronde 2006-2011 (HR2006). Augustus 2007.

E.H. van Velzen, D. Beyer, M.J.M. Scholten, C. Stolker, (2007). Achtergrondrapport; HR2006 voor de Maas; Thermometerrandvoorwaarden 2006. RWS RIZA Rapport 2007.022. December 2007.

Deltares (2010). JAMM2009; Jaarlijkse Actualisatie Modellen Maas 2009. 1200027-000-ZWS-0017, 2 juli 2010.

Svašek (2007). WAQUA berekeningen; Project Over De Maas. ECOL/07117/1426/D

8.2.5 Germany

General information	
Model name	Promaides
Version	The model is being continuously developed at the IWW. Version used: end 2010.
Author/first publication	Bachmann, Kamrath, Kufeld
Contact person	Bachmann@iww.rwth-aachen.de
Institute	Institute of Hydraulic Engineering and Water Resources Management
Web site	na
General modelling objective	The model is designed for risk assessment exercises and includes a protection line failure model, damage calculation and decision support tool. The hydraulic component uses the diffusive wave form of the St. Venant equations in 1D open channel and 2D overland flow.
Domain of applicability (flow regimes, slopes, ...)	The model is stable for all flow regimes. When being applied to supercritical flow the error that is being made by application of the diffusive wave approximation needs to be considered.

Model description	
Model type	Combined unsteady 1D channel and 2D overland flow model
Spatial discretization	Average river length between cross sections of the main channel is less than 100 Meter. The two dimensional elevation model of the floodplain has a regular grid cell size of 50 by 50 Meters in the lower reaches.
Short description of the model detailing mathematical background	The model utilizes the diffusive wave equation and the Poleni weir equation. A one-dimensional model of the main river channel is coupled to a two-dimensional rectangular grid model of the floodplains. The coupling is done vertically, so water can flow over either side of the channel bank into the floodplain model.

Model parameters	
Distribution of roughness	Each cross section segment defined by a measured cross

parameter	section point is assigned with a discrete Manning roughness. The floodplain roughness is derived from land use data (ATKIS) with values ranging from kst=15 $m^{1/3}/s$ for dense forest to 50 $m^{1/3}/s$ for urban areas.
Procedure for parameter calibration	Roughness parameters were taken from an existing validated 1D model for the main river channel. No inundation extend has been measured during floods. Flood extend modelled is checked by expert review.

Model inputs and outputs

Characteristics of inputs	The Rur is modelled downstream of the last reservoir Obermaubach, where an unsteady discharge boundary condition is applied. The four main tributaries are considered by lateral boundary conditions. Only the major flood water contributing tributary Inde is modelled by an unsteady boundary condition. The tributaries Ellebach, Merzbach and Wurm are modelled as steady boundary conditions. The downstream boundary condition is given by the waterlevel in the Meuse, which is taken as steady as well.
List and characteristics of model outputs	The model results are unsteady distributions of waterdepth, waterlevel, velocity as well as the maximum values of these results.

Examples of previous model applications

The model has been specifically set up for the AMICE project and not been applied before.

Minimum 5 selected references (research papers / reports)

Kamrath, P. (2009): Über die gekoppelte multidimensionale Modellierung von Fließgewässern und Überflutungsflächen. Dissertation

Huber et al. (2009): Entwicklung eines risikobasierten Entscheidungshilfesystems zur Identifikation von Schutzmaßnahmen bei extremen Hochwasserereignissen – REISE –Abschlussbericht

Kufeld, M.; Schüttrumpf, H.; Bachmann, D. (2009): Assessment of flood retention in polders using an interlinked one-two-dimensional hydraulic model. In: research and practice ; proceedings of the European conference on flood risk management research into practice (Floodrisk 2008), Oxford, UK, 30 september - 2 october 2008 / Ed.: P. Samuels [et al.]. Boca Raton, Fla.: CRC Press, Taylor & Francis Group, pp. 75,667-75,675. - ISBN 978-0-415-48507-4

Kamrath, P.; Huber, N.P.; Kufeld, M.; Schüttrumpf, H.; Köngeter, J. (2008): Interlinked model-

ling of large floods by combinig one and two-dimensional diffusive wave approaches. In: Managing flood risk, reliability and vulnerability: 4th International Symposium on Flood Defence, proceedings, Toronto, Canada, May 6-8, 2008 / Ed.: S. P. Simonovic et al. Toronto, Canada: Institute for Catastrophic Loss Reduction, pp. 109,1-109,8.

8.3 Extraction points for the results

				Lambert 1 Nord		Lambert 72		Rijksdriehoek		DHDN, GK 2		Lat/Long ETRS89	
Extraction point n° (mobile dam MB,border B or measurment station MS)	Name	Point Type	Length from mouth (FR,W,FL,NL) or length from Roermond (GE)	X	Y	X	Y	X	Y	X	Y	X	Y
1	Neufchâteau	MS	66	847 959	78 590							48.36	5.68
2	Saint-Mihiel	MS	173	834 235	135 038							48.87	5.53
3	Verdun	MS	231	822 379	166 938							49.16	5.39
4	Stenay	MS	297	805 847	203 255							49.49	5.18
5	Sedan	MS	346	787 450	225 610							49.70	4.94
6	Aiglemont	MS	394	773 964	233 294							49.77	4.75
7	Monthermé	MS	414	772 019	245 036							49.88	4.73
8	Chooz	MS	474	776 721	268 770							50.09	4.81
9	Givet	MD	482	778 329	274 799							50.15	4.83
10	BE-F border	B	485			182620	95500					50.17	4.82
11	Hastière	MD	488			182192	98869					50.20	4.82
12	Waulsort	MD	493			184622	99066					50.20	4.85
13	Anseremme	MD	501			188563	103306					50.24	4.91
14	Dinant	MD	505			188256	106397					50.27	4.90
15	Houx	MD	508			187604	109598					50.30	4.90
16	Hun	MD	513			185853	114019					50.34	4.91
17	Rivière	MD	518			185875	116807					50.36	4.87
18	Profondeville	MS	522			186108	119470					50.38	4.88
19	Tailfer	MD	524			186516	121211					50.40	4.88
20	La Plante	MD	530			184990	126749					50.45	4.86
21	Grands-Malades	MD	534			187663	128553					50.47	4.90
22	Andenne	MD	548			199749	131556					50.49	5.07
23	Ampsin	MD	568			215747	136262					50.53	5.30
24	Ampsin	MS	569			216632	136114					50.53	5.31
25	Ivoz-Ramet	MD	582			227356	142939					50.59	5.46
26	Monsin	MD	600			239234	149746					50.65	5.63
27	Lixhe	MD	613			242967	160956					50.75	5.69
28	Borgharen	MD	627			243441	174107					50.87	5.70
29	Lanaken	B	628.4			242245	175300					50.88	5.68
30	Maaseik	MS	663.89			250379	199234					51.09	5.80
31	Kessenich	B	674.4			254013	204847					51.14	5.85
32	Linne	MD	681			258594	207578					51.17	5.92
33	Eijsden Grens	B	615					175810	307627			50.76	5.68
34	St. Pieter	MS	624					176868	315464			50.83	5.70
35	Weir Borgharen upstream	MD	628					176878	319982			50.87	5.70
36	Borgharen Dorp	MS	629					176377	320325			50.87	5.69
37	Weir Linne upstream	MD	681					193857	352398			51.16	5.94
38	Weir Roermond upstream	MS	692					197032	357976			51.21	5.99
39	Roermond	MD	693					196315	356736			51.20	5.98
40	Lith Dorp	MD	815					158168	424653			51.81	5.43
41	Keizersveer	B	860					120857	414625			51.72	4.89
42	Stah	MS	25.3							2507340	5662510	51.10	6.11
43	Linnich	MS	47.1							2519320	5649600	50.98	6.28
44	Jülich Stadion	MS	57.9							2524598	5643350	50.93	6.35
45	Selhausen	MS	68.4							2530574	5636131	50.86	6.44

8.4 Extraction reaches for the results

Reach N°	From	To	Length	
0	Neufchâteau	Saint-Mihiel	107.1	Neufchâteau-Saint-Mihiel
1	Saint-Mihiel	Verdun	57.9	Saint-Mihiel-Verdun
2	Verdun	Stenay	66.6	Verdun-Stenay
3	Stenay	Sedan	48.7	Stenay-Sedan
4	Sedan	Aiglemont	48.0	Sedan-Aiglemont
5	Aiglemont	Monthermé	20.6	Aiglemont-Monthermé
6	Monthermé	Chooz	59.7	Monthermé-Chooz
7	Chooz	Givet	7.9	Chooz-Givet
8	Givet	BE-F border	2.9	Givet-BE-F border
9	BE-F border	Hastière	3.5	BE-F border-Hastière
10	Hastière	Waulsort	4.7	Hastière-Waulsort
11	Waulsort	Anseremme	7.8	Waulsort-Anseremme
12	Anseremme	Dinant	3.9	Anseremme-Dinant
13	Dinant	Houx	3.5	Dinant-Houx
14	Houx	Hun	5.1	Houx-Hun
15	Hun	Rivière	5.0	Hun-Rivière
16	Rivière	Tailfer	5.5	Rivière-Tailfer
17	Tailfer	La Plante	6.1	Tailfer-La Plante
18	La Plante	Grands-Malades	3.6	La Plante-Grands-Malades
19	Grands-Malades	Andenne	14.8	Grands-Malades-Andenne
20	Andenne	Ampsin	19.2	Andenne-Ampsin
21	Ampsin	Ivoz-Ramet	14.4	Ampsin-Ivoz-Ramet
22	Ivoz-Ramet	Monsin	17.6	Ivoz-Ramet-Monsin
23	Monsin	Lixhe	13.1	Monsin-Lixhe
24	Lanaken	Kessenich	46	Lanaken-Kessenich
25	Kalkmas1		8.24	Kalkmas1
26	Kalkmas2		4.04	Kalkmas2
27	Grensms1		1.16	Grensms1
28	Grensms2		36.73	Grensms2
29	Grenms3a		1.1	Grenms3a
30	Grenms3b		11.22	Grenms3b
31	Grenms3c		2.25	Grenms3c
32	Zandmas1		0.06	Zandmas1
33	Zandmas2		17.72	Zandmas2
34	Zandmas3		22.4	Zandmas3
35	Zandmas4		16.52	Zandmas4
36	Zandmas5		8.11	Zandmas5
37	Zandmas6		33.67	Zandmas6
38	Zandmas7		36.58	Zandmas7
39	Getijms1		17.65	Getijms1
40	Getijms2		10.6	Getijms2
41	Getijms3		4.45	Getijms3
42	Getijms4		12.56	Getijms4
43	Obermaubach	Roermond	88.3	Obermaubach-Roermond

