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Adaptation of the Meuse to the impact of climate change

Subreport I: Bibliographic study of climate change and impact on hydrology of the Meuse basin for high and low water situations

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Moeskops, S.; Smets, S.; De Sutter, R.; Holvoet, K.; Vanneuville, W.; Mostaert, F.

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Waterbouwkundig Laboratorium

Flanders Hydraulics Research

Berchemlei 115
B-2140 Antwerp
Tel. +32 (0)3 224 60 35
Fax +32 (0)3 224 60 36
E-mail: waterbouwkundiglabo@vlaanderen.be
www.watlab.be

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Abstract

The present subreport I – Bibliographic study of climate change and impact on hydrology of the Meuse basin for high and low water situations – fits within the AMICE study for a coordinated strategy for the Adaptation of the Meuse to the Impacts of Climate Evolutions on floods and low-flows with the perspective of sustainable development in the Meuse international catchment basin. This literature review focuses on the Flemish part of the Meuse basin.

Climate change will induce effects on precipitation and by so, on discharges and water levels, as the Meuse is a typical rain fed river. Precipitation will be more clustered with more and longer periods of precipitation in winter and more and longer periods of drought in summer. The changes in discharge regime are less pronounced due to increased evaporation and the natural storage capacity of the catchment, although different studies predict an increase in average discharge at the end of the winter and a decrease of average summer discharge.

As the water in the Meuse is being used for agriculture, navigation, drinking water, energy production and industry, the Meuse has an economical value of hundreds million euros a year. To ensure these economic activities in the future, water hazard mitigation measures should include climate change. However, the existing projects in Flanders mainly focus on flood control and ecological development. To assess the impact of on the one hand climate change and on the other hand change in water management and river works, mathematical models are applied. Such models are also utilized in flood and low water forecasting.

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Samenvatting

De studie – Adaptatie van de Maas aan de gevolgen van klimaatverandering (Bestek nr. WL/09/19) – wordt uitgevoerd in het kader van het Interreg IV B AMICE project. De globale doelstelling van AMICE (Adaptation of the Meuse to the Impacts of Climate Evolutions) is te komen tot een gecoördineerde strategie voor de adaptatie van de Maas aan de impact van klimaatsverandering op wateroverlast en watertekort in het perspectief van een duurzame ontwikkeling van het internationale stroomgebieddistrict Maas (www.amice-project.eu). AMICE verenigt overheden, universiteiten en NGO's uit vijf lidstaten uit Noordwest Europa. Het Waterbouwkundig Laboratorium is partner van AMICE.

De hieronder beschreven deelrapporten vallen onder het Werkpakket I - Impact van toekomstige overstromingen en laagwatersituaties – van het AMICE project. WP I omvat een technische en wetenschappelijke analyse van door klimaatverandering geïnduceerde overstromingen en watertekorten door inzet van (voorspellings-)modellen, efficiëntie van waterbeheermaatregelen, schadeberekeningen en voorstellen voor oplossingen. In de opdracht worden volgende deelopdrachten voorzien:

- Deelrapport I: Bibliografische studie van klimaatverandering en impact op hydrologie Maasbekken voor hoog- en laagwatersituaties
- Deelrapport II: Aanpassingen hydraulisch model Maas en scenarioberekeningen

Het literatuuroverzicht in deze deelopdracht heeft als doel de kennis van het stroomgebied Maas te vergroten en internationaal uit te wisselen om ook toekomstige eigenschappen en hydrologisch gedrag van het Maasbekken in te schatten. Het voorliggende deelrapport behandelt het Vlaamse gedeelte van het Maasbekken. Een belangrijke bron aangaande dit deel van de Maas is het inventarisatierapport "Bekken van de Gemeenschappelijke Maas" uitgevoerd door het Waterbouwkundig Laboratorium in 2004 (Baetens et al., 2004). Dit rapport zal als uitgangsbasis genomen worden, waarbij hoofdzakelijk documenten van na 2004 beschouwd zullen worden voor onderhavig rapport. Hierbij vormt het Bekkenbeheerplan van de Maas (CIW, 2009) een belangrijke bijdrage. De opbouw van het rapport is overgenomen van de AMICE referentie databank (www.amice-project.eu/biblio). Alle referenties uit deze studie zijn opgenomen in deze databank.

Zoals beschreven in Hoofdstuk 2 Geographical area kent het Vlaamse gedeelte van het Maasbekken een oppervlakte van 1596 km² en vormt de Maas tussen Lanaken en Smeermaas de grens met Nederland – de Grensmaas – over een afstand van 47 km. Hoofdstuk 3 Physiography bevat uitleg over geologie, pedologie, topografie, hydrogeologie, geomorfologie, landgebruik, biodiversiteit en waterkwaliteit.

Het Maasbekken ligt in een zone met gematigd maritiem klimaat met een gemiddelde neerslag van 900 mm/jaar. Regen wordt hoofdzakelijk aangebracht door westenwinden. Om de schommeling van neerslag te bestuderen in klimaatmodellen moet dus gekeken worden naar de frequentie van de westelijke circulatiepatronen (Hoofdstuk 4 Climatology).

Het jaargemiddelde debiet van de Maas ter hoogte van Borgharen ligt op 276 m³/s (Hoofdstuk 5 Hydrology). In extreme situatie kan het debiet echter sterk verschillen. Zo bedraagt het maximum dagdebiet 3039 m³/s (1993) en het minimum dagdebiet 9 m³/s (1976) (Hoofdstuk 5 Hydrology).

Klimaatsverandering zal effecten hebben op neerslag, en bijgevolg ook op afvoeren, aangezien de Maas een typische regenrivier is. Neerslag zal meer geclusterd vallen, met meer en langere regenperiodes in de winter en meer en langere droogteperiodes in de zomer. De verandering in afvoer z al minder uitgesproken zijn ten gevolge van de verhoogde evaporatie en de natuurlijke bergingscapaciteit van het bekken, maar toch voorspellen verschillende studies een verhoogde afvoer in de winter en een vermindering van debiet in de zomer (Hoofdstuk 6 Trend analysis).

Het water van de Maas wordt in verschillende sectoren gebruikt, zoals landbouw, scheepvaart, drinkwater, energieproductie en industrie. Bijgevolg heeft de Maas in zijn volledige stroomgebied een economische waarde van honderden miljoenen euro per jaar (Hoofdstuk 7 Water uses). Om deze economische activiteiten in de toekomst te kunnen blijven verzekeren dienen risico beperkende maatregelen genomen te worden. De bestaande projecten, zoals "Levende Grensmaas" leggen echter de nadruk op overstromingsbeheersing en natuurontwikkeling, maar houden echter nog niet expliciet rekening met de klimaatsverandering (Hoofdstuk 8 Water hazard mitigation).

Om een inschatting van enerzijds klimaatsverandering en anderzijds verandering in waterbeheer en rivierinrichting te kunnen maken, wordt gebruik gemaakt van mathematische modellen. Deze modellen worden aangewend om overstromingskaarten te genereren en om voorspellingen te maken in verband met hoog- en laagwater. De overstromingskaarten worden gecombineerd met schadekaarten om het overstromingsrisico te bepalen. Deze risico methodologie benadering wordt in Vlaanderen toegepast, terwijl in Nederland met een maximum afvoer rekening wordt gehouden (Hoofdstuk 9 Water management system).

1 Introduction

The study – adaptation of the Meuse to the impact of climate change (Bestek nr.WL/09/19) – is part of the Interreg IV B AMICE project. The aims of AMICE (Adaptation of the Meuse to the Impacts of Climate Evolutions) are the development of a basin-wide climate adaptation strategy for the Meuse, coordinated transnationally and focused on water discharges and the functions influenced by them and the realisation of a set of measures against low flows and floods (www.amice-project.eu). AMICE unites public authorities, universities and NGOs from five NWE regions. Flanders Hydraulics Research is a partner of AMICE.

The subreports described below fall under Work Package I – Impacts of future floods and low flows – of the AMICE project. WP I focuses on a technical and scientific analysis of climate-change-induced floods and low flows by application of prospective modelling, efficiency of water management measures, damage calculation and proposition of solutions. The following subreports are distinguished:

- Subreport I: Bibliographic study of climate change and impact on hydrology of the Meuse basin for high and low water situations
- Subreport II: Adaptations of the hydraulic Meuse model and scenario calculations

The purpose of the bibliographic study is to enlarge the knowledge of the Flemish part of the Meuse basin to make it possible to internationally exchange knowledge and assess future characteristics and hydrological behaviour of the Meuse basin. The present subreport I takes the Flemish part of the Meuse basin into account. An important document in describing this part of the Meuse is the inventory executed by Flanders Hydraulics Research in 2004 (Baetens et al., 2004). This document will be taken as a starting point and mainly the documents updating this inventory will be included in this report. For this purpose, the basin management plan of the Meuse (CIW, 2009) is an important source of information.

The structure of the report is being adopted of the AMICE references database (www.amice-project.eu/biblio). First, the geography (Chapter 2) and physiography (Chapter 3) of the Flemish Meuse basin are discussed. Chapter 4 contains a description of the present climate. The hydrology of the Border Meuse is treated in Chapter 5. An analysis of trends in precipitation, evaporation and discharges can be found in Chapter 6. Information about water uses is written down in Chapter 7. Chapter 8 acts on water hazard mitigation. Finally, the water management system in Flanders is explained in Chapter 9. All references of this study are included in the AMICE references database.

2 Geographical area

The Meuse basin contains parts of France, Luxembourg, Belgium, Germany and the Netherlands. The total basin area amounts to 34 359 km², of which 1 596 km² (<5%) in Flanders. The basin is situated in the provinces of Limburg (1043 km²) and Antwerp (553 km²). The total length of the River Meuse is 935 km. Between Lanaken (Smeermaas) and Kinrooi (Kessenich) the Meuse forms the border between Flanders and the Netherlands ("The Border Meuse") over a length of 47 km (CIW, 2009).

A general situation of the Meuse basin in Flanders is given in
Figure 1.The division of the basin in sub basins is presented in
Figure 2. Table 1 gives an overview of Flemish municipalities in the Meuse basin. A list and figure of linear and planar surface water bodies can be found in the Bekkenbeheerplan Maas (CIW, 2009).

This report mainly focuses on the Limburg part as this encloses the Flemish River basin of the Meuse. The Antwerp part of the Meuse basin flows towards the Netherlands into the Dutch Meuse, and by so, is not the object of this study of the Flemish Meuse River basin.

