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

Analysis of climate change, high-flows and low-flows scenarios on the Meuse basin

WP1 report - Action 3

Title	Analysis of climate change, high-flows and low-flows scenarios on the Meuse basin WP1 report – Action 3
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Partners involved	UPVM, EPAMA, RWTH Aachen, Rijkswaterstaat, ULg, Gx-ABT, Deltares, Flanders Hydraulics Research
Work package	1
Action	3

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 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

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INTERREG IVB

INTRODUCTION

Objectives of the AMICE Project

Climate change experts are increasingly pointing-out the possible consequences of global warming (IPCC). It is clear that reduction of the emissions is not enough and that we also have to adapt to expected changes, as opposed to waiting until impacts are irreversible. Consequences of climate change on river basins can be potentially catastrophic. Floods are the main 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 put high on the agenda in the EU: Green Paper on climate change, 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 4 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 in sharing data and methodologies, it is intended to develop a 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.

We created the ‘AMICE’ Project: 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’s Member States and Regions. It will last 4 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), Center for geographical studies, the University of Metz
- CETMEF (Centre d’Etudes Techniques Maritimes et Fluviales), technical center 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
- Gembloux Agro-Bio Tech, the department of Hydrology and Hydraulic Eng., University of Liege.
- ULg – HACH, the department of Hydrology, Applied Hydrodynamics and Hydraulic Constructions of the University of Liège
- APS (Agence Prévention et Sécurité), the regional agency for overall prevention and security
- Community 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, and 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 used by 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 were:
-increased frequency of floods in winter, extreme events in particular,
-increase in low-flows, more likely the result from higher water demand than higher air temperatures,
-need to agree on common scenarios, jointly examine the effect of an improved coordination of water management policies.
The transnational cooperation will result in basin-wide scenarios on climate change and discharges, used as input for the adaptation strategy.

The Project is divided into 5 Work Packages (WP) (Figure 1). The present report is part of WP1.

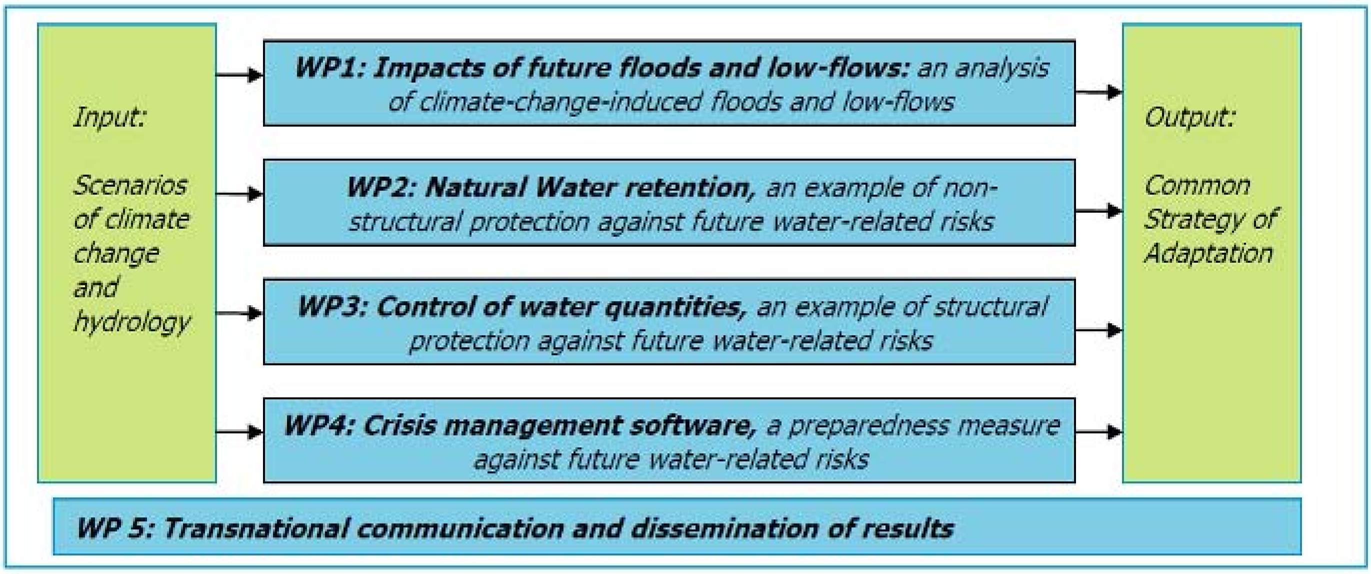


Figure 1 : AMICE project organization chart

Objectives of action 1 and action 3

AMICE's Work Package 1 is dedicated to the impacts of future floods and low-flows on the Meuse basin. Partners will perform a technical and scientific analysis of climate-change-induced floods and low-flows through prospective modeling, efficiency evaluation of water management measures, damage calculation, and proposition of solutions.

Scenarios of the future climate are already exchanged by i.e. Meteorological offices and Research institutes in FP6 and FP7 projects, but many others need to be shared, especially regarding the borderless question of climate evolutions. There is no point in developing complex techniques if the outputs cannot be shared with the neighbour specialists. The AMICE project provides the opportunity to use common scenarios, tools and methods to evaluate measures and elaborate strategies that can finally be comparable between countries.

The present report details methods and results from Actions 1 and 3 which have been carried-out in 2009 and supervised by the University of Metz.

The WP1's objectives will be carried-out in 9 Actions scheduled according to Table 1:

1 : Bibliography
2 : Mapping
3 : Hydrological modeling
4 : Meetings
5 : Reports
6 : Hydraulic modeling
7 : Impact assessment
8 : Climate check
9 : Adaptation strategy

AMICE Action	Reference Partner	2009 J F M A M J J A S O N D	2010 J F M A M J J A S O N D	2011 J F M A M J J A S O N D	2012 J F M A M J J A S O N D
Workpackage 1 : Risk assessment					
common database	Metz University				
maps	Wallon region (GTI)				
scenarios of climate change and hydrology	Metz University				
hydraulic simulation of the Meuse	Liege University				
impacts of future floods and low-flows	Aachen University				
"climate-proof" of existing and new measures	Flanders Hydraulics				
strategy of adaptation	Rijkswatertstaat				

research
reporting
meeting
communication

Table 1. AMICE Workpackage 1 organization chart

<u>Action 1 description:</u>

The objective is to share our knowledge on the present and future characteristics and hydrological behaviour of the Meuse river basin.

Knowledge on this topic is still scattered and hardly available within the 3 official languages spoken on the Meuse basin. Information has been gathered by the Partners, translated into English, French, Dutch or German when required and organized by topics into an online database.

<u>Action 3 description:</u>

This Action is dedicated to the study of downscaled climate simulations for 2020-2050 and 2070-2100 and their consequences in terms of floods and low-flows on the Meuse river basin. The following questions will be answered:
- which discharges can be expected on the river Meuse and main tributaries?
- how the return period, duration, extent of floods and low-flows will change from now to 2020-2050 and 2070-2100?

Partners have analyzed climate simulations from meteorological institutes (IPSL, Cerfacs, KMI, KNMI, ...), national and EU research programs (Prudence, Ensembles, ADAPT, etc): bibliographies, interviews of users, experts invited to meetings. They have checked if they can be applied to the Meuse basin, assess their uncertainty and the required corrections.

New production or acquisition of climate data was not carried-out because:
- The project is more oriented on climate change consequences rather than on its causes,
- The length of the project is insufficient for running new meteorological simulations,
- There are existing scientific publications and data that can be used to document the issue.

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 the basis research that will be used throughout the AMICE project. The climate and hydrological scenarios 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 present report details the hypotheses that were made and the knowledge used to define the climate scenarios for the Meuse basin.

It is thus extremely important to emphasize that the AMICE adaptation strategy will respond to two climate scenarios (a wet and a dry ones) – the most reliable we could find but not the only possible ones – with their assumptions and uncertainties. These climate scenarios represent what could, most likely, happen on the Meuse basin.

1 Presentation of the study area

1.1 The Meuse river basin

The Meuse river basin is one of the most densely populated areas of Western Europe and a major geographic link between Belgium, France, Germany, Luxembourg and the Netherlands. The river itself is navigable and provides drinking water for more than 5 million inhabitants.

The main characteristics of the Meuse Basin are (De Wit et al., 2007):

Length : 900 km Drainage area : 35.000 km² Number of inhabitants : 9 million

Its discharge fluctuates considerably with seasons: it reached 3000 m^3/s in winter 1993 in Liege and can be as low as 10-40 m^3/s in the summer season. Classed as a rain-fed river, it has no glacier and little groundwater storage capacity to buffer precipitations. Most of the water comes from the Walloon tributaries in the Ardennes.

A direct link exists between climate evolutions/change and changes in high and low-flows, putting at risk the assets of the basin, including major infrastructures, industries, priceless historical and ecological heritage.

The 5 European countries are working together in the International Meuse Commission (IMC), created in 2002 to coordinate the application of the Water Framework Directive (2000/60/CE). The Commission will now coordinate the application of the EU Flood Directive (2007/60/CE).

1.2 Sub-basins selected for the hydrological impact assessment of climate change

Figure 2 presents a map of gauging stations selected by the Amice partners for the hydrological simulations. Nine stations were chosen within the Meuse basin (Table 2):

- Four stations on the French part of Meuse
- One at the Walloon/Netherlands border.
- Four stations on Walloon and German right-side tributaries located on the Lesse, the Vesdre, the Niers and the Rur rivers.

For practical reasons (short delay, existing models calibration, etc) it was not possible to take into account others stations. For each selected station, hydrological simulations were realized in order to estimate the evolution of high-flows and low-flows discharges during the 21st century (2021-2050 and 2071-2100).

Figure 2. Drainage network of the Meuse river and gauging stations selected for the AMICE project

	Station	Drainage area (km2)	Source of discharge data	River kilometers for tributaries confluence with the Meuse (km)*	Main lithological formation	Main land-use	Highest gauging discharge value in high flows	Lowest gauging discharge value in low flows	Anthropogenic influence on natural flows
Meuse	Saint-Mihiel	2540	http://www.hydro.eaufrance.fr/	-	Mesozoic	Forest & Agriculture	596 m³/s	-	-
Meuse	Stenay	3904	http://www.hydro.eaufrance.fr/	298	Mesozoic	Forest & Agriculture	600 m³/s	-	-
Meuse	Montcy-Notre-Dame	7724	http://www.hydro.eaufrance.fr/	-	Mesozoic	Forest & Agriculture	960 m³/s	-	Agriculture
Meuse	Chooz	10120	http://www.hydro.eaufrance.fr/	477	Mesozoic	Forest & Agriculture	1610 m³/s	-	Nuclear plant
Lesse	Gendron	1284	SETHY	505	-	Forest	390.8 m³/s	0.6 m³/s	-
Vesdre	Chaudfontaine	683	SETHY	597	-	Forest	274.5 m³/s	0.2 m³/s	dams
Meuse	Sint Pieter	20.200	KNMI	631	Mesozoic	Forest	3039 m^3/s	< 20 m^3/s	Important water diversions to upstream channels, water use by agriculture, industry and households
Rur	Stah	2135	LANUV NRW	694	Unconsolidated rock (north) consolidated rock (south)	Arable land	129 m³/s (27.5.1983)	8.1 m³/s (15.07.1996)	Reservoirs Lowering of groundwater table Admissions of water
Niers	Goch	1203	LANUV NRW	771	Unconsolidated rock	Arable land	42,4 m³/s (7.12.1960)	1,2 m³/s (24.08.1976)	Lowering of groundwater table Admissions of water

*Table 2. Main characteristics of gauging stations selected for the Amice project. *De Wit et al. (2007)*

1.2.1 The French part of the Meuse basin

The French basin is located upstream of the transnational basin (Figure 3). It is oriented from the south to the north and can be divided into two parts:

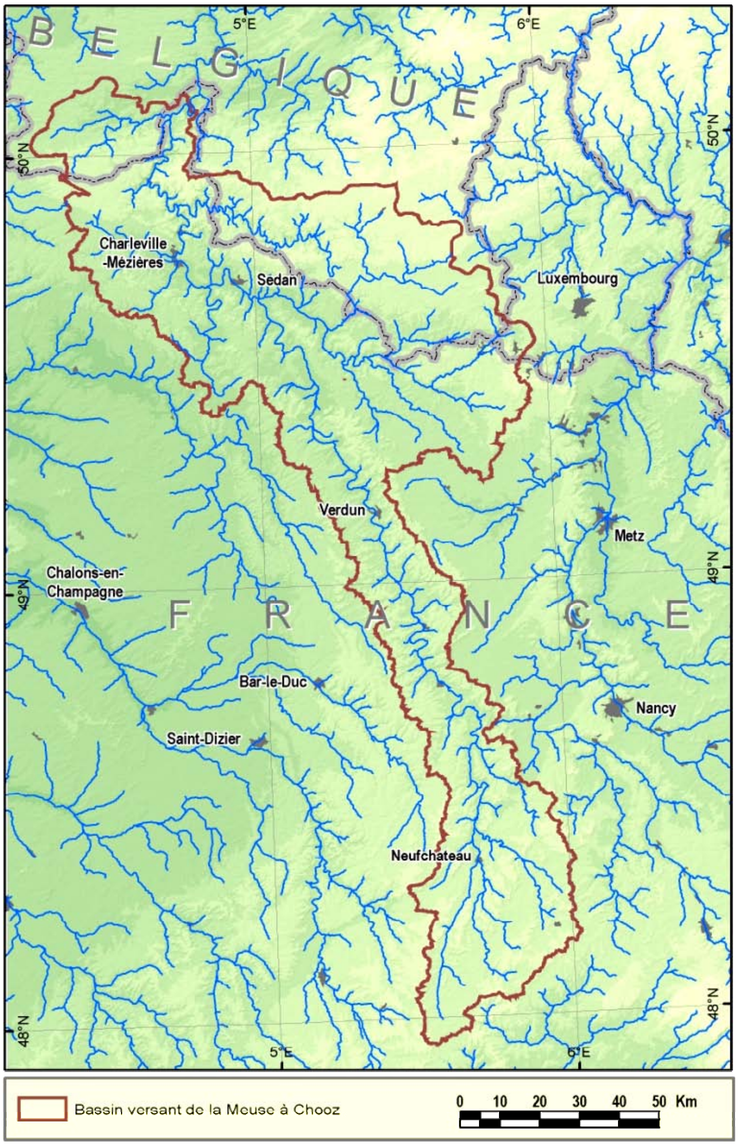


Figure 3. French sub-basin of the Meuse

- The first part extends from the source, on the plateau de Langres (384m above sea level) to Verdun. This area is very elongated because the basin is limited by the Côtes de Moselle in the east and the Côtes de Meuse in the west. Agriculture is dominant in this region.

- The second part includes the French Ardennes and presents higher altitudes (400-500 meters). The orographic effect we can observe in this area results in more precipitations than in the south (>1000mm/y). There are few medium-sized cities like Verdun (20.000 inhabitants), Sedan (20.000), and Charleville-Mézières (100.000). This area is predominantly forested.

The climate of the French sub-basin is semi-oceanic: rainfalls are fairly regular throughout the year (approximately 80mm/month). The hydrological regime is unimodal (only one low flows period each year in summer, and one high flows period in winter). The French part covers approximately one third of the whole Meuse basin in terms of surface, length, and mean annual flows.

Flows of the French part of Meuse are mainly conditioned by the amounts of precipitation and potential evapotranspiration (PET).

Mapping portal
The Géoportail (*Ministère de l'écologie, de l'énergie, du développement durable et de la mer, IGN, BRGM*) gives access to a lot of dynamical maps, regularly updated : http://www.geoportail.fr/

	Transnational basin	French sub-basin
Surface	33.000 km²	10.120 km²
Length	950 km	355 km
Average discharge	350 $m^3.s^{-1}$	148 $m^3.s^{-1}$

1.2.2 Walloons sub-basins

The Meuse reaches Belgium at the Heer's level. It runs through the Ardennes via the Fagnes in the Province of Namur where it successively receives the Lesse and the Sambre in the city of Namur. It runs through the Province of Liège where it receives the Houyoux close to Tihange and the Ourthe at Liège. The Meuse leaves the Walloon Region at Visé. After a turn in the Netherlands via Maastricht, it acts as a border between Belgium and the Netherlands in the Province of Limburg. It runs through Maasmechelen and Maaseik before leaving Belgium.

In the Walloon Region, the Meuse sub-basins are (Figure 4): Meuse-aval, Sambre, Meuse amont, Lesse, Vesdre, Ourthe, Amblève and Semois-Chiers. One third of the Meuse river basin area is located in the Walloon Region, let approximately 12000 km² *(Ashagrie et al., 2006).*

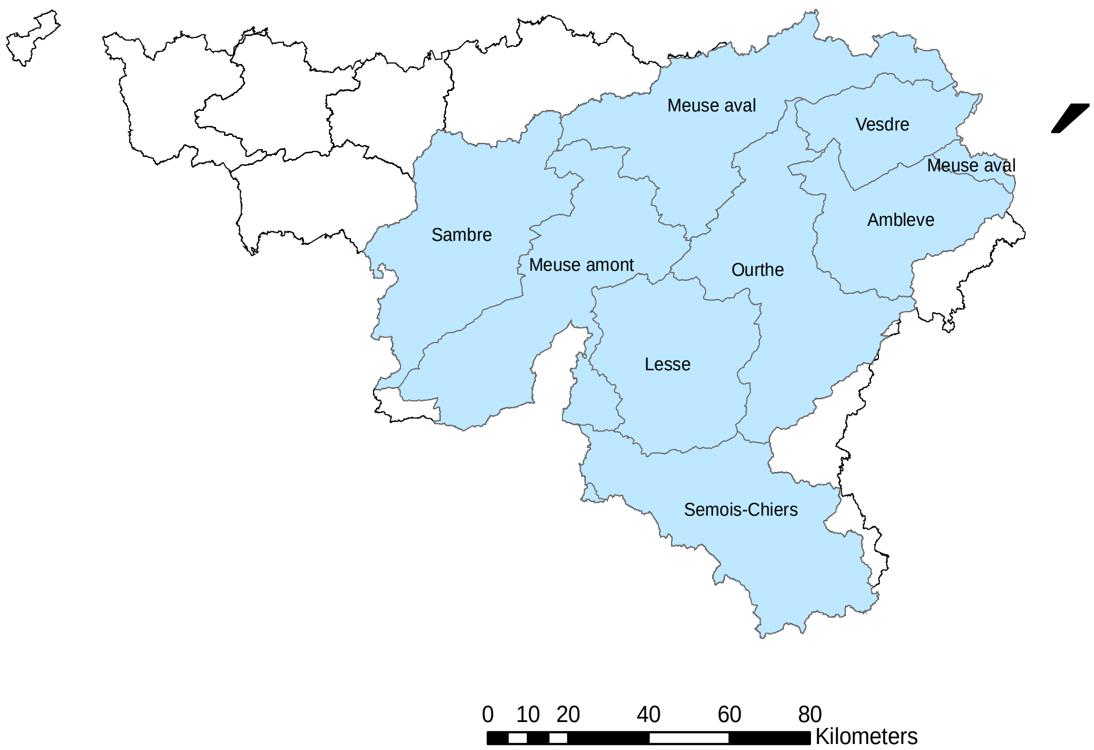


Figure 4. Walloons sub-basins of the Meuse

<u>Climate of the Meuse basin in Walloon Region</u>

Belgium has a maritime, wet temperate climate due to its latitude and its proximity to the sea. Air temperatures are moderate with a yearly mean of 10°C. Prevailing winds blow from South-West and West sectors. Cloud coverage is important and rain is common and regular, weak snowfall can be observed in the Ardennes.

Between the south and the north of the country, difference in air temperature are weak in summer but more pronounced in winter due to an hilly relief in the south.

Concerning rainfall, the Semois valley and the Hautes-Fagnes receive about 1.400 mm per year whereas the centre and north of the country receive less than 800 mm per year. Usually, all Ardennes receive more rainfall. There, it rains for about 200 days a year, against 160 to 180 days in the centre *(Ministère de la Région wallonne, Direction Générale des Ressources naturelles et de l'Environnement, Observatoire des Eaux de Surface, Direction des Eaux de Surface Direction des Eaux souterraines, 2005)*.

Soils

The main soils associations for the Walloon basin of the Meuse are stony loam soils, loamy soils, slightly stony loam soils, loamy sand soils (Figures 5 and 6).