8.5 Hydrographs

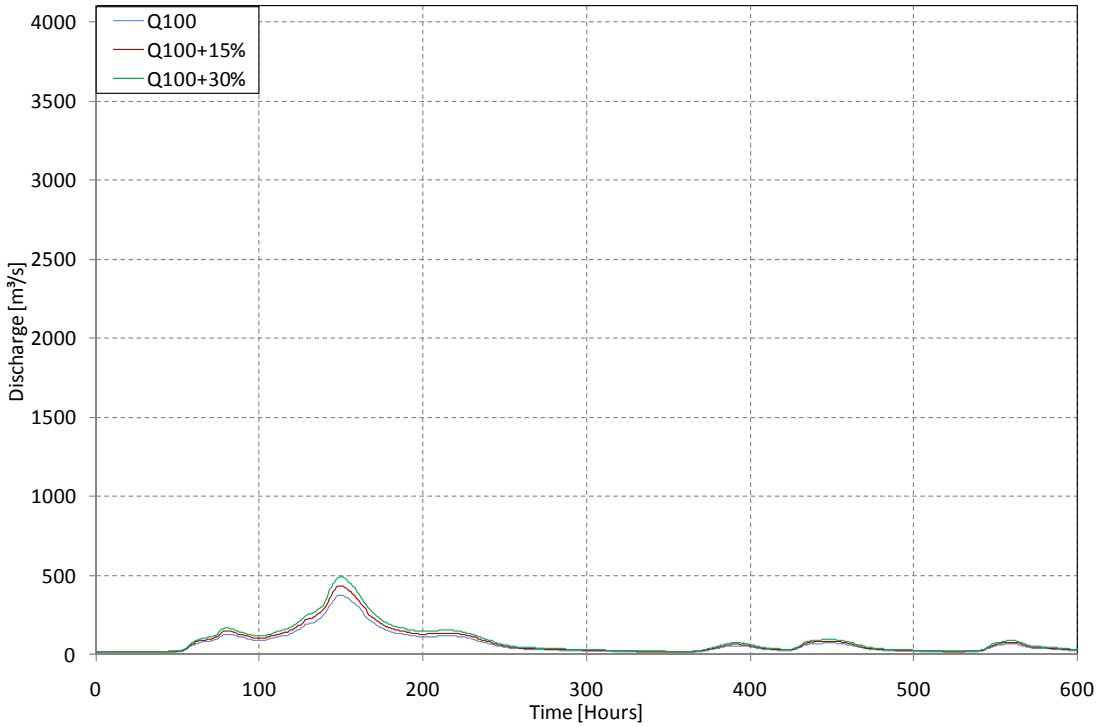


Figure 8-1: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Neufchâteau

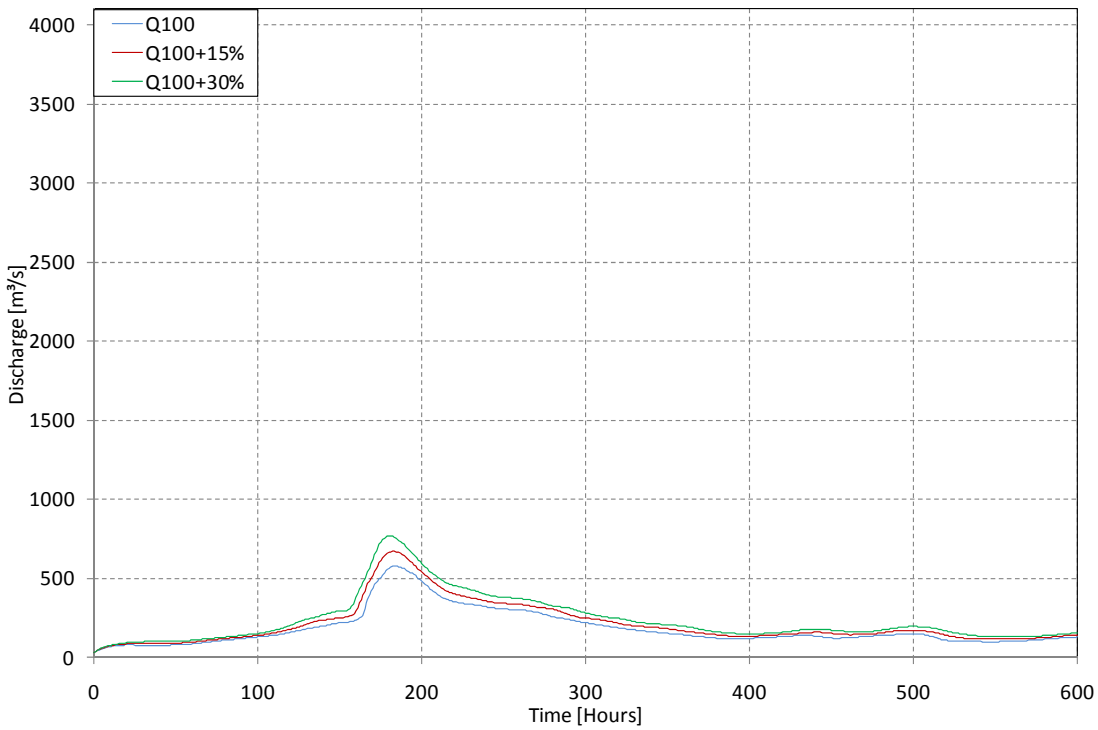


Figure 8-2: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Saint Mihiel

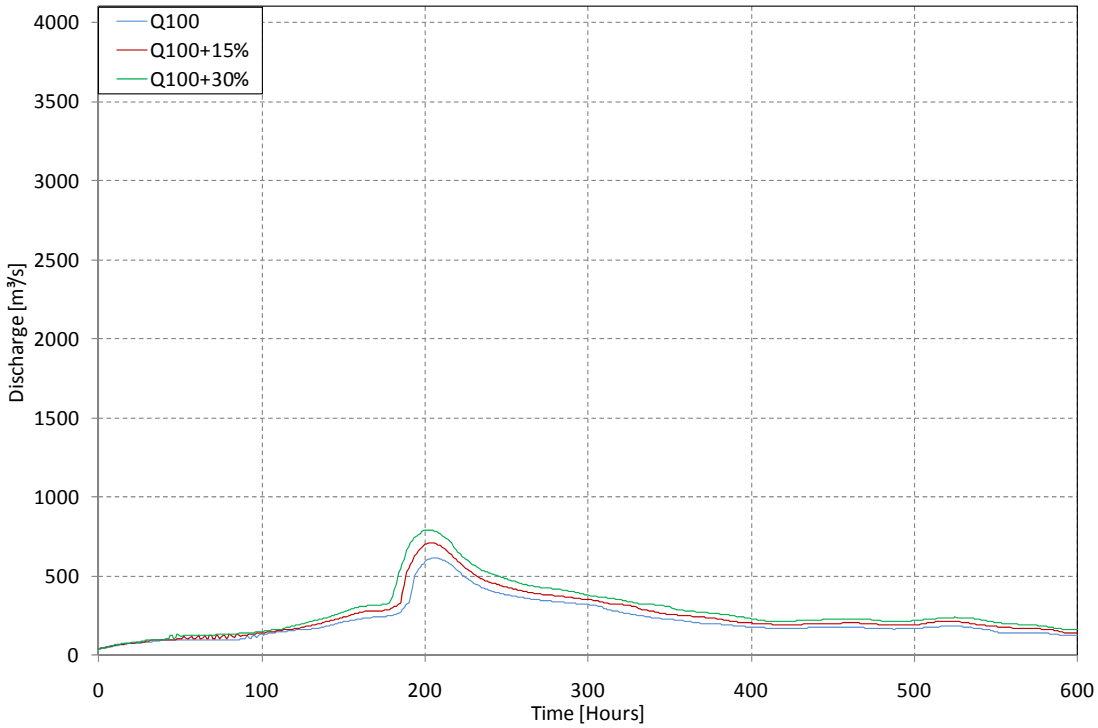


Figure 8-3: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Verdun

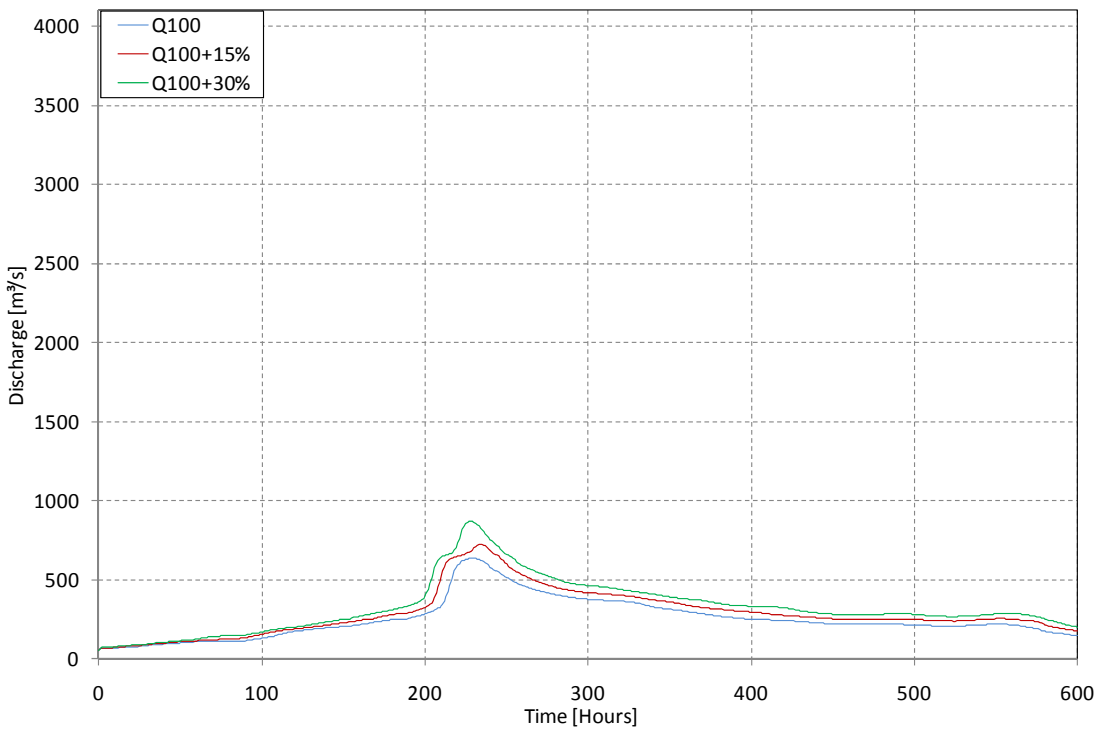


Figure 8-4: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Stenay

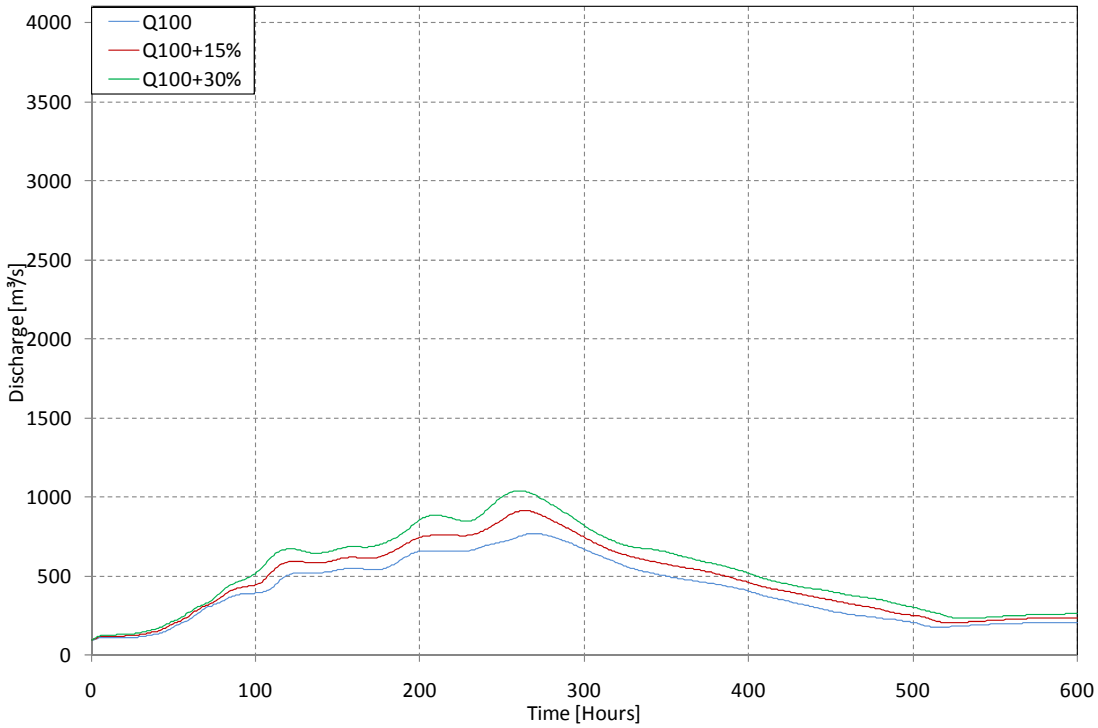


Figure 8-5: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Sedan