Figure 1 – Situation of the Meuse basin in Flanders (CIW, 2009)

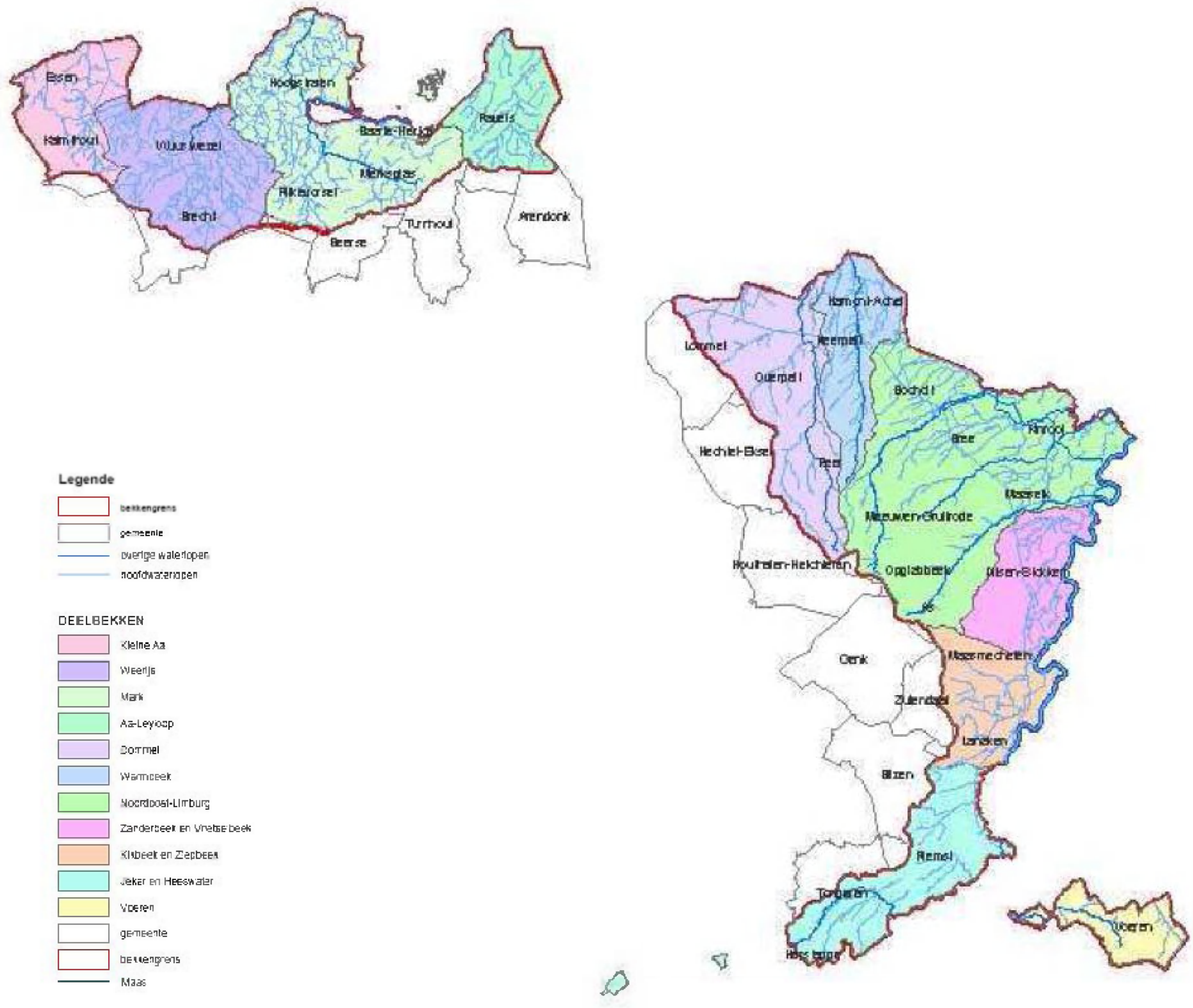

Figure 2 – Sub basins of the Meuse basin (CIW, 2009)

Table 1 – Municipalities in the Meuse basin (CIW, 2009).

Province	Municipality *Underlined municipalities are lying completely in the Meuse basin; non-underlined municipalities are lying partly in the Meuse basin*
Limburg	As, Bilzen, <u>Bocholt</u>, <u>Bree</u>, <u>Dilsen-Stokkem</u>, Genk, Gingelom, <u>Hamont-Achel</u>, Hechtel-Eksel, Heers, <u>Herstappe</u>, Houthalen-Helchteren, <u>Kinrooi</u>, <u>Lanaken</u>, Lommel, <u>Maaseik</u>, <u>Maasmechelen</u>, Meeuwen-Gruitrode, <u>Neerpelt</u>, Opglabbeek, Overpelt, <u>Peer</u>, Riemst, Tongeren, <u>Voeren</u>, Zutendaal
Antwerp	Arendonk, <u>Baarle-Hertog</u>, Beerse, Brecht, <u>Essen</u>, <u>Hoogstraten</u>, Kalmthout, Merksplas, Ravels, Rijkevorsel, Turnhout, Wuustwezel

3 Physiography

3.1 Geology

Concerning geology, the Meuse basin can be divided into 3 zones (Baetens et al., 2004):

- The Lorraine Meuse (upstream of Charlesville-Mézières): sedimentary Mesozoic rock formations
- The Ardennes Meuse (between Charlesville-Mézières and Liège): Palaeozoic rocks of the Ardennes Massif
- The Lowland Meuse (downstream Liège): Cainozoic unconsolidated sedimentary rocks (sand, gravel, loess, clay)

The Flemish part of the Meuse basin belongs to the Lowland Meuse. Geology and relief are described widely in the inventory of Baetens et al. (2004).

3.2 Pedology

Information about the pedology can be found in the inventory of Baetens et al. (2004). In summary, the region southwards of the Albertkanaal and Voeren is dominated by a very dry loamy soil, the valley of the Meuse to the border of the Kempisch Plateau has a very dry sandy loamy soil and the Plateau van de Kempen consists of a very dry sandy soil. The valleys of the Abeek, Lossing, Itterbeek, Bosbeek and the Kempens Broek are wet zones.

Figure 3 shows the soil map of the Flemish Meuse basin.

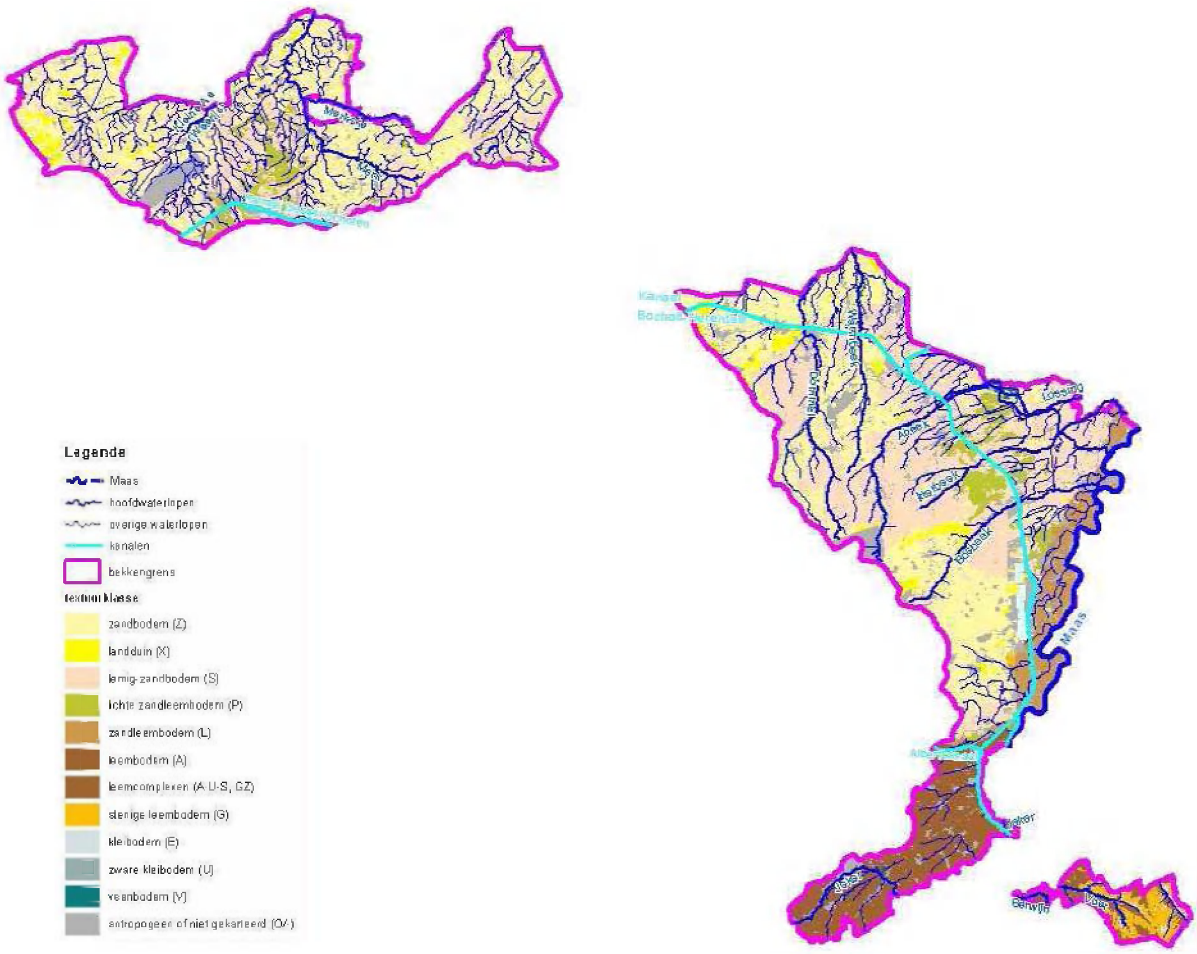

Figure 3 – Soil map of the Meuse basin (CIW, 2009)

3.3 Topography

The Limburg part of the Meuse basin has an elevation between 20 and 160 m TAW. However, Voeren has a higher elevation of 140 to 285 m TAW. More downstream, in the Antwerp part, altitudes are between 5 and 40 m TAW. The topography of the Flemish Meuse basin can be seen in Figure 4 (CIW, 2009).

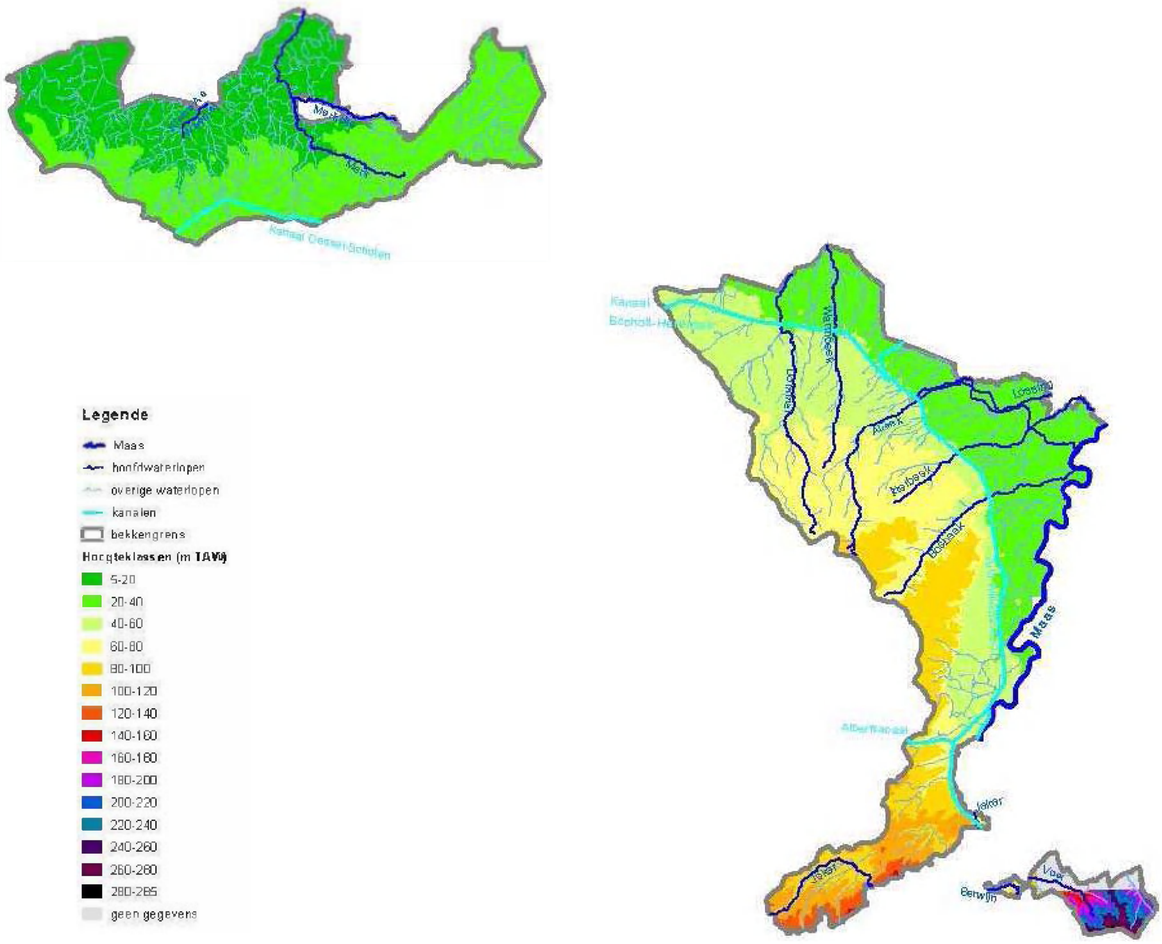

Figure 4 – Topography of the Meuse basin (CIW, 2009)

3.4 Hydrogeology

The deeper groundwater does not follow necessarily the hydrographical border of the basin. Three groundwater systems are present in the Meuse basin: the entire Maassysteem, the northern part of the Centraal Kempisch Systeem and a small eastern part of the Brulandkrijtsystem (D'Hondt et al., 2008a).