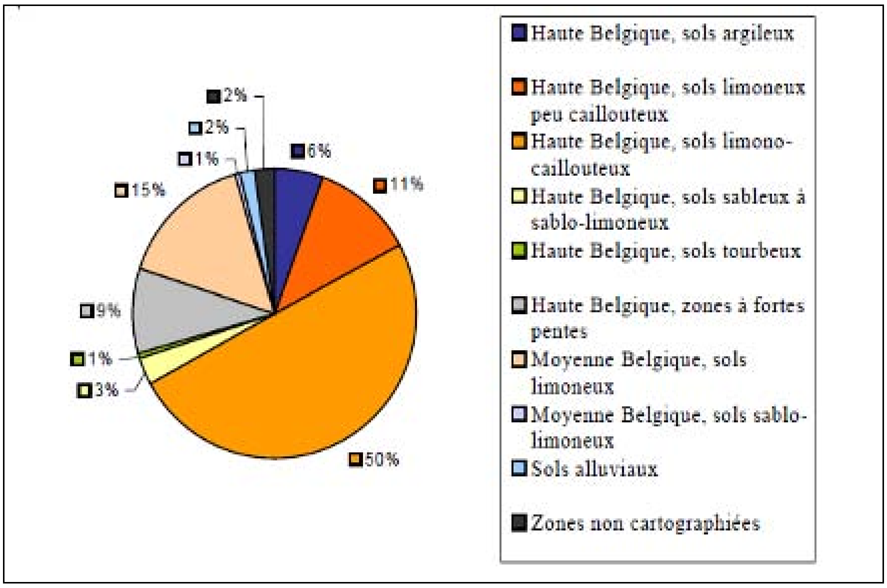


Figure 5. Distribution of the main soils associations for the Meuse river basin in Wallonia. *Source: Ministère de la Région Wallonne, Direction Générale des Ressources naturelles et de l'Environnement, 2002.*

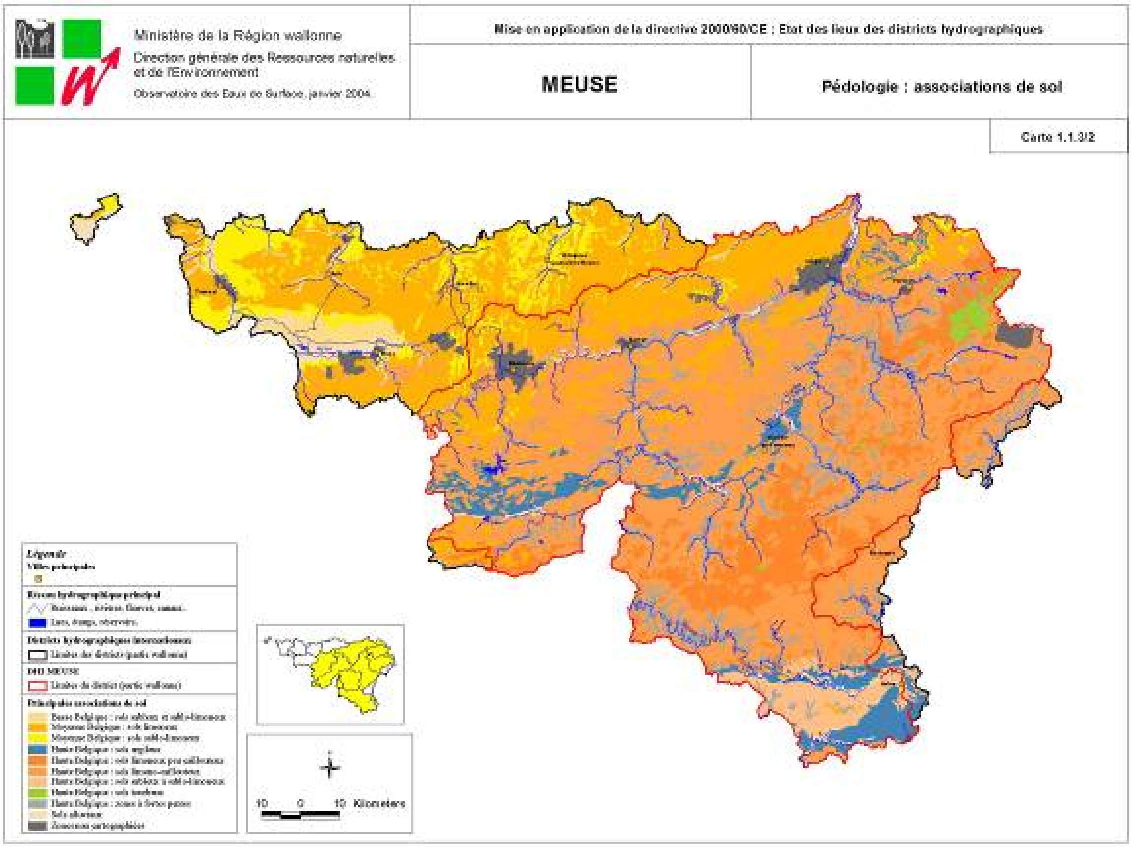


Figure 6. Pedology in Walloon Region. *Source: Ministère de la Région wallonne, Direction générale des Ressources naturelles et de l'Environnement, 2002.*

Land-uses

Land-uses of the Meuse river basin in the Walloon Region are constituted by 25% of grassland, 24% culture, 18% deciduous forest, 18% coniferous forest. Urban area covers 7% of the territory. (Figure 7)

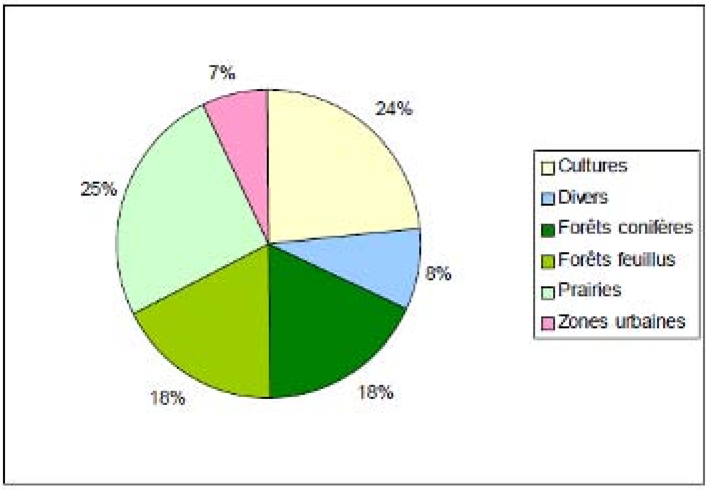


Figure 7. Land uses for the Meuse river basin in Walloon Region. *Source: Ministère de la Région Wallonne, Direction générale des Ressources naturelles et de l'Environnement, 2002.*

Mapping portal

- The Walloon Region gives access to a lot of dynamical maps, regularly updated : http://cartographie.wallonie.be
- Geological maps are viewable at the address : http://environnement.wallonie.be/cartesig/cartegeologique/

1.2.3 Flemish sub-basins

Compared to the total area of the Meuse basins, the Flemish part is relatively small and hydrologic models covering the whole international Meuse basin already exist in the Netherlands. The Dutch delegation of the International Meuse Commission brought researchers at FHR and Deltares together and a study to calculate the 3 Belgian climate change scenarios for hydrologic impact with the models from Deltares was ordered by FHR.

1.2.4 German sub-basins

The following tables 3 and 4, give an overview of the size of the basin area and the mean discharge at lower reaches of the German tributaries to the Meuse. It can be stated, that Rur and Niers have for both aspects a higher order of magnitude than all other German tributaries together.

For the mentioned reasons we share the opinion that Rur and Niers are the decisive German tributaries to the Meuse and we think that it is thus justified to take only Rur and Niers into consideration for the present study.

Table 3. Basin areas and percentage of Meuse basin for main German tributaries to the Meuse (values taken from (*MUNLV, 2005-1*))

	Basin area [km²]	**percentage of Meuse basin [%]**
Meuse	**34.548**	
Rur	**2.338**	**6,77**
Niers	**1.382**	**4,00**
Schwalm	**273**	**0,79**
other northern Meuse inflows	**158**	**0,46**
other southern Meuse inflows	**129**	**0,37**

Table 4. Mean discharges at lower reaches for Rur, Niers, Schwalm (values taken from (*MUNLV, 2005-1*))

	mean discharge at lower reaches [m³/s]
Meuse	
Rur	**22,71**
Niers	**7,79**
Schwalm	**1,66**

1.2.4.1 Rur basin area

The Rur basin area covers parts of Germany, Belgium and the Netherlands. With 89%, the majority of the area is located in Germany. The headwaters are located in Belgium, the estuary in the Netherlands with the outlet into the Meuse at Roermond (NL). In Figure 8 an overview is given.

The Rur has a run length of 163 kilometers of which 10 kilometers are located in Belgium, 132 in Germany and 21 in the Netherlands. The main tributaries are Urft for the upper reaches, Inde for the middle reaches and Wurm for the lower reaches. The size of the basin area is 2.338 km². The average total annual precipitation is 855 mm (*MUNLV, 2005-1*).

The basin area is divided into two totally different landscape-regions. The southern part of the basin area with mostly consolidated rock belongs to the Rhenish Massif. Its northern border is in line with the cities of Aachen, Eschweiler and Düren. The area northern of this line with mostly unconsolidated rock is part of the Lower Rhine lowlands. This area is intensively used for the recovery of drinking- and industrial water.

For the German parts of the basin area the main land use categories are arable land (approx. 30%), grassland (approx. 20%) and forests (approx. 30%). But they are not homogeneously distributed over the basin. Settlement areas take about 10% of the German part of the basin area. Most of them are lying right beside the major rivers and cover partly wide parts of the former floodplains. Another important land-use is the open pit mining. Although the percentage is low it has great impacts due to the necessary rearrangement of the area and the extensive lowering of groundwater. Within the Netherlands the area is mostly used for agriculture. In the Belgian part of the basin area there is, with 57%, a great percentage of forests. The agricultural area is, with 25%, lower than in the Netherlands (*MUNLV, 2005-1*).

The discharge behaviour is heavily influenced by the nine reservoirs in the Eifel and the approximately 50 flood control basins. Further influences are the river development with standard sections and water management structures and extractions and discharges.

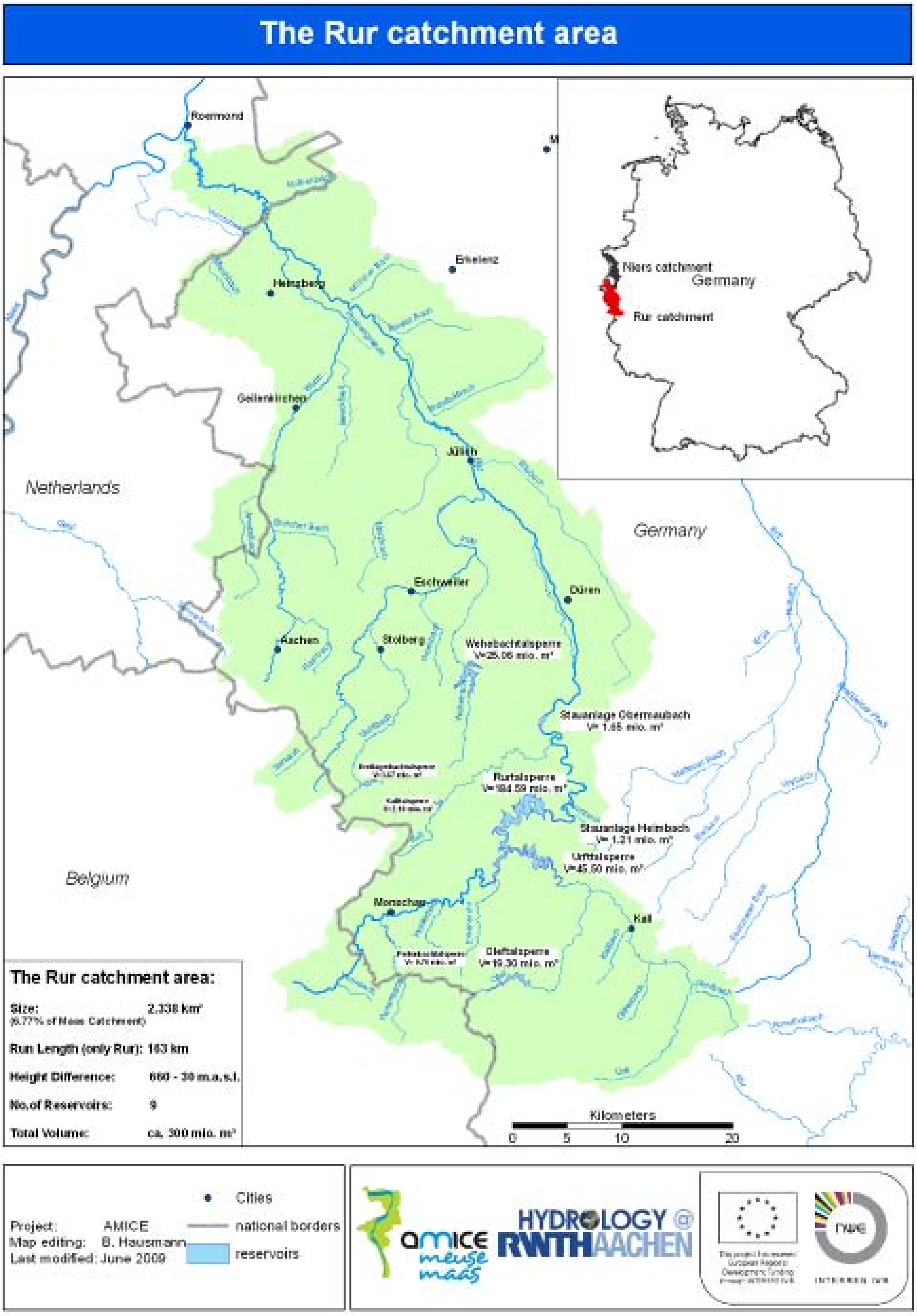


Figure 8. Overview over the Rur basin area

The nine reservoirs have a total storage volume of about 300 million m³. They serve among other purposes for drinking water supply, flood control, low-flows enrichment, power generation or recovery. For the optimization of the water resources management the reservoirs in the upper Rur reaches including Urft and Olef are operated in a linked system.

Within the middle and lower reaches of the Rur there are many admissions of municipal or industrial clarification plants. The settled areas cause increased surface runoff and the rivers are stressed by combined wastewater or rainwater admissions.

The Rhenish brown coal mining area covers parts of the Rur basin area. To mine the brown coal in open pits it is necessary to lower the groundwater table by draining the mines. The effects of this lowering go beyond the Rur basin area. About 50% of this draining water is used for water supply, the other part is within the Rur basin area mainly discharged into the Inde. By these interventions the water balance of the area with unconsolidated rock has been heavily influenced since the 1950s. This influence will remain in the next decades. The end of the open pit mining in the Rur basin area is aimed for about 2030 (*MUNLV, 2005-1*). For the mining area “Inden” it is planned to create a lake by filling the remaining pit with water. For this several strategies concerning the details of the filling are discussed.

1.2.4.2 Niers basin area

The Niers basin area covers parts of Germany and the Netherlands. The estuary is in the Netherlands with the outlet into the Meuse at Gennep (NL). In Figure 9 an overview is given.

The Niers has a run length of 118 kilometers of which 8 kilometers are located in the Netherlands. The total size of the basin area is 1.382 km². The average total annual precipitation is 708 mm (*MUNLV, 2005-2*).

The Niers can be divided into three parts. The upper Niers with its main tributary Gladbach reaches until gauge Trabrennbahn. This area is mainly influenced by the brown coal mining and the associated lowering of the water table. As adjustments there are several admissions of draining water into the rivers or into wetlands. The discharge behaviour is impressed by the surface runoff from the city of Mönchengladbach.

The middle Niers with the main tributaries Nette, Cloer and Gelderner Fleuth reaches until gauge Geldern. This part is influenced by the sewage treatment plant Mönchengladbach-Neuwerk.

The lower Niers is impressed by the agricultural area of the environment. Main tributaries are Issumer Fleuth and Kervenheimer Mühlenfleuth.

The basin area of the Niers is impressed by unconsolidated rock and is part of the Lower Rhine lowlands. Particularly in the north-west of Mönchengladbach (near Krefeld) are many facilities for the recovery of drinking water. Besides the water bodies are partly area-wide used for industrial purposes.

In the German part of the Niers basin area the land use is dominated by agricultural and silvicultural purposes. About 50% of the area is used as arable land. Grassland and silvicultural areas make 15% each of the basin area. In the Dutch part of the basin area the distribution of land use is comparable to the one in Germany (*MUNLV, 2005-2*).

The discharging of the admissions of municipal or industrial sewage treatment plants is an important task for the rivers in the basin area of the Niers. There are many admissions from combined wastewater or rainwater.

Due to the very flat topography in the basin area flood control measures are necessary. The retention is done, besides the natural one within the floodplains, via regulated flood retention basins. Dikes along the rivers ensure the flood protection for small and middle size flood events (*MUNLV, 2005-2*).

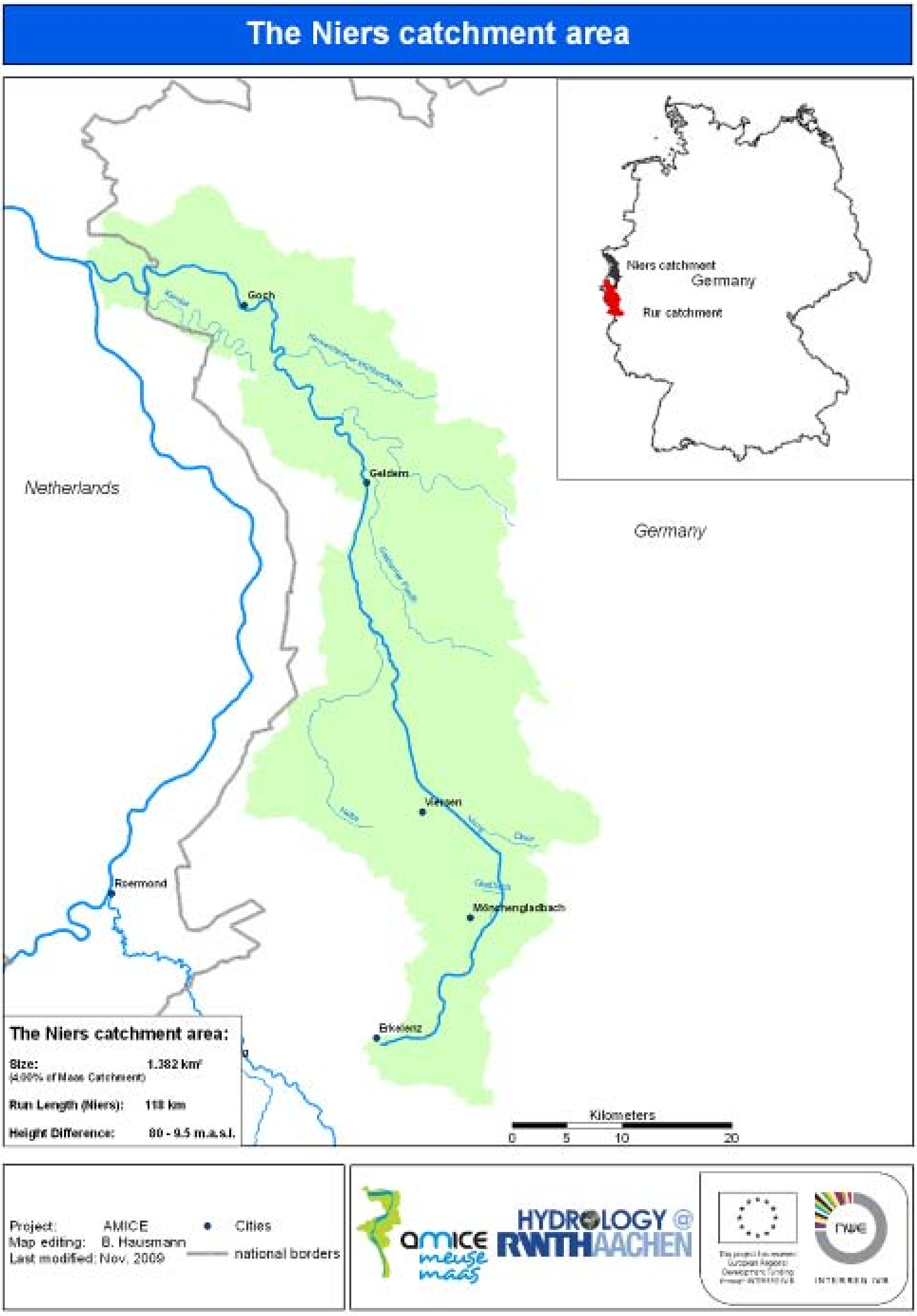


Figure 9. Overview over the Niers basin area

1.2.5 Dutch part of the Meuse basin

The Dutch part of the Meuse basin counts with 3,5 million inhabitants and has a surface area of 7.700 km2. The Dutch Meuse is the last stretch of the Meuse River where after around 250 horizontal kilometres and 45 vertical meters from the Dutch-Belgium border it drains into the North Sea. Several large cities are situated next to or close to the Meuse river, such as Roermond, Venlo, Nijmegen and ‘s-Hertogenbosch.

Most of the land surface in the Dutch Meuse basin is used for agriculture: about 550.000 ha or 70% (*Internationale Maascommissie, 2005*). About 15% of the surface has a nature function. Recreation, urban areas and industry also occupy about 15% of the land surface of the Meuse basin. However, urbanization, transport, industry and agriculture increasingly take more space in the basin. The southern part of the basin is relatively open (lower rates of urbanization etc.).The percentage of open water is limited (*Arcadis, 2007*).

The Meuse basin represents about 22% of the national production value and is of great importance for the Dutch industry. Sand and gravel is excavated from some parts of the basin. Intensive animal husbandry and mixed farms (both agriculture as well as cattlebreeding) are strongly represented. Especially in the province of Noord Brabant intensive animal husbandry has increased. Near the mouth of the Meuse, salinification has a negative impact on agriculture (*Arcadis*, 2007).

The Meuse enters the Netherlands at Eijsden, south of Maastricht (Figure 10).Historically, the discharge is measured at Borgharen, a small town just north of Maastricht. Currently, discharge is measured at St. Pieter as morphology downstream is being changed by the Maaswerken project. From Eijsden to Borgharen, the Meuse is called “Upper” Meuse (Bovenmaas). At Borgharen, the Meuse water is divided over the “Border” Meuse (Grensmaas), which forms the natural border with Belgium for about 40 km, and the Julianakanaal next to it. Note that the Julianakanaal is not shown in Figure 10. The Julianakanaal has been constructed for navigation, and most of the navigation towards Belgium occurs through this canal. Near Roermond, the Julianakanaal and the Meuse join again, to be divided over the Zuid Willemsvaart (which cuts off part of the original Meuse, see Figure 11) and the Meuse, which are both navigable.

At Mook (near Nijmegen), the Meuse bends towards the west, and a canal through Nijmegen connects the rivers Waal and Meuse. The river continues to flow as one stream to Heusden, near ‘s Hertogenbosch. In older days, the Meuse split into two streams here. Today, the connection with the Merwede is closed and the Meuse as a whole flows via the Bergsche Maas and the Amer through the natural park Biesbosch towards the Northsea.