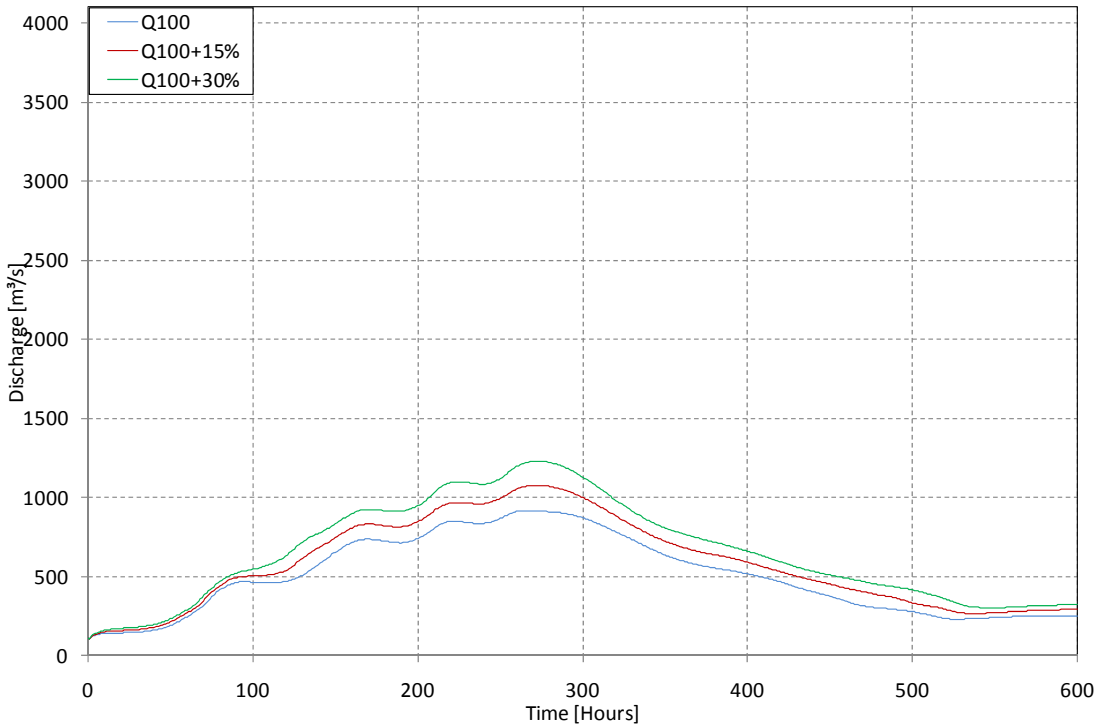


Figure 8-6: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Aiglemont

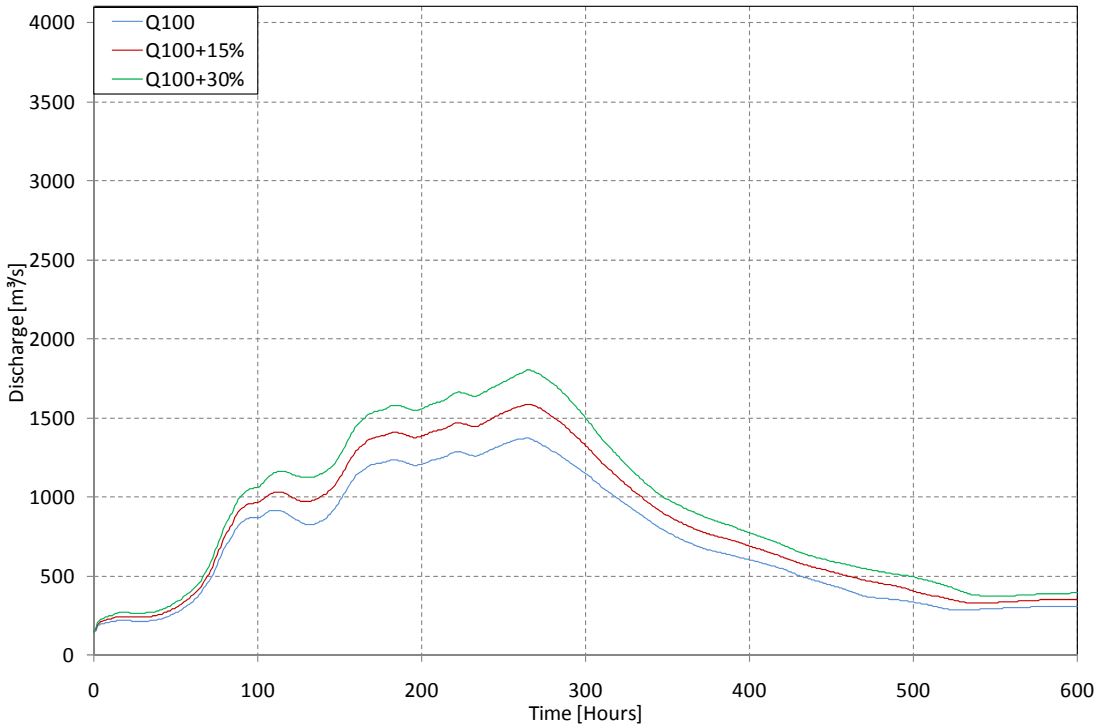


Figure 8-7: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Monthermé

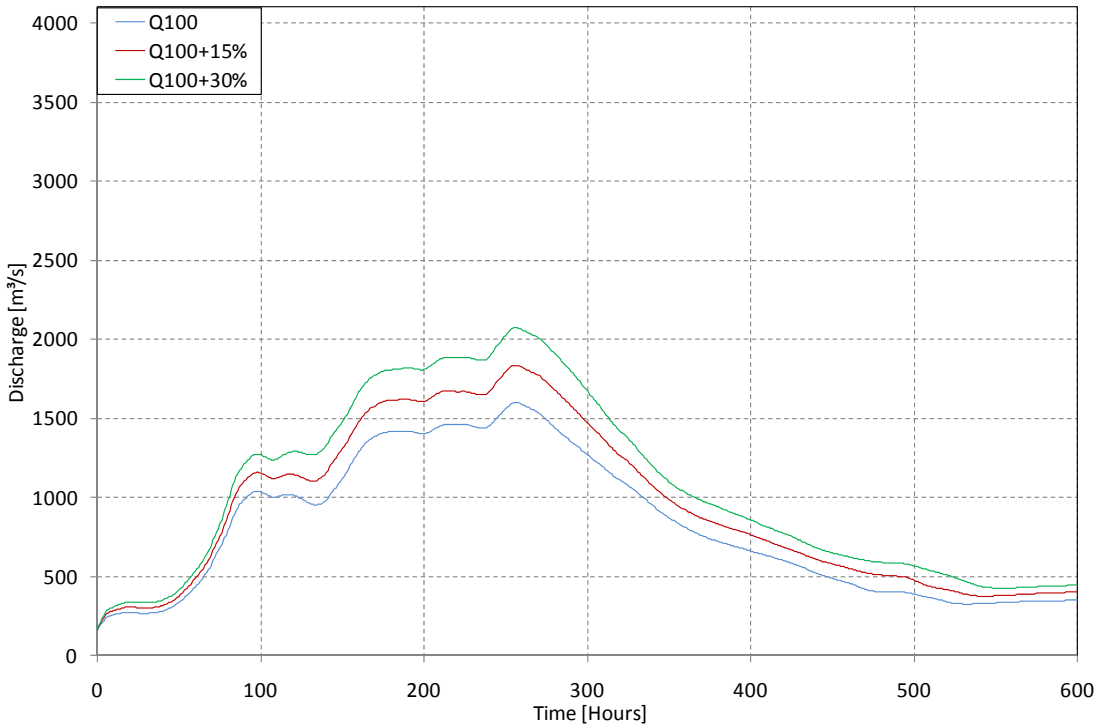


Figure 8-8: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Chooz

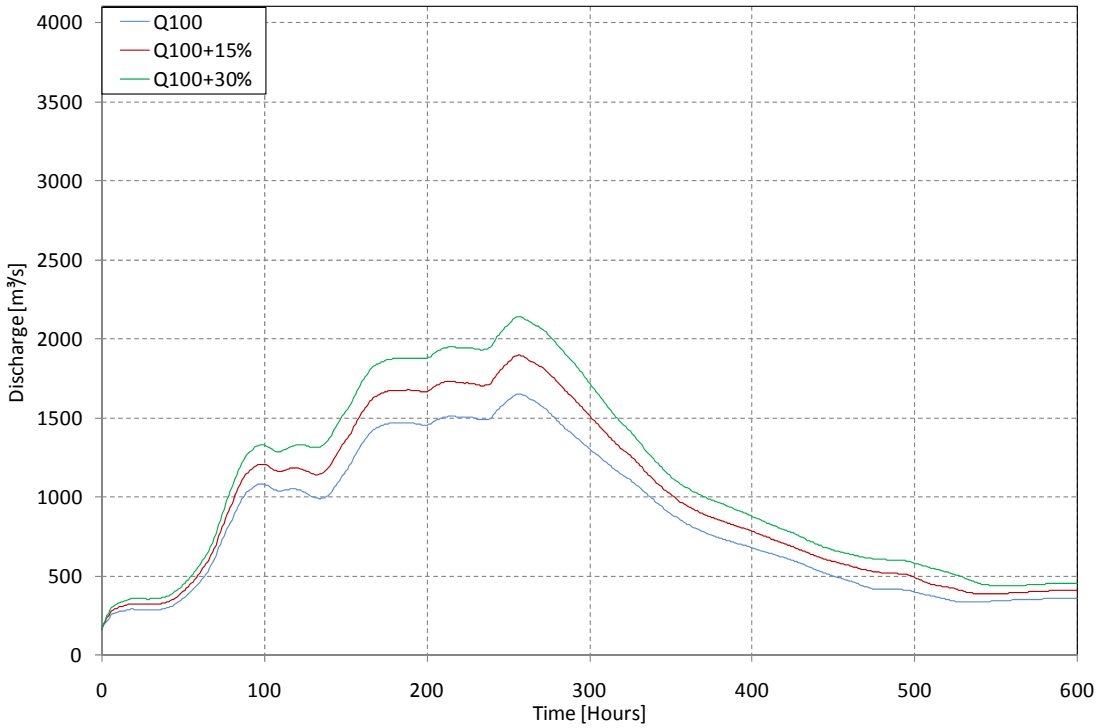


Figure 8-9: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Givet

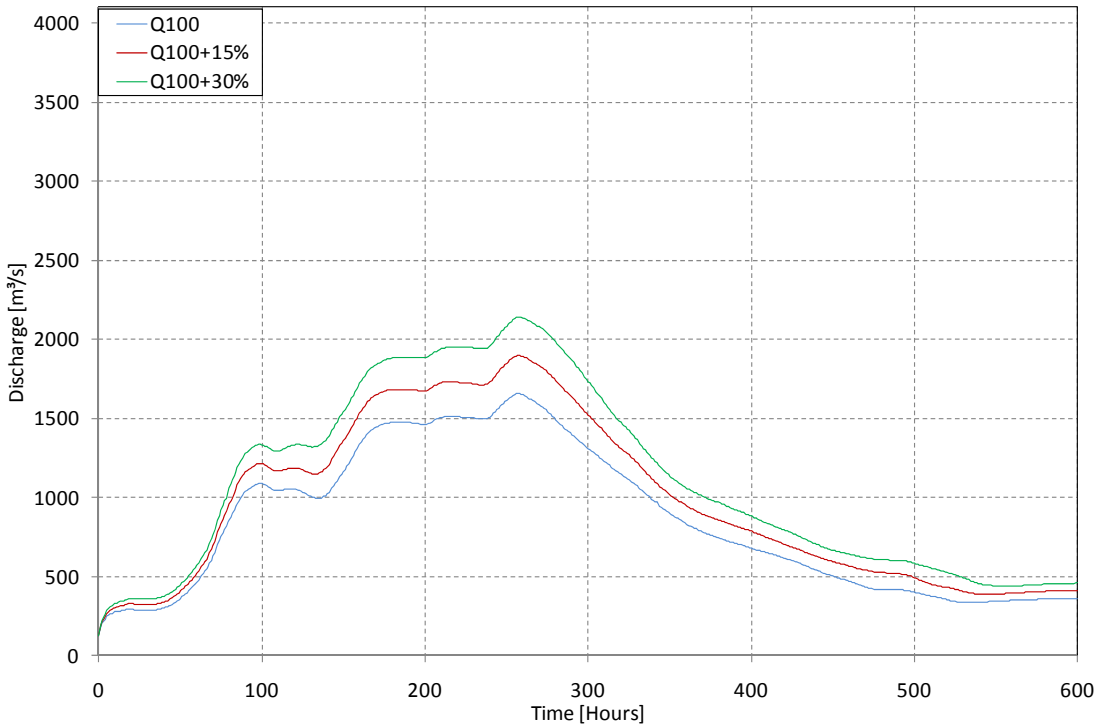


Figure 8-10: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% at France-Wallonia border