Figure 5 shows the situation of the Flemish groundwater systems. More information about these groundwater systems can be found in the VMM reports (D'Hondt et al., 2008a, 2008b, 2008c). A quantitative and qualitative evaluation is also given by the Bekkenbeheerplan Maas (CIW, 2009).

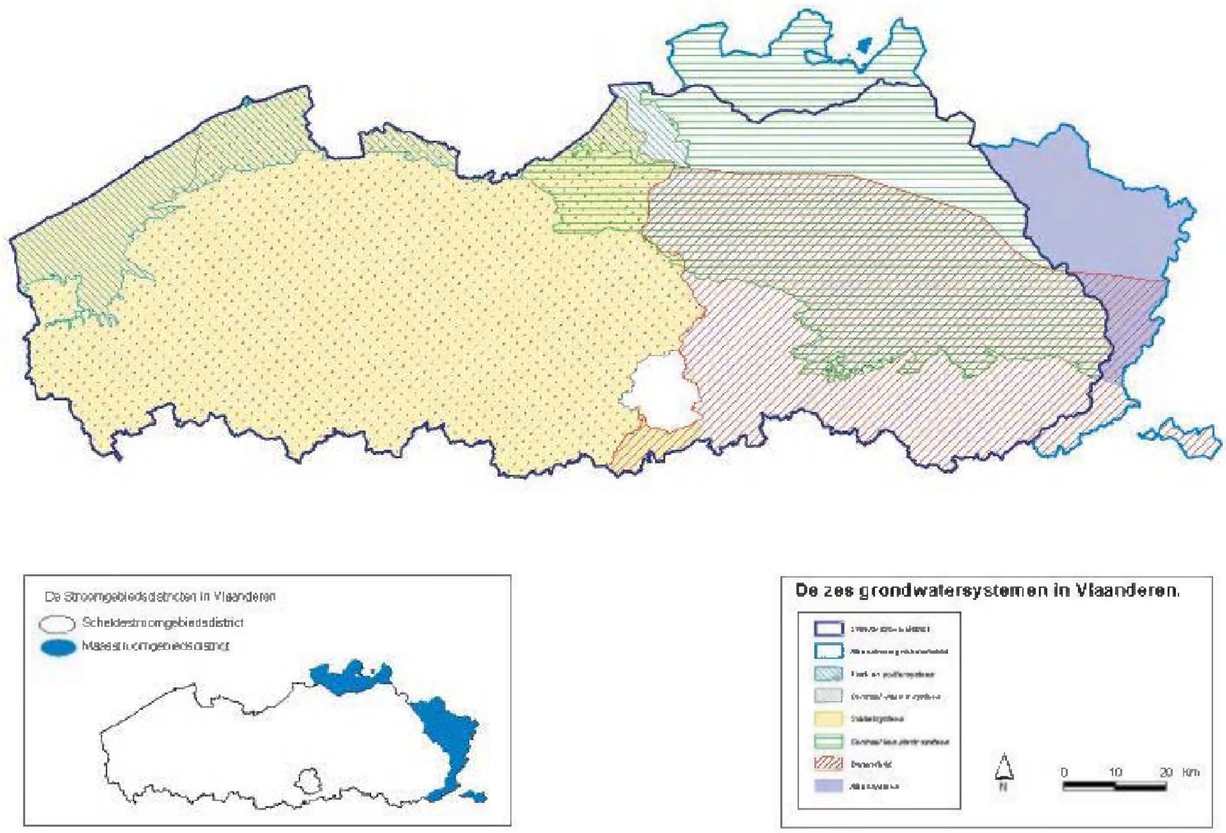

Figure 5 – The six groundwater systems in Flanders (D'Hondt et al., 2008a)

A regional groundwater model of the Maassysteem is made by Severyns et al. (2004). The report also contains a broad description of the hydrogeological layers and fractures. The most important fractions are the Feldbiss- and Heerlerheidebreuk. The Quaternary layers are classified in three entities: sand and gravel from the Afzettingen van het Hoofdterras (HCOV 0171), sand and gravel from the Afzettingen van het Tussenterras (HCOV 0172) and alluvial sediment from the Afzettingen van de Maasvlakte (HCOV 0173). The Tertiary formations are subdivided in the sedimentations northwards and southwards from the Feldbiss fraction zone.

In the groundwater model of Severyns et al. (2004), data is used from 330 groundwater level measuring points, of which 88 contain data of more than 10 years including the year 2000. On these points, a time series analysis is being executed. It is concluded that the Quaternaly aquifers display no trend and that the seasonal influence is limited, except for the Afzettingen van de Maasvlakte (HCOV 0173). In the upper layers of the sedimentations northwards of the Feldbissbreuk, a positive trend and seasonal influences are remarked. Both conclusions can be explained by the water levels on the Meuse. The groundwater collection is an explanation of the remarked decreasing trends and breakages in trends in deeper layers.

The report of Severyns et al. (2004) also contains groundwater level maps created for the year 2000. The maps show clearly that the global groundwater flow is orientated from the Kempisch Plateau towards the lower lying Vlakte van Bocholt and the alluvial plain. The groundwater level decreases from circa 65 m TAW at the watershed crest on the Kempisch Plateau to 25 m TAW at the northern part of the alluvial plain.

The flow of subsoil water is influenced by the following factors (Baetens et al., 2004):

- Fluctuating water levels in the Meuse
- Damming structures like weirs, locks, retaining walls, …
- Artificial waterways like canals
- Water collection by water companies and industries
- Collection of gravel
- Collapsing of mines

The average supply of soil water towards the Meuse amounts to 1.16 m³/s coming from the Plateau van de Kempen and 1.6 m³/s coming from the eastern side of the valley. In dry periods, with low water levels on the Meuse, more soil water is migrating towards the river, about 7.3 m³/s to 4.3 m³/s (Baetens et al., 2004). As a consequence, the groundwater table has lowered at the end of the summer. Compared to the end of the winter, the difference in groundwater table is about 125 mm, or 5 km³ for the entire basin of the Meuse (De Wit, 2008).

There is a clear interaction between the surface water system and the groundwater system. The groundwater level follows the Meuse level almost without retardation, due to the good porosity of the gravel/sand layer in the Meuse valley (Michielsen et al., 2007).

At some places, the surface level is beneath the natural groundwater level as a consequence of the mine collapsing. Pumping stations have to keep the groundwater beneath a safe distance under the surface level (Baetens et al., 2004).

3.5 Geomorphology

The part of the Meuse basin situated in the province of Antwerp has a flat landscape. The dominating relief is the east-west microcuesta, with a relatively steep southern slope and a slight northern slope formed under the influence of the Klei van de Kempen. The most important relief characteristics of the Limburg part of the Meuse basin are the Kempisch Plateau, the Maasvallei and the higher located, inclining loam grounds in Voeren and southwards the Albertkanaal (CIW, 2009).

As a consequence of the exploiting of coal in Limburg during the 20th century, the extracted coal layers were filled up by the collapsing of the upper lying layers. This resulted in subsidence of the surface ground. Three mine collapsing centres are lying in the Meuse basin: northwards Eisden, north-eastwards Meeswijk and towards Leut. The mine collapsing centre of Waterschei (basin of the Demer) reaches towards the Meuse basin (CIW, 2009).

3.6 Land uses

The principal land use types in the Flemish Meuse basin are arable farming (41%), built-on or paved surfaces (18%), forests (17%) and grasslands (16%).
Figure 6 gives the division of the land use in terms of percentage. Arable farming is dominant southwards the Albertkanaal, in North-east Limburg and in the sub basins of Mark and Weerijs. Grasslands are typical for Voeren and most of the valley areas. Forests appear at the east of the Kempisch Plateau and at the north of Limburg. Most paved surfaces can be found in North-Limburg, the Meuse valley and centres as Tongeren, Hoogstraten and the axe Essen-Kalmthout (CIW, 2009).

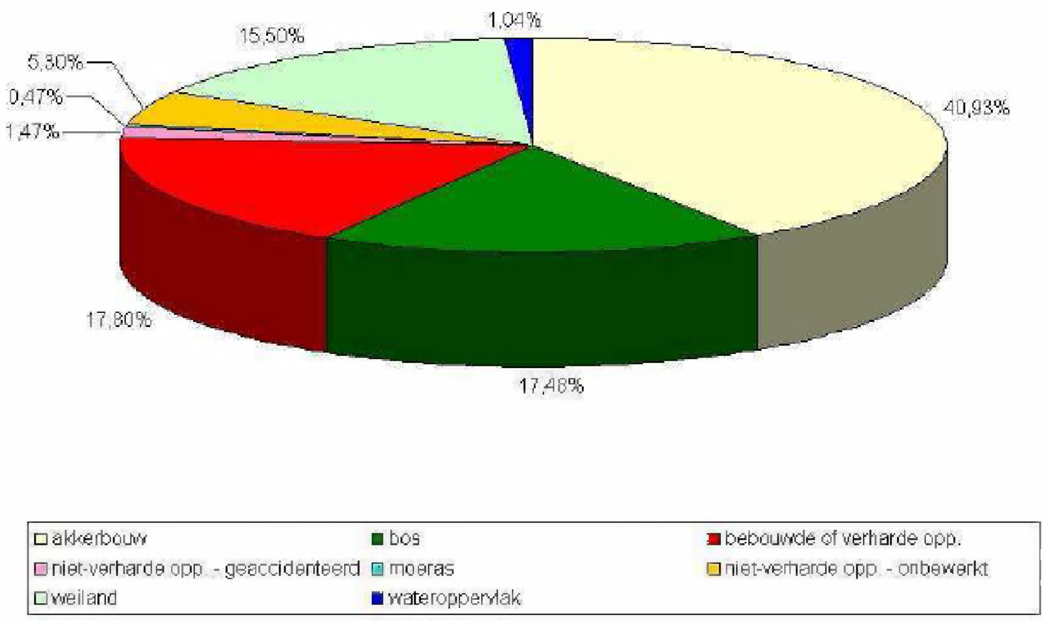

Figure 6 – Division of the land use in terms of percentage in the Meuse basin (CIW, 2009)

Considering the entire Meuse basin, about 60% is used for agricultural purposes (including pastures) and 30% is forested (De Wit et al., 2007a). About 10% of the Meuse basin has been built-on. The resulting increased discharge due to run-off from paved areas is only a few percents. This lies within the margin of accuracy of discharge measurements. In other words, there are no clear effects of urbanisation. As a consequence, measures such as a decoupled sewer system, rainwater retention buffers or zones of infiltration have only an impact at the local scale (De Wit, 2008).