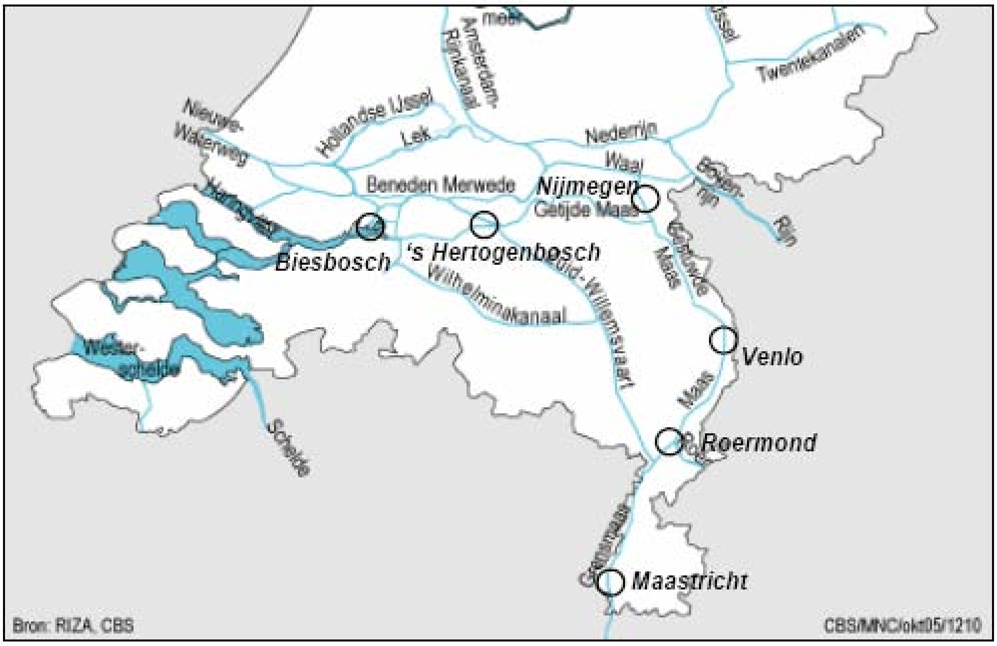


Figure 10. The Meuse in the Netherlands

Several (small) tributary streams join the Meuse in the Netherlands. The main ones are the Jeker, Voer, Geul, Roer, Niers, Dieze, Dommel and Aa. Important canals that are fed by the Meuse are Zuid-Willemsvaart, Wilhelminakanaal and Julianakanaal.
Table 5. The most important subcatchments of the Meuse in the Netherlands and their surface areas. Note that some subcatchments areas are partly situated in Belgium (B) or Germany (G) and therefore the sum of the catchments is larger than the Meuse basin area in the Netherlands. *Source table: Ministerie V&W, 2005*

Stream	**Area (km^2)**
Geul	388 (B)
Jeker	138 (B)
Voer, Margratenplateau, other streams	121
Geleenbeek	400
Vlootbeek	123
Roer	2436 (D)
Neerbeek	386
Peel	504
Niers	1320 (D)
Dommel, Aa, Dieze and Drongelens kanaal	2283 (B)

Weirs have been constructed along most of the Meuse to facilitate shipping; the only non-navigable part of this river is the southernmost part, the Grensmaas. Here, the Meuse meanders over shallow gravel banks; there are no weirs and the river flows swiftly at times of high discharge. Shipping goes along the Julianakanaal, which runs parallel to the Grensmaas. At Roermond, large lakes have been formed following gravel dredging. During the course of the years, the Meuse has cut increasingly deeper into the surrounding country between Cuijk and the Belgian border, resulting in a step-like terraced landscape in which the top terraces are the oldest river beds. This is a unique landscape by Dutch standards due to the vast differences in height. Old villages are situated at the transition point between low terraces and central terraces. No dykes are required here, since the banks are naturally high. Following the river downstream from Cuijk, the Meuse valley becomes a plain where both Meuse and Rhine have left sediment deposits. At this point, the river flows through high natural levees and low-laying sedimentary basins; this part of the river has been embanked. The major bed has levelled up rapidly since the dykes were constructed, so that the floodplains are currently situated at a much higher level than the surrounding area. The water pursues its course to the sea through the Bergsche Maas and the Nieuwe Waterweg; it also flows through the Haringvliet at times of high discharge *(Liefveld, W.M & Postma, R., 2007: Two rivers: Rhine and Meuse).*

The Rhine-Meuse estuary
Rhine and Meuse meet at the Rhine-Meuse estuary. Here, water levels are mainly determined by sea tides and to a considerably lesser extent by river discharge. Tidal influence runs through the entire course of the Nieuwe Waterweg. This influence is already noticeable in the river's downstream sections at Hagestein (Lek), Zaltbommel (Waal) and Lith (Meuse). At high tide, salt water enters the Nieuwe Waterweg, and travels as far as Dordrecht when the river discharge is low. If high sea tides coincide with low water discharges, this salt water can even reach the Haringvliet and the Hollandsch Diep (*Liefveld, W.M & Postma, R., 2007: Two rivers: Rhine and Meuse*).

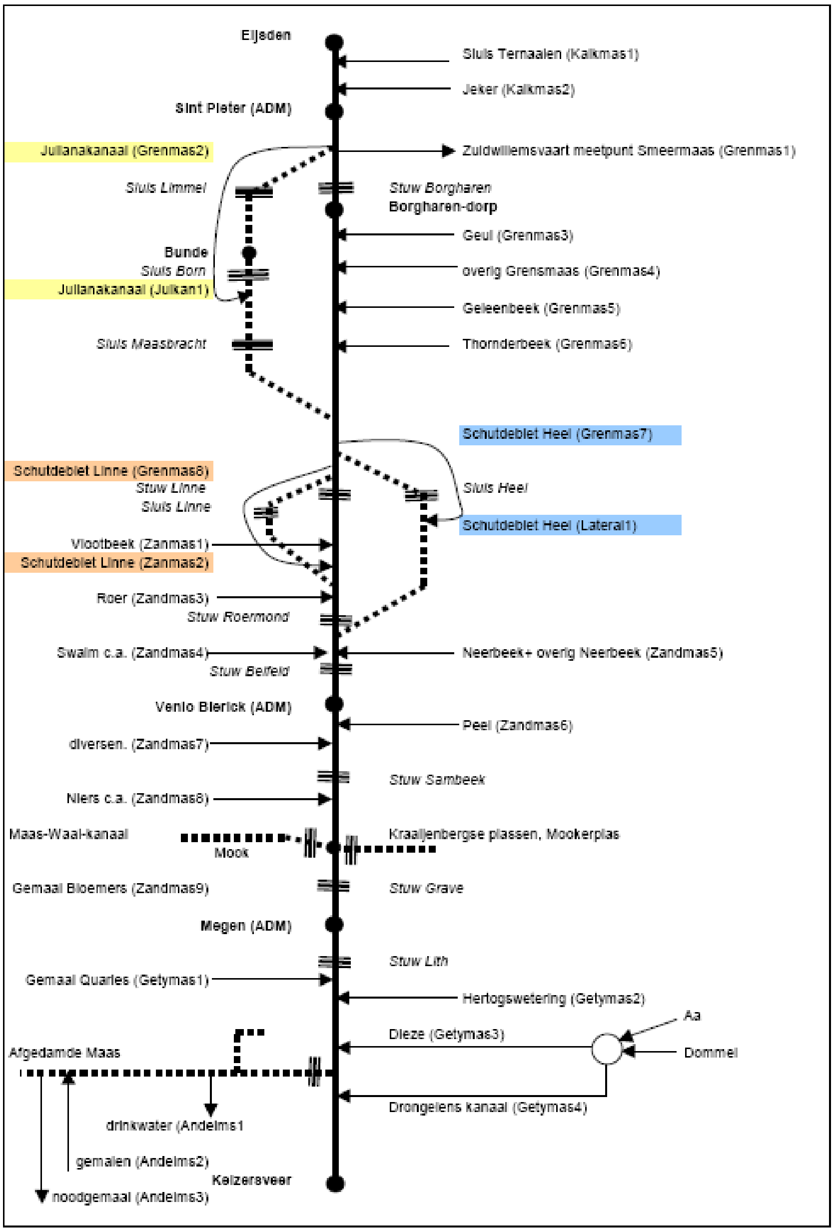


Figure 11. Schematic overview of the Dutch Meuse and its tributaries (*Ministerie V&W, 2005*)

At the Rhine-Meuse estuary, the Haringvliet sluices constitute the regulating cock for the distribution of discharge among the various tributaries. During times of average discharge, most of the river water flows to the sea through the Nieuwe Waterweg. A small part flows into the sea via the Haringvliet, where the river water reaches the North Sea at low tide through the 17 discharge sluices in the Haringvliet dam. When discharge is high, the sluices open still wider, and more river water ultimately flows out through the Haringvliet than through the Nieuwe Waterweg. With a Rhine discharge of approximately 9000 m^3/s, the sluices are completely open at low tide, while at high tide, they are always closed to prevent salt water from flowing into the Haringvliet. This transition area from river to sea consists of a tangle of watercourses. At low tide, the small banks, with their characteristic reed lands, are dry. The Biesbosch used to be a unique freshwater tidal area, but these tides have largely disappeared since the damming of Haringvliet and Hollandsch Diep. Despite this, it is still an attractive area with its mud flats, salt marshes, creeks, osier thickets, embankments, agricultural polders and riparian woodlands. The waters of the Rhine-Meuse estuary flow through low-lying country that is sometimes way below sea level (*Liefveld, W.M & Postma, R., 2007: Two rivers: Rhine and Meuse*).

2 Analysis and synthesis of the literature on future climate and hydrological scenarios on the Meuse river basin

2.1 Presentation of the AMICE TORD

The first action of the AMICE project has consisted in the implementation of a tool for sharing bibliographic references in order to pool knowledge. This tool is called AMICE TORD (Transnational Online Reference Database) and each partner (in particular those involved in the Work Package 1) can view and add references dealing with the Meuse, climate change and other topics of interest to AMICE.

2.1.1 Structure of the TORD and statistics

2.1.1.1 Structure of the TORD

The application that was chosen is *Wikindx*®. One of its advantages is the possibility to create as many user accounts as needed. Visitors can see the references, however a user account is necessary to modify the database and to add or delete publications (Figure 12).

In addition to entering basic bibliographic information (title, authors, years...), it is also possible to attach files (picture, pdf, doc...) and URL. Queries can be based on keywords, author and publisher by using two search forms available (quick & power search).

A system of categories based on issues of the AMICE project has also been developed to refine search (Figure 13).

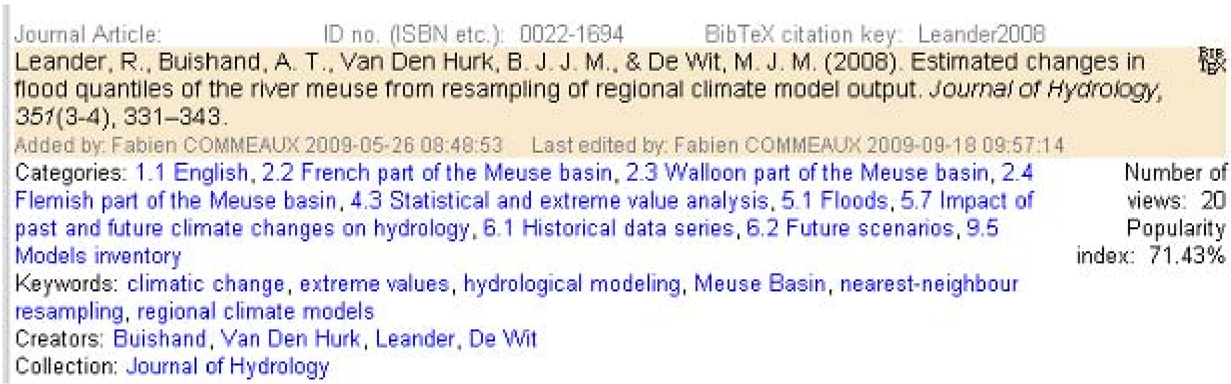

Journal Article: ID no. (ISBN etc.): 0022-1694 BibTeX citation key: Leander2008
Leander, R., Buishand, A. T., Van Den Hurk, B. J. J. M., & De Wit, M. J. M. (2008). Estimated changes in flood quantiles of the river meuse from resampling of regional climate model output. *Journal of Hydrology*, *351*(3-4), 331–343.
Added by: Fabien COMMEAUX 2009-05-26 08:48:53 Last edited by: Fabien COMMEAUX 2009-09-18 09:57:14
Categories: 1.1 English, 2.2 French part of the Meuse basin, 2.3 Walloon part of the Meuse basin, 2.4 Flemish part of the Meuse basin, 4.3 Statistical and extreme value analysis, 5.1 Floods, 5.7 Impact of past and future climate changes on hydrology, 6.1 Historical data series, 6.2 Future scenarios, 9.5 Models inventory
Number of views: 20 Popularity index: 71.43%
Keywords: climatic change, extreme values, hydrological modeling, Meuse Basin, nearest-neighbour resampling, regional climate models
Creators: Buishand, Van Den Hurk, Leander, De Wit
Collection: Journal of Hydrology

Figure 12. Interface of the AMICE TORD (screenshot of a reference)

Nine categories were created, comprising 45 sub-categories. The two firsts categories pertain to language (one of the three official languages or English) and geographic area (national sub-basin of the Meuse, Meuse transnational basin, outside of the basin…). The seven other categories are optional and give information on topics (physiography, climatology, hydrology, trend analysis, drinking water, water hazard mitigation, water management system). When entering a new reference, the user can select as many categories as topics.

Thanks to this system it is possible to refine the researches of bibliographic references and to have an overview of the most (and least) represented subjects in the AMICE TORD.

Main categories and sub-categories

1. Language
1.1 English
1.2 French
1.3 Dutch
1.4 German

2. Basin
2.1 Meuse river
2.2 French basin
2.3 Walloon part
2.4 Flemish part
2.5 Dutch part
2.6 German part
2.7 Luxemburgish part
2.8 Adjacent basin
2.9 Outside of the basin

Optional categories and sub-categories

3. Physiography
3.1 Geology
3.2 Pedology
3.3 Topography
3.4 Hydrogeology
3.5 Geomorphology
3.6 Land Uses
3.7 Biodiversity
3.8 Water quality

4. Climatology
4.1 General features
4.2 Climate mechanisms
4.3 Statistical and extreme value analysis
4.4 Climatological mapping
4.5 Downscaling techniques

5. Hydrology
5.1 Floods
5.2 Low flows
5.3 Hydrological regime and hydrography
5.4 Hydraulic characteristics of the river bed
5.5 Hydrometry
5.6 Origin of water, natural and artificial water pathways
5.7 Impact of past and future climate changes on hydrology

6. Trend analysis
6.1 Historical data series
6.2 Future scenarios

7.1 Drinking water
7.2 Fluvial navigation
7.3 Agriculture
7.4. Hydropower, nuclear plant
7.5. Industries

8. Water hazard mitigation
8.1 Flood control
8.2 Low water supply
8.3 Impacted economic activities

9. Water management system
9.1 Flood forecasting
9.2 Low flows forecasting
9.3 Design flood
9.4 Water management services
9.5 Models inventory

Figure 13. List of categories and sub-categories created for the AMICE TORD

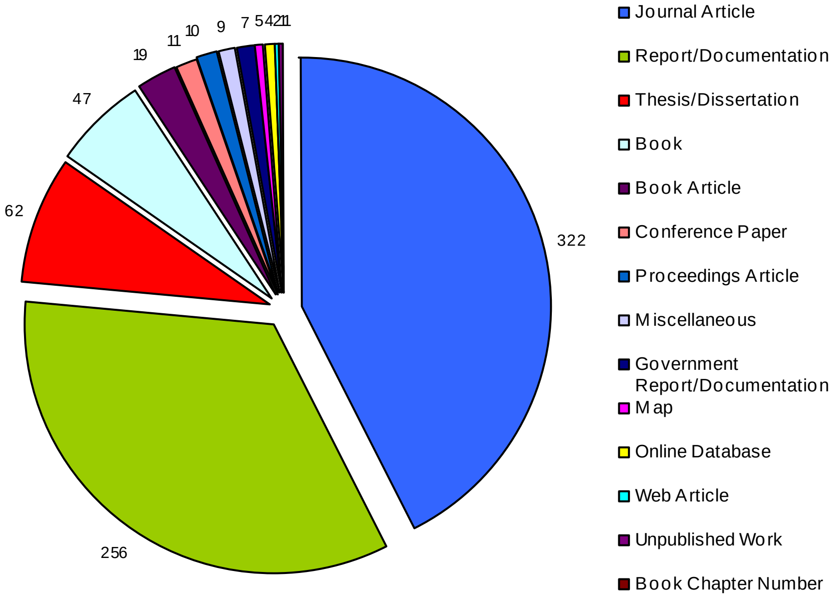
Another feature of *Wikindx*® is to allow each user to comment on the references by adding new fields as quotes, paraphrases, musings, and comments. Annotated references then enjoy a better visibility. Finally, this software is compatible with the *Bibtex* (.bib) file format, making it possible to import and export several references at once with Zotero for example (extension for Mozilla Firefox).

Since December 2009, hosting and administration of TORD are insured by the EPAMA and accessible on the official website of the AMICE project (www.amice-project.eu/biblio).

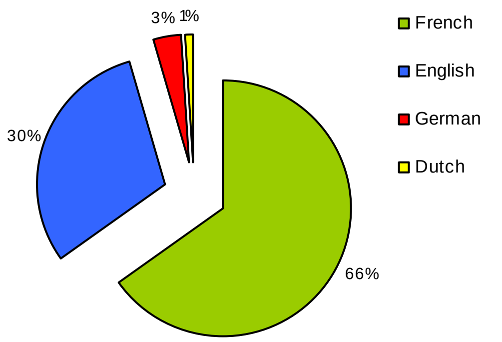
2.1.1.2 Statistics

Early 2010, 8 months after its start, the AMICE TORD had about 800 references and more than 1.000 authors (Figure 14).

Figure 14. Overview of the TORD references

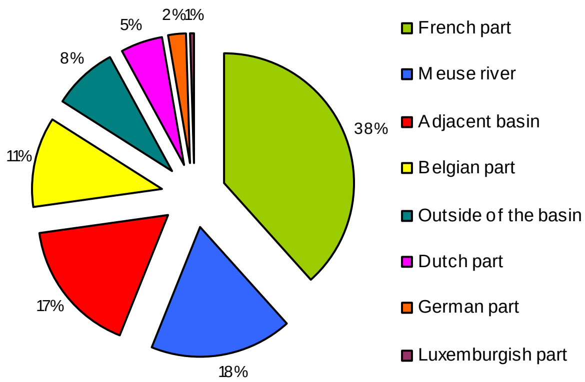


- Most references (≈80%) are journal articles or reports/documentations. 9% are books or book articles. Finally, PhD thesis and dissertations represent 8% of the total content of the database.



- About two thirds of the publications are written in French. The rest is predominantly written in English. Only 40 references are in German or in Dutch.

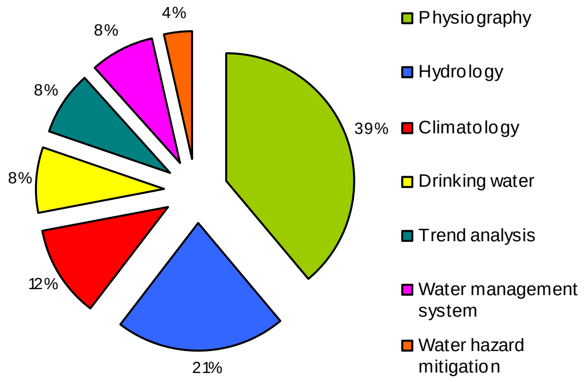
The origin and language of publications depend largely on the contributions of Partners. The low proportion of German and Dutch publications only reflects the lack of time to carry this task.



- About 60% of the references study one or several national sub-basin, often the French (66%) or Belgian (20%) parts of the Meuse. The Dutch part is less documented (only 5%). 18% of the TORD deals with the whole Meuse basin and 17% concern an adjacent basin interesting for the AMICE project because of its proximity (often the Rhine). 8% are considering a further away area (e.g. climate change on another basin in the world) or general topics that can sometimes be transposed to the Meuse (e.g. method of downscaling)

The filling and using of the database is an ongoing process. The share between the different topics and languages may evolve with the development of the AMICE actions until 2012.

- More than one third of the topics cern physiography. Among these publications, 20% deals with geology and 12% with climatology (often climate change).



2.1.2 Identification of gaps and missing knowledge / promotion of new studies

The most important study on climate change impacts on the Meuse basin was carried out by De Wit et al., 2007. The conclusions are on the possible increase of extreme events, both high and low flows. But the exact impacts need to be detailed.

In France, no study exists specifically on the Meuse basin. Research institutes have started analyzing the possible effects of climate change, but they are working at the national scale. The diversity of climates in France, with a huge contrast between the Mediterranean region and the North-East area, calls for more detailed studies. However, the methods developed can be used again in AMICE. The Ministry of Environment has selected the Meuse basin has one of the pilot basins for climate impact studies. The AMICE project will provide methods for the other river basins in France.

To our knowledge no studies concerning the impacts of climate change on the water balance and stream flows have been undertaken specifically for the Rur and Niers basin areas. Such studies have only been carried out for the adjacent sub basins of the Meuse (e.g. (*de Wit et al., 2007), (van Pelt et al., 2009)*) or the Rhine (e.g. (*Pfister et al., 2004), (Middelkoop et al., 2001*)). Thus in the framework of AMICE impact studies specifically for the Rur and Niers basin areas will be undertaken for the first time. For the impacts of climate change on the water balance of the Rhine basin area (*Gerlinger, 2009*) states that there are large regional differences in the simulation results. Therefore our studies will provide new findings.

2.2 Future climate scenarios

2.2.1 Fundamentals on climate scenarios

The greenhouse gases emission scenarios commonly used in studies of climate change have been developed by the IPCC (Intergovernmental Panel on Climate Change) since 1996 and they have been described in the SRES (Special Report on Emission Scenarios). Four groups of scenarios exist depending on factors determining the emissions of greenhouse gases, their quantity and the evolution of their concentration in atmosphere. A total of forty scenarios consider different possibilities of demographic, economic, and technological evolutions and their impacts on emissions.

For each group of scenarios, one scenario of reference has been selected by the IPCC (A1B, A2, B1 and B2) (Figure 15). Thereafter, two other scenarios related to new forms of technological progress have been added (A1FI and A1T). These 6 scenarios are the most used for GCM simulations and for impact studies of climate change (Figure 16).