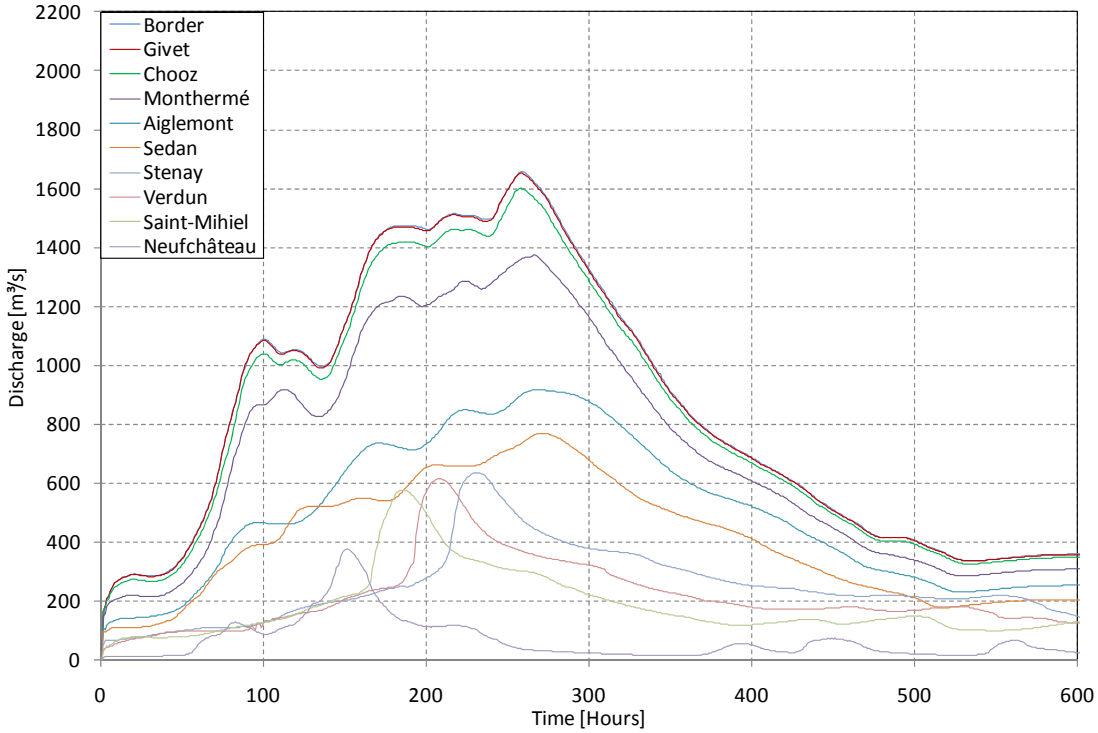


Figure 8-11: Flood propagation in France for Q_{100}

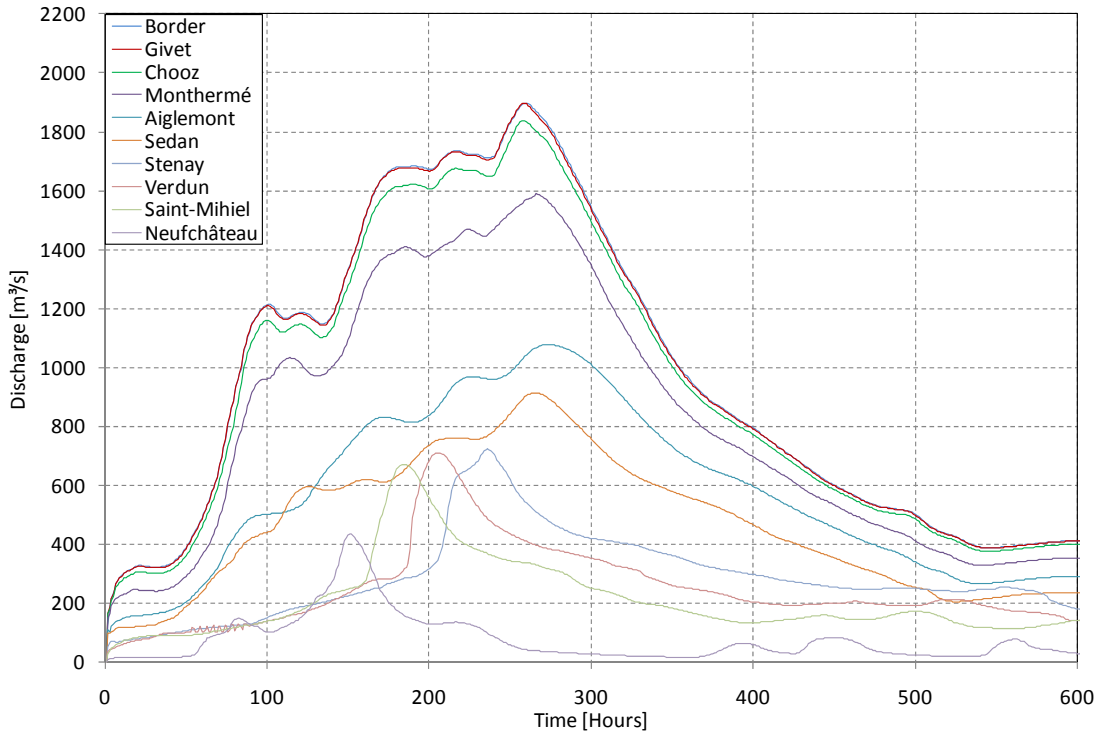


Figure 8-12: Flood propagation in France for Q_{100}+15%

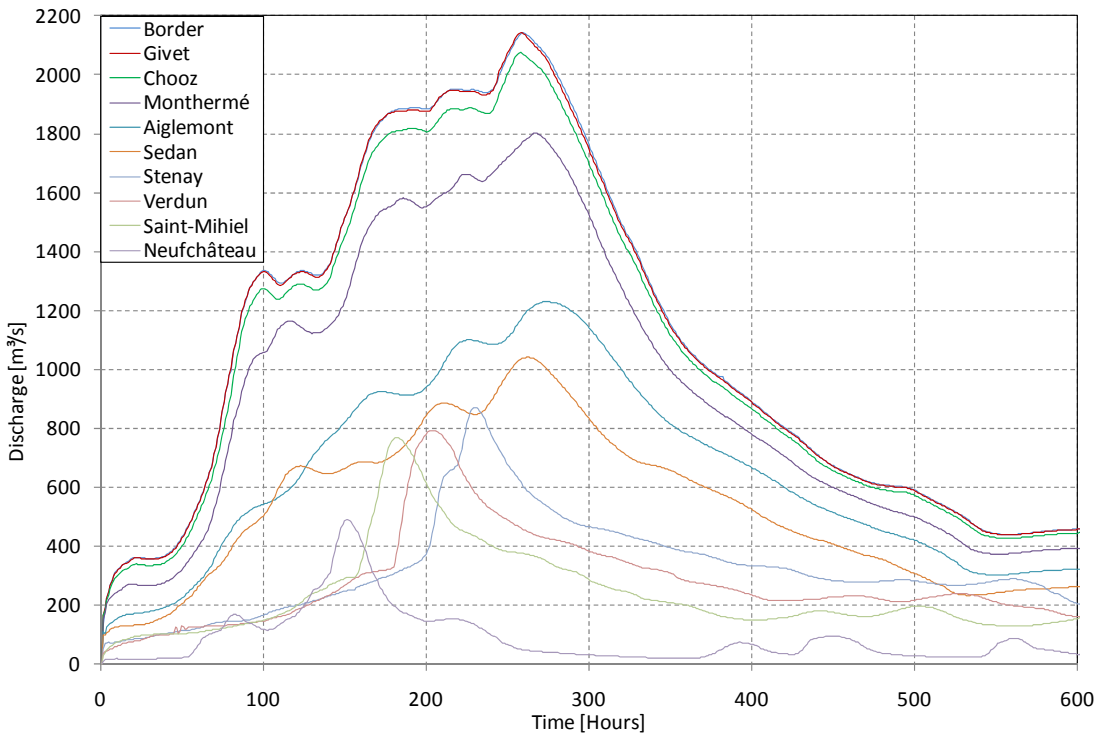


Figure 8-13: Flood propagation in France for Q_{100}+30%

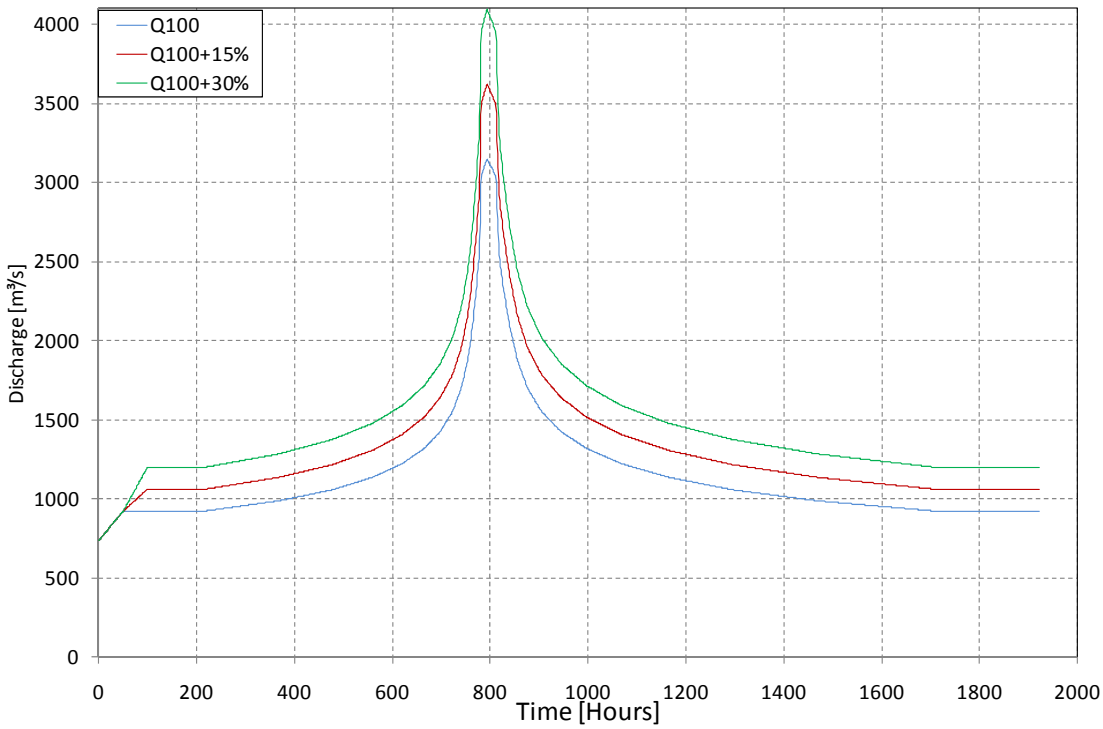


Figure 8-14: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Borgharen (Flanders model)

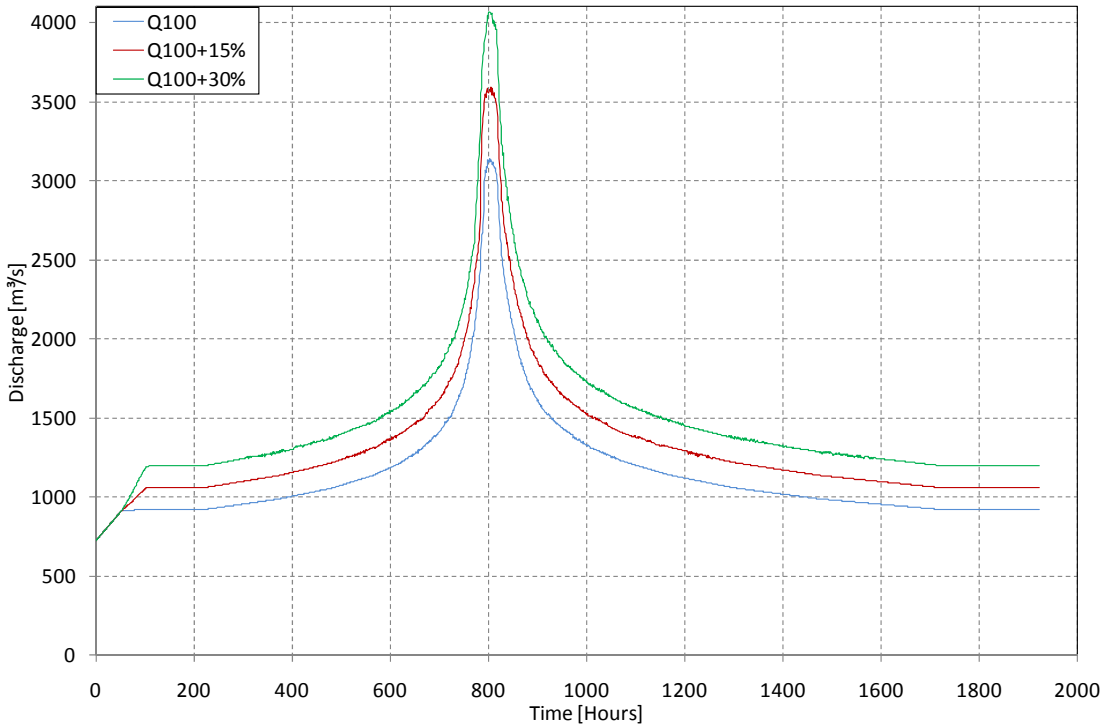


Figure 8-15: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Maaseik (Flanders model)

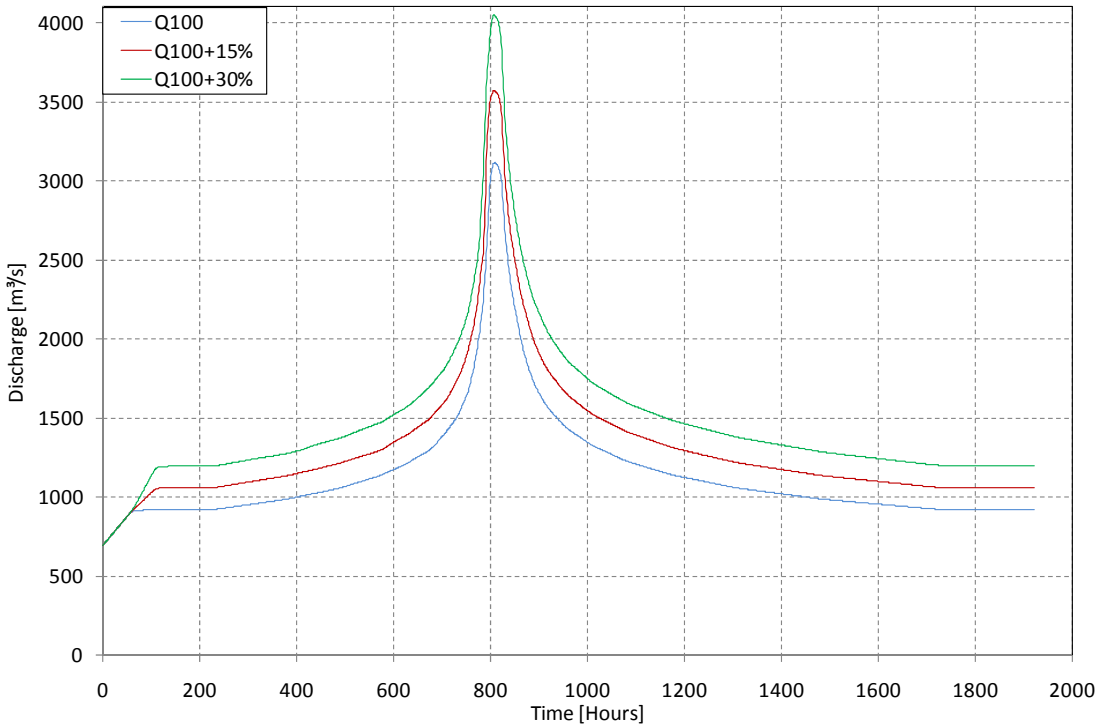


Figure 8-16: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Linne (Flanders model)