Urbanisation, intensification of agricultural practices and a shift from deciduous to coniferous forest are the most important land use changes during the 20th century in the Meuse River basin. WL Delft Hydraulics found an increase of the runoff ratio in the Meuse after 1933. However, the overall impact of land use changes in the Meuse basin is too small to be detected given the uncertainties in the available records. The more frequent occurrence of floods over the last decade cannot convincingly be explained only by the major land use change since the 1950s (Ashagrie et al., 2006).

3.7 Biodiversity

The ecological quality is described in the Bekkenbeheerplan Maas (CIW, 2009). The actual biodiversity of the diked Meuse system is less developed than would be the case under natural circumstances. However, the present diversity of plants is quite high.

3.8 Water quality

A qualitative analysis of the surface water and groundwater is made by CIW (2008). Point and diffuse sources resulting in discharges of oxygen depleting substances, nutrients, heavy metals and pesticides, are described. An extensive report on water quality is published by the Flemish Environment Agency (Vlaamse Milieumaatschappij) (Bourgoing et al., 2003).

In the year 2003, 56% of the sampled measure points fulfilled the minimum biological quality standard (BBI > 7) and 38% reached the target of the Prati index for oxygen saturation. Criteria exceedings are noticed for the chemical oxygen demand, dissolved oxygen, pH and nitrate/nitrite (CIW, 2009).
Figure 7 shows the biological water quality (BBI) between 1999-2003.

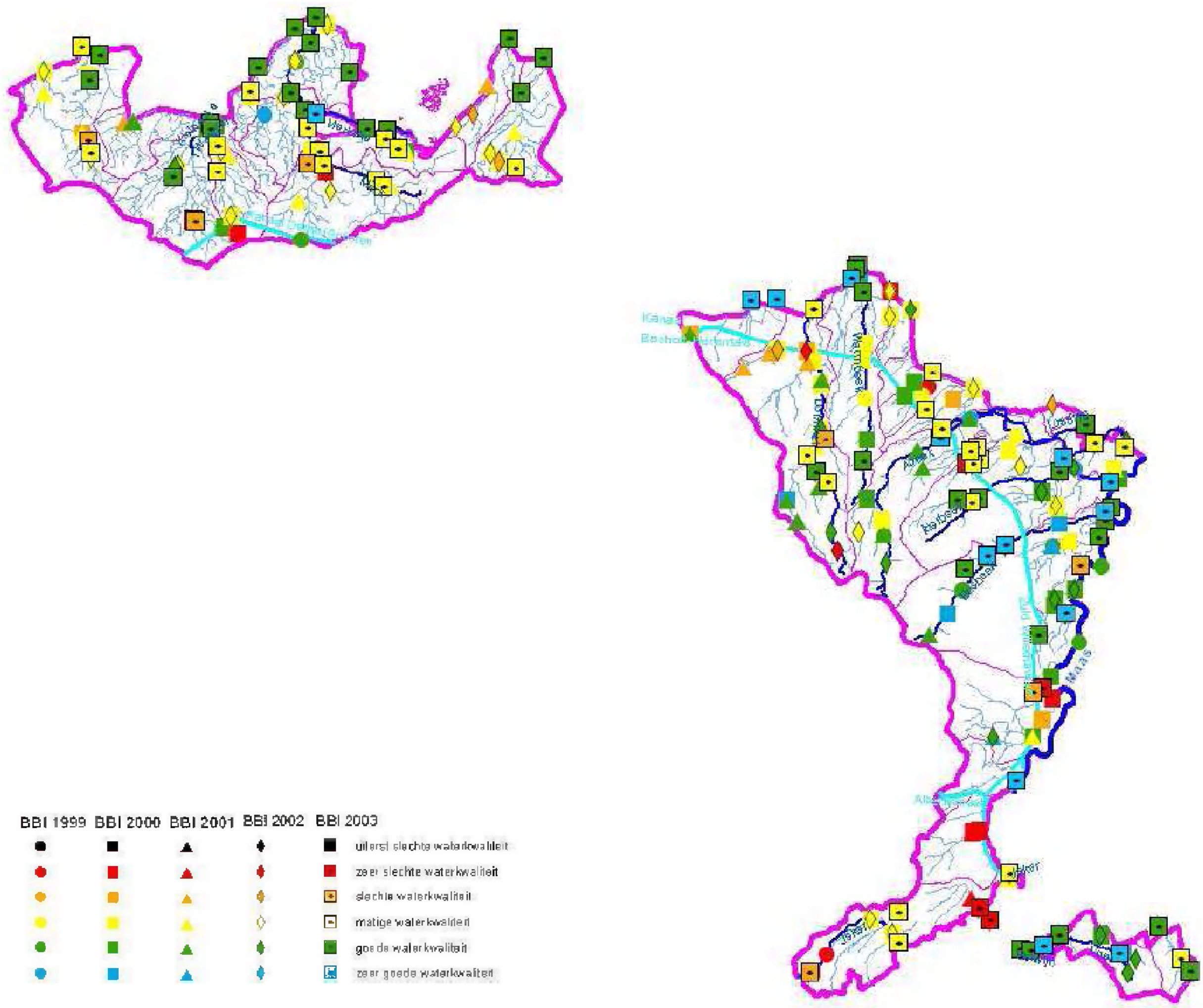

Figure 7 – Biological water quality (BBI) between 1999-2003 (CIW, 2009)

4 Climatology

4.1 General features

The Meuse basin lies within a zone of **moderate maritime climate** with mild winters and cool summers (De Wit, 2008). The prevailing westerly winds in mid-latitude Europe bring precipitation throughout most of the year (Tu, 2006).

The Koninklijk Meteorologisch Instituut van België (KMI) gives an overall picture of the Belgian climate on its website (www.kmi.be). The Belgian climate is mainly influenced by the seasonal cycle of sunshine, the proximity of the Atlantic Ocean and the atmospheric dynamics typical for the middle latitude. On the middle latitude, the cold northerly air meets the warm air of subtropical origin. Our climate is characterized by fresh and moist summers and relative soft and rainy winters.

The average **precipitation** in the Meuse basin is 900 mm/year. The variation in precipitation has a west-east gradient, caused by the influence of the Atlantic Ocean, whereby moist air and precipitation comes from the West. The variation in precipitation is mainly due to the differences in elevation. The average precipitation lies between 700 mm/year for low parts and 1200 mm/year for elevated parts of the basin (De Wit, 2008).

The KMI mentions an annual average precipitation between 750 mm and 850 mm in Low and Middle Belgium (Flanders). Southwards of Sambre and Meuse (High Belgium) the annual precipitation increases from 750 mm to 1400 mm. In Low and Middle Belgium, the average number of rainy days (> 0.1 mm/day) is 200 and most rain falls in July and August. Towards High Belgium, the average number of rainy days increases to 230 with most rain in July/August and December/January.

Averaged over the period 1961-1998, the winter (October-March) precipitation and summer (April-September) precipitation for Uccle are respectively 417 mm and 405 mm (Leander et al., 2005).

Evaporation is of big influence. On a warm, sunny, windy day in the summer 7 mm can evaporate, as much as the average evaporation during the whole month of January. The evaporation varies with the seasons, in contrary to precipitation which falls during the whole year (De Wit, 2008). The average annual potential evapotranspiration (calculated for grass land) is 537 mm, while the summer half-year (May–October) and the winter half-year (November–April) account for 76% and 24%, respectively. The average annual air temperature amounts to 9°C (Ashagrie et al., 2006).

Climatological overviews of several years can be found at the website of the KMI (www.kmi.be).

4.2 Climate mechanisms

Atmospheric circulation, particularly in mid-latitudes, is the main control behind regional changes in temperature, precipitation and other climatic variables. In describing the circulation patterns over Europe and the eastern part of the North Atlantic Ocean, the Grosswetterlagen system and the North Atlantic Oscillation (NAO) index is most used. The zonal circulations, particularly the sub-type “West cyclonic” (Wz), are often associated with rain. The sub-types Southwest cyclonic (SWz) and Northwest cyclonic (NWz) within the half-meridional group refer to weather conditions similar to those associated with the sub-type Wz. The NAO is a prominent mode of low-frequency variability of the Northern Hemisphere atmosphere and has its strongest effects in the winter season (Tu, 2006).

Understanding the climate system is made possible by the **global climate models** or general circulation models (GCMs), e.g. powerful computer programs that simulate the function of the global climate system in three spatial dimensions and in time. A description of the climate system, use of climate models and the role and types of climate scenarios is realized by Boukhris (2008).

Since the early 1990s, the more sophisticated third generation of climate models began to emerge. Known as coupled atmospheric-ocean general circulation models (AOGCMs) or more simply as coupled climate models, they include an atmospheric GCM that is fully coupled to a detailed three-dimensional model of the ocean. There exist around 20 general climate models around the world (Boukhris, 2008).

For each model, a **scenario** is set up generally depending on the increase of the concentration of greenhouse gases in air. The IS92 series scenario of the IPCC consists of an assumption of increasing the CO_2 concentration due to human activities by 1% a year. This would lead to a doubling of the carbon dioxide concentration by 2050 and the triple by the year 2100 (Boukhris, 2008).

The SRES scenarios of the IPCC, developed to update the IS92 series, encompass four combinations of demographic change, social and economic development, and broad technological developments (A1, A2, B1, B2). These developments cause changes in the concentrations of greenhouse gases and aerosols in the atmosphere (Boukhris, 2008).

- A1: a fast growing economy, the introduction of new and efficient technologies and a population that peaks at around mid-century and declines thereafter.
- A2: a heterogeneous world, where the local identities are preserved and the population grows continuously. Economic growth and technological progress are more fragmented and slower than in other storylines.
- B1: the global population evolves as in the A1 storyline, but the economic structures change rapidly towards a services and information model, while new clean and resource efficient technologies are developed.
- B2: a world with global population evolving as in the A2 storyline but more slowly, and where emphasis is given on local solutions to sustainability. Intermediate economic development is expected while the technology would have a more diverse evolution than in the A1 and B1 storylines.

4.3 Statistical and extreme value analysis

The **frequency of the western circulation patterns** in the months of December and January has increased after 1973, while the frequency in the months of April and May has decreased after 1968. It can be found also that there was an increase in the duration of zonal circulation patterns in winter (Tu, 2006).

The **winter NAO** shows large inter-annual and inter-decadal variability. From 1900 until about 1930, there were strong positive anomalies in the winter (December–March) NAO index; from the early 1940s until the early 1970s, the winter NAO index was low and exhibited a downward trend; since then, a sharp reversal has occurred, with unprecedented strongly positive values since 1980. The late 1980s and early 1990s can be described as the period with the highest values (strongest westerlies) and the winter of 1995–1996 as a dramatic switch in the winter (November–March) NAO index (Tu, 2006).