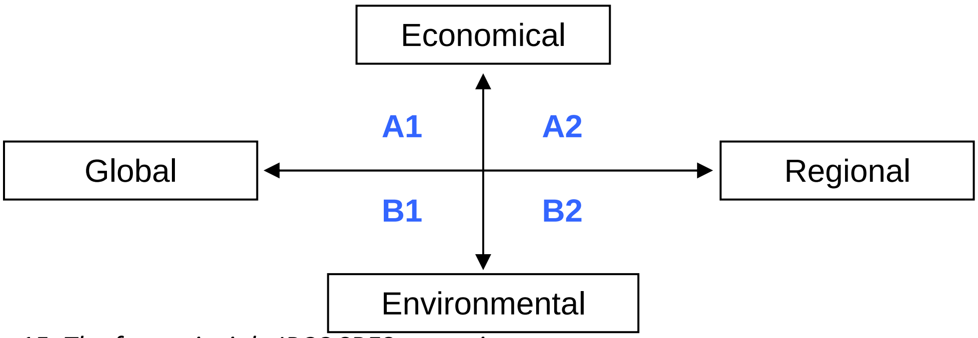


Figure 15. The four principle IPCC SRES scenarios

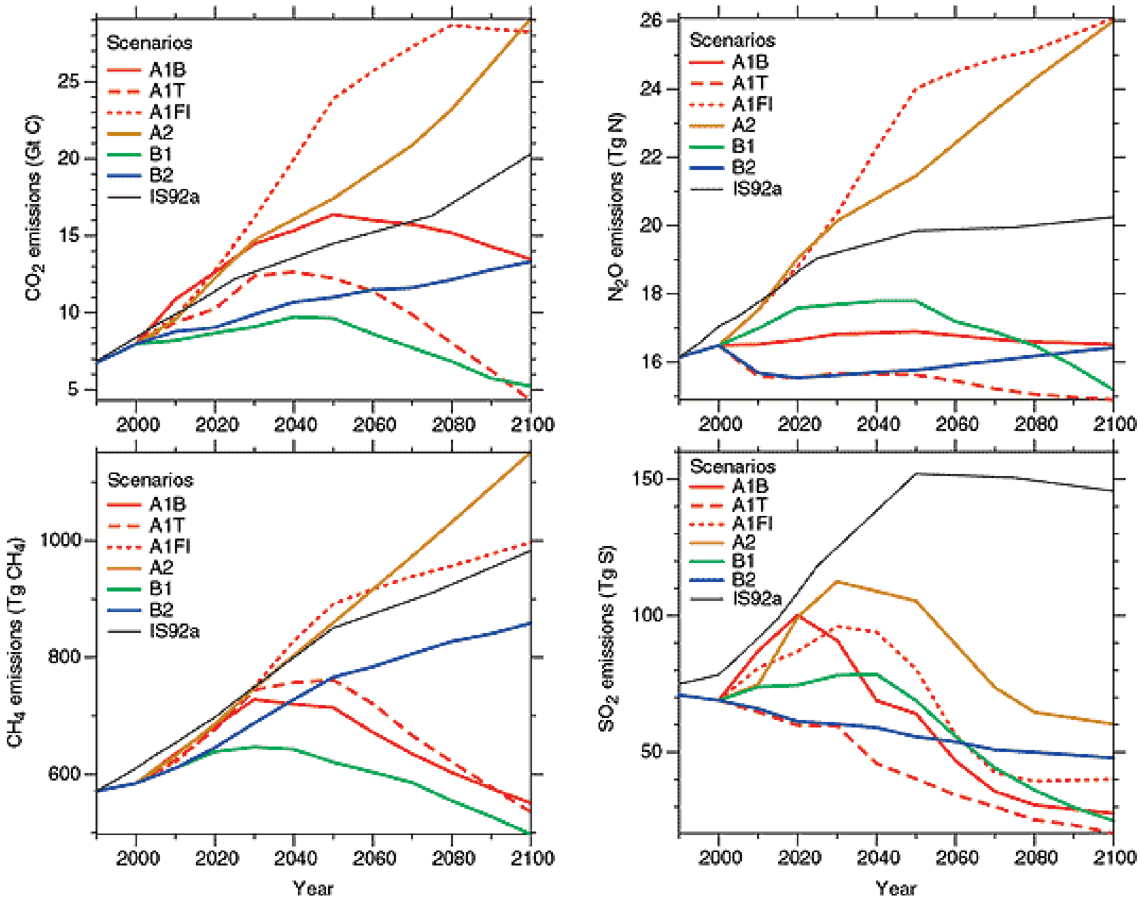


Figure 16. Evolution of some GHG during the 21st century (IPCC, 2001).

For example, emission scenarios A2 and B1 are described in the SRES report as follow:

A2 : "The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines."

B1 : "The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives."

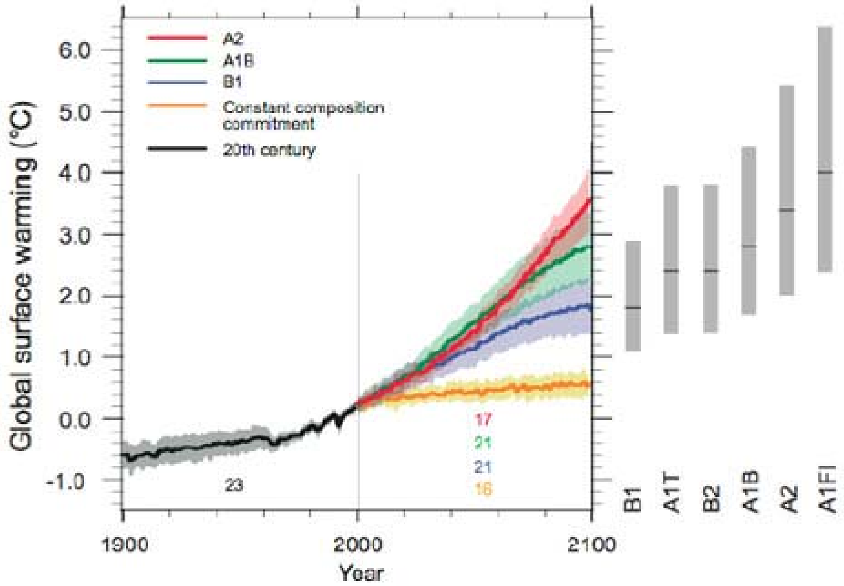


Figure 17. Evolution of the global surface warming during the 21st century (IPCC, 2001).

B1 and A2 scenarios are respectively the most optimistic scenario and the most pessimistic scenario in terms of global warming (Figure 17). Consequently impact studies produced by AMICE come to a fairly complete range of variation in air temperature and precipitation.

For climate simulations, the most used models are the GCM (Global Climate Model). They model the atmospheric circulation throughout the earth, climatic influences of the ocean and ocean/atmosphere interactions. Because of their low resolution (only few hundreds kilometers and daily step) it is not possible to use them for impact studies at the scale of a basin or sub-basin. Hydrological impact studies require data at a finer scale and at hourly step (especially for high flows), depending however on the size of the basin.

A data processing for the change of spatial (and eventually temporal) scale is also necessary (Figure 18). There are several approaches:

- Statistical downscaling:

These approaches are based on the assumption that there is a direct or indirect link between the local meteorological variables and atmospheric circulation variables. The model assigns a climatological observed structure to each atmospheric simulated daily state. This method requires a long and homogeneous climatological dataset.

- Dynamical downscaling :

There are three types of approaches:

- The increase in the resolution of the atmospheric model outputs (important computation time).

- Using a high resolution climatic model (RCM) only on the study area and forcing the limits with low resolution climatic model (GCM).

- Using a climatic model with variable resolution: high resolution on the study area and gradual decrease as the distance (e.g. ARPEGE Climate)

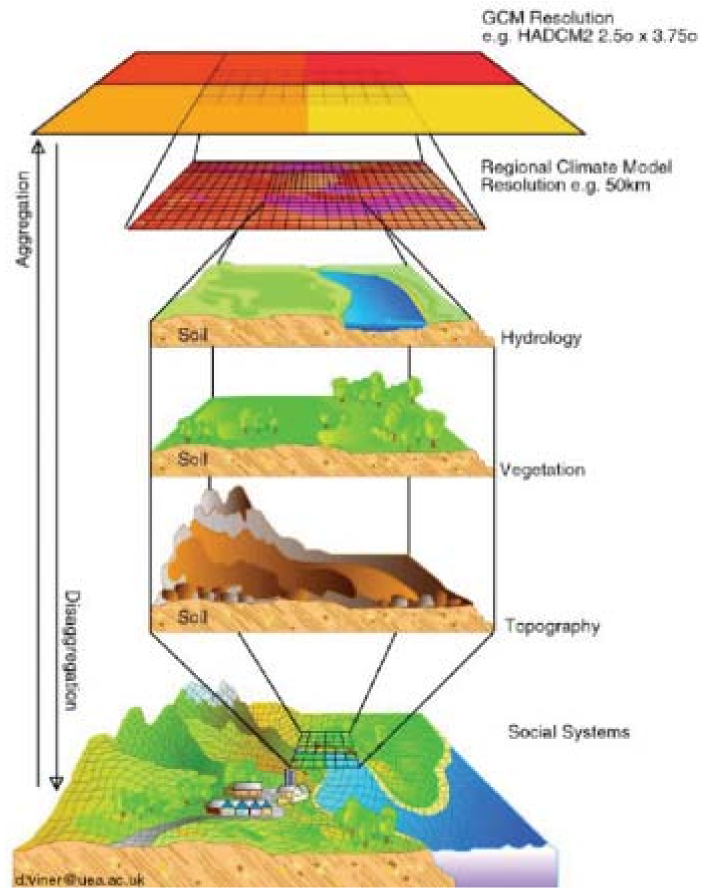


Figure 18. From global to local scale (D. Viner on http://www.cru.uea.ac.uk/link)

2.2.2 Overview of existing climate scenario databases

The WP1 began with a questionnaire sent to all partners involved in action 3. Thus a list of all databases known and used by partners has been established to make an inventory (Table 6). The objective was to see if one of them could be used as such.

Existing climate scenarios databases													VS AMICE PROJECT
SRES scenarios	**Climate experiment or model**	**Data provider and contact person**	**Downscaling method**	**Time step of simulation**	**Climate variables**	**Source of data**	**Data access and availability**	**Spatial resolution of the grid**	**control run**	**Time period for the scenarios**	**Data format**	**Geographical area**	**Suitability of climate simulations for Actions 6,7, 8, 23, 24**
A1B/A2/B1	ARPEGE-climat v4.6	Météo-France (L. Labbé)	Bias correction (Q-Q plot)	Daily	Tm, RH, precipitation, wind, PET	Météo France	convention with DIREN Lorraine	25x25 km	1971 2000	2001-2100		French part of the Meuse basin	Not suitable for calculating the impact of climate change on High flows variables (e.g. Qhx100)
A1B/A2	ENSEMBLES	ENSEMBLES EU project	No bias correction	Sub-daily	Air temperature, precipitation, etc.	ENSEMBLES GCM/RCM	http://ensemblesrt3.dmi.dk/extended_table.html	25x25 km 50x50 km	1950 2000	2001-2100	Netcdf	Europe	ditto
A2-B2 A1B/ A2/B1/B2	HadCM2 CGCM1 CCI-HYDR	UK Canada KU Leuven (P. Willems)	By RMI (E Roulin) By RMI (E Roulin) Perturbation approach	Daily Daily Daily Hourly	P and ETo perturbations factors per season (winter – summer) P, ETo, Air temperature, wind speed	A2/B2 PRUDENCE; A1B/B1 IPCC AR4	Restricted access Restricted access http://www.kuleuven.be/hydr/CCI-HYDR.htm, available	1 perturbation factor by tributary (2 tested)	1961 1990	2010-2039 2040-2069 2070-2099 2071-2100	ASCII ASCII	? Flemish part of the Meuse basin	ditto limited suitability for AMICE (absence of hydrologic models for Meuse in Flanders, tackled by research of Deltares with Belgian perturbation tools on their models)
A2-B2	PRUDENCE GCM/RCM matrix	PRUDENCE EU project	No bias correction	Sub-daily	Air temperature, precipitation, etc.	PRUDENCE EU project	http://prudence.dmi.dk/, available	50x50 km	1961 1990	2070-2099	Netcdf	Europe	ditto (only one future time slice available)
A1B/A2/B1	ARPEGE-climat v4.6/15 IPCC GCMs	CERFACS (C. PAGE)	Weather regime	Daily, Hourly	Air temperature, precipitation, PET, etc.	CERFACS	Public access	8x8 km	1961 1990	2001-2100	ASCII	French part of the Meuse basin	Suitable for all Actions Do not cover the whole basin

Table 6. Existing climate scenarios databases (v.11/2009)

2.2.3 Climate projections for the Meuse basin

In addition to the existing databases list, a synthesis of literature about the climate change on the Meuse basin was performed. The purpose of this step is to know if the subject has already been sufficiently documented to allow the execution of AMICE works based on the findings of existing studies. These studies are presented in Figure 19 for the future change in precipitation and in Figure 20 for the future change in air temperature.

Several GCMs and RCMs are used in the studies. They all give quite clear trends for the Mediterranean region (very strong increase of temperature and decrease of precipitations) and the Scandinavian region (strong increase of temperature and increase of precipitation). But the Meuse basin lies between these two regions and, depending on the models used, the Meuse basin gets dryer or has increased precipitation.

The Amice partners decided to split climate model outputs into two future climates to study the two possible evolutions of the basin's climate: a wet one and a dry one. This pragmatic approach was adopted due to: (1) a limited time to use what was available, (2) the uncertainty of some climate models saying it will be drier and others indicate a wetter future. However most models indicate a drier summer. And most models in the Rhine catchment say that winters will be wetter.

We can mention here that, in the framework of the EU PRUDENCE project, Blenkinsop and Fowler (2007) tested several regional climate models, in particular on the Meuse basin. The regional climate models yielded a wide range of abnormalities: from 0% change to 60% change on a same month. It is thus not surprising that the AMICE Partners are confronted with very distinct outputs from their national climate simulations. The same authors mention also that several models demonstrate the spatial variability of climate change. It is noted that the drought effect will be more pronounced in the southernmost and northernmost parts of the Meuse basin.

In the Netherlands, until 2006, the climate scenarios of Waterbeheer 21e eeuw or WB21 (Water Management 21st century, 2000) were used as a reference for future water management. Based on more recent insights from worldwide climatological research, these scenarios were replaced by the KNMI 2006 scenarios, presented by the Royal Netherlands Meteorological Institute (KNMI). These (four) scenarios now serve as the national standard in adaptation policies in the Netherlands (Hurk et al., 2006; Ministerie van Verkeer en Waterstaat (2009) Nationaal Waterplan).

The scenarios proposed by the AMICE Partners are plausible scenarios: they are not much different from the trends used in other climate impacts studies. However, it does not mean that the wet or dry climate scenario will indeed happen. The water managers and decision makers should be very aware that our results only represent two possible future climate trends, without any absolute certainty on which climate will occur.

Figure 19 : Future Trends of Precipitation on the Meuse river Basin: A Synthesis from the Literature

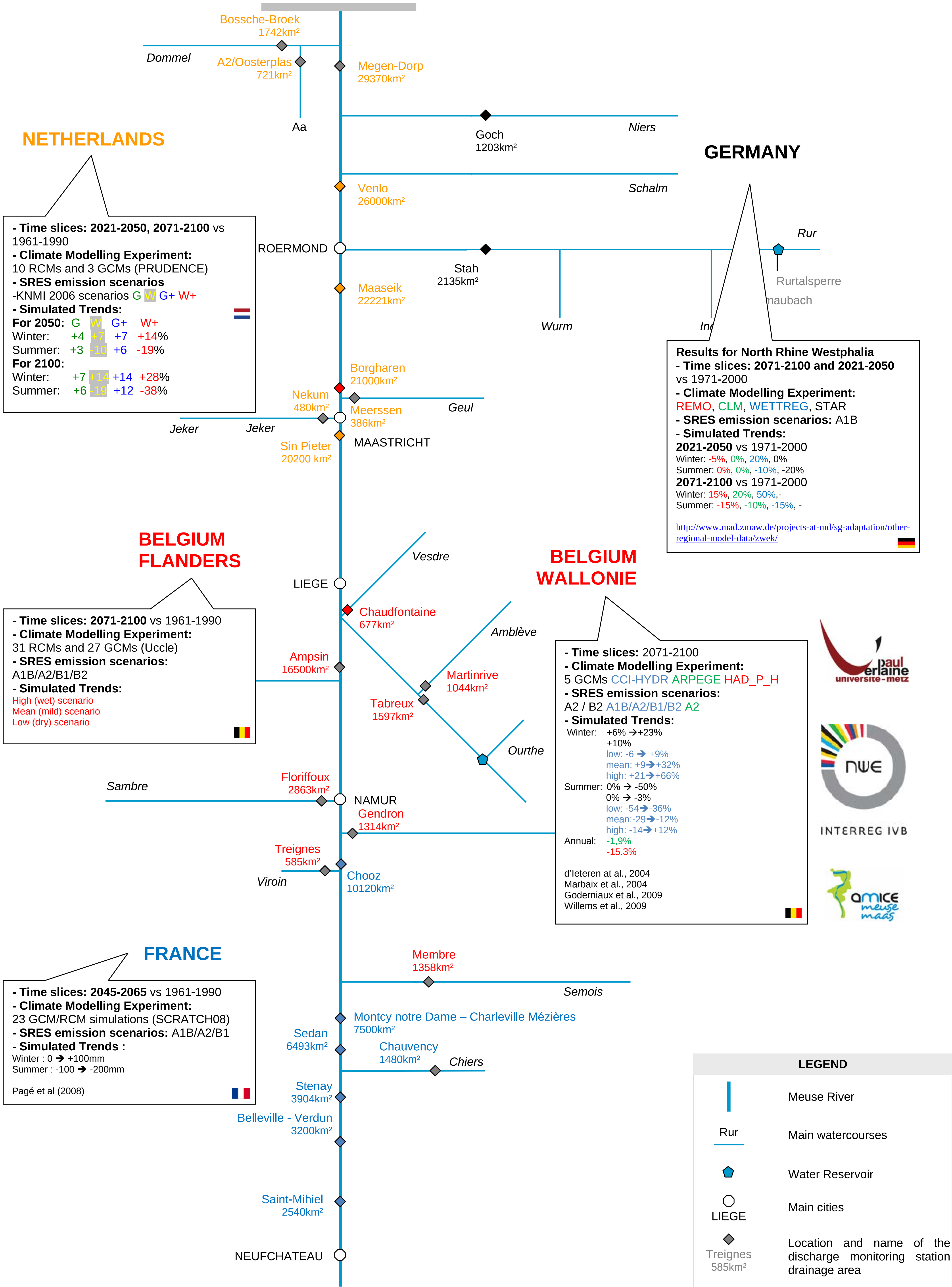
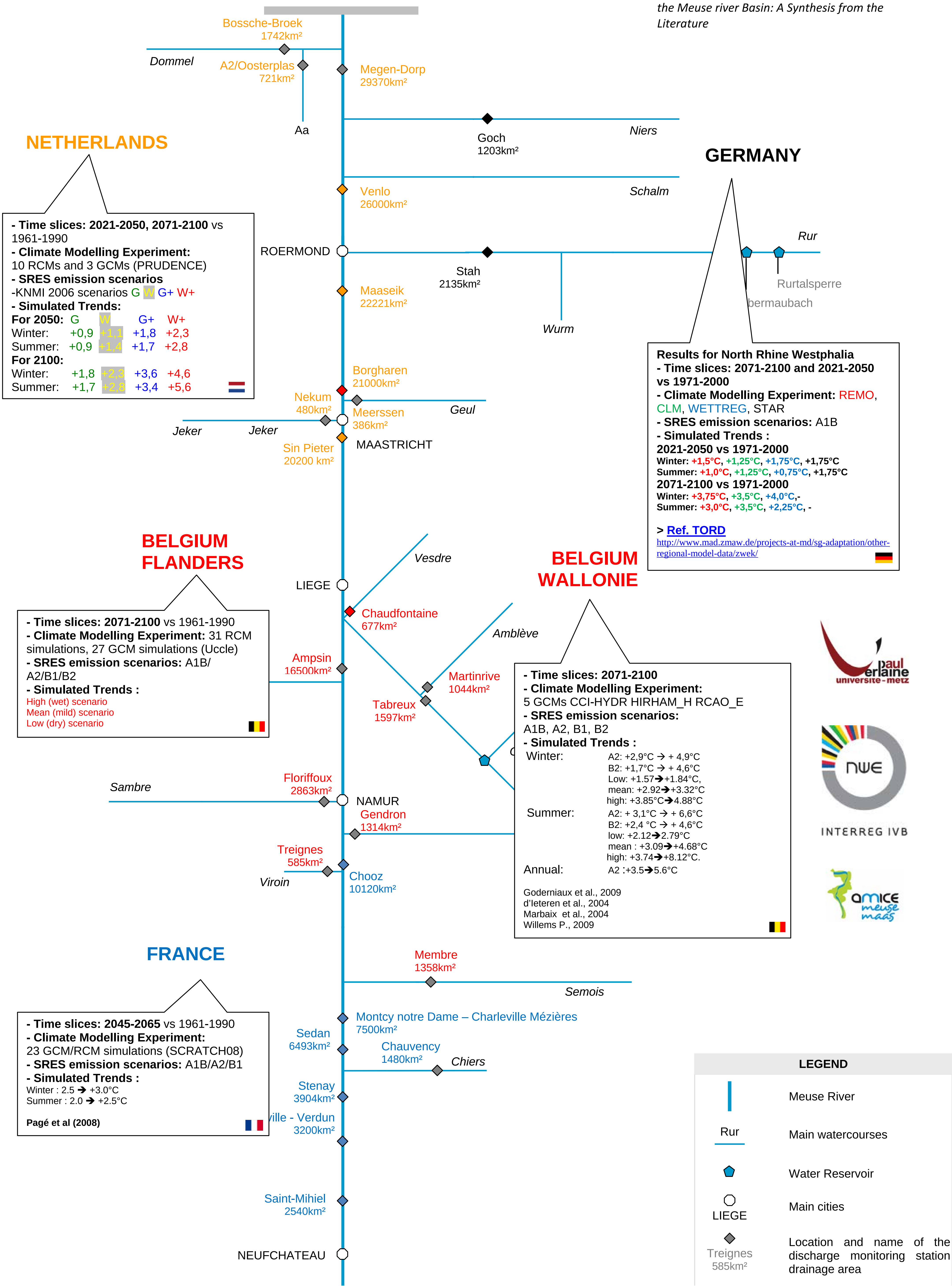


Figure 20 : Future Trends of Air temperature on the Meuse river Basin: A Synthesis from the Literature



2.3 Future hydrological scenarios

In the same way as made for climate change, a synthesis of the literature was conducted about impacts of climate change on the hydrology of the Meuse. The existing studies are indexed in Figure 21 for high flows and in Figure 22 for the low flows.

This bibliographic step shows that there is no climate database ready to use for the AMICE Project. Indeed in most of the cases the climate databases do not cover the whole basin. When it does, a bias correction is always necessary which was not achievable within the time-frame of the project.

Concerning the climate change studies, the literature contains interesting works but the results are generally too heterogeneous and sporadic to be used at the scale of the whole Meuse basin. Hydrological studies are difficult to use and generally do not use the same impact variables which makes them difficult to compare.

Time slices used in former studies are also different. The most widely used is 2071-2100. The climate trends are indeed clearer towards the end of the century. The 30 years span is most common in hydrology: most discharge monitoring stations have been installed in the 1960s or 1970s and thus our reference period is now 30 years long. In AMICE, we decided to study also the 2021-2050 period: we intend to propose an adaptation strategy and knowledge of the medium-term situation will help us define priorities and urgent adaptation measures. Information on the medium-term is more useful for local policy-makers than the long-term.

The main finding that emerges is that the easiest solution for the AMICE Project was to create new climate and hydrological scenarios. To this end, the optimal solution is to apply the delta change approach to existing national climate scenarios.