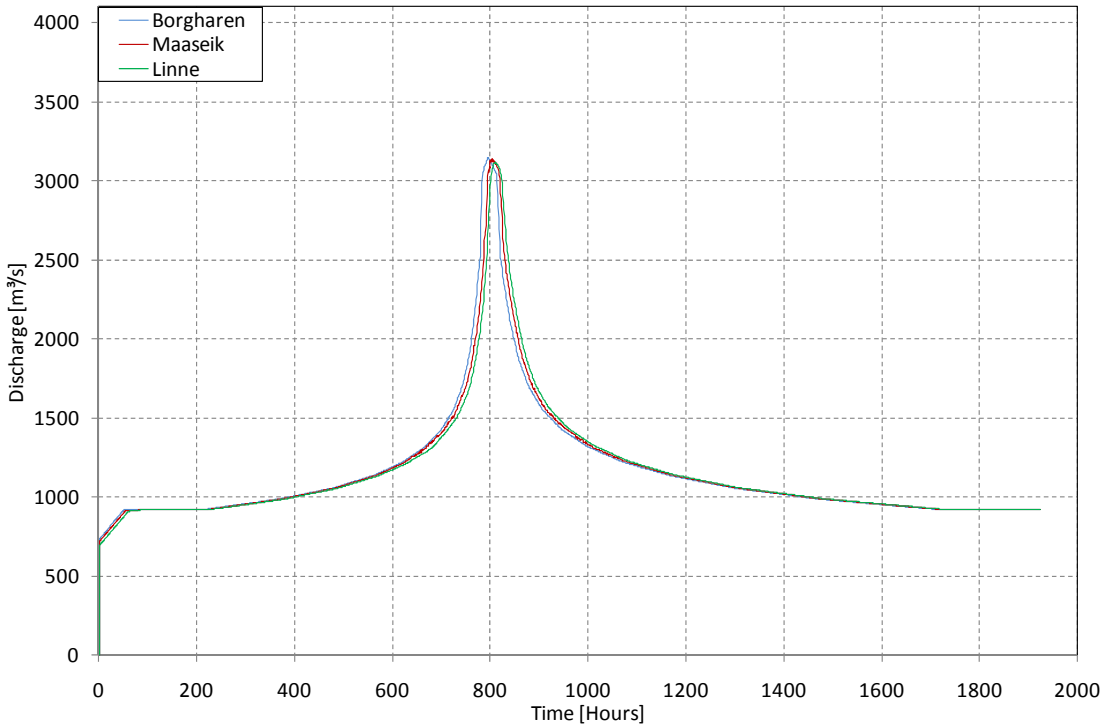


Figure 8-17: Flood propagation in Flanders for Q_{100}

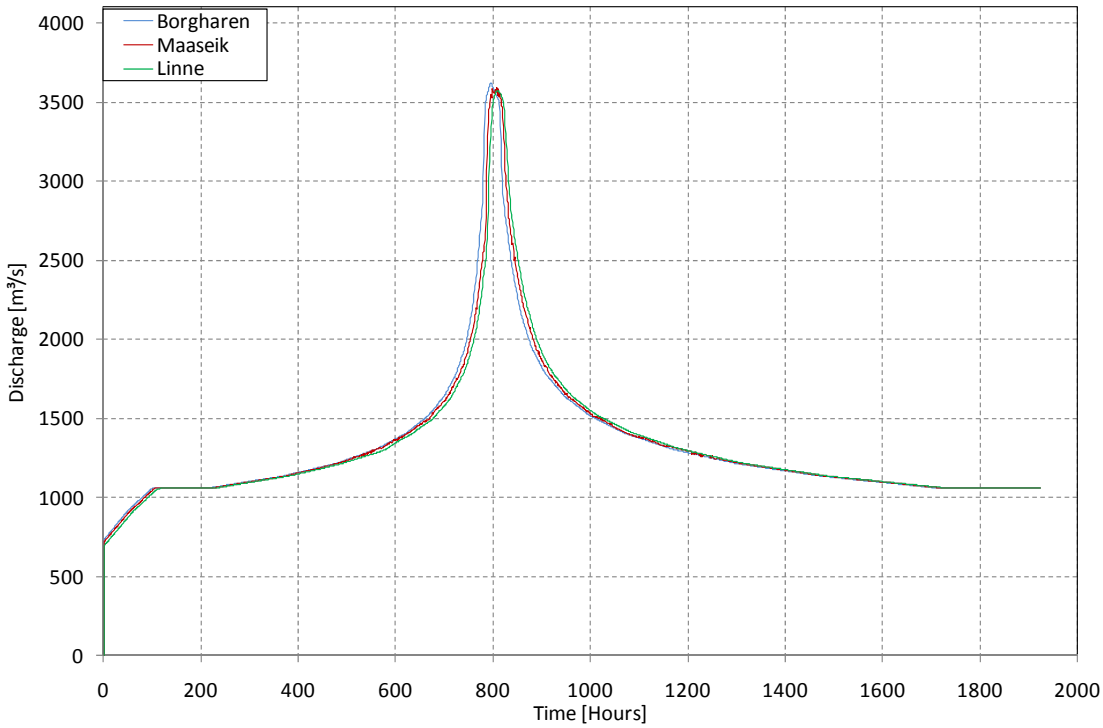


Figure 8-18: Flood propagation in Flanders for Q_{100}+15%

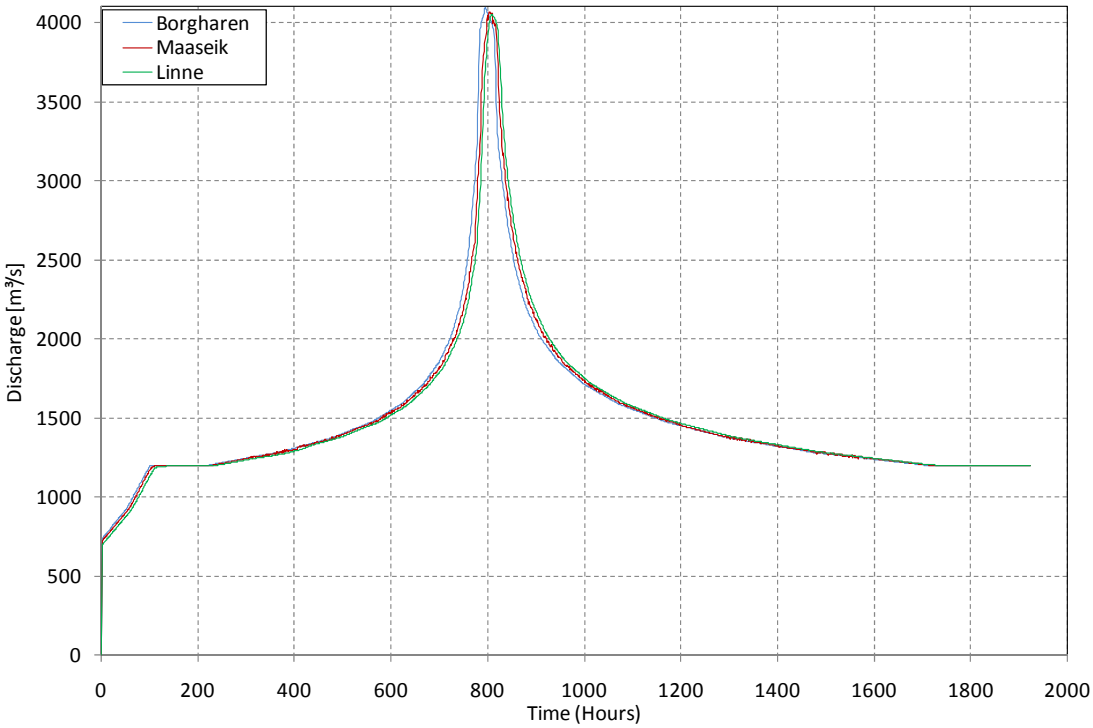


Figure 8-19: Flood propagation in Flanders for Q_{100}+30%

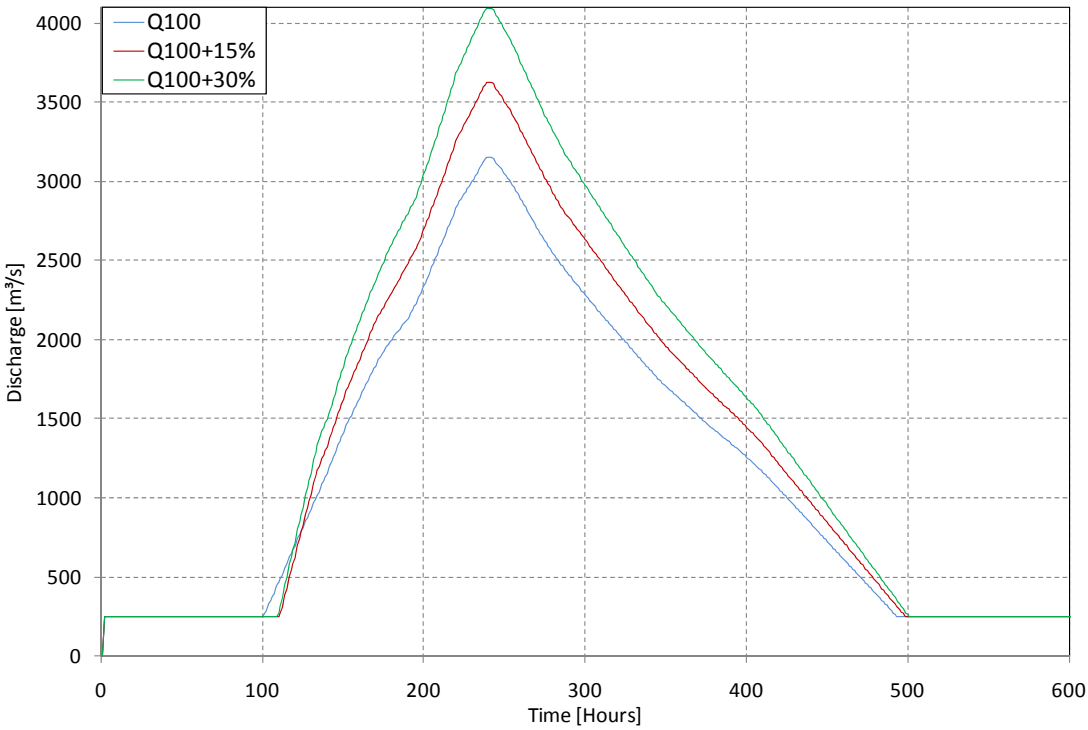


Figure 8-20: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Eisden (NL model)

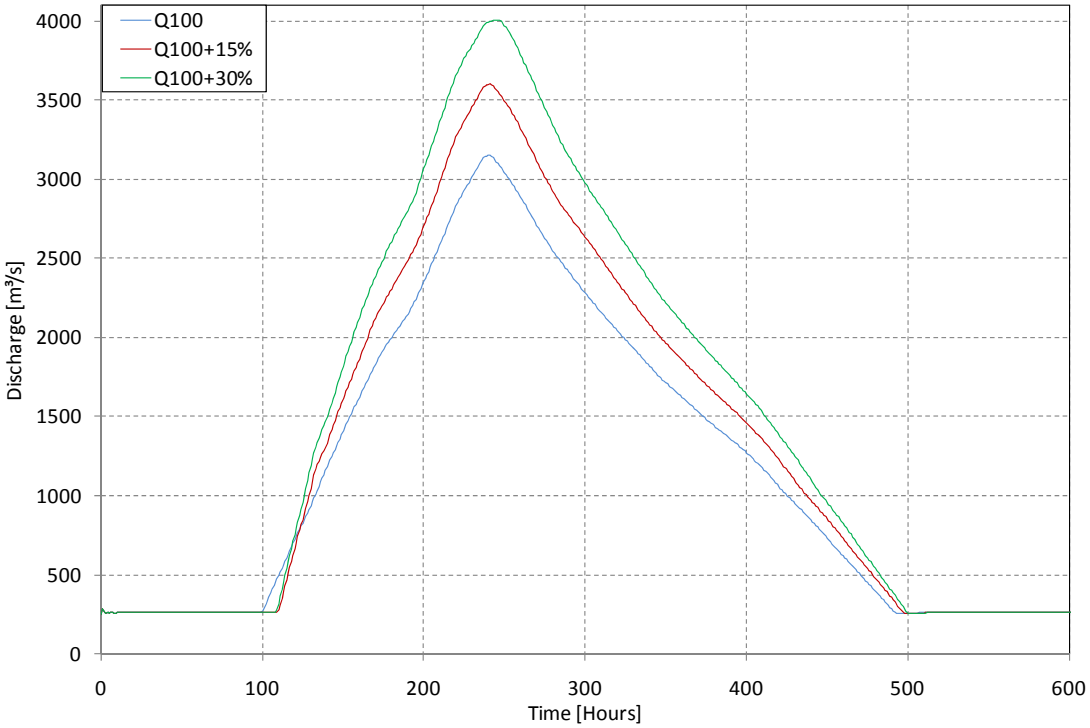


Figure 8-21: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Sint-Pieter (NL model)

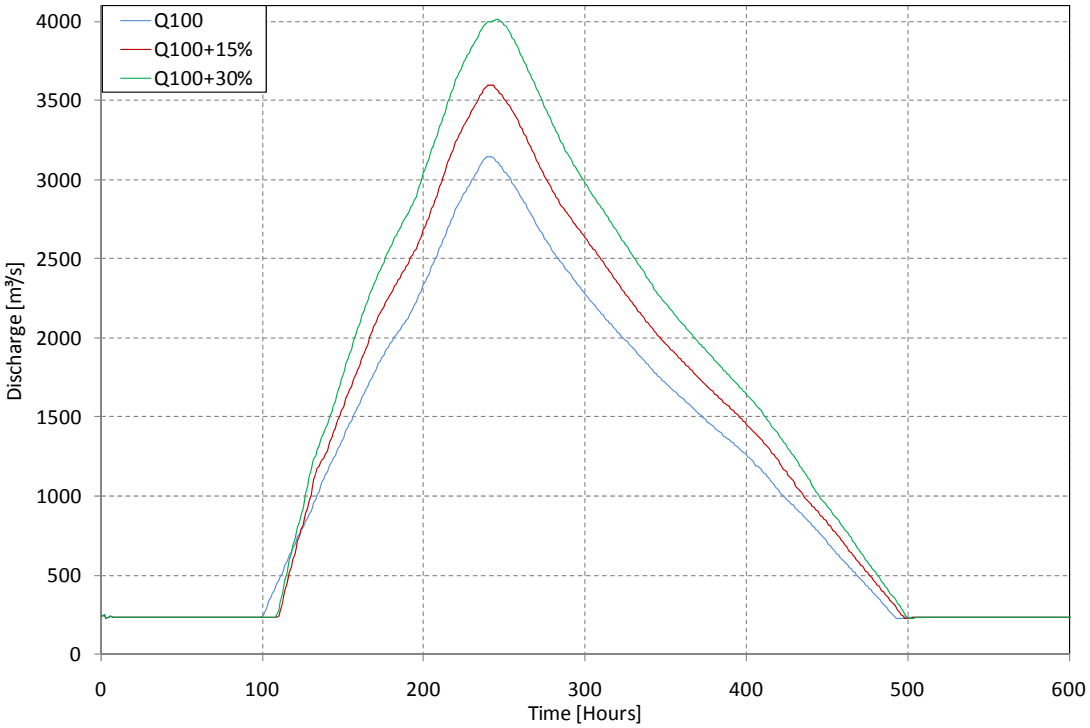


Figure 8-22: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% at Borgharen weir (NL model)

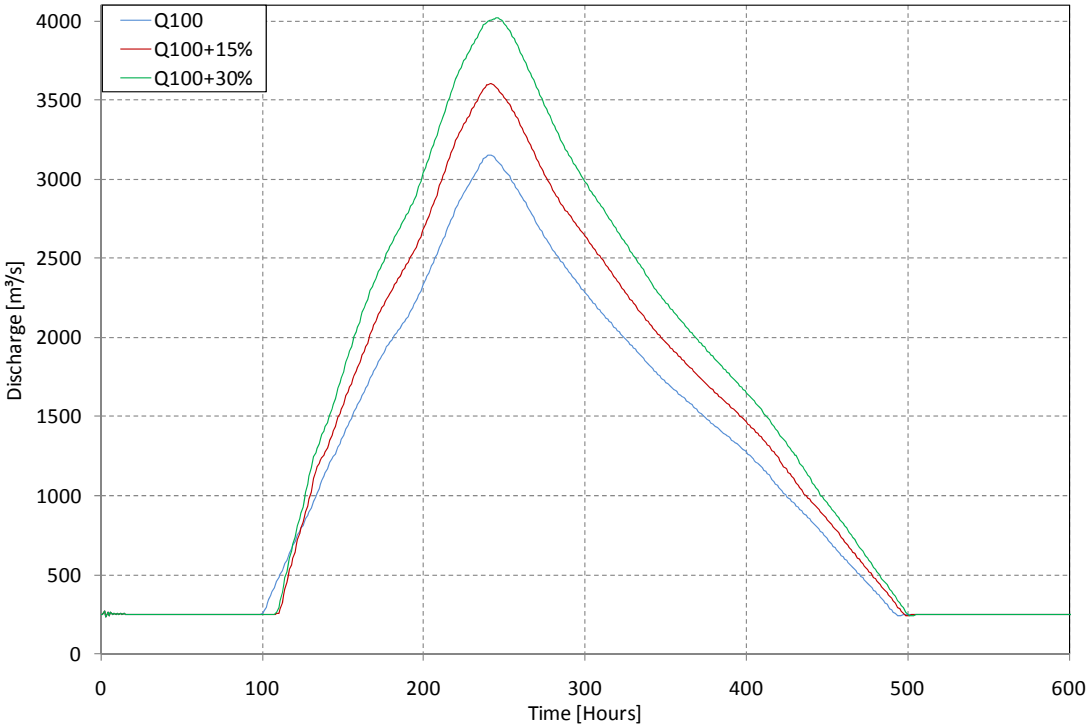


Figure 8-23: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Borgharen Dorp (NL model)

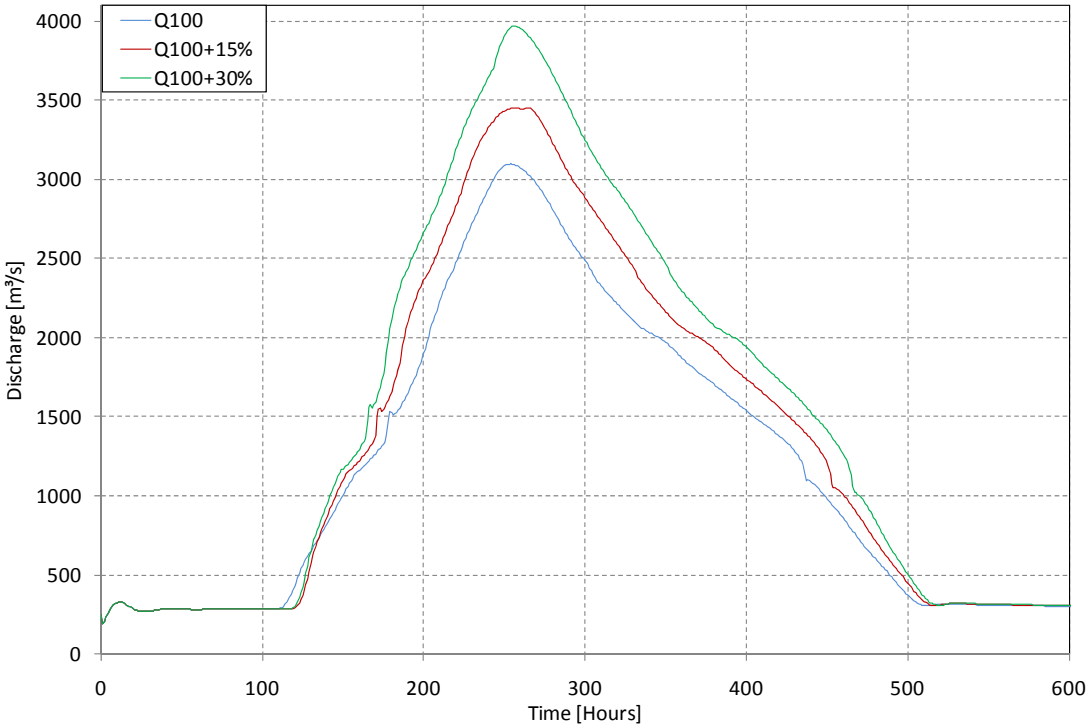


Figure 8-24: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% at Linne weir (NL model)