In a study of Klein Tank (2004), a dataset is collected which comprises 199 **station series of daily temperature** and 195 **station series of daily precipitation**, observed at meteorological stations in Europe and the Middle East. Almost all series cover the standard normal period 1961–1990, and about 50% extends back to at least 1925. An extreme value and trend analyses was executed. The extreme value analysis examines a set of 13 indices of climate change. The trend analysis gives similar results as the studies mentioned in Paragraph 6.1.

The study executed by Ntegeka and Willems (2008) has investigated the seasonal behaviour of the **rainfall extremes** at different aggregation levels relevant for both rural and urban hydrology. The extreme precipitation has become more intense during the most recent decade (the 1990s) for all aggregation levels studied. Furthermore, there has been an increase in the number of events especially for the short durations during the winter season. However, the trend in the summer season quantile perturbation for the most recent decade is not significant although there have been significant periods in the past, e.g., the significantly wet 1960s. In the two transitional seasons, spring showed evidence of significant positive trends for the most recent decade, while this was not the case for autumn.

From the analysis, it is also apparent that high rainfall extremes do not occur randomly in the time, but are clustered: there is evidence of temporal clustering. The clustering of wet events in summer for the periods of the 1910s-1920s, 1960s and the 1990s is consistent for most of the aggregation levels studied. For most seasons' oscillation, high and low values for evaporation are found in same periods as for rainfall: high in the 1910s-1920s, 1950s -1960s and 1990s; low in the 1930s-1990s and the 1970s-1980s, the later only in summer and spring (Ntegeka and Willems, 2008).

4.4 Climatological mapping

The **synoptic-climatological analysis** carried out by Tu (2006) improves our understanding of the precipitation variability in the Meuse basin. The apparent changes identified in the precipitation events, amounts and extremes are likely to be climate related.

The precipitation pattern change in the Meuse basin since 1980 is very likely linked to the fluctuation of large-scale atmospheric circulation, as characterised by the Grosswetterlagen system. The annual and the winter half-year frequencies of wet days and very wet days in the basin contributed by the rain-associated circulation patterns (e.g. Wz, SWz and NWz) have increased considerably since 1980 (Tu, 2006).

The winter precipitation in the Meuse basin shows a positive correlation with the winter NAO index during the entire periods under study. The tendency to more abundant precipitation in winter in the Meuse basin, roughly since 1980, is likely to be a consequence of the strengthened NAO that brings stronger westerly winds across the North Atlantic into Europe (Tu, 2006).

4.5 Downscaling techniques

To investigate the impact of climate change on a regional scale, it is necessary to downscale the Global Climate Model. Methods and different models are described by Boukhris (2008). The downscaling approaches can mainly be divided into two different kinds: dynamical downscaling and statistical downscaling. While the **dynamical downscaling method** takes into account the changes of probability density functions of most of the climate variables introduced into the climate models, the **statistical downscaling methods** generate information on high resolute scales while giving possibility to assess uncertainty. The downscaling method developed by Boukhris (2008) is a combined dynamical-statistical downscaling approach based on perturbations. These last, which present the difference between current and future climate, will account for variable frequency and its dependency on time scale.

5 Hydrology

5.1 Floods

The mean annual discharge of the Meuse and its lateral canals at the Dutch/Belgian border amounts to 276 m^3/s; the winter and summer half-year mean discharges are respectively 406 m^3/s and 146 m^3/s, (Ashagrie et al., 2006). High discharges appear in the months December till March (Baetens et al., 2004; De Wit, 2008).

When the discharge is higher than 1500 m^3/s, the river leaves the summer bed (high water). For discharges above 2000 m^3/s, there is flooding of certain residential areas. Important damage takes place for discharges higher than 2500 m^3/s (Baetens et al., 2004).

An overview of recent floods is given in Table 2. These flood events were used in a research on the contribution of tributaries to floods in the Meuse basin (Peeters, 2005). Historical floods took place 1571, 1643, 1740 and 1926 (De Wit, 2008).

Table 2 – Flood events at Borgharen (Peeters, 2005)

Event	**Peak time**	**Maximum day averaged discharge at Borgharen**	**Recurrence frequency**	**Type of wave**
1993	22/12/1993	3039 m^3/s	1:130	Short
1995	31/01/1995	2743 m^3/s	1:50	Extended
2002	14/02/2002	2488 m^3/s	1:25	Short
2003	04/01/2003	2731 m^3/s	1:50	Short

Figure 8 shows a map with recently flooded areas in the Meuse basin. The map contains all areas flooded at least one time in the period 1988-2005. If no measures are taken, these areas can be considered as sensible to future inundations (http://geo-vlaanderen.agiv.be/geo-vlaanderen/overstromingskaarten).

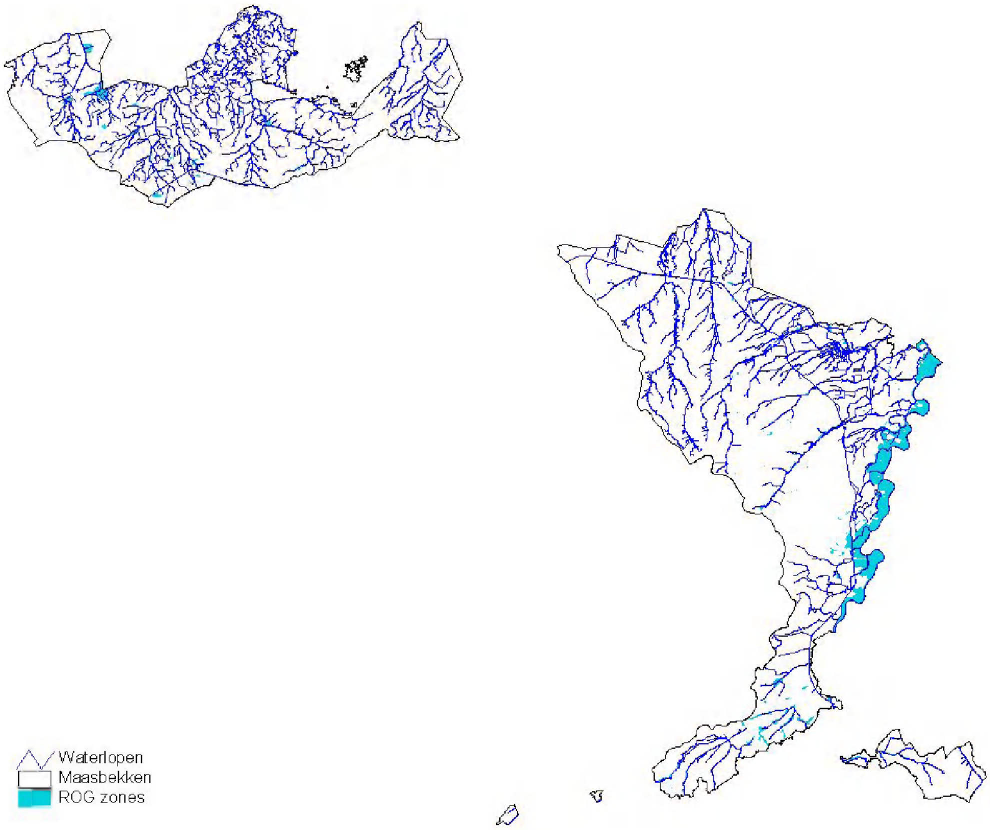

Figure 8 – Recently flooded area's (http://geo-vlaanderen.agiv.be/geo-vlaanderen/overstromingskaarten)

5.2 Low flows

A period of low water is not only dependent of the precipitation in the summer, but also of the precipitation in the preceding winter. In a dry winter, the subsoil water reserves are not supplied. Moreover, the Border Meuse contains no weirs to dam the available water (Baetens et al., 2004).

Low flows in a dry season are generally composed of a base flow from groundwater reservoirs, which are significantly affected by the catchment geology and long-term climatic fluctuations. In the upper section of the Meuse basin, the lithology is largely formed by limestone and thus in dry periods the discharge of the Lorraine Meuse is relatively high. In the middle section of the Meuse basin, a great part consists of poorly permeable rocks and thus has a limited groundwater storage capacity (Tu, 2006).

In summer and autumn, low water levels can be a problem. Low water is defined by a discharge lower than 60 m^3/s measured at Monsin. Below this critical level the discharge of the Meuse is too low to fulfil all functions in the Dutch/Flemish Meuse and the connected canals. Discharges lower than 10 m^3/s are harmful for nature (Baetens et al., 2004).

If a year counts 100 days on which low water appears, one speaks of a dry year. A dry year has a return period of 8 years. In dry periods, measures should be taken, for example re-pumping of water lost by lockages, limitations on the number of lockages, or limitations on water use by agriculture and industry (Baetens et al., 2004). More information about low water supply is written under paragraph 8.2.

A historic overview of low waters between 1910 and 1983 is given in Table 3. More recent low flows took place in 2003 (De Wit, 2008) and 2009 (www.lin.vlaanderen.be/awz/waterstanden/hydra/laagwbericht/index.htm). The most extreme low water event happened in 1976, with a discharge of 8 to 9 m^3/s at Maasbracht (Baetens at al., 2004).

Table 3 – Duration of low water periods with discharge < 50 m³/s at Monsin (Baetens at al., 2004)

Date	Number of days discharge at Monsin < 50 m³/s
1921	142
1934	115
1947	106
1949	77
1959	90
1964	89
1971	101
1973	90
1976	167

5.3 Hydrological regime and hydrography

The **hydrological regime** is divided into a winter and a summer. The hydrological winter starts on the 1st of October. About that time, the evaporation is less than the precipitation and so the aquifers can be supplied. At the end of the hydrological winter, the highest discharges are noticed, while the lowest discharges occur at the end of the hydrological summer. The hydrological summer starts the 1st of April. The evaporation increases and generally spoken, a precipitation shortage takes place (Baetens et al., 2004).

High water on the Meuse is usually not caused by local showers, like 242 mm precipitation in 12 hours (Herbesthal, 24/06/1953). Only if there is a large amount of precipitation in a significant part of the basin, flooding problems can occur. In the Walloon part of the basin, the amount of precipitation in the wettest month was 366 mm (Dec. 1993). In the driest month, only 1 mm rain falls (Oct. 1972, Jul 1976, Jul 1949) (De Wit, 2008).

Snow and ice have almost no influence on the discharge of the Meuse. The coldness can cause low water levels, as well as high water levels. Low water levels result from snow, which is not being drained off immediately like rain. Also, when ice forming occurs, the weirs have to be opened to prevent damage and as a consequence, the water is not dammed up anymore. When a cold period is followed by a wet, warm period, high discharges occur, resulting from rain that cannot infiltrate in the frozen soil and snowmelt. Extreme ice forming can cause the formation of an ice-dam, resulting in high water and flooding upstream (De Wit, 2008).

The **hydrography** of the Flemish part of the Meuse starts in fact in Liège, where water is been drawn off to the Albertkanaal and the Channels of the Kempen. A considerable part of this water flows back to the Meuse via the Channel of Monsin, the water use of Chertal, the Channel of Haccourt – Visé and the Channel of Lanaye (Baetens et al., 2004).

The Border Meuse has a natural character, without weirs. Navigation is not possible. However, the weir in Linne dams up the water, so the Meuse is navigable between Maaseik and Kessenich (the Netherlands). The weir of Borgharen is in the first place meant to ensure navigation in the upstream (Dutch) part, but the management of the weir also causes a flattening of the high, unnatural, discharge peaks caused by the hydropower plant in Lixhe (Baetens et al., 2004).