Figure 21. Future Trends of the Meuse High Flows and Mean Annual Flows
A Synthesis from the Literature

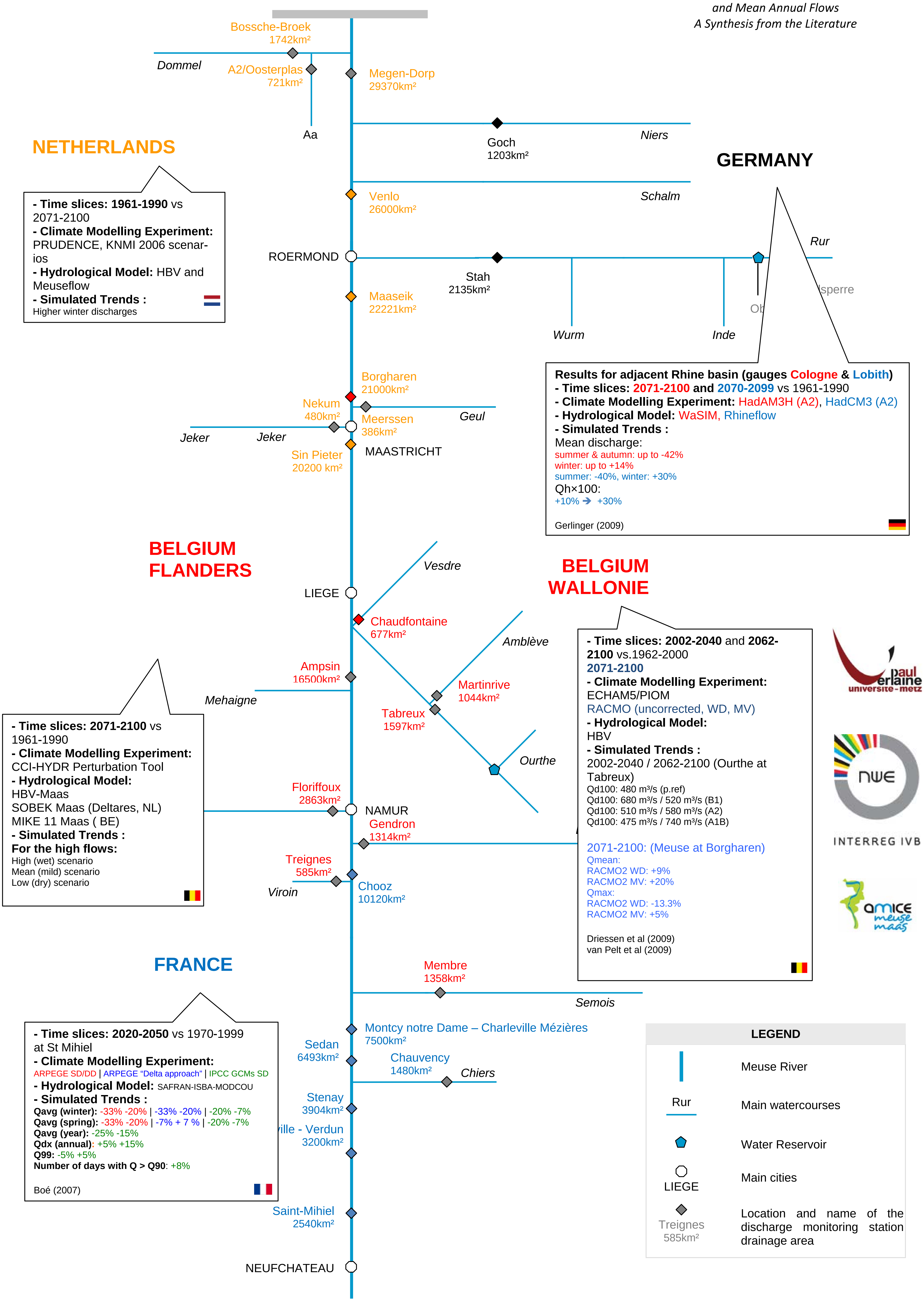
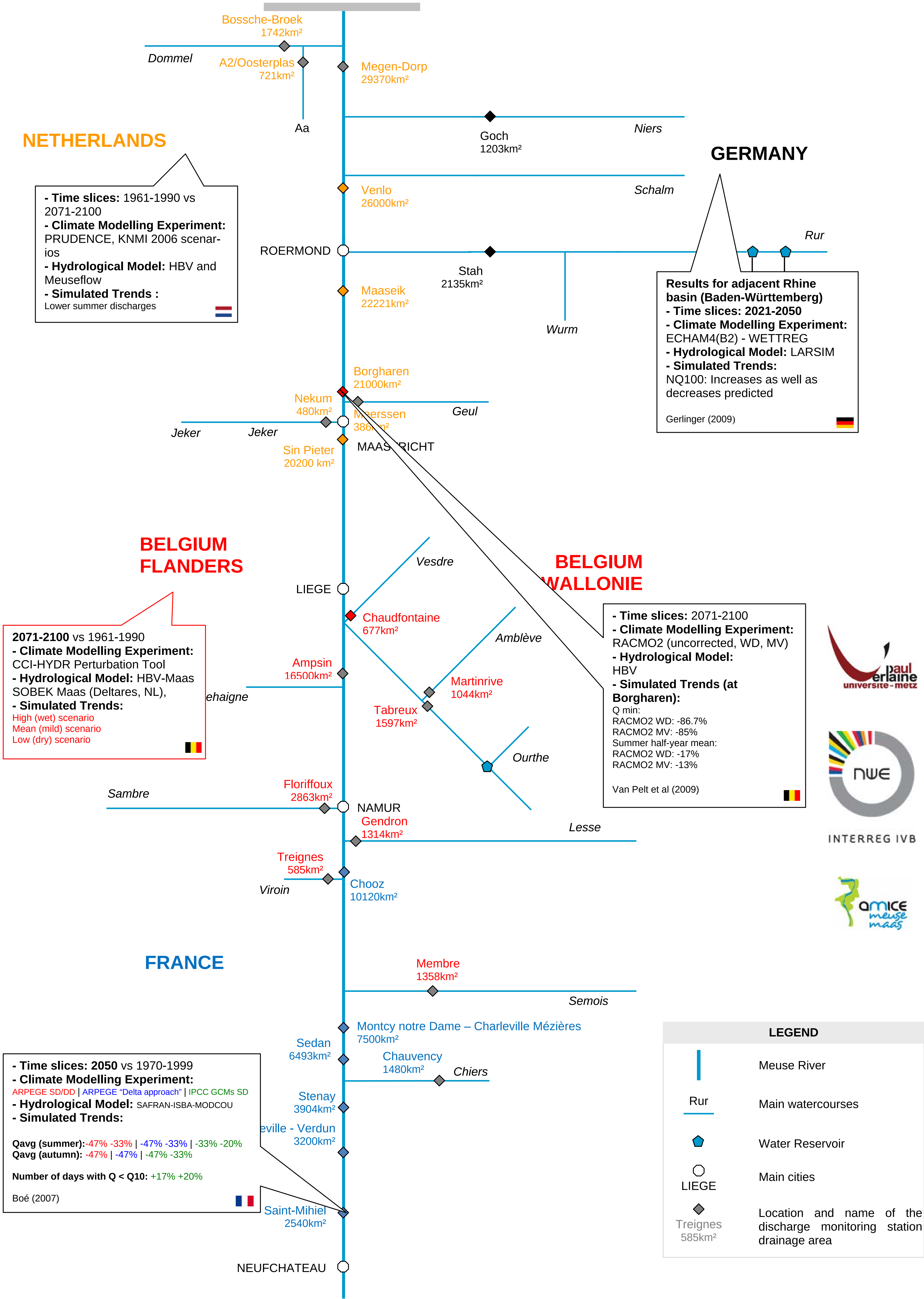


Figure 22. Future Trends of the Meuse Low Flows
A Synthesis from the Literature



3 Production of future climate scenarios

3.1 Material and methods

3.1.1 The delta change approach

The delta change approach is the method selected by the AMICE partners for producing hydrological scenarios. Seasonal trends (% for ΔP and °C for ΔT) have been provided by meteorological national agencies for the 2021-2050 and 2071-2100 periods based on GCM simulations forced with emission scenarios (Figure 23). The seasonal trends have then been used to force a present climatology (i.e. E-OBS gridded climatology) on the 1961-1990 or 1971-2000 periods.

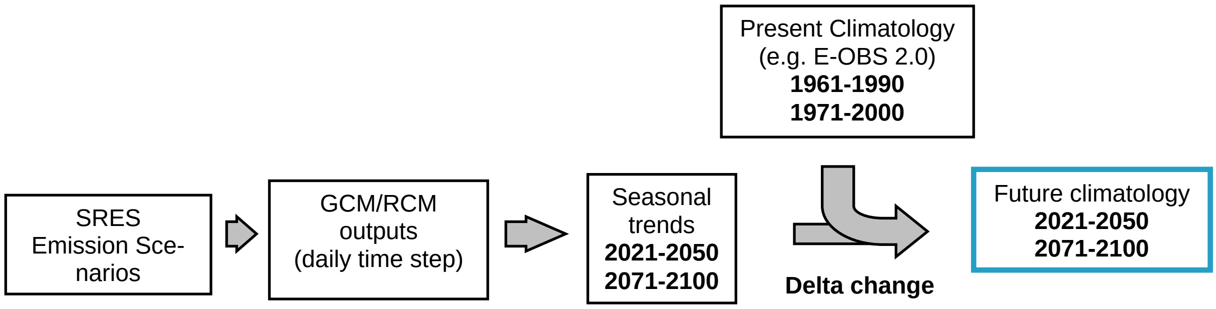


Figure 23. Flowchart of the delta change approach applied for climate scenarios generation.

This downscaling method has been implemented to create one wet and one dry scenario for each period and for each national sub-basin.

3.1.2 Presentation of the baseline climatology

3.1.2.1 Partners' hourly database

The SAFRAN database was used by EPAMA. It is a mesoscale (8km resolution on extended Lambert-II projection) atmospheric analysis system for surface variables. It is managed by Météo-France. SAFRAN produces an analysis at the hourly time step using ground data observations. One of SAFRAN's main features is that it is based on climatically homogeneous zones (600 over France) and is able to take vertical variations into account. SAFRAN takes into account all of the observed data in and around the area under study. The analyses are computed every 6 hours, and the data are interpolated to an hourly time step.

EPAMA accessed the data through a Convention signed between Météo-France, owner of the data, and the DREAL Lorraine (Direction Régionale de l'Environnement, de l'Aménagement et du Logement), funder of the AMICE project. The points for which climate data are available on the Meuse basin are represented on Figure XX (French basin area of the Meuse basin, hydrological simulation).

For the Walloon part (Figure 24) of the Meuse basin, four measured stations provide hourly rainfall from 1967 to 2000 (Table 7):
- Rochefort (longitude : 5°13'26,086'', latitude : 50°13'23,356'')
- Bierset (longitude : 5°26'54,071'', latitude : 50°30'40,172'')
- Nadrin (longitude : 5°40'53,067'', latitude : 49°59'35,928'')
- St-Hubert (longitude : 5°24'04,089'', latitude : 49°52'31,675'')

Data are provided by the SETHY (Service Public de Wallonie, Direction générale opérationnelle Mobilité et voies hydrauliques, Direction de la Gestion hydrologique intégrée, Service d'Etudes Hydrologiques).

Station's name	River	Measure's name	Owner	Longitude	Latitude	First hourly d.	Last hourly d.
Rochefort	Lesse	PVG IRM	IRM	5°13'26.086''	50°13'23.356''	03/01/0967	30/04/2005
Bierset	Meuse	PVG IRM	FAe	5°26'54.071''	50°30'44.172''	02/01/0967	30/04/2005
Nadrin	Ourthe	PVG IRM	IRM	5°40'53.067''	49°59'35.928''	02/01/1967	30/04/2005
Saint_Hubert Aéro	Ourthe Occidentale	PVG IRM	RVA	5°24'04.089''	49°52'31.675''	03/01/1967	30/04/2005

Table 7. Measuring stations in Walloon Region.

For these stations, only daily air temperature data are available. For the stations of Rochefort, Nadrin and St-Hubert data are available from 1967 to 2000, for the station of Bierset, they are available from 1979 to 2000.

Some rainfall data are missing:
- At Rochefort, 812 days of data are missing on 34 years,
- At Nadrin, 638 days of data are missing on 22 years,
- At Bierset, 276 days of data are missing on 34 years,
- At St-Hubert, 32 days of data are missing on 34 years.

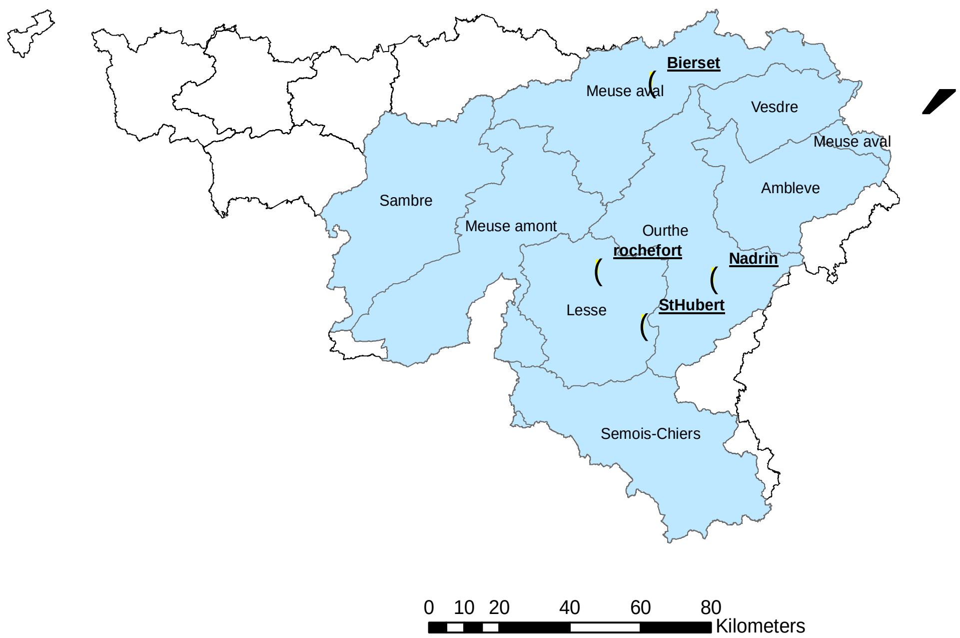


Figure 24. Location of measured stations in Walloon Region.

For the Flemish part, Input data are the 30 year time series for precipitation, air temperature and PET_0 on a daily base. For the control period (1969-1998) the series from KNMI (Dutch Royal Meteorological Institute) for all sub basins of the Meuse based on data from KMI and Météo France. More information about this can be found in Leander et al. (2005).

The North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection (LANUV) has kindly given us the permission to use precipitation data from the ExUS project. The air temperature data from the DWD of the KLAVE project were also kindly provided by the LANUV. Both data have been recorded by pointwise measurements.

In Figure 25 an overview of the locations of the provided precipitation records is given. The green dots show all stations where data was available. Since not all records were long enough for the necessary simulations of a thirty year period, only the stations with an additional red point could be used for our purposes. Only these stations had records covering the period from at least 1970-2000. As one can see, most stations are assigned to an area of several hundred square kilometers. The maximum appears for station Borschemich (about 620 km²). For none of the stations the assigned area is smaller than 25 square kilometers. At least for statistical precipitation values this is the upper limit up to which the precipitation values may be used without reducing the values depending on the assigned area and the duration of a specific event (Verworn, 2008).The thirty year period from 1961-1990 would have caused an even much coarser resolution of the data and thus even larger areas to be assigned to the stations.

Since no models for the area upstream of the reservoir Obermaubach were available only recordings from the stations Raffelsbrand, Kornelimünster, Borschemich, Dülken, Heiligendorf, Kronen and Hoppenstedt were used.

The data result from continuous recordings. Before they were used as input for the rainfall-runoff models they have been aggregated to an hourly resolution.

In Table 8 an overview over the mean annual sum of precipitation is given. It can be seen that the 1980s have been wetter than the antecedent and the subsequent decade. Concerning the Rur basin area an increase in annual sum of precipitation from north to south can be seen. As more detailed studies (Bogena et al., 2005) have shown this is known to be at least qualitatively correct. Concerning the Niers basin area the mean annual sum of precipitation for station Heiligendorf seems to be extraordinary high. Both to the north and to the south the mean annual sum of precipitation decreases following the available records.

Table 8. Overview of mean annual sum of precipitation for 1971-2000 and for according decades

	1971-1980 [mm]	1981-1990 [mm]	1991-2000 [mm]	1971-2000 [mm]
Hoppenstedt	**611**	**717**	**713**	**680**
Kronen	**760**	**906**	**845**	**837**
Heiligendorf	**838**	**1.085**	**984**	**969**
Dülken	**633**	**734**	**739**	**702**
Borschemich	**625**	**789**	**727**	**714**
Kornelimünster	**763**	**915**	**851**	**843**
Raffelsbrand	**827**	**1.112**	**1.077**	**1.005**

In Figure 26 an overview over the air temperature stations that have been used for the hourly high-flows simulations is given. The temporal resolution of the data is – different to the precipitation data - one day. The recordings have been done in the morning at 7:30 am. Again the spatial resolution of the data is very coarse. In comparison to precipitation data we regard this to be less crucial.

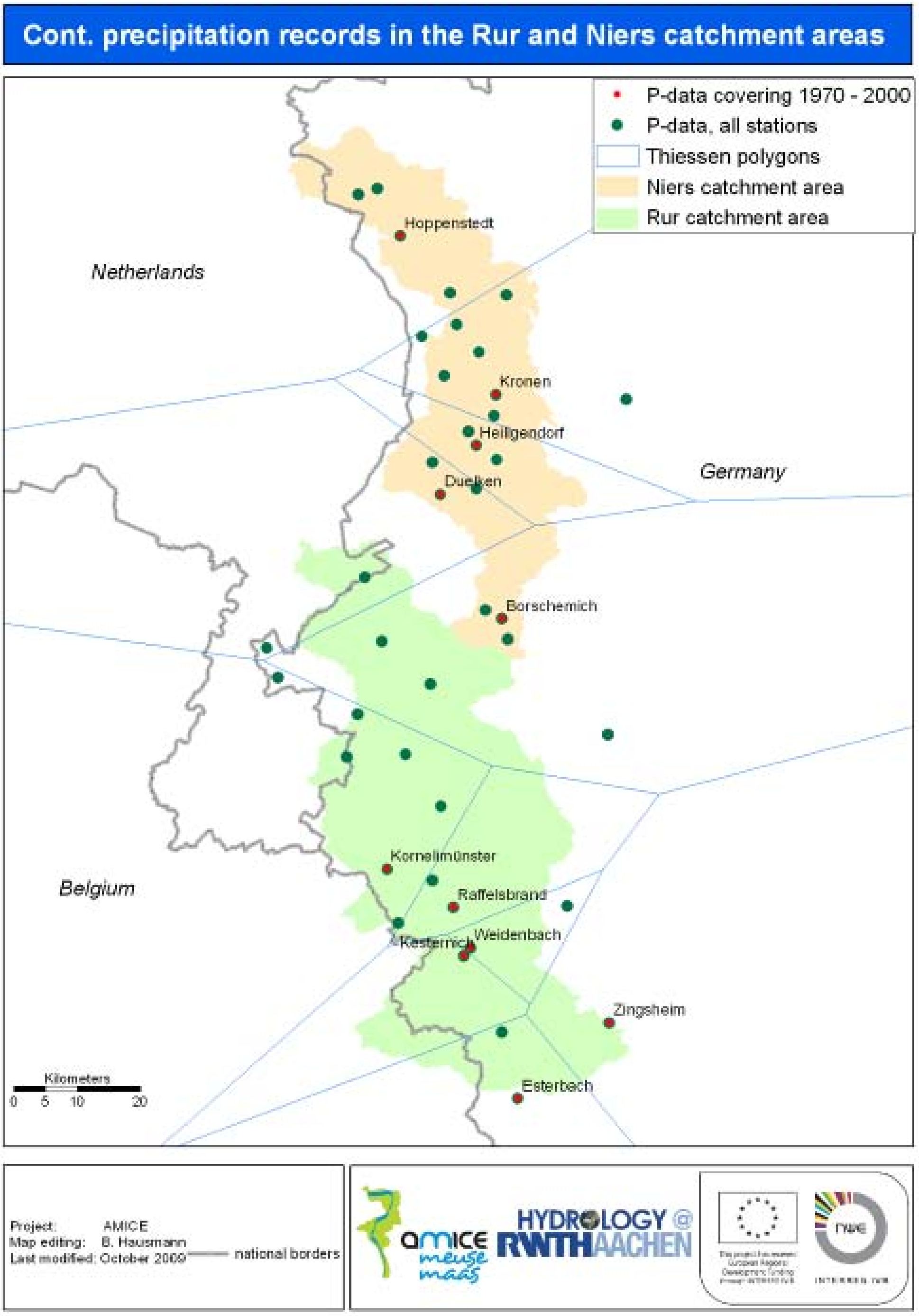


Figure 25. Overview over the spatial distribution of the precipitation records

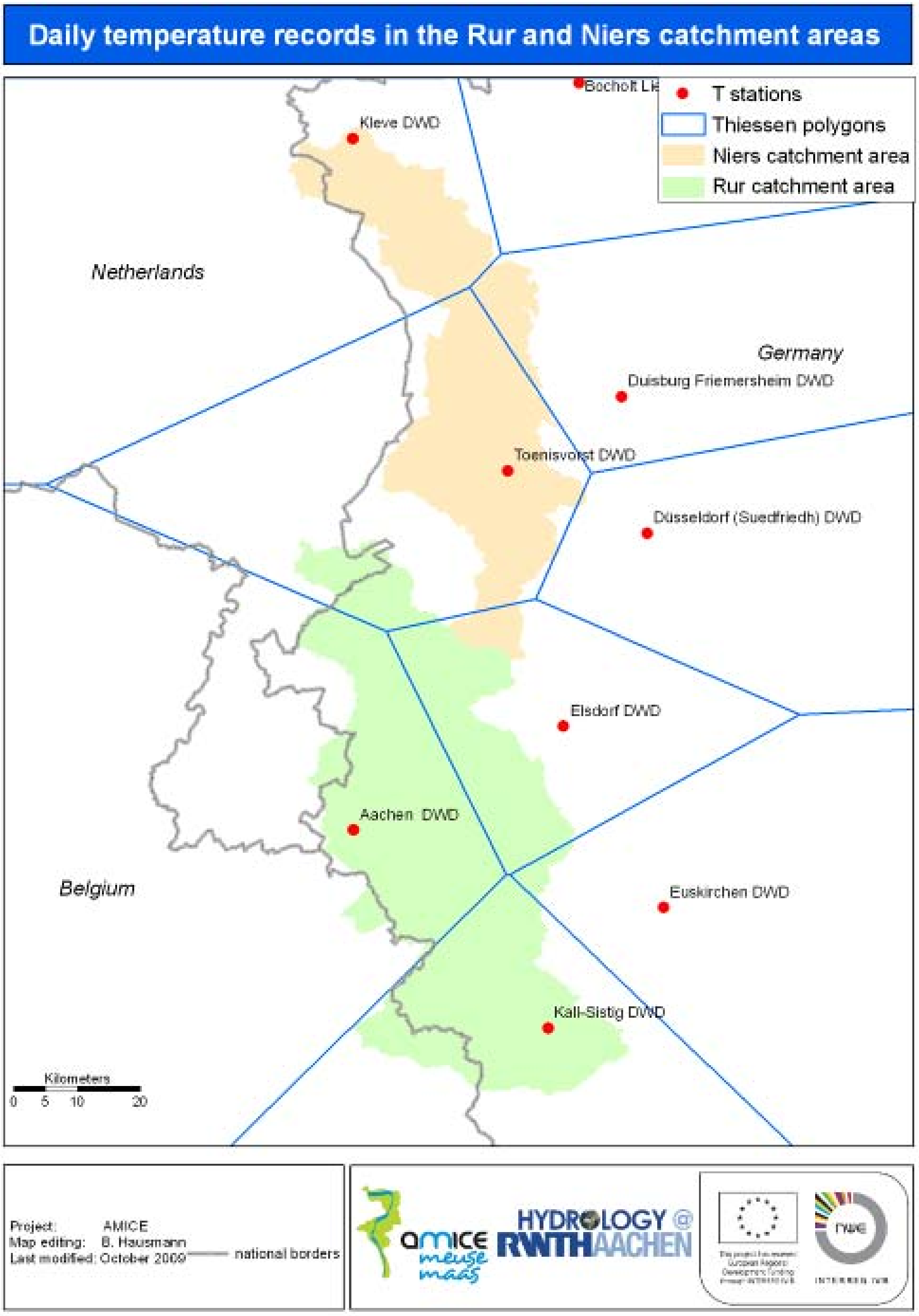


Figure 26. Overview over the air temperature stations

As shown in figure 27 the mean monthly air temperatures are very similar for the stations. The only exception is Kall-Sistig. One reason for this is its elevation of 505 m above sea level. The next highest station is Aachen with 202 meters above sea level. The other stations have elevations between 31 and 85 meters.