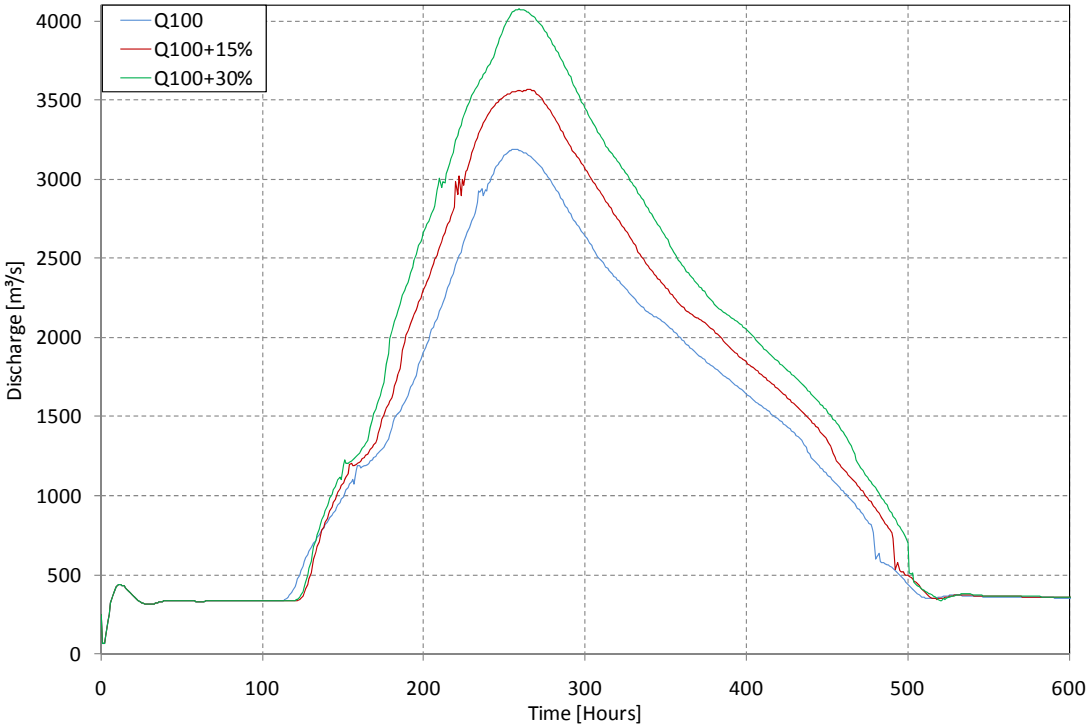


Figure 8-25: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% at Roermond weir (NL model)

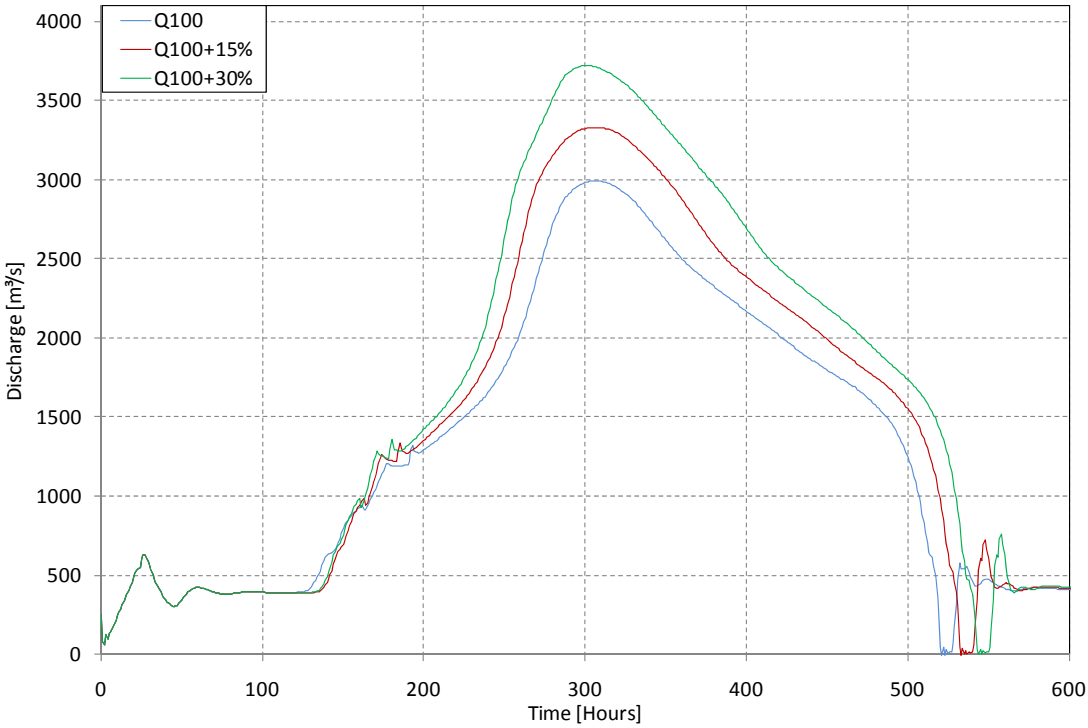


Figure 8-26: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Lith Dorp (NL model)

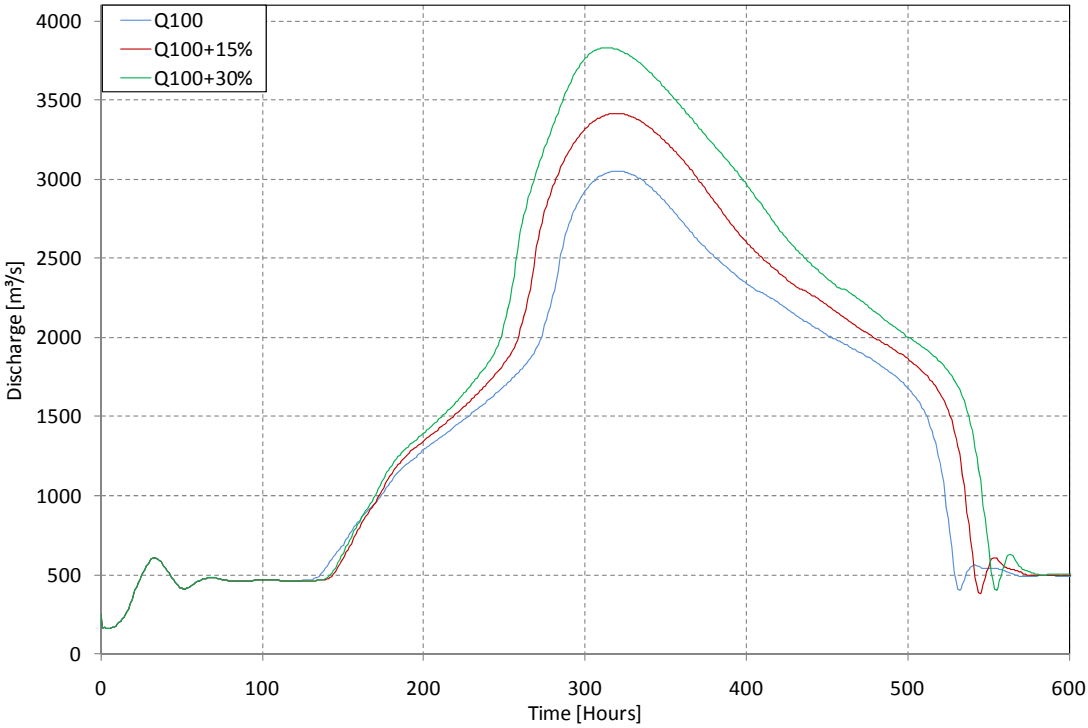


Figure 8-27: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Keizersveer (NL model)