The watercourses of 1st category which flow out into the Meuse are the Berwijn, the Bosbeek and the Abeek. Also, some smaller watercourses of 2nd category flow out in the Meuse via one-way valves or pump installations. Several canals cross the Meuse basin: the Albertkanaal, the Kanaal Briegden-Neerharen, the Zuid-Willemsvaart, the Kanaal Bocholt-Herentals and the Kanaal Dessel-Turnhout-Schoten. Locks are present on the Zuid-Willemsvaart and the Kanaal Briegden-Neerharen, while the watercourse Mark has weirs. A water retention basin is located at the Dommel. Water division works are placed between the Abeek and the Itterbeek, between the Bosbeek and the Witbeek, between Witbeek and the Border Meuse and between the Jeker and the Oude Jeker (CIW, 2009).

The above mentioned toponyms and water courses are represented in
Figure 9,
Figure 10,
Figure 11,
Figure 12 and
Figure 13.

The hydrography is also described by Severyns et al. (2004) when explaining the structure of the groundwater model of the Meuse.

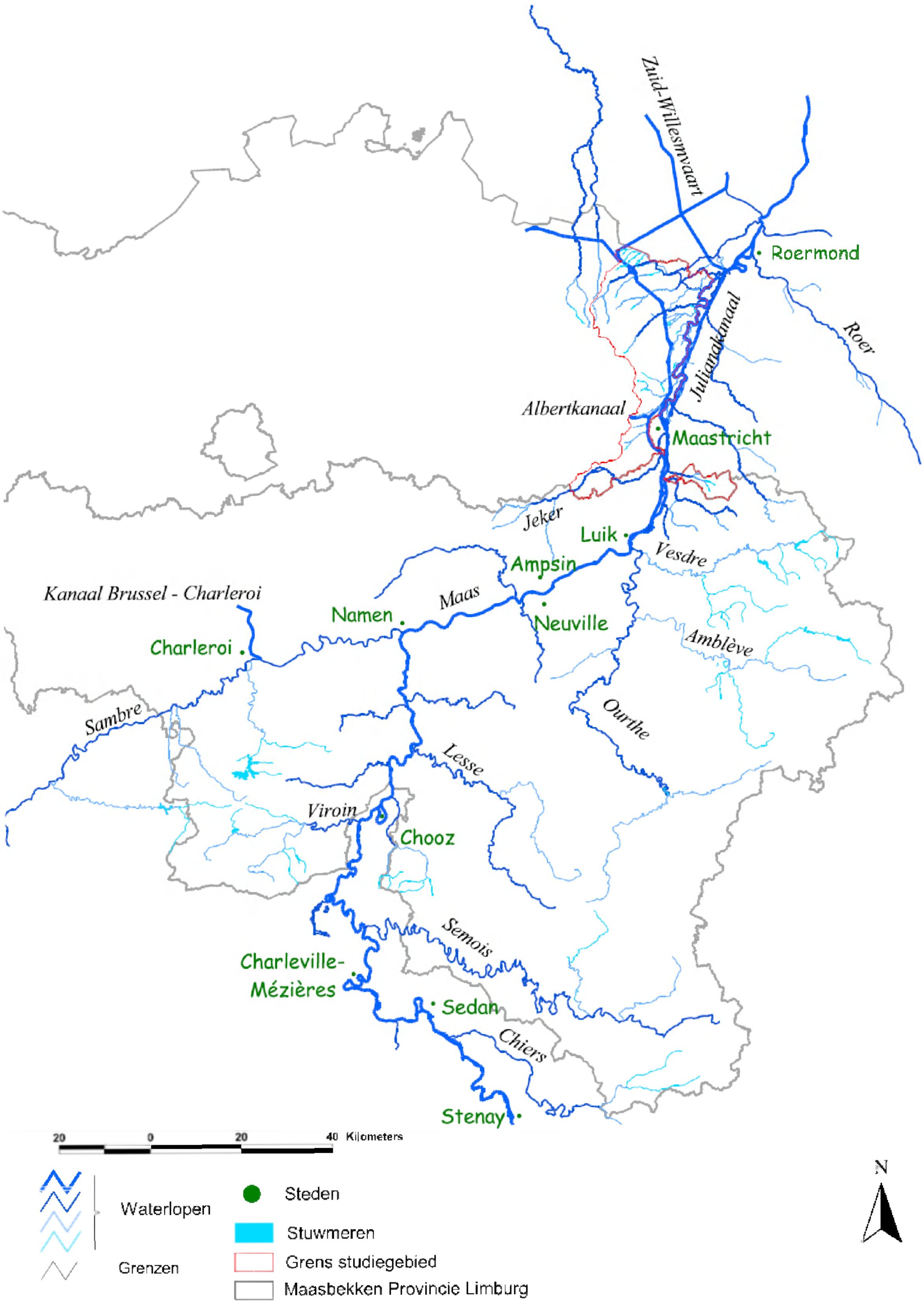

Figure 9 - Overview of the Meuse basin (Baetens et al., 2004)

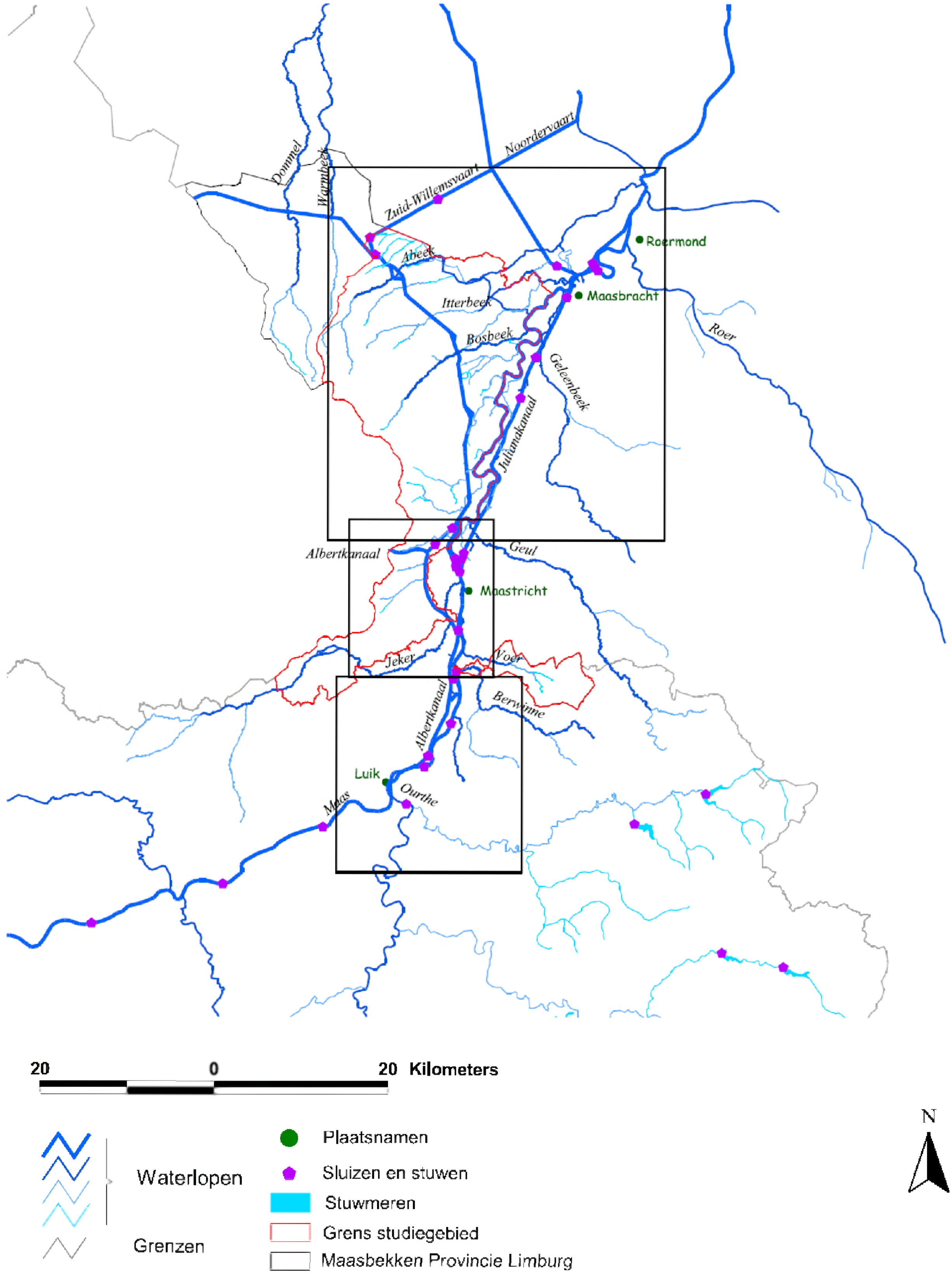

Figure 10 – Overview of the Border Meuse, with indication of zones of detail figures (Baetens et al., 2004)

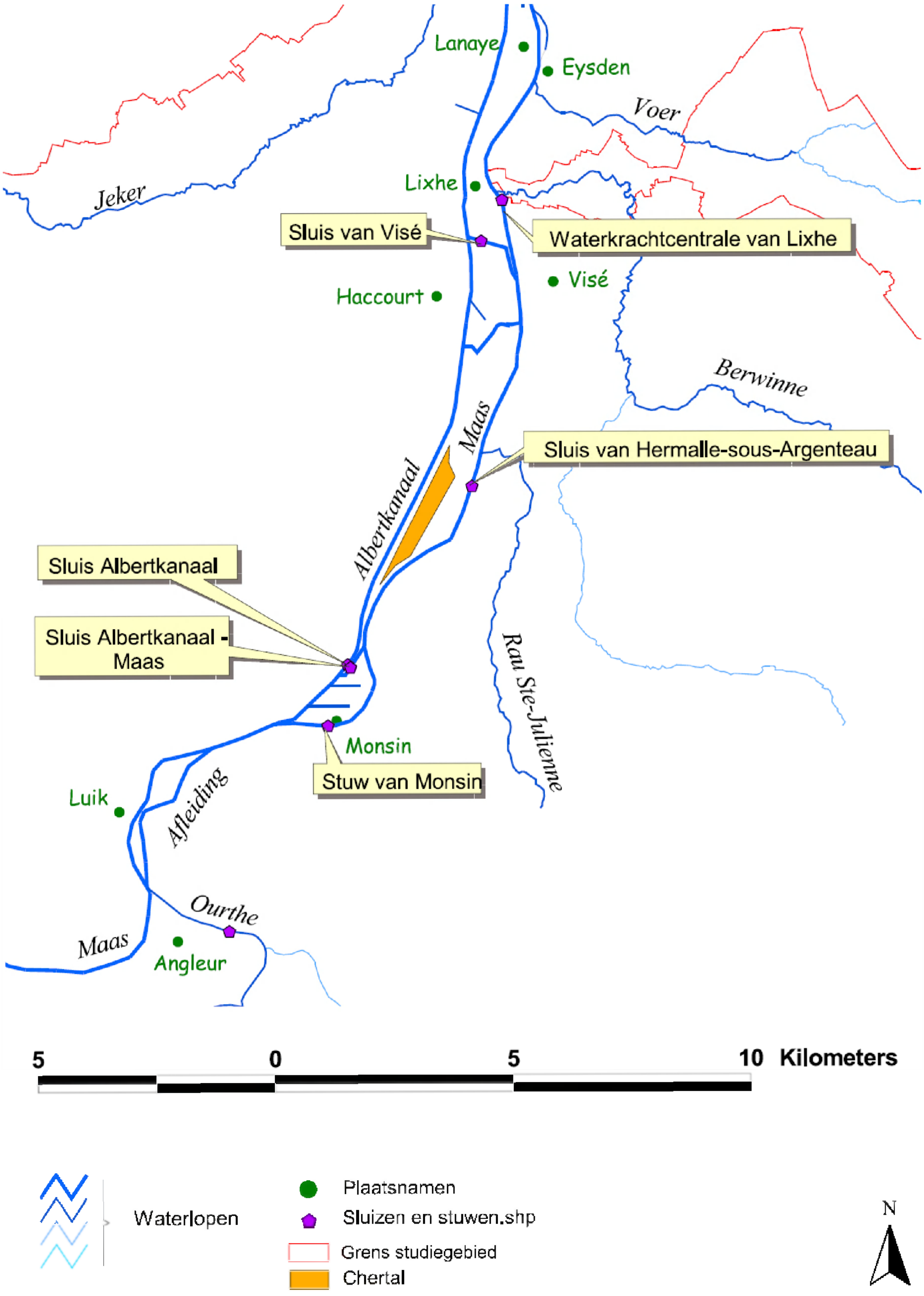

Figure 11 - Detail figure 1: the Meuse at Liège (Baetens et al., 2004)