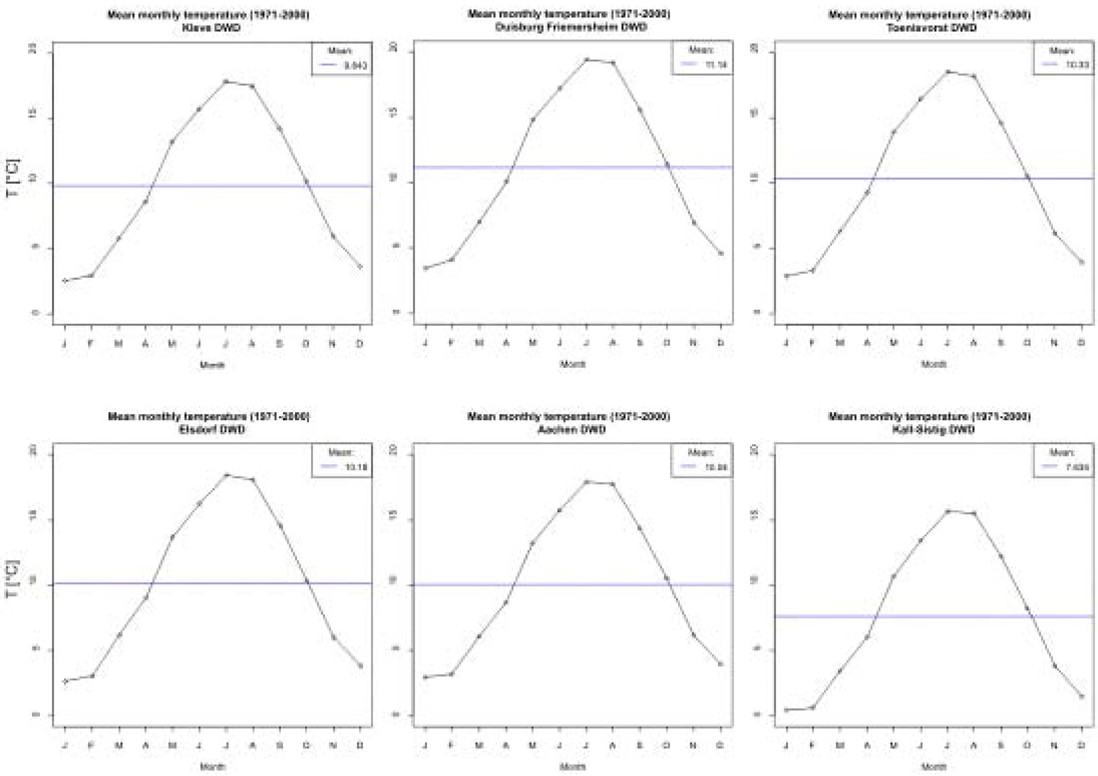


Figure 27. Measured mean monthly air temperatures for 1971-2000

3.1.2.2 Daily E-OBS gridded database

The daily climatological database used for hydrological simulations is the E-OBS 2.0 climatology provided by the European Climate Assessment & Dataset project. This database contains daily precipitations and air temperatures (2 meters) from 1950 to 2008 for Europe (Haylock et al. 2008). Data from meteorological stations are collected and distributed on two regular grids 0.5° and 0.25°.

For the HBV-model used to calculate the discharges for Sint Pieter in the Netherlands, the E-OBS dataset gives (still) unsatisfactory results. This might be due to the fact that in the E-OBS dataset, fewer weather stations are included than in the dataset the HBV-Meuse model was calibrated with.

KNMI provided Deltares with a dataset with mean values for the 15-HBV sub-basins. It consists of daily precipitation, temperature reference evaporation data for the period 1969 to 1998, and is based on a large amount of meteorological data from France and Belgium.

3.1.3 Evapotranspiration Calculation

For modeling purposes we also need daily potential evapotranspiration values (PET). This third variable is calculated from mean daily air temperature and latitude on each point of the grid by the method of Oudin (2004).

3.1.4 Selection of climate modeling experiment and scenarios

The Table 9 presents the characteristics of the national scenarios used by each partner to create its own wet and dry scenarios (France, Walloon, Germany, and Netherlands/Flanders).

It makes a big difference that it rains 20% stronger or 20% longer. The climate scenarios available presently cannot precise this point. However, most climate-related projects are modifying the intensity of rainfalls but not their duration. The AMICE project will follow this line. This decision was mainly agreed because our interest is on the maximum or minimum discharges, and less on the volume of the flood. The maximum discharge is related to the water height and determines the area which is flooded. The volume is related to the duration of the flood itself and is important to calculate how long the area will be flooded. In AMICE we assume that the flooded area can be modified but that the flood durations will remain the same as present days.

Table 9. Main characteristics of national climate scenarios

	SRES scenarios	Climate experiment or model	Data provider and contact person	Downscaling method	Source of data	Type of simu-lation	Time period for the control run
French part of the basin	A2/A1B	ARPEGE-climat v4.6	Météo-France (L. Labbé)	Bias correction (Q-Q plot)	Météo France	Transient simulation	1961-1990
Walloon part of the basin	A1B/ A2/B1/B2	CCI-HYDR Perturba-tion Tool	KULeuven (P. Willems)	statistical	Royal Institute Bel-gium		1961-1990
German part of the basin	A1B	WETTREG (wet scenario) CLM (dry scenario)	DWD (T. Deutschländer)		WETTREG: Meteo Research pp Um-weltbundesamt CLM: MPI-M-M/MaD pp BMBF	Transient simulation	1971-2000
Dutch and Flemish parts of the basin	A2/B1	PRUDENCE	KNMI	dynamical & statisti-cal	KNMI	Transient	1961-1990

3.2 Results of the climate projections for the Meuse basin

Figures 28 and 29 present seasonal trends obtained with the delta change approach for each national sub-basin. The results are presented in percentage for the change in rainfall and in Celsius degree for the change in air temperature. Results of both scenarios (wet & dry) and both time slices (2021-2050 & 2071-2100) are presented (Table 11).

We can observe clear heterogeneities between the climate scenarios coming up from the four areas. In order to maintain downstream consistency of discharges, especially at boundaries, a transnational scenario was established. To this end national trends were weighted according to the drainage area of each sub-basin (Table 10).

	Drainage area (km^2)	**Weighting coefficient**
France	10.120	0,31
Walloon	10.880	0,33
Flanders & Netherlands	8.662	0,26
Germany	3.338	0,10
Transnational Meuse	**33.000**	**1,0**

Table 10. Weighted coefficients used to create the transnational seasonal trends

Figure 28. Seasonal trends in precipitation (%) and air temperature (°C) for the national Meuse sub-basins and for the two time slices (2021-2050 & 2071-2100) – Wet scenario

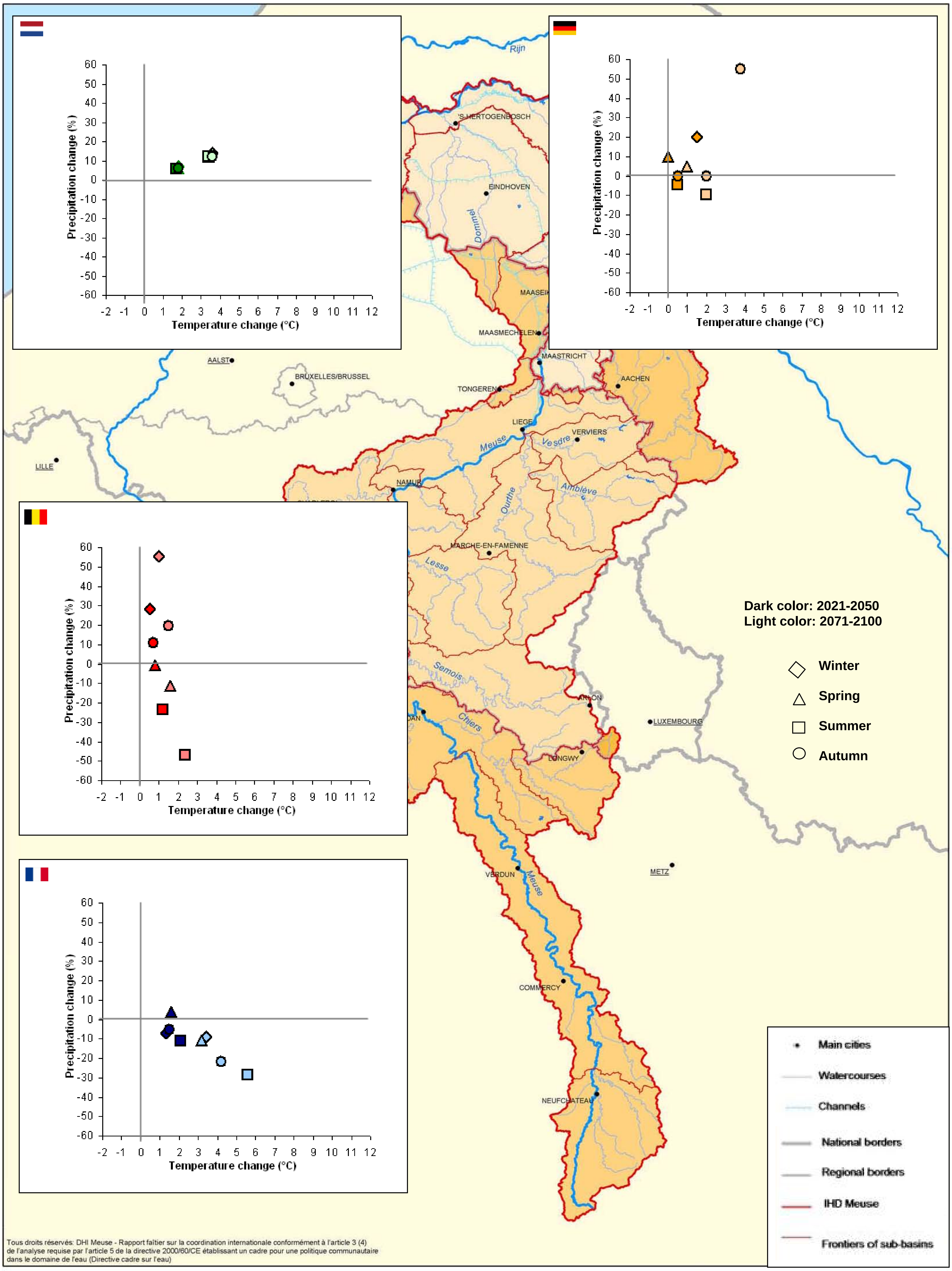
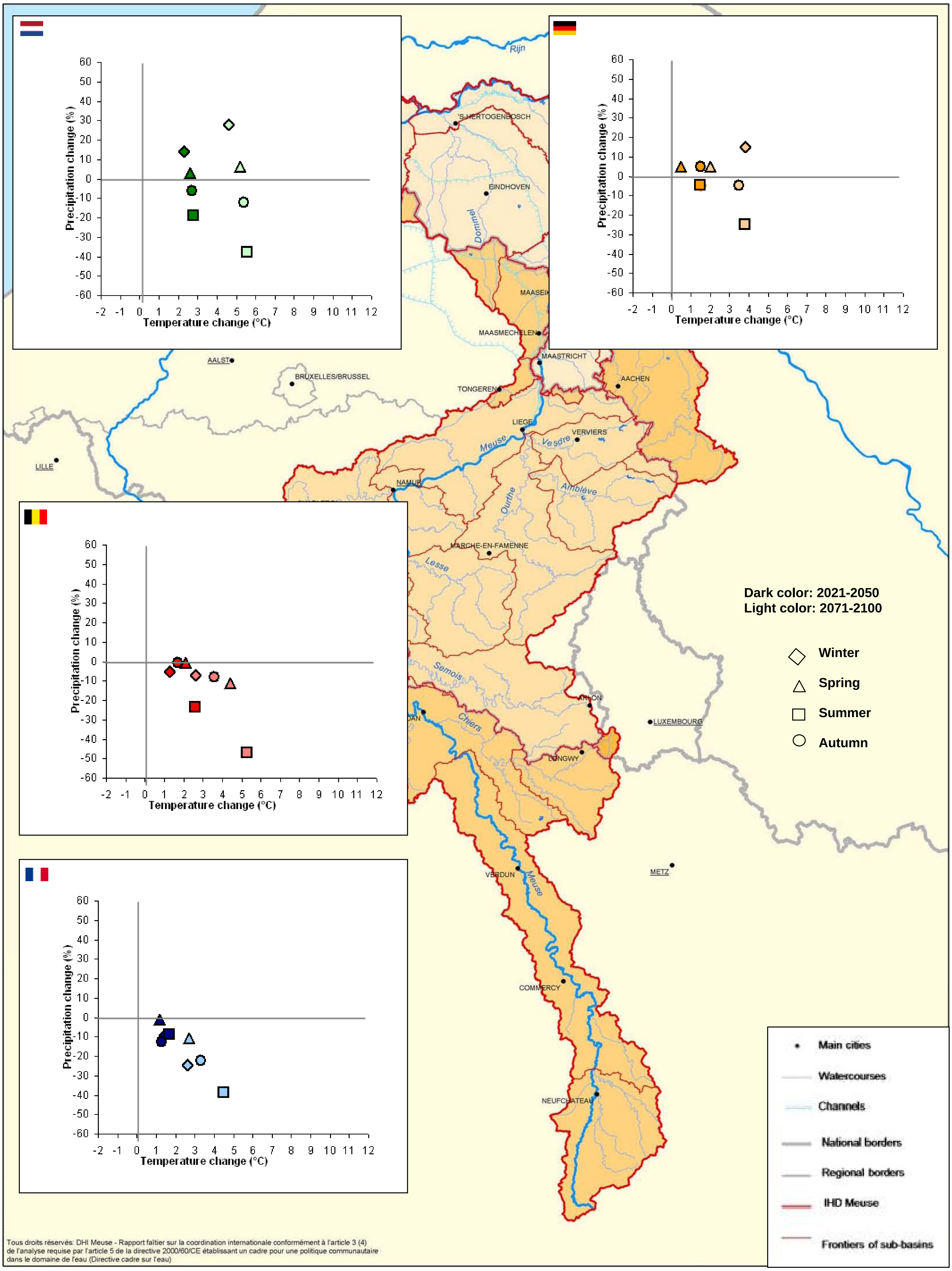


Figure 29. Seasonal trends in precipitation (%) and air temperature (°C) for the national Meuse sub-basins and for the two time slices (2021-2050 & 2071-2100) – Dry scenario



Period	Scenario	Region	Annual	Winter	Spring	Summer	Autumn
2020-2050	**WET SCENARIO**		**Annual**	Winter	Spring	Summer	Autumn
		France	**1,6**	1,3	1,6	2,1	1,5
	Temperature change (°C)	Walloon	**0,8**	0,5	0,8	1,2	0,7
		Flanders & Netherlands	**1,8**	1,8	1,8	1,7	1,8
		Germany	**0,6**	1,5	0,0	0,5	0,5
		Meuse	**1,3**	**1,2**	**1,2**	**1,5**	**1,2**
	DRY SCENARIO		**Annual**	Winter	Spring	Summer	Autumn
		France	**1,4**	1,4	1,2	1,7	1,3
	Temperature change (°C)	Walloon	**1,9**	1,3	2,1	2,6	1,7
		Flanders & Netherlands	**2,6**	2,3	2,6	2,8	2,7
		Germany	**1,3**	1,5	0,5	1,5	1,5
		Meuse	**1,9**	**1,6**	**1,8**	**2,3**	**1,8**
2020-2050	**WET SCENARIO**		**Annual**	Winter	Spring	Summer	Autumn
		France	**-4,9**	-7,3	4,0	-11,3	-5,1
	Precipitation change (%)	Walloon	**3,6**	28,2	-0,8	-23,6	10,7
		Flanders & Netherlands	**6,1**	7,0	6,0	5,5	6,0
		Germany	**6,3**	20,0	10,0	-5,0	0,0
		Meuse	**1,9**	**10,9**	**3,5**	**-10,3**	**3,5**
	DRY SCENARIO		**Annual**	Winter	Spring	Summer	Autumn
		France	**-8,0**	-9,2	-1,0	-9,1	-12,8
	Precipitation change (%)	Walloon	**-7,6**	-5,1	-0,8	-23,6	-0,7
		Flanders & Netherlands	**-2,0**	14,0	3,0	-19,0	-6,0
		Germany	**0,0**	-5,0	5,0	-5,0	5,0
		Meuse	**-5,5**	**-1,3**	**0,7**	**-16,1**	**-5,2**
2070-2100	**WET SCENARIO**		**Annual**	Winter	Spring	Summer	Autumn
		France	**4,1**	3,4	3,2	5,6	4,2
	Temperature change (°C)	Walloon	**1,6**	1,0	1,6	2,4	1,5
		Flanders & Netherlands	**3,5**	3,6	3,4	3,4	3,6
		Germany	**2,2**	3,8	1,0	2,0	2,0
		Meuse	**2,9**	**2,7**	**2,5**	**3,6**	**2,9**
	DRY SCENARIO		**Annual**	Winter	Spring	Summer	Autumn
		France	**3,3**	2,6	2,7	4,5	3,3
	Temperature change (°C)	Walloon	**4,0**	2,6	4,4	5,3	3,6
		Flanders & Netherlands	**5,2**	4,6	5,2	5,6	5,4
		Germany	**3,3**	3,8	2,0	3,8	3,5
		Meuse	**4,0**	**3,2**	**3,8**	**5,0**	**4,0**
2070-2100	**WET SCENARIO**		**Annual**	Winter	Spring	Summer	Autumn
		France	**-17,6**	-8,9	-10,7	-28,7	-22,0
	Precipitation change (%)	Walloon	**4,2**	55,3	-11,2	-47,2	19,7
		Flanders & Netherlands	**12,5**	14,0	12,0	12,0	12,0
		Germany	**12,5**	55,0	5,0	-10,0	0,0
		Meuse	**0,5**	**24,7**	**-3,3**	**-22,2**	**2,9**
	DRY SCENARIO		**Annual**	Winter	Spring	Summer	Autumn
		France	**-24,0**	-24,6	-10,7	-38,7	-22,2
	Precipitation change (%)	Walloon	**-18,4**	-7,1	-11,2	-47,2	-8,1
		Flanders & Netherlands	**-4,0**	28,0	6,0	-38,0	-12,0
		Germany	**-2,5**	15,0	5,0	-25,0	-5,0
		Meuse	**-14,7**	**-1,0**	**-4,9**	**-39,9**	**-13,1**

Table 11. Seasonal trends in precipitation (%) and air temperature (°C) for the national sub-basins and for the transnational scenario for the two time slices (2021-2050 & 2071-2100) - Dry & wet scenarios

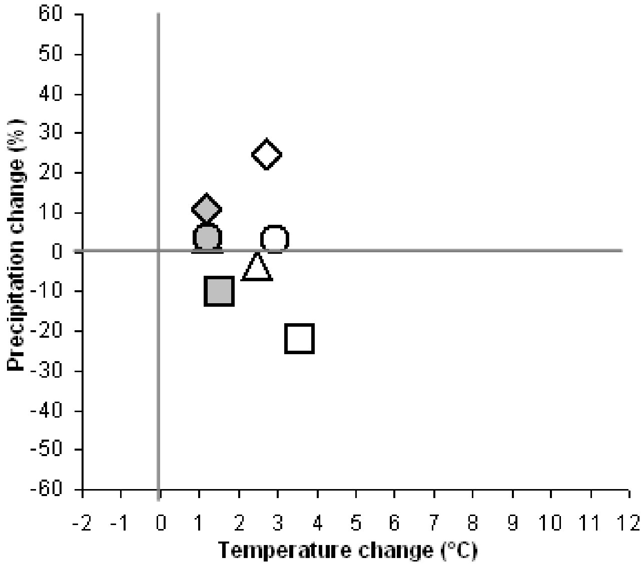


Figure 30. Seasonal trends in precipitation (%) and air temperature (°C) for the trans-national scenario and for the two time slices (grey: 2021-2050 - white: 2071-2100)

Wet scenario

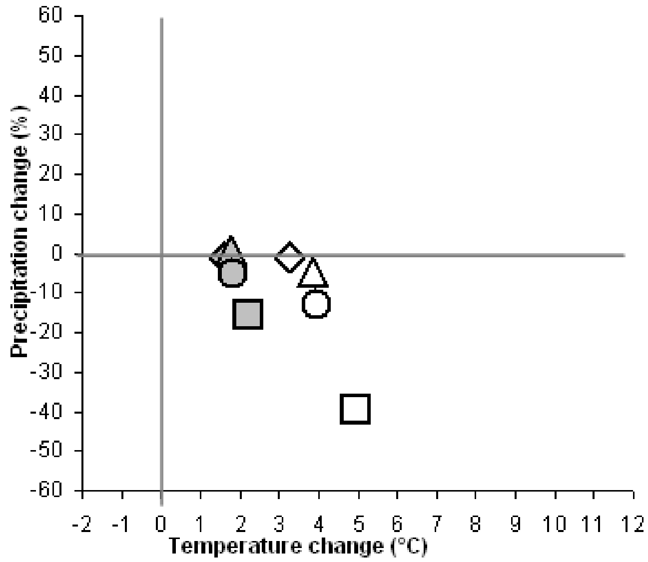


Figure 31. Seasonal trends in precipitation (%) and air temperature (°C) for the transnational scenario and for the two time slices (grey: 2021-2050 - white: 2071-2100)

Dry scenario

In order to validate our methodology, the transnational seasonal trends (Figures 30 and 31) have been compared to the PRUDENCE RCM simulations (*De Wit & al 2007*) for the end of 21st century. The Figure 32 shows that the AMICE Project values are matching closely the PRUDENCE RCM simulations.