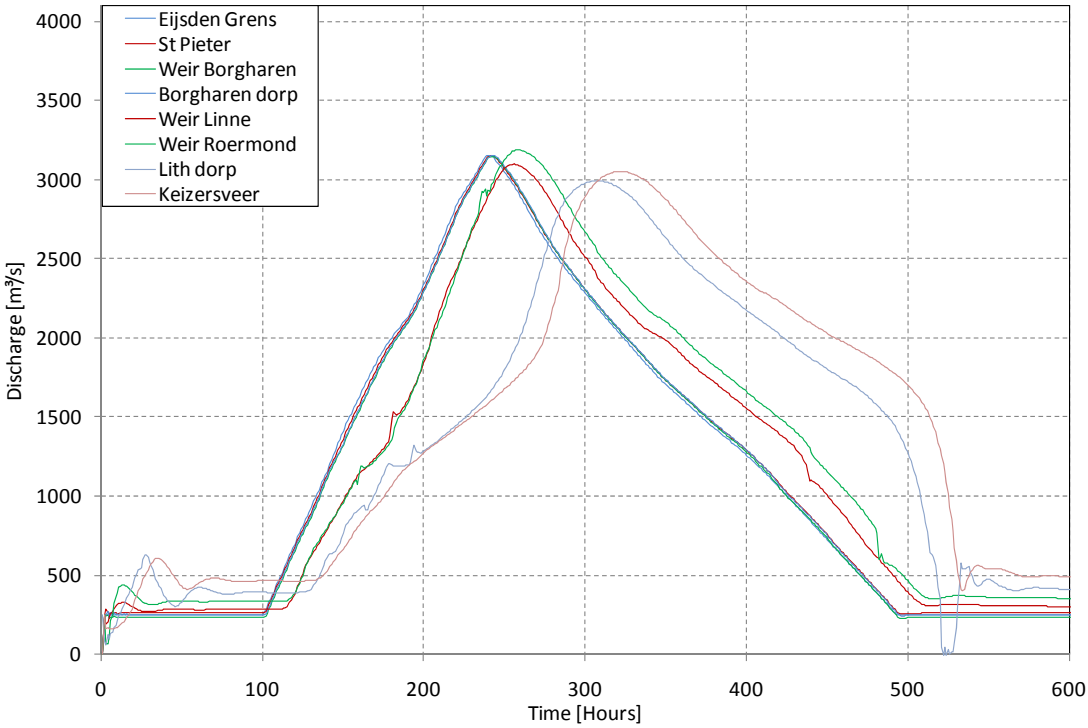


Figure 8-28: Flood propagation in the Netherlands for Q_{100}

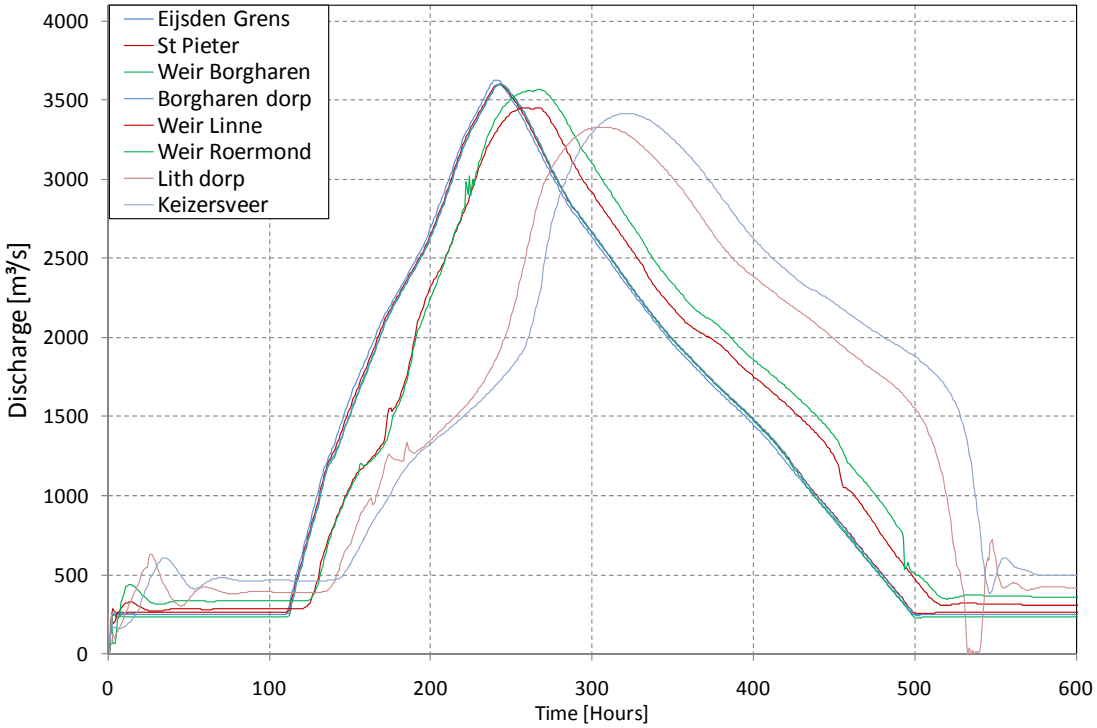


Figure 8-29: Flood propagation in the Netherlands for Q_{100}+15%

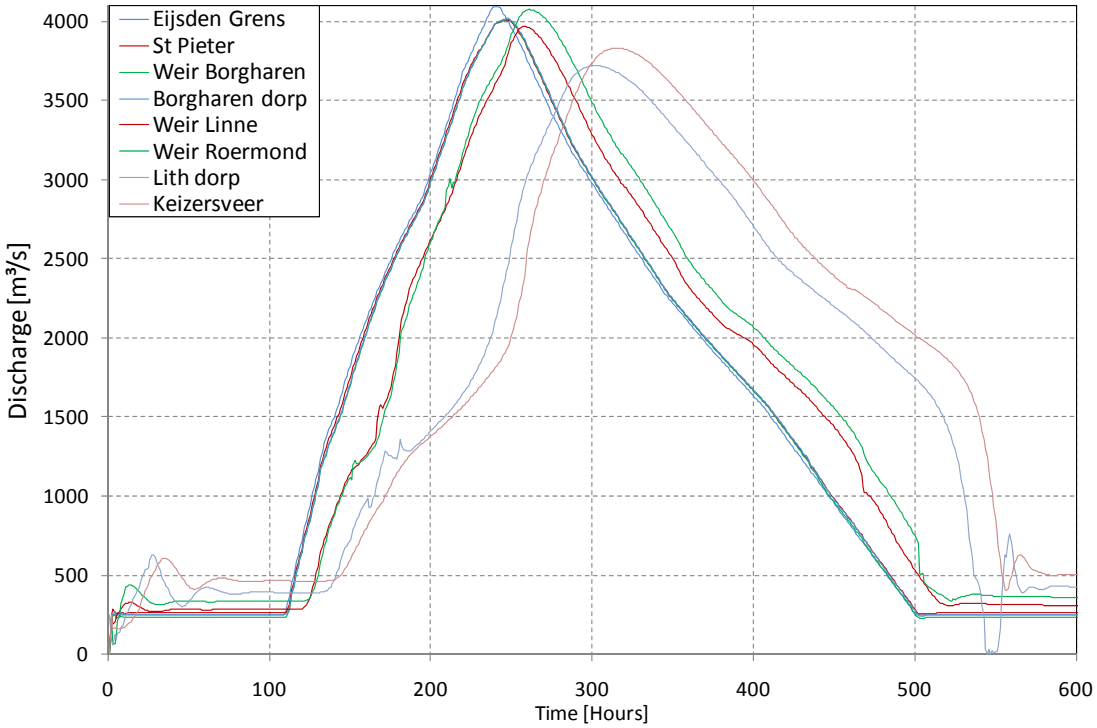


Figure 8-30: Flood propagation in the Netherlands for Q_{100}+30%

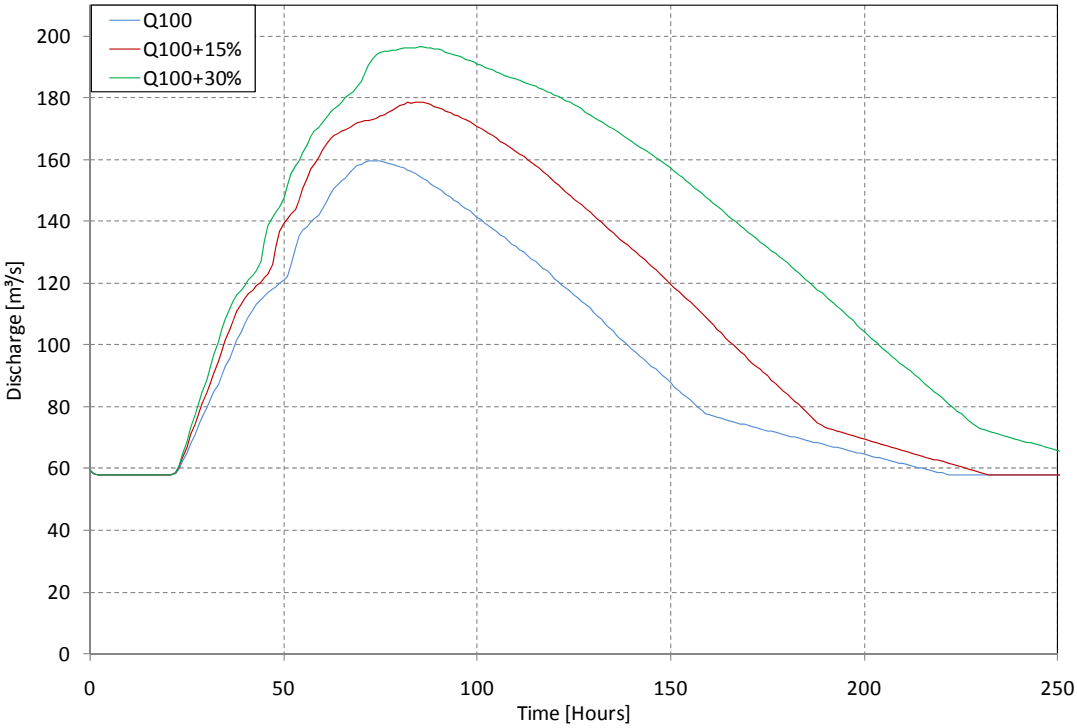


Figure 8-31: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Stah (Rur)

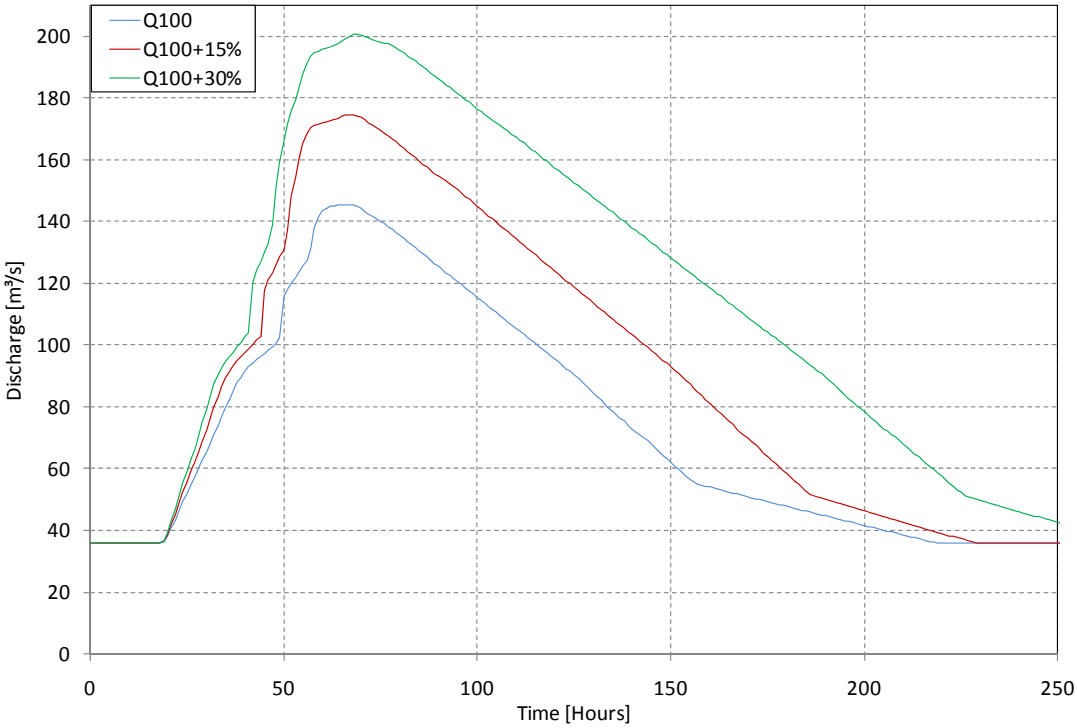


Figure 8-32: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Linnich (Rur)

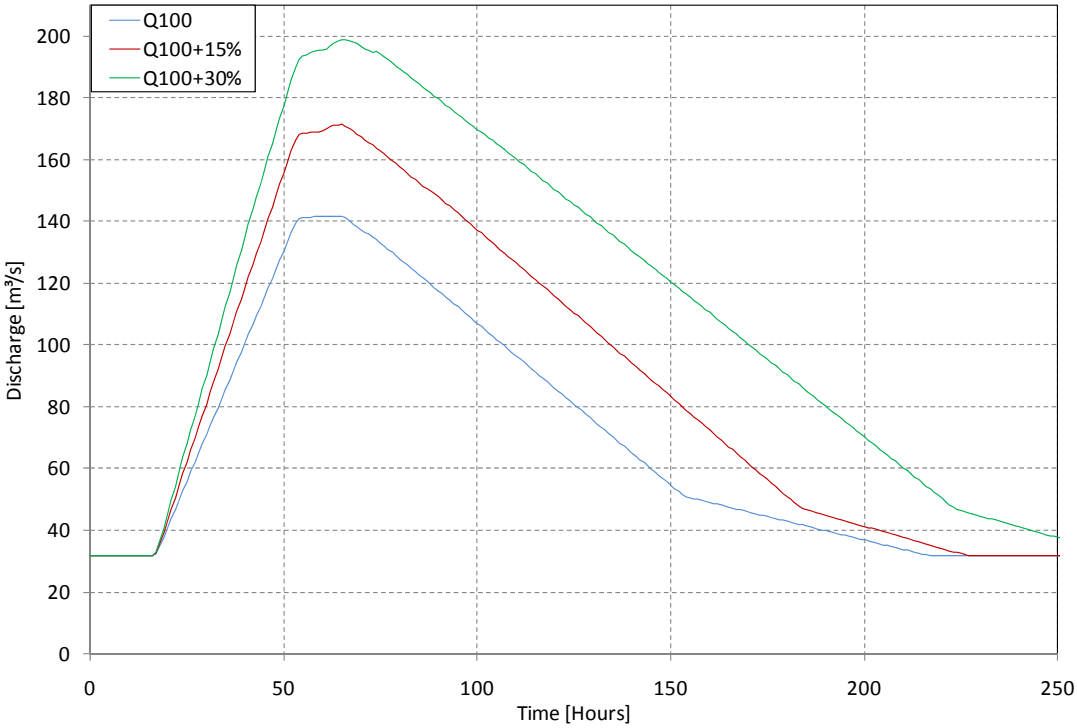


Figure 8-33: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Jüllich (Rur)

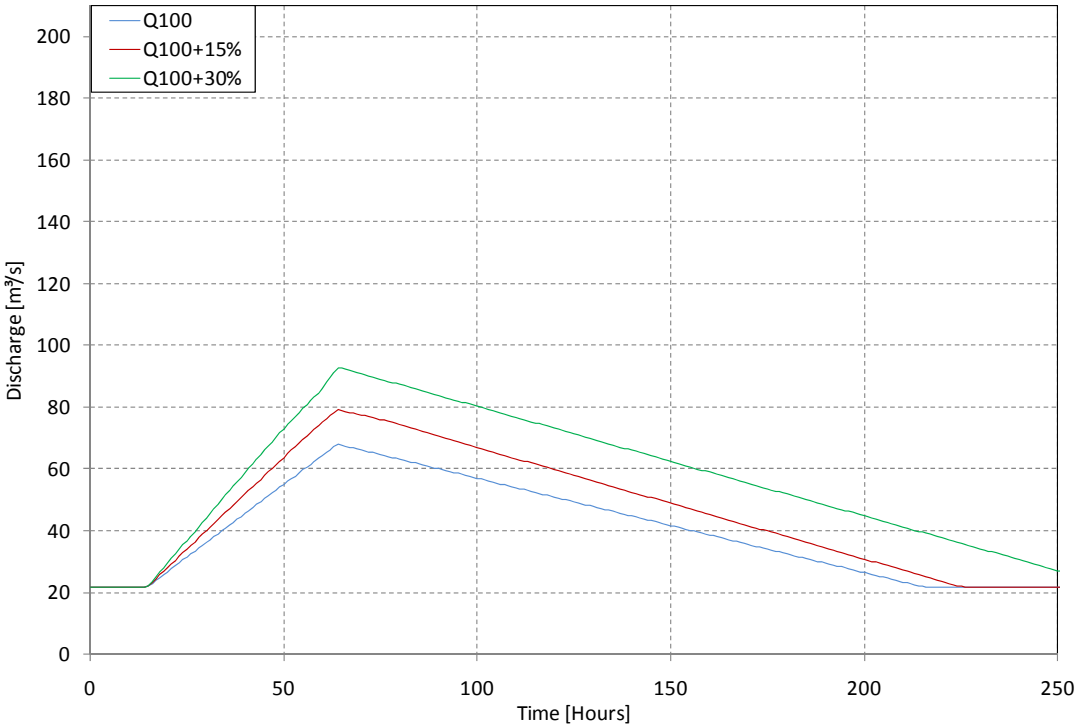


Figure 8-34: Hydrograph for Q_{100}, Q_{100}+15% and Q_{100}+30% in Selhausen (Rur)