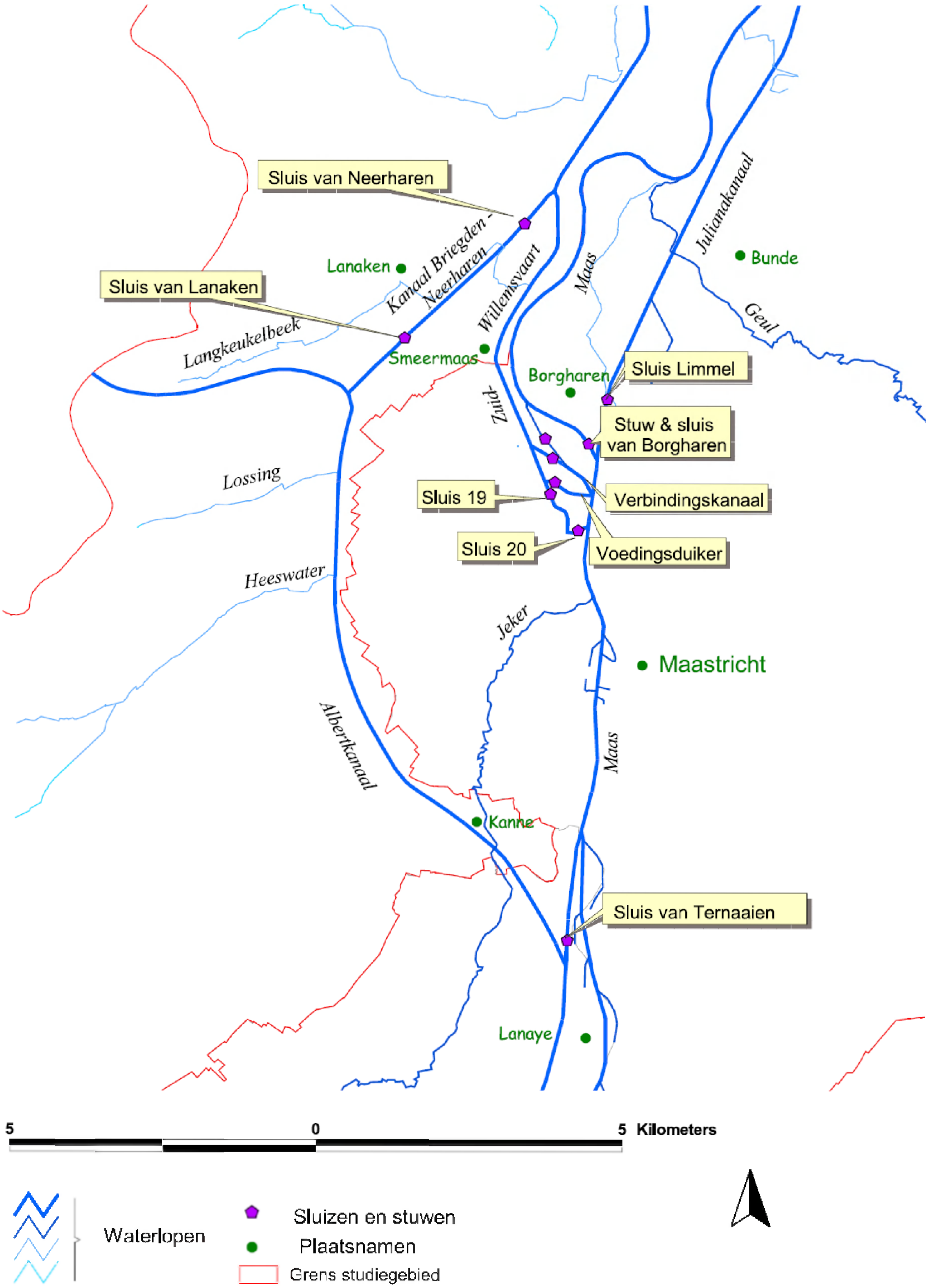

Figure 12 - Detail figure 2: the Meuse at Maastricht (Baetens et al., 2004)

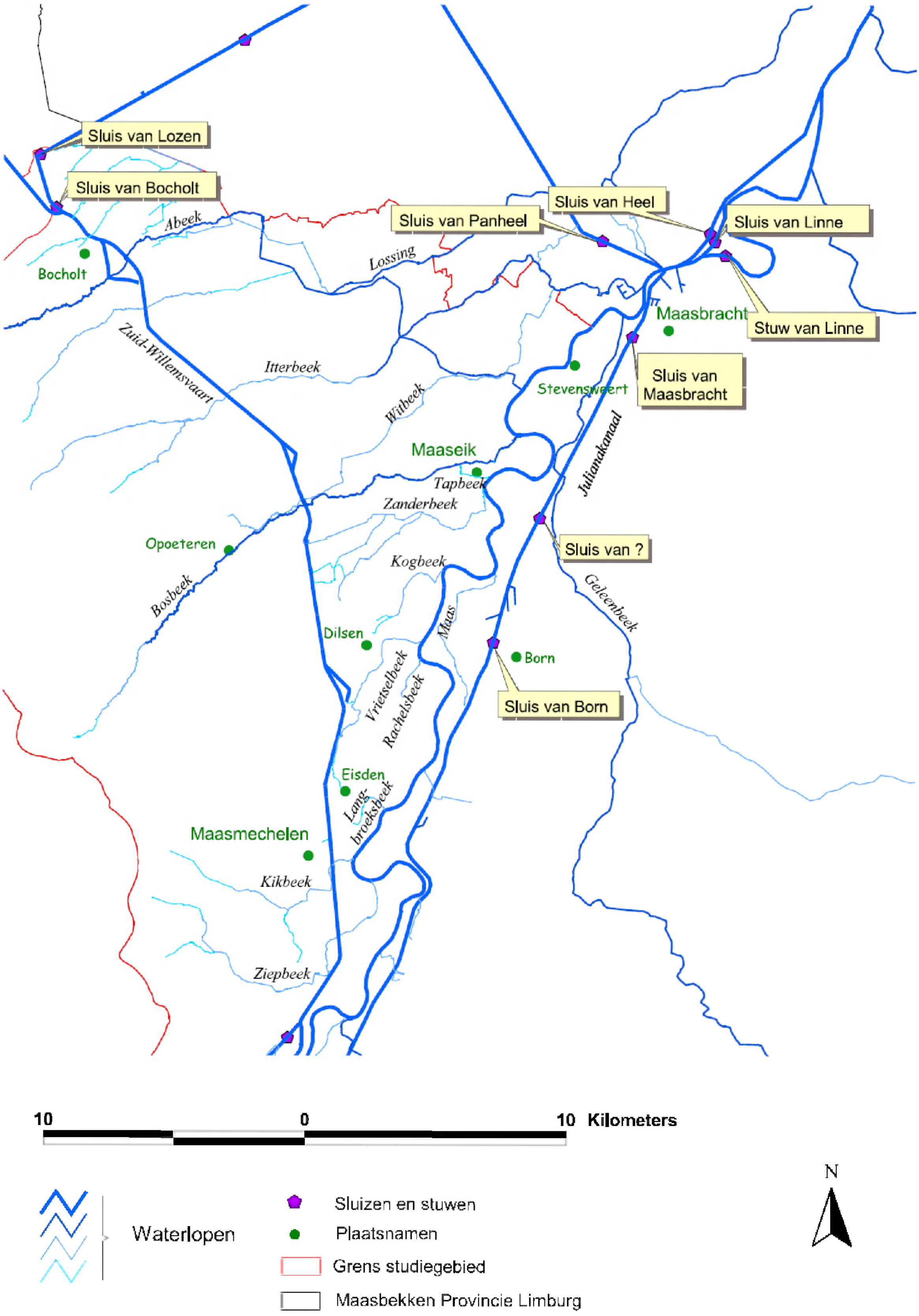

Figure 13 - Detail figure 3: the Meuse between Herbricht and Maastricht (Baetens et al., 2004)

5.4 Hydraulic characteristics

In a study of IMDC (2007), **stage-discharge relations** are being deduced for St-Pieter, Borgharen-dorp and Maaseik. The study also offers a method to generate actual stage-discharge curves (Q-H curve) in an unambiguous, efficient way. The Q-H curve for Maaseik has been adapted in 2008 and 2009 (IMDC, 2008; IMDC, 2009).

Erosion occurs mainly on the inclined loam soils at the south of the Albertkanaal and in Voeren. The fields in the winter bed are sensible to erosion in periods of high water at the Meuse. The total amount of eroded soil material from arable land amounts to 94 000 ton/year. Of this amount, 11 000 ton/year flows to the water courses. The subbasins of Jeker and Voer have the highest sediment supply (CIW, 2009). Figure 14 shows the soil erosion map of the Meuse basin.

The annual **sedimentation** amount is estimated on 56 000 ton dry matter (tds) for the Albertkanaal and the navigable watercourses northwards from it, and 3 000 tds for the unnavigable watercourses from 1st category. For the Flemish part of the Meuse basin, the historical arrear in dredging and removing of spoil amounts to 856 000 tds in the categorized water courses, 576 000 tds in the not navigable water courses and 367 000 tds in the watercourses of 2nd category (CIW, 2008).