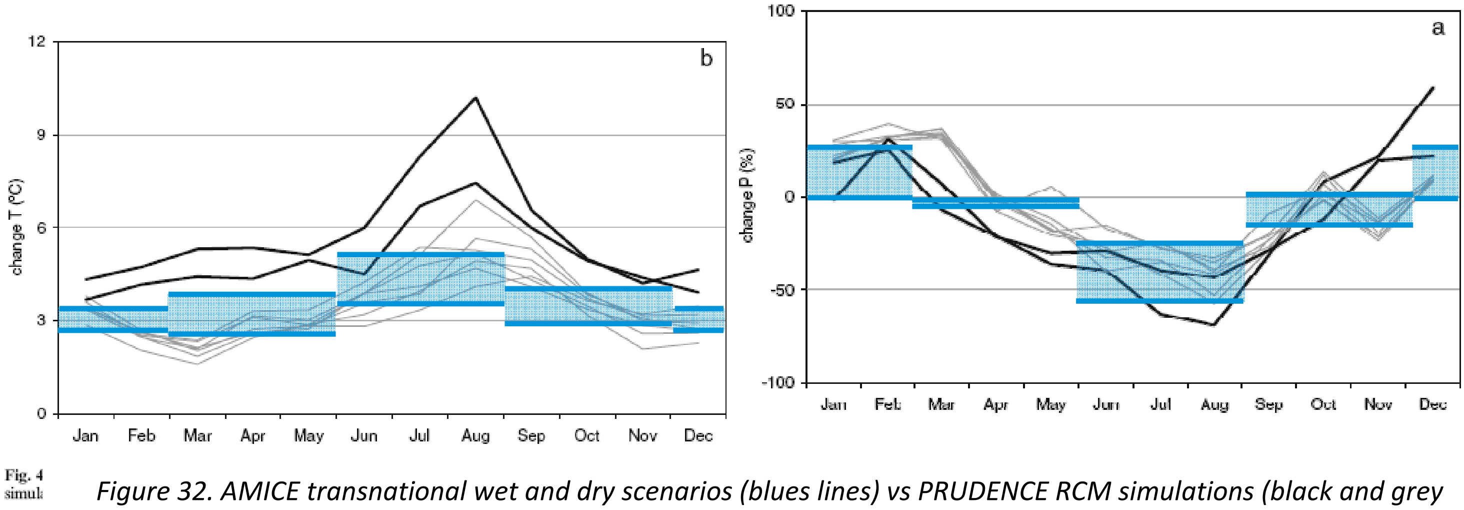


Figure 32. AMICE transnational wet and dry scenarios (blues lines) vs PRUDENCE RCM simulations (black and grey curves) - 2071-2100 (De Wit & al 2007)

4 Production of future hydrological scenarios

4.1 Material and methods

4.1.1 Presentation of the hydrological models

For the hydrological simulations each partner has used its own models except in Germany where NASIM and GR4J were calibrated especially. The Table 12 presents the main characteristics of hydrological models used along the Meuse river for the AMICE Project.

4.1.1.1 AGYR

AGYR is a rainfall-runoff model. It is used by EPAMA. It is made of 150 sub-basins. Each sub-basin uses a GR4 model to transform rainfall data into discharge values. The discharge calculated at each sub-basin's outlet is spread downstream through a simplified 1D model. The model was calibrated on 20 measured floods between 1965 and 1997. Inputs are the measured discharges (instant values) and the measured rainfalls (hourly timestep), as well as values defining the basin scale, the reservoirs, the rivers. The PET is assumed to be zero in flood periods.

4.1.1.2 GR4J

GR4J is a daily conceptual model with 4 parameters, developed by the CEMAGREF (institut de recherche en sciences et technologies pour l'environnement). The version used for AMICE has been revised by Perrin (2000). The operating principle is as follow (Figure 33):

- The first step consists in a neutralization of the precipitation (Pn) by the PET. If this interception consumes the entire precipitated amount, the excess PET results in a decrease of water level (S) in the production store. Otherwise some of the excess of rain (Ps) supplies the production store. The rest (Pn-Ps) flows to the basin outlet. After the production store, the flows are divided into two parts:

- The first one (10%) is routed by a hydrogram (UH2) and go to the outlet.

- The second part (90%) goes to a second reservoir called routing store via a second hydrogram (UH1)

Finally, a function is applied to drain the routing store.

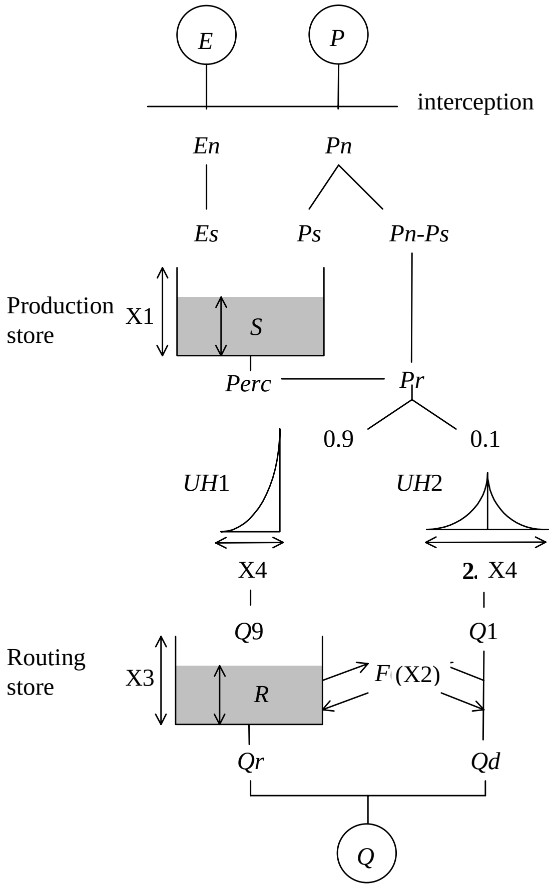


Figure 33. Flowchart of the GR4J hydrological model

The exchange function F reflects others interactions between the flows and the reservoir.

GR4J requires precipitations air temperatures and PET values as input. For the AMICE Project, the model has been calibrated for the whole French basin (low and high flows) and for German tributaries for low flows (Rur and Niers).

Name of the model	GR4J PRESAGES	AGYR	TOPMODEL	MIKE11 Maas	EPIC-Grid	HBV	NASIM	GR4J
Partner	*U. of Metz (CEGUM)*	*EPAMA*	*FHR*	*FHR*	Gx-ABT	*RWS*	*RWTH*	*RWTH*
Originally developed by	Cemagref (Perrin et al. 2003)	Cemagref (Perrin et al. 2003)		FHR	Williams, (Sohier C. et al., 2009)	SMHI	Hydrotec Ingenieurge-sellschaft für Wasser und Umwelt	Cemagref (Perrin et al. 2003)
Type of RR model	Lumped reservoir-based	Lumped reservoir-based		Conceptual RR model: HBV Maas (Deltares, NL)	Distributed physically-based/conceptual model	Semi-distributed conceptual model	Distributed physically-based/conceptual model	Lumped reservoir-based
Type of running	Continuous simulation	Continuous simulation	Continuous simulation	Continuous simulation	Continuous simulation	Continuous simulation	Continuous simulation	Continuous simulation
Number of optimized parameters	4	4				5 - 6	several	4
Groundwater infiltration and recharge	Percolation function + basin water exchange	Percolation function + basin water exchange			Capacitive method	Percolation function	Percolation function + basin water exchange	Percolation function + basin water exchange
Runoff components	Overland flows Base flows	Overland flows Base flows			SCS method (runoff, hypodermique, base flows)	Fast and slow runoff response	Overland flows Interflows Base flows	Overland flows Base flows
Flows routing	Two unit hydrographs	Two unit hydrographs		Saint-Venant equa-tions		Simplified unit hydro-graph	Kalinin-Miljukov-method	Two unit hydrographs
No. of land use types	-	-	-	-		2 (forest and field)	Several (5-...)	-
Input climate data	P, PET	P, PET	P, PET	P, PET	P, PET	P, PET	P, T, PET	P, PET
Precipitation (hourly) Precipitation (daily)	- 0.5° E-OBS gridded dataset 2.0*	Partner's data set 0.5° E-OBS gridded dataset 2.0	Partner's data set 0.5° E-OBS gridded dataset 2.0	Partner's data set 0.5° E-OBS gridded dataset 2.0	Partner's data set 0.5° E-OBS gridded dataset 2.0	Partner's data set 0.5° E-OBS gridded dataset 2.0	Partner's data set 0.25° E-OBS gridded dataset 2.0	- 0.25° E-OBS gridded dataset 2.0*
PET (hourly) PET (daily)	- Oudin et al. (2005)	- Oudin et al. (2005)	- Oudin et al. (2005)	- Oudin et al. (2005)	Prestley-Taylor	- Daily PET based on mean monthly values + 4% per °C air temperature increase	Oudin et al. (2005) Oudin et al. (2005)	- Oudin et al. (2005)
Temporal resolution of output data	1 day	Minutes to hour	1 hour 1 day	min, hour, day	1 day	1 day	15 min (Rur) 30 min (Niers)	1 day
Reference period for calibration/validation	-	-	-	20/01-15/03 2002 22/12 – 16/01 2003	1961-2000	1969-1984/1985-1998	2001/2003 (Wurm &Rur) Calibration for several high flows events between 1965-1995 (Niers) and 1982-2002 (Inde)	1960-1980/1981-2000 (1985-1992/1993-2000)
Method of optimization	Steepest descent or PEST	-	-	Expert judgment	Expert judgment	Expert judgment (based on sensitivity analysis with GLUE)	Trial and error	Steepest descent or PEST
Objective-function	Nash-Sutcliffe effi-ciency coefficient on (Oudin et al. 2006): - $Q^{1/2}$ for the entire hydrograph - Q for the high flows - log(Q) for the low flows	-	-	-	Nash Statistic extreme	Nash-Sutcliffe effi-ciency coefficient, relative volume error, relative extreme value error	-	Nash-Sutcliffe effi-ciency coefficient on (Oudin et al. 2006): - $Q^{1/2}$ for the entire hydrograph - Q for the high flows - log(Q) for the low flows
Efficiency in high flows	-	good	poor	good	good	good	good	good
Efficiency in low flows	-	Not tested	good	Not available	Quite good	moderate	Not available	good

Table 12. Main characteristics of hydrological models used in the framework of the AMICE Project

4.1.1.3 EPICGrid

The EPICGrid hydrological model (Figure 34) has been developed at the FUSAGx (ULg, Gx-ABT). EPICGrid is a physically based distributed model. It affords to realize daily simulations at basin scale. This model is built upon a “major components” approach and takes into account , inside every surface element (1 km x 1 km), the balanced values of land-use, slope, weather and soil characteristics (root zone and vadose zone), growing culture and agricultural practices like fertilization, ploughing, … (*Sohier C. et al., 2009*).

Simulations are realized at daily time step (or hourly time step for some applications), they could be based upon water fluxes, particle fluxes and solute towards surface water and groundwater.

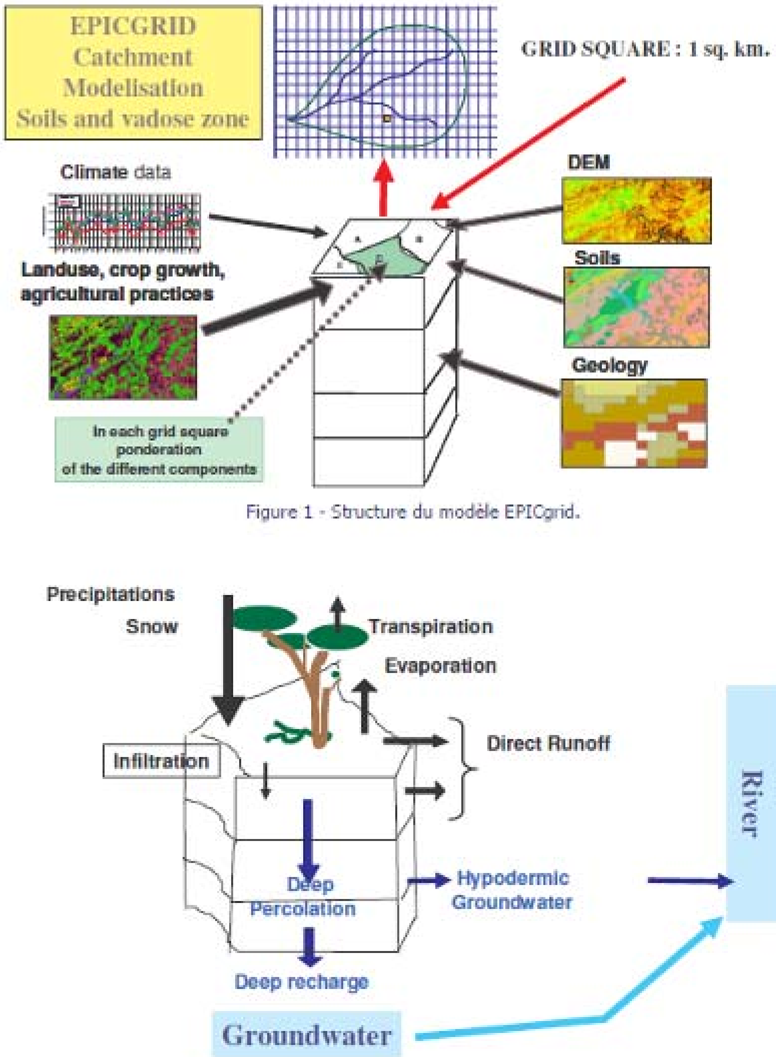


Figure 34. Simulation structure of the EPICGrid model inside an elementary element (*Dautrebande et Sohier, 2006*).

4.1.1.4 RS-PDM

The RS-PDM© software is used to simulate hydrographs for the Meuse sub-basins in the Walloon Region at hourly time step. The RS-PDM © 6.0 is a software from the InforworksTM series, edited by Wallingford software. It implements the Moore theory in order to simulate chronological flows rates.
This conceptual model principle is to attribute a “stock capacity C” in every basin point. The flows rate at the outlet is composed by surface runoff (fast transfer) and a contribution of low hypodermics. Routings are simulated by different transfer functions between successive reservoirs (*Degré et al., 2008*).

4.1.1.5 HBV-96

HBV-96 is a conceptual semi-distributed rainfall-runoff model. Its structure allows deriving discharges based on meteorological data for basins. HBV-Meuse has been calibrated for the period 1969-1984 and validated for the period 1985-1998. The reliability is based on Nash-Sutcliffe efficiencies, standard R2, accumulated difference and visual inspection. It has to be mentioned that Nash and R2 coefficients are more sensitive for deviations in high water periods. Influence of the parameters for low water situations is not researched during calibration as the model is primarily used for high discharge periods and in particular low discharges in the lower part of the basin are heavily influenced by hydraulic infrastructure.

Different calibrations exist for the HBV-Meuse model. Here we applied the 50% parameter set of the Glue analysis by Kramer and Weerts (2008).

4.1.1.6 NASIM

NASIM is a commercial (Hydrotec Ingenieurgesellschaft für Wasser und Umwelt mbH, Aachen) semi-distributed conceptual/physically based rainfall runoff model. It can be used for single event and for continuous simulations. The model provides a breakup of the basin area into a tree structure of tributaries with the fundamental runoff producing units arranged as leaves on the channel tree. The model structure and algorithms defined aim for a compromise between a sufficient degree of sophistication and general applicability under given conditions (*Masoudian, 2009*). The main components of NASIM are

- rainfall formation and distribution,

- runoff components separation: separation into interception, evapotranspiration, infiltration and runoff. The rate at which the different processes occur is closely linked to the soil moisture, which depends on soil specific hydraulic characteristics. The soil properties affecting soil water movement are hydraulic conductivity and characteristics of water retention. A soil layer behaves as a single reservoir. Its content is the soil moisture, inflows are infiltration and capillary suction and outflows are evapotranspiration and percolation. For infiltration and percolation linear and non-linear functions are provided and may be chosen by the user. For the calculation of the interflows several different methods exist and may also be chosen by the user. The actual evapotranspiration is calculated by the approach of Ostrowski, where the determining factors are potential evapotranspiration and soil moisture, assuming a linear relationship. Concerning the overland flows NASIM applies different procedures depending on the surface characteristics. For sealed surfaces surface runoff, evapotranspiration and channel flows are considered. For unsealed surfaces also infiltration, interflows, percolation and base flows are taken into account (*Masoudian, 2009*).

- Runoff concentration: delay and transport in the runoff components. For sealed surfaces translation and retention are calculated following the principal of linear cascades of storages. For unsealed surfaces retention is calculated by a single linear storage. Translation is calculated by a time area function that can either be calculated by a Geographic Information System or be idealized by the user by setting several parameters determining an abstract shape of the watershed (*Masoudian, 2009*).

- Channel flows: deformation of the runoff wave by channel retention using the Kalinin-Miljukov-method. At this the relation between discharge, velocity and flows-depths can be taken from hydraulic models.

NASIM requires time series of precipitation, air temperature and potential evapotranspiration as input. For each subbasin mean elevation, area and percentage of sealed surface have to be provided. The different soils in the basin are described with parameters for field capacity, wilting point, total pore volume, saturated hydraulic conductivity and maximum infiltration capacity. Each land use type is defined with the parameters of root depth, interception storage and sealing. For each basin that receives water from another subbasin, a transport element has to be defined, which can either be a pipe or a stream segment. Depending on the structure and drainage of the basin further elements such as storage basins or channel separation devices may be defined. These require additional information concerning the relation between volume and water level, outflows curves, emergency overflows curves etc (*Masoudian, 2009*).

4.1.2 Calculation methods applied to the Hydrological Impact Variables (HIV)

For achieving the WP1 objectives, the partners decided to work on a common hydrological impact variable set. For low flows, the selected single variable is the MAM7 (mean annual 7-day minimum flows). It was calculated for several return periods: 2-5-10-25-50 years. Concerning the high flows two variables were retained: The Qdx (annual daily maximum discharge) and Qhx (annual hourly maximum discharge). The corresponding return periods are 2-5-10-25-50-100 (+250-1250 for the downstream). Table 13 presents the calculation methods applied to the hydrological impact.

The winter maximum discharge values for different recurrence intervals for the observations and simulations have been calculated using a maximum-likelihood fitting of the Gumbel distribution. Although the goodness of fit cannot be of equal quality for all simulations, according to the Kolmogorov-Smirnov test for a significance level of 5% the Gumbel distribution was never refused.
For the hourly timesteps of both gauges we were faced with the problem that for a significance level of 5% some – not all – of the simulations were identified to hold a trend. We assume that the trend estimation on a significance level of 5% is not representative.

The Mean Annual Minimum 7 days (April to September) discharge values for different recurrence intervals for the simulations and observations were calculated using a maximum-likelihood fitting of the lognormal distribution. According to the Kolmogorov-Smirnov test for a significance level of 5% the lognormal distribution was never refused. The problem of adjusting trends did not occur here.

AGYR is made of 150 sub-basins which make it difficult to update. It was chosen to work on a small number of sub-basins and to try to extrapolate results to the whole French basin (Figure 35).

Rainfall data, modified by the future trends, were applied to a small number of sub-basins (see map) in different places of the French Meuse basin (upstream, middle, downstream). Impact of the modified rainfalls on the discharges was studied for 7 floods: December 1992, January 1993, December 1993, January 1994, December 1994, January 1995, and February 1995.
Each modified flood was compared to present-time flood by comparing the peak discharges.

The study showed that :

- for identical climate variations (same scenario and time-slice) and for the same flood, the modification of the peak discharge is similar wherever the sub-basin is located. We made the assumption that the peak discharge modification could be extrapolated to the whole basin.

- for identical climate variations (same scenario and time-slice), the modification of the peak discharge is different between floods. There are three groups of floods that can be distinguished : major floods with a return period higher than 50 years (Jan. 1993, Dec. 1993, Jan. 1995), medium floods (Dec. 1992, Jan. 1994, Dec. 1994) and small floods with a return period lower than 10 years (Feb. 1995). Each group of flood presents a similar modification of the peak discharge due to climate change scenarios. We concluded that, for similar climate variations and for similar floods, the peak discharge is modified in the same proportions.

Major floods react differently than medium and smaller floods because the underground water and the potential evapotranspiration are negligible in such extreme events. On the contrary, smaller floods are very much influenced by initial conditions.