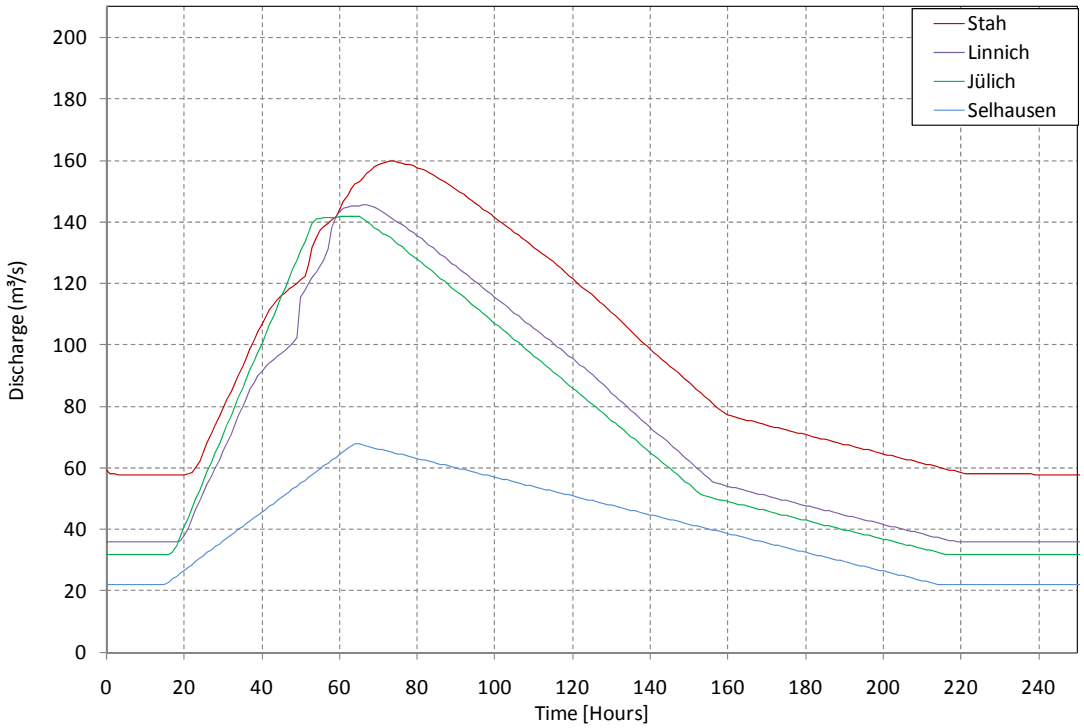


Figure 8-35: Flood propagation in Germany (Rur) for Q_{100}

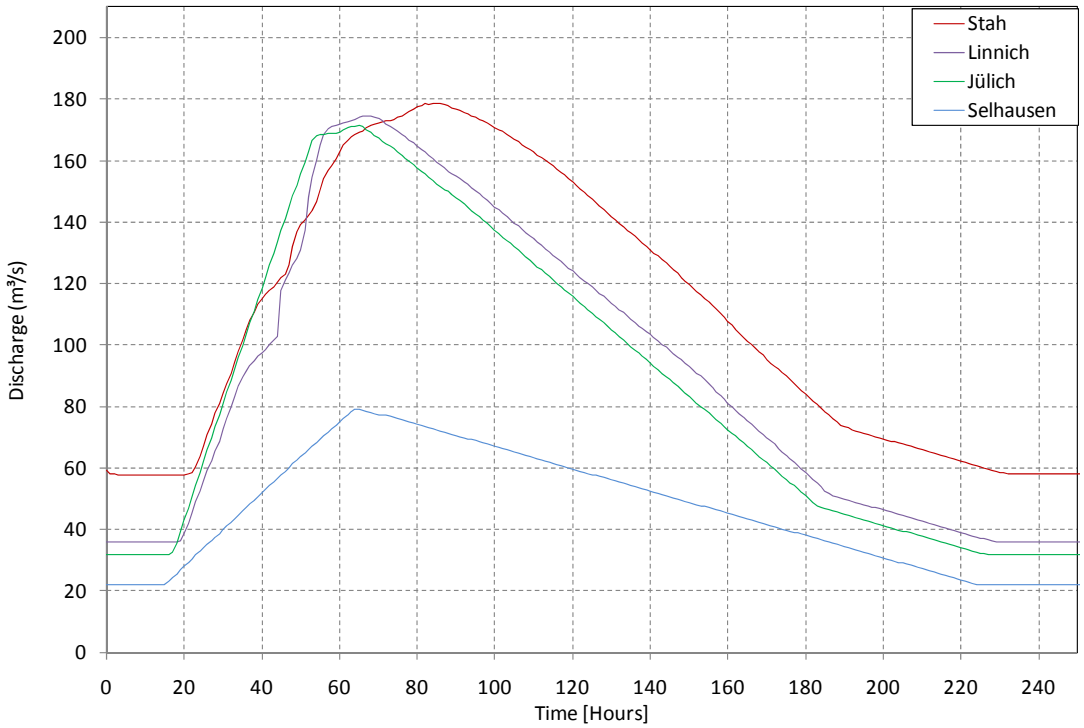


Figure 8-36: Flood propagation in Germany (Rur) for Q_{100}+15%

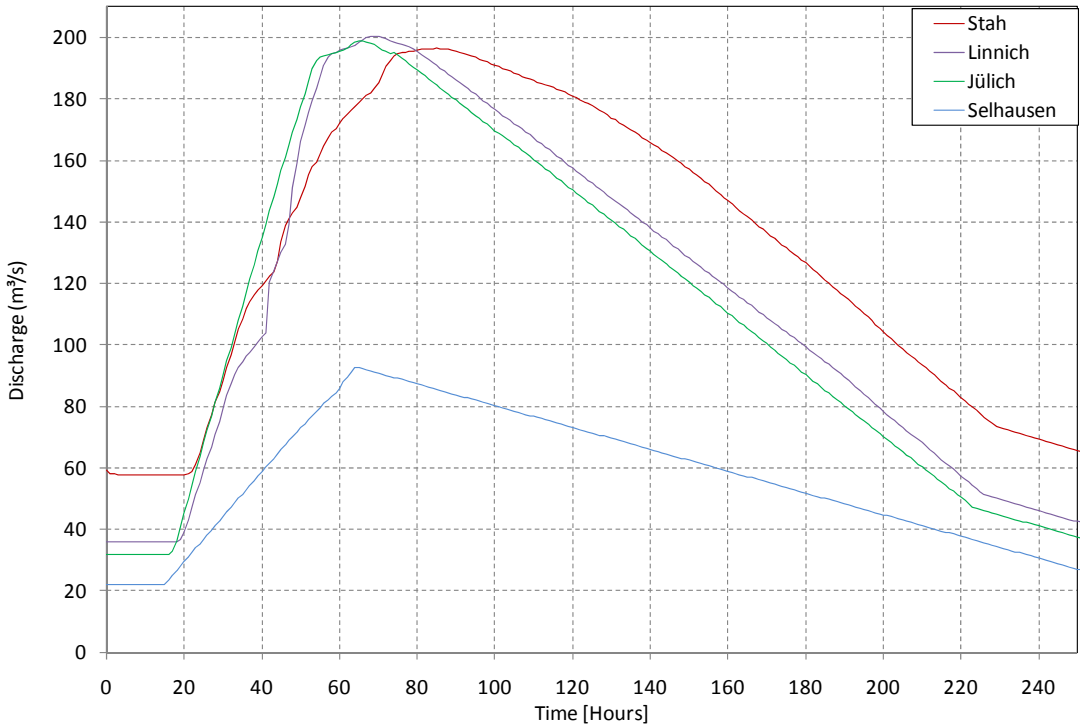


Figure 8-37: Flood propagation in Germany (Rur) for Q_{100}+30%

8.6 Reshaped hydrograph in Flanders

The upstream boundary condition is a discharge timeserie in Borgharen. Three kinds of timeseries were considered:

- The original composite storms for return periods T1, T2, T5, T10, T25, T50, T100, T500, T1000, T2500, T4000 and T10000 in the actual climate.
- Rescaling of the discharge from the original composite storms for return period T100 in the actual climate, as the discharges used in the model of Flanders were significantly higher compared to the discharges used in Wallonia and the Netherlands.
- Perturbation of the rescaled discharges for the return period T100. Two perturbation factors were used: $PF^{20\text{-}50}$ (+15%) and $PF^{70\text{-}00}$ (+30%)

Together with Wallonia and the Netherlands, Flanders agreed on an upstream maximum discharge of 3150 m³/s for the return period T100. The rescaling of the original discharge has been performed in two ways: (i) either the original T100 discharge with a maximum of 3554 m³/s was used, (ii) or the original T25 discharge with a maximum of 3202 m²/s was used, as this is the closest peak discharge to 3150 m³/s.

Original storm	Max discharge [m³/s]	Rescaled discharge	Max discharge [m³/s]	Perturbed discharge	Max discharge [m³/s]
T1	1520	Q100 based on T25	3150	Q100PF20-50 based on T25	3623
T2	1882	Q100 based on T100	3150	Q100PF20-50 based on T100	3623
T5	2361			Q100PF70-00 based on T25	4095
T10	2723			Q100PF70-00 based on T100	4095
T25	3202				
T50	3503				
T100	3554				
T500	3702				
T1000	3781				
T2500	3900				
T4000	3971				
T10000	4117				

Table 8-1 : Maximum discharge upstream boundary

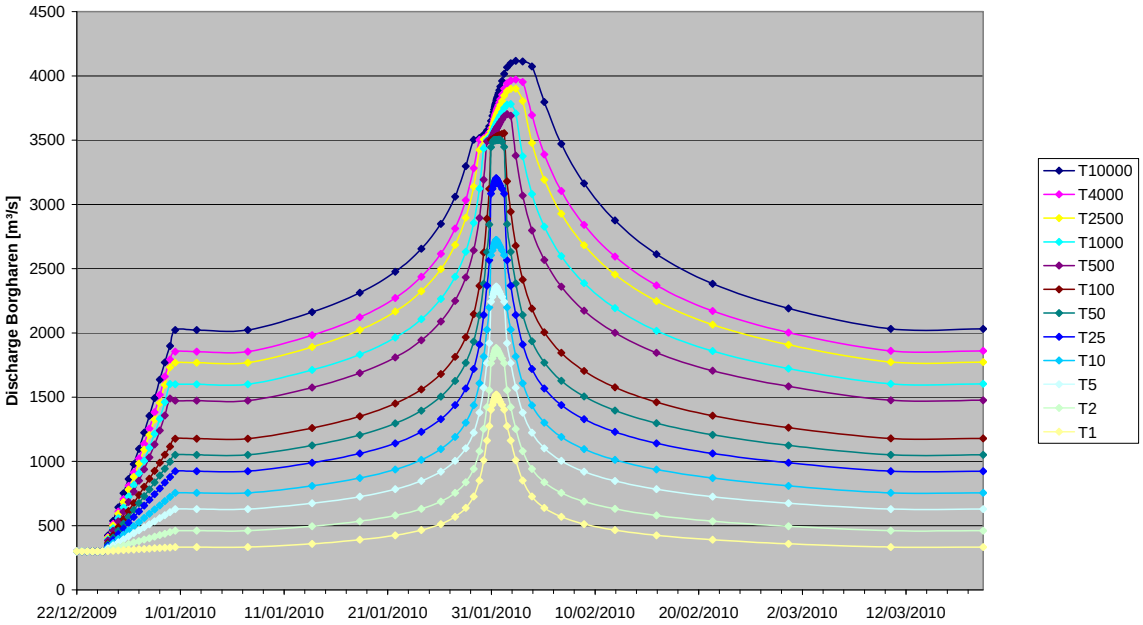


Figure 8-38: Upstream boundary original composite storms (actual climate)

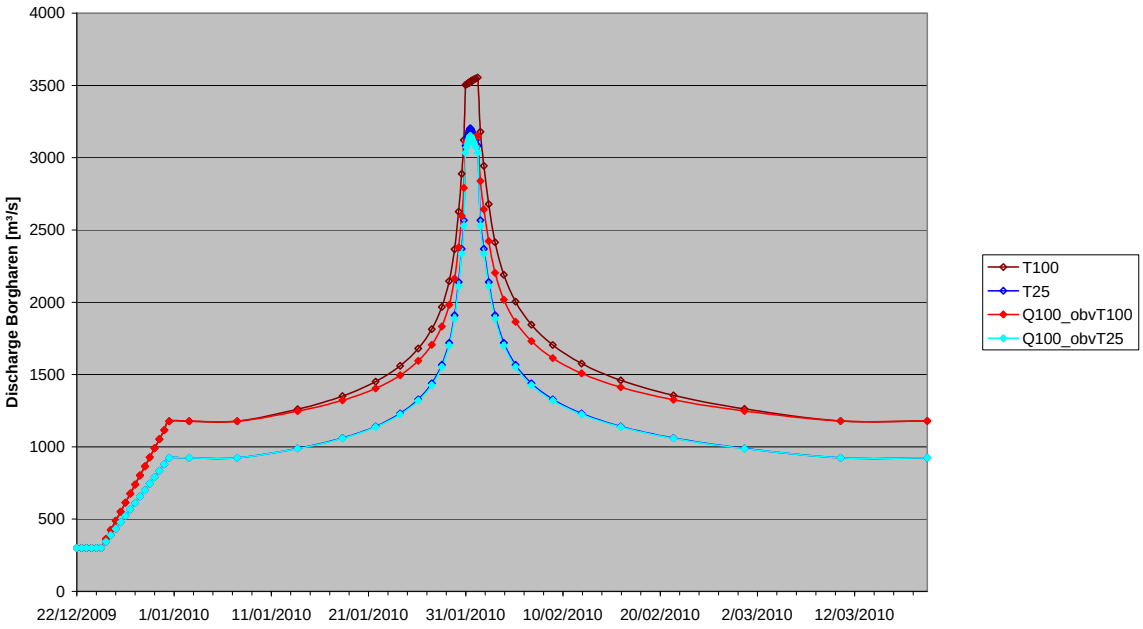


Figure 8-39: Upstream boundary rescaled discharges (actual climate)

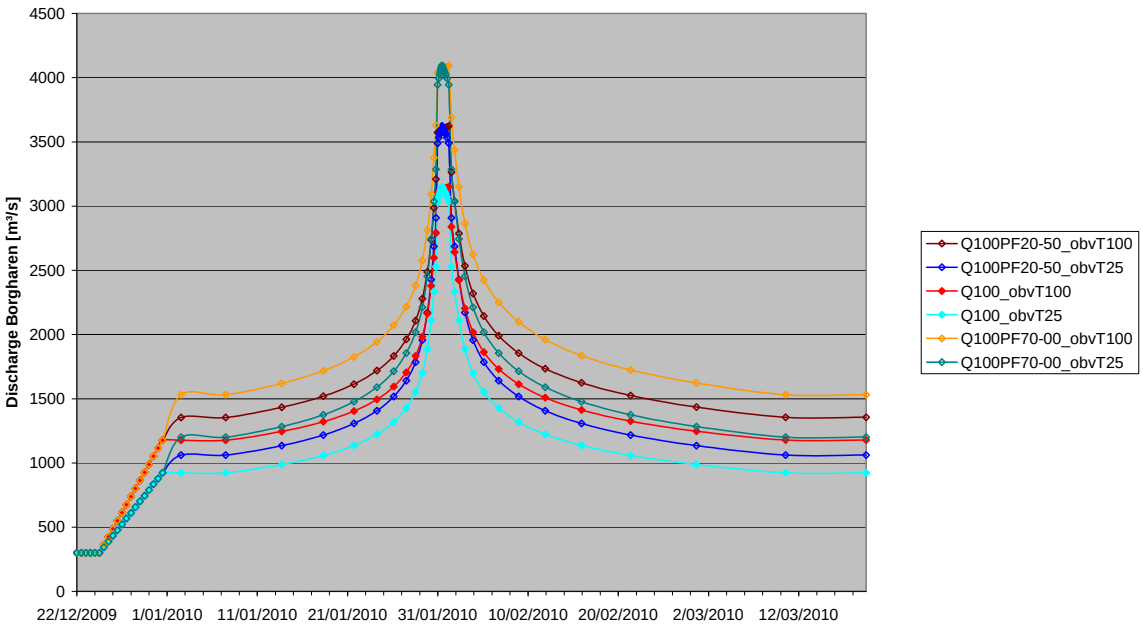


Figure 8-40: Upstream boundary perturbed discharges (future climate)