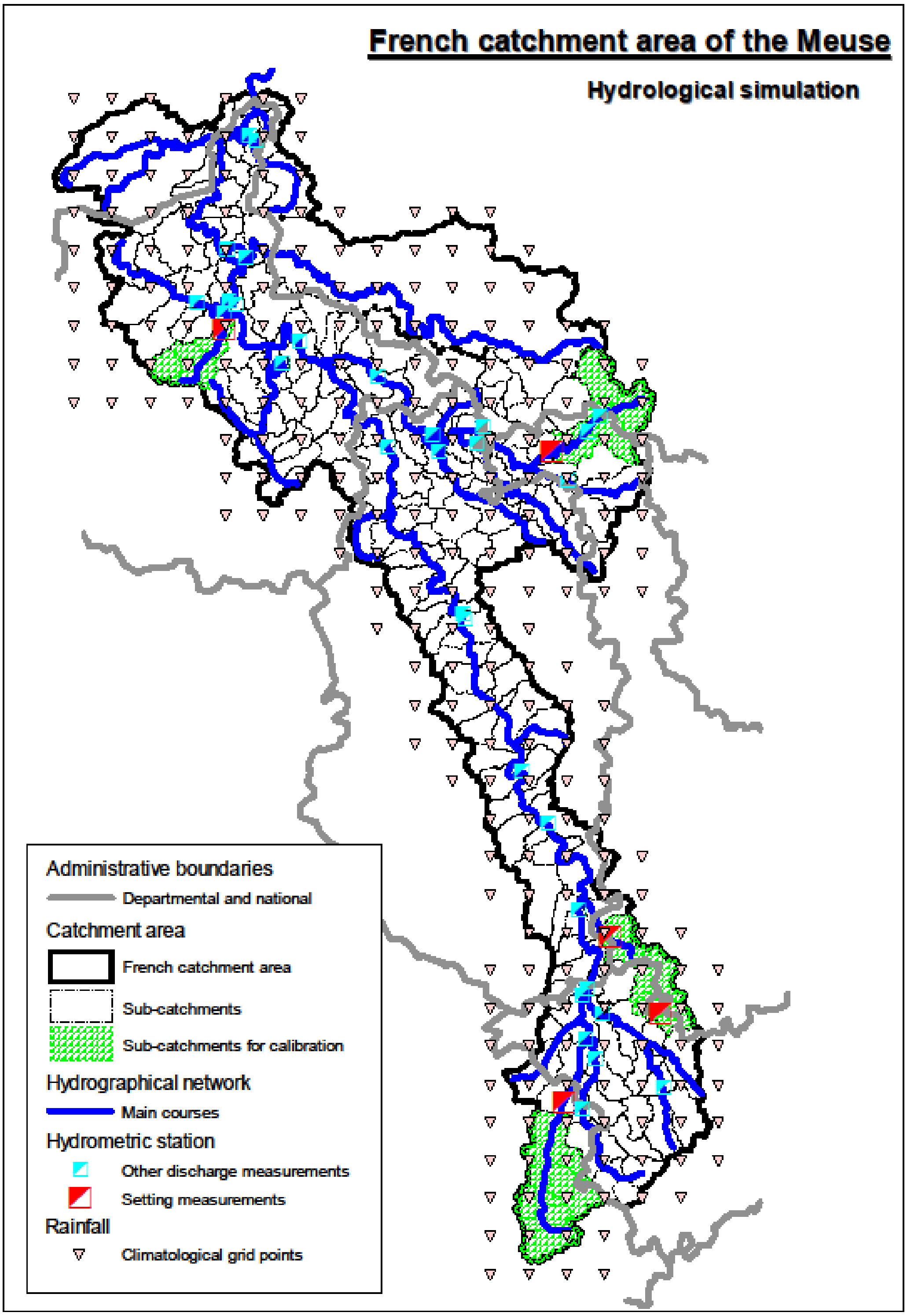


Figure 35. French basin area of the Meuse

		Qhx100		**Qdx100**		**MAM7**	
	Station	**Statistical law**	**Method of parameters estimation**	**Statistical distri-bution**	**Method of parameters esti-mation**	**Statistical law**	**Method of parameters esti-mation**
Meuse	Saint-Mihiel	Gumbel	Maximum-Likelihood	Not calculated		...	...
Meuse	Belleville	/		Not calculated		...	...
Meuse	Stenay	Gumbel		Not calculated		...	...
Meuse	Montcy-notre-Dame	Gumbel		Not calculated		...	...
Meuse	Chooz	Gumbel		Not calculated		...	...
Vesdre	Chaudfontaine	Weibull	Maximum-Likelihood	Weibull/ gamma inverse/gamma	Maximum-Likelihood	Weibull /Gamma	Maximum-Likelihood
Lesse	Gendron	Log-normale/ gamma	Maximum-likelihood	Log-normale	Maximum-likelihood	Weibull	Maximum-Likelihood
Meuse	Sint Pieter	-	-	Gumbel	Maximum-Likelihood		Mean of minimum 7-day sum found for each year
Meuse	Borgharen						
Rur	Stah	Gumbel	Maximum-Likelihood	Gumbel	Maximum-Likelihood	Lognormal	Maximum-Likelihood
Niers	Goch	Gumbel	Maximum-Likelihood	Gumbel	Maximum-Likelihood	Lognormal	Maximum-Likelihood
		Qhx100		**Qdx100**		**MAM7**	
	Station	**Statistical law**	**Method of parameters estimation**	**Statistical distri-bution**	**Method of parameters esti-mation**	**Statistical law**	**Method of parameters esti-mation**
Meuse	Saint-Mihiel	Gumbel	Maximum-Likelihood	Not calculated		...	...

Meuse	Belleville	/		Not calculated		...	...
Meuse	Stenay	Gumbel		Not calculated		...	...
Meuse	Montcy-notre-Dame	Gumbel		Not calculated		...	...
Meuse	Chooz	Gumbel		Not calculated		...	...
Vesdre	Chaudfontaine	Weibull	Maximum-Likelihood	Weibull/ gamma inverse/gamma	Maximum-Likelihood	Weibull /Gamma	Maximum-Likelihood
Lesse	Gendron	Log-normale/ gamma	Maximum-likelihood	Log-normale	Maximum-likelihood	Weibull	Maximum-Likelihood
Meuse	Sint Pieter	-	-	Gumbel	Maximum-Likelihood		Mean of minimum 7-day sum found for each year
Meuse	Borgharen						
Rur	Stah	Gumbel	Maximum-Likelihood	Gumbel	Maximum-Likelihood	Lognormal	Maximum-Likelihood
Niers	Goch	Gumbel	Maximum-Likelihood	Gumbel	Maximum-Likelihood	Lognormal	Maximum-Likelihood
		Qhx100		**Qdx100**		**MAM7**	
	Station	**Statistical law**	**Method of parameters estimation**	**Statistical distribution**	**Method of parameters estimation**	**Statistical law**	**Method of parameters estimation**
Meuse	Saint-Mihiel	Gumbel	Maximum-Likelihood	Not calculated		Lognormal	Maximum-Likelihood
Meuse	Stenay	Gumbel	Maximum-Likelihood	Not calculated		Lognormal	Maximum-Likelihood
Meuse	Montcy-notre-Dame	Gumbel	Maximum-Likelihood	Not calculated		Lognormal	Maximum-Likelihood

Meuse	Chooz	Gumbel	Maximum-Likelihood	Not calculated		Lognormal	Maximum-Likelihood
Vesdre	Chaudfontaine	Weibull	Maximum-Likelihood	Weibull/ gamma inverse/gamma	Maximum-Likelihood	Weibull /Gamma	Maximum-Likelihood
Lesse	Gendron	Log-normal/ gamma	Maximum-likelihood	Log-normal	Maximum-likelihood	Weibull	Maximum-Likelihood
Meuse	Sint Pieter	Gumbel	Maximum-Likelihood	Gumbel	Maximum-Likelihood	Lognormal	Maximum-Likelihood
Rur	Stah	Gumbel	Maximum-Likelihood	Gumbel	Maximum-Likelihood	Lognormal	Maximum-Likelihood
Niers	Goch	Gumbel	Maximum-Likelihood	Gumbel	Maximum-Likelihood	Lognormal	Maximum-Likelihood

Table 13. Presentation and calculation methods applied to the hydrological impact variables

For the Walloons part, the hydrological simulations have been conducted for the Lesse at Gendron and for the Vesdre at Chaudfontaine.

The following data have been used for the Lesse at Gendron :

- Hourly flows rate between 1968-2000
- Hourly rainfall between 1968-2000
- Daily flows rate between 1980-2000
- Daily rainfall between 1980-2000

The following data have been used for the Vesdre at Chaudfontaine:

- Hourly flows rate between 1968-2000
- Hourly rainfall at Battice between 1987-2008
- Hourly rainfall at Balmoral between 1987-2008
- Hourly rainfall at Jalhay between 1987-2008
- Hourly rainfall at Ternell between 1987-2008
- Daily rainfall at Ternell between 1959-2007

Rainfall data have been perturbed with common perturbation factors for the Meuse River Basin for time slices 2020-2050 and 2070-2100.

Estimation of maximum high-flows discharge values

The method of yearly maximums is the classical method used to evaluate exceptional high-flows discharge values. It consists in adjusting a statistical law to the set of yearly maximum flows rate observed or simulated. The work was done on the basis of hydrological years, from October 1st to September 30th of the following year.

The HYFRAN software, developed by the University of Québec, allows testing no less than 15 classical statistical laws, among them Gumbel law, Gamma, Weibull, exponential, Pareto, lognormal, Pearson III and GEV. The HYFRAN software allows classifying the laws tested based upon the posterior probability, this one takes into account the statistical quality of the adjustment and parsimony principle, giving priority to the 2 parameters laws.

The 5 best classed are retained and the χ^2 test is applied in order to control the adequacy of laws to the sample of observed values. Afterwards, a choice of the best law is performed visually by graphical analysis of the 5 best adjustments (Dautrebande and Sohier, 2006).

Estimation of low-flows discharge values

The method of the "mean annual 7-days minimum flows" (MAM7) has been used here. The HYFRAN software has also been used in order to adjust a statistical law to the observed and simulated MAM7 set by hydrological year.

The methodology is the same as the one used for maximum high flows discharge values.

For the Flemish part, the climate scenarios are constructed with a transformation routine from Belgian Science Policy Project "Climate Change Impact on Hydrology" (CCI-Hydr, www.kuleuven.be/hydr/cci/CCI-HYDR) by the Hydraulics Laboratory from the KULeuven University and the Belgium Royal Meteorological Institute (KMI) for the period 2071-2100. The Belgian climate change scenarios are time series on a daily base for precipitation, air temperature and potential evaporation (ETo). For all three scenarios and a control period simulation is done with HBV-Maas by Deltares. The simulated discharges at Borgharen (boundary between

Belgium and the Netherlands) are analysed. The three highest discharges are selected in each scenario and from 10 days before till 10 after the peak and simulated in SOBEK-Maas. HBV results are analysed based on average yearly and seasonal discharges and the 90% percentiles of the discharges of all simulation runs. An analysis is done to compare the highest discharge in the HBV-Maas and SOBEK-Maas models.

For the Netherlands values have been calculated using HBV for Sint Pieter, close to the border with Belgium. In a later phase of the AMICE project with hydraulic simulations more down-stream locations will be added.

Extreme high discharges are calculated for 2, 5, 10, 25, 50, 100, 250, 500 and 1250 year return periods. For return periods with T < 25 years the Pareto distribution with a threshold of 1300 m3/s has been applied. For return periods longer than 25 years the censored Gumbel distribution has been applied to the year maxima. In the Netherlands for the Meuse at Sint Pieter flows below 1000 m3/s are censored. Values have been adjusted linearly to values resulting from extensive statistical analysis, which are based on a much longer discharge record (ca. 100 years).

For low discharges no standard method exists. As measured discharges at Sint Pieter are strongly influenced by hydraulic infrastructure upstream, care should be taken with these values as only hydrological modelling is applied in this part of the study. However, the relative change is expected to give a good indication of the expected trend according to the climate scenario.

4.2 Results of hydrological simulations

This paragraph presents the hydrological simulations performed on the four national sub-basins for the 9 gauging stations. In order to compare the trends we calculated the climate change factor (derived from winter maximum hourly discharge series) for :

- The two time slices : 2021-2050 & 2071-2100
- The transnational scenario and the national scenarios
- The wet & dry scenarios

The climate change factor is defined as : Qsimulated(scenario)/ Qsimulated (present climate) which is the same as writing : Qscenario/Qcontrol

A value above 1 means an increase of the present discharge value whereas a value below 1 means a decrease of the present discharge value. Results are presented in tables 14 to 17.

For the transnational scenario the change in discharge is logically homogeneous across the basin (increase in discharge for the wet scenario and decrease in discharge for the dry scenario). These trends are more pronounced for the end of the century.

Concerning the national scenarios the results are more divergent especially on the French part of Meuse where the discharges decrease whatever the scenario is (wet or dry).

Climate change factors based on the Mean Annual Minimum 7-days (April-Sept.) discharge values (MAM7) were also calculated and are presented in table 18.

T[y]	Meuse St-Mihiel	Meuse Stenay	Meuse Montcy	Meuse Chooz	Meuse Sint Pieter	Lesse Gendron	Vesdre Chaudfontaine	Rur Stah	Niers Goch
2	1.12 0.96	1.12 0.96	1.12 0.96	1.12 0.96	1.12 0.92	1.17 0.97	1.02 0.86	1,07 0,84	1,08 0,88
5	1.12 0.96	1.12 0.96	1.12 0.96	1.12 0.96	1.15 0.91	1.17 0.98	1.05 0.88	1,05 0,86	1,10 0,88
10	1.12 0.93	1.12 0.93	1.12 0.93	1.12 0.93	1.16 0.93	1.18 0.98	1.06 0.89	1,04 0,87	1,10 0,89
25	1.12 0.93	1.12 0.93	1.12 0.93	1.12 0.93	1.13 0.95	1.18 0.98	1.07 0.89	1,03 0,87	1,11 0,89
50	1.12 0.96	1.12 0.96	1.12 0.96	1.12 0.96	1.14 0.95	1.19 0.98	1.08 0.90	1,02 0,88	1,11 0,89
100	1.12 0.96	1.12 0.96	1.12 0.96	1.12 0.96	1.14 0.95	1.19 0.98	1.08 0.90	1,02 0,88	1,11 0,89

Table 14. Climate change factors (derived from winter maximum hourly discharge series) as a function of the recurrence interval T[y] for different sub-basins of the Meuse River
Period **2021-2050** vs 1961-1990 - wet scenario & dry scenario - **Transnational climate scenarios**

T[y]	Meuse St-Mihiel	Meuse Stenay	Meuse Montcy	Meuse Chooz	Meuse Sint Pieter	Lesse Gendron	Vesdre Chaudfontaine	Rur Stah	Niers Goch
2	0.89 0.86	0.89 0.86	0.89 0.86	0.89 0.86	1.09 1.07	1,48 0,86	1,42 0,85	1.14 0.90	1.21 0.93
5	0.89 0.86	0.89 0.86	0.89 0.86	0.89 0.86	1.11 1.11	1,52 0,82	1,49 0,87	1.15 0.92	1.23 0.93
10	0.89 0.82	0.89 0.82	0.89 0.82	0.89 0.82	1.10 1.12	1,56 0,80	1,53 0,88	1.15 0.93	1.24 0.93
25	0.89 0.82	0.89 0.82	0.89 0.82	0.89 0.82	1.08 1.11	1,58 0,79	1,55 0,88	1.16 0.94	1.24 0.93
50	0.90 0.86	0.90 0.86	0.90 0.86	0.90 0.86	1.07 1.11	1,59 0,78	1,57 0,88	1.16 0.94	1.25 0.93
100	0.90 0.86	0.90 0.86	0.90 0.86	0.90 0.86	1.07 1.11	1,60 0,77	1,59 0,89	1.16 0.95	1.25 0.93

Table 15. Climate change factors (derived from winter maximum hourly discharge series) as a function of the recurrence interval T[y] for different sub-basins of the Meuse River
Period **2021-2050** vs 1961-1990 - wet scenario & dry scenario – **National climate scenarios**

T[y]	Meuse **St-Mihiel**	Meuse **Stenay**	Meuse **Montcy**	Meuse **Chooz**	Meuse **Sint Pieter**	Lesse **Gendron**	Vesdre **Chaudfontaine**	Rur **Stah**	Niers **Goch**
2	1.27 0.89	1.27 0.89	1.27 0.89	1.27 0.89	1.21 0.79	1.33 0.83	1.11 0.74	1,11 0,60	1,16 0,70
5	1.27 0.89	1.27 0.89	1.27 0.89	1.27 0.89	1.30 0.88	1.40 0.86	1.18 0.77	1,11 0,60	1,20 0,71
10	1.29 0.81	1.29 0.81	1.29 0.81	1.29 0.81	1.33 0.92	1.45 0.87	1.21 0.78	1,10 0,61	1,21 0,71
25	1.29 0.81	1.29 0.81	1.29 0.81	1.29 0.81	1.31 0.90	1.49 0.88	1.23 0.79	1,10 0,61	1,22 0,71
50	1.27 0.89	1.27 0.89	1.27 0.89	1.27 0.89	1.32 0.91	1.52 0.89	1.25 0.80	1,10 0,61	1,23 0,71
100	1.27 0.89	1.27 0.89	1.27 0.89	1.27 0.89	1.33 0.91	1.55 0.90	1.27 0.81	1,10 0,61	1,24 0,71

Table 16. Climate change factors (derived from winter maximum hourly discharge series) as a function of the recurrence interval T[y] for different sub-basins of the Meuse River
Period **2071-2100** vs 1961-1990 - wet scenario & dry scenario - **Transnational climate scenarios**

T[y]	Meuse **St-Mihiel**	Meuse **Stenay**	Meuse **Montcy**	Meuse **Chooz**	Meuse **Sint Pieter**	Lesse **Gendron**	Vesdre **Chaudfontaine**	Rur **Stah**	Niers **Goch**
2	0.84 0.64	0.84 0.64	0.84 0.64	0.84 0.64	1.17 1.18	1,79 0,79	1,66 0,81	1,51 0,98	1.62 1.00
5	0.84 0.64	0.84 0.64	0.84 0.64	0.84 0.64	1.21 1.26	1,81 0,75	1,76 0,81	1,51 1,00	1.70 1.02
10	0.74 0.56	0.74 0.56	0.74 0.56	0.74 0.56	1.20 1.28	1,82 0,74	1,81 0,81	1,51 1,01	1.73 1.03
25	0.74 0.56	0.74 0.56	0.74 0.56	0.74 0.56	1.16 1.25	1,83 0,72	1,84 0,80	1,51 1,02	1.75 1.04
50	0.83 0.63	0.83 0.63	0.83 0.63	0.83 0.63	1.16 1.26	1,83 0,72	1,87 0,80	1,51 1,02	1.77 1.04
100	0.83 0.63	0.83 0.63	0.83 0.63	0.83 0.63	1.16 1.26	1,84 0,71	1,89 0,80	1,51 1,02	1.78 1.05

Table 17. Climate change factors (derived from winter maximum hourly discharge series) as a function of the recurrence interval T[y] for different sub-basins of the Meuse River
Period **2071-2100** vs 1961-1990 - wet scenario & dry scenario – **National climate scenarios**

One of the main lacks in the AMICE project is the study of extreme rainfalls on small basins. Extreme rainfalls concentrated on small-scale areas can create devastating mudfloods. The impact is very limited on the water level in the main rivers but the damages are very costly locally. Contrary to large floods that happen mostly in winters, extreme rainfalls can occur anytime of the year. Such events happened for example in the eastern neighbourhood of Liege in May 2009.

Climate scenarios predict that these extreme events will occur more frequently. But this phenomenon is hardly known in the Meuse basin. There is no detailed monitoring or analysis of their frequency and causes. It is also very hard to forecast the location and intensity of such event, even harder to model it. It would be much too hazardous to apply climate change on an already uncertain phenomenon. Consequently, the AMICE Partners will limit themselves to mentioning that extreme rainfalls could be more frequent in the future century (Christensen and Christensen, 2003).

5 Selection of hydrological scenarios

In order to synthesize the results presented above, table 18 shows the four final hydrological scenarios selected for the AMICE project for most extreme low/high flows, wet and dry climate scenarios. These final hydrological scenarios aggregate results of transnational (France, Belgium and Netherlands) and national scenarios (Germany) for the two main impact variables: Qhx100 for high flows (centennial flood peak) and MAM7 (Mean Annual Minimum 7-days (April-Sept.) discharge values) for low flows.

		Meuse **St-Mihiel**	Meuse **Stenay**	Meuse **Montcy**	Meuse **Chooz**	Meuse **Sint Pieter**	Lesse **Gendron**	Vesdre **Chaud-fontaine**	Rur **Stah**	Niers **Goch**
MAM7	**2021-2050**	0.79 0.61	0.73 0.64	0.88 0.75	0.88 0.74	0.82 0.65	1.00 0.83	1.17 0.93	0.68 0.56	0.84 0.63
	2071-2100	0.60 0.43	0.50 0.47	0.71 0.52	0.65 0.52	0.60 0.33	0.96 0.57	1.10 0.67	0.71 0.36	0.60 0.27
Qhx100	**2021-2050**	1.12 0.96	1.12 0.96	1.12 0.96	1.12 0.96	1.14 0.95	1.19 0.98	1.08 0.90	1.02 0.88	1.11 0.89
	2071-2100	1.27 0.89	1.27 0.89	1.27 0.89	1.27 0.89	1.33 0.91	1.55 0.90	1.27 0.81	1.10 0.61	1.24 0.71

Table 18. Values of climate change factors for the most extreme hydrological scenarios selected for the AMICE project for low flows/high flows/wet and dry climate scenarios.

The AMICE Partners met on March 11th, 2010 at the University of Metz to discuss their results and present them to a panel of stakeholders operating within the Meuse river basin.

The table 18 thus displays MAM7 from the summer season (i.e. from April to September) and Qhx100 from the winter season (i.e. from October to March).

These hydrological scenarios will be used by AMICE partners involved in the next actions, particularly the one dedicated to hydraulic modeling. It is indeed important to agree on similar values between countries and to limit the number of simulations. The AMICE Partners selected the most extreme values only: the wet climate scenario value for high-flows and the dry climate scenario value for low-flows.

All other simulations under the transnational climate scenarios lie within this range of hydrological situations.

The **final selected hydrological scenarios** correspond to:

- An increase in **Qhx100 (centennial hourly flood peak)** of **+15% for 2021-2050** and **+30% for 2071-2100**
- A decrease in **MAM7** (Mean Annual Minimum 7-days (April-Sept.) discharge values) of **-10%** for **2021-2050** and **-40% for 2071-2100**

6 Outlook

In the process of checking if there is a reasonable scientific backing for the AMICE climate scenarios, the AMICE partners involved in Action 3 had a post-meeting discussion after the meeting of March 11th, 2010.

Another possible approach that could be tested is to analyse the FP7 Ensemble results for the Meuse to get a more scientific understanding of how changes can happen. This could be done in parallel with the AMICE project. The University of Metz already compared the AMICE scenarios with the results of the Prudence project. The next step would be to compare the AMICE scenarios with more recent ENSEMBLE results. This might be done during the third year, when AMICE partners are able to start the additional work. The idea is not to change the AMICE scenarios, but to compare them with the most recent climate model results.

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