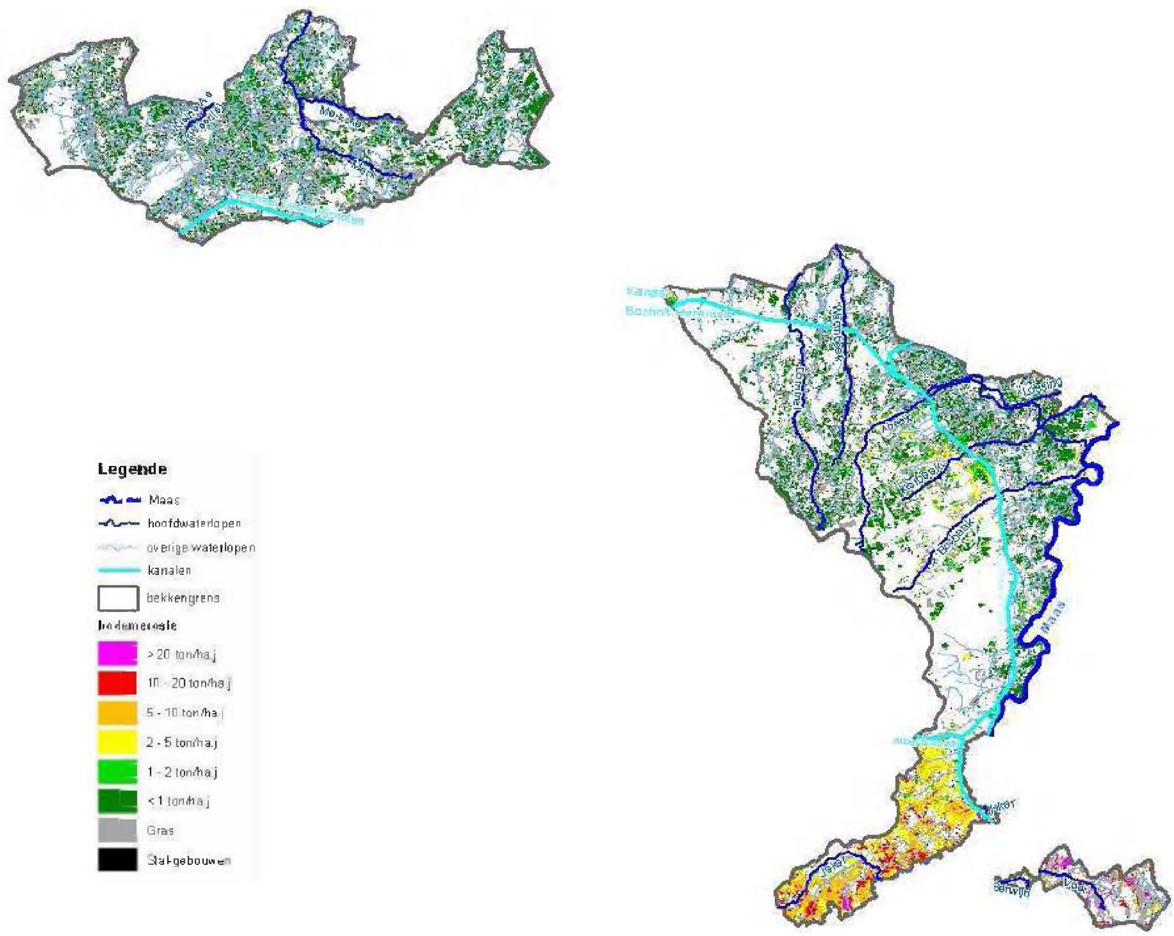

Figure 14 – Soil erosion map (CIW, 2009)

5.5 Hydrometry

Two measuring networks are being used in Flanders. On the one hand Hydronet, which contains all actual and historical measurements registered by the Flemish Environment Agency (Vlaamse Milieumaatschappij - VMM)? Since 2006, the VMM is authorized to measure the water quantity in all non-navigable water courses in Flanders (www.hydronet.be). On the other hand, the Hydrological Information Centre (Hydrologisch Informatiecentrum - HIC) collects and manages all hydrological data relevant to the navigable watercourses (www.lin.vlaanderen.be/awz/waterstanden/hydra). The HIC is part of Flanders Hydraulics Research (Waterbouwkundig Laboratorium - WL), department of Mobility and Infrastructure (Mobiliteit en Openbare Werken - MOW).

The measuring points situated in the province of Limburg are summarized in Table 5, with the exception of the measuring points in Voeren which are given in Table 6. Table 7 contains the measuring points in the province of Antwerp. The starting day of the measurements is mentioned between brackets.

Table 4 – Parameter symbols

Symbol	Parameter	Symbol	Parameter	Symbol	Parameter
H	Water level	***Ta***	Air temperature	***F_gr***	Ground warmth flux
Q	Discharge	***Ts***	Soil temperature	***U***	Wind velocity
V	Flow velocity	***Td***	Dew point temperature	***Ud***	Wind direction
P	Precipitation	***E***	Evaporation	***Pa***	Atmospheric pressure
Pi	Precipitation intensity	***RH***	Relative humidity		
T	Temperature at ground level	***F_rad***	Radiation flux		

Table 5 – Overview measuring locations Limburg

Watercourse	Location	Source	Parameter
Abeek	Bree	VMM	H (1/1984), Q (1/1984), P (1/1984)
Abeek verdeelwerk	Ophoven	VMM	H (1/1998)
Albertkanaal	Kanne	HIC	H (10/1998), Q (10/1998)
Albertkanaal	Kanne (2 measuring points)	HIC	H (9/1992)
Bosbeek	Opoeteren	VMM	H (1/1984), Q (1984), P (1/1984)
Bosbeek verdeelwerk	Neeroeteren	VMM	H (4/1975)
Dommel	Overpelt	VMM	H (1/1967), Q (1967), P (1/1971)
Dommel	Peer	VMM	H (1/2006), Q (1/2006)
Dommel in-doorlaat	Overpelt	VMM	H (1/1979)
Holvenloop	Overpelt	VMM	H (1/2007), V (1/2007)
Jeker	Kanne	VMM	H (1/1971), Q (1/1986)
Jeker	Nerem	VMM	H (1/1968), Q (1986), P (1985)
Jeker	Kanne Opwaarts	HIC	H (1/1992)
Jeker	Kanne	HIC	H (1/1975), Q (1/1975)
Maas	Maaseik	HIC	H (1/1979), Q (1/1979)
Maas	Dilsen-Rotem	HIC	H (8/1984)

Watercourse	Location	Source	Parameter
Maas	Meeswijk	HIC	H (1/2007)
Maas	Eisden-Mazenhoven	HIC	H (11/2006)
Maas	Uikhoven	HIC	H (9/2007)
Maas	Lanaken-Smeermaas (2 measuring points)	HIC	H (1/1988)
Maasplas	De Spaenjerd	HIC	H (1/2007)
Maasplas	Heerenlaak	HIC	H (1/2007)
Maasplas	Maasbeempder Greend	HIC	H (11/2006)
S1-S2 Nieuwe-Oude Jeker	Tongeren	VMM	H (1/1985)
Warmbeek	Achel	VMM	H (1/1987), Q (1/1977), P (1/1977)
Witbeek verdeelwerk	Ophoven	VMM	H (9/1983)
	Kanne	VMM	P (1/2006), Pi (10/2005), E (1/2006)
	Neeroeteren	VMM	P (1/1988), Pi (5/2008), E (1/2008), T (5/2008)
	Overpelt	VMM	P (1/2005), Pi (1/1950), T (1/2000), Ta (1/2008), Ts (1/2008), Td (1/2008), E (1/2004), Pa (1/2008), RH (1/2008), F_rad (1/2008), F_gr (1/2008), U (1/2008), Ud (1/2008)

Table 6 – Overview measuring locations Voeren

Watercourse	Location	Source	Parameter
Berwijn	Moelingen	VMM	H (1/1990), Q (1/1971)
Berwijn	Moelingen	HIC	H (1/1991), Q (1/1991)
Voer	Sint-Martens-Voeren	VMM	H (1/1987), Q (9/1987)
Voer	s-Gravenvoeren	VMM	H (1/2005), V (1/2005)

Table 7 – Overview measuring locations Antwerp

Watercourse	Location	Source	Parameter
Kleine Aa	Essen	VMM	H (1/1981), Q (1/1982), P (1/1991)
Kleine Aa	Wuustwezel	VMM	H (1/1981), Q (1/1982), P (1/1992)
Kleine Aa	Brecht	VMM	H (1/2005), Q (1/2005)
Mark	Minderhout	VMM	H (1/1981), Q (1/1982), P (1/1991)
Mark	Rijkevorsel	VMM	H (1/2006), Q (10/1970), V (1/2006)
Mark	Merksplas	VMM	H (1/1968), Q (1/1967), P (1/1982)
Pompstation Sluiskensweg	Meer	VMM	H (1/2006)
	Loenhout	VMM	P (1/2004), Pi (5/2004), E(1/2004), T (1/2004)

5.6 Origin of water, natural and artificial water pathways

The Meuse basin contains about 500 km³ groundwater, 10 km³ soil water and 0.5 km³ surface water. The annual precipitation is 30 km³, of which 18 km³ evaporates and 12 km³ is been carried off (De Wit, 2008).

The discharge of domestic and industrial waste water can be considered as a net incoming discharge. The Flemish sewage treatment plants discharge an amount of 110 280 m³ a day in the Border Meuse. For the Dutch sewage treatment plants this is 114 309 000 m³ a year. Together, the discharge is 4.90 m³/s (Baetens et al., 2004).

5.7 Impact of past and future climate changes on hydrology

Due to climate change, higher intensities of **precipitation** are expected, both in winters and summers. However, the frequency of rain events will vary with more storms in winters and less in summers. It is uncertain how the North Atlantic Drift will develop, which is determining for the climate in Northwest Europe. It remains to be seen whether the wind will come more often from the (dry) East or from the (wet) West (De Wit, 2008). Tu et al. (2005a) provided evidence of climate-induced change in the precipitation pattern in the Meuse basin area over the last two decades.

The IPCC (Bates et al., 2008) predicts reduced **water availability**. This may result from:

- Longer and more frequent dry periods
- Decreased summer precipitation leading to a reduction of stored water in reservoirs fed with seasonal rivers
- Reductions in inland groundwater levels
- The increase in evapotranspiration as a result of higher air temperatures, lengthening of the growing season and increased irrigation water usage

The change in climate will make the soils more sensitive to **erosion** (De Groof et al., 2006). During summertime, soils might get dryer as a result of an increase in temperature, evaporation and dry periods. Very dry soils with a bad structure are many times more sensitive to erosion than humid ones. This reality will therefore contribute to the expected damaging effects of increased rainfall amounts and intensities on erosion.

The expected higher discharges will lead to an increased erosion rate of the river bed. On the other hand, sedimentation of watercourses and flood retention basins in low discharge periods becomes also an important consequence, causing problems with the navigability and, above all, increases the risk of flooding (De Groof et al., 2006).

A greater variation between seasons with wetter winters and dryer summers is expected. Concerning the **discharge** of the Meuse, this will result in an increased discharge in winter and a decreased discharge in summer. During winter, the Meuse will more often leave her bed. At the moment, the storm with a return period of 1250 year is taken as a reference for the safety infrastructure in the Netherlands. The intensity of this storm will increase in the future (Table 8). The basis discharge in summer will not necessarily decrease, as the higher winter precipitation will have supplied the groundwater reserves (De Wit, 2008).

Table 8 – Expected reference discharges in the future for the Netherlands (De Wit, 2008)

Year	Expected discharge with a return period of 1250 year
2006	4000 m³/s
2050	4200 m³/s
2100	4600 m³/s

Vansteenkiste et al. (2009) executed a study on the **effect of climate change on extreme high and low discharges** in the Meuse River. The hydrological and hydraulic models of DELTARES were run using the predictions of meteorological parameters for 2100 of the CCI-HYDR project (Ntegeka and Willems, 2009). See paragraph 6.2 for more information.

Results are presented in Figure 15 and Figure 16. In the high (wet) scenario, the high discharges will increase. On the contrary, the high discharges will decrease in the low (dry) scenario. The high discharges will change with -20%, +6% and +35%, respectively for the low, mean and high scenario. The low discharges will decrease in all scenarios, depending on the scenario with -75% (low), -60% (mean) and -76% (high) (Ntegeka and Willems, 2009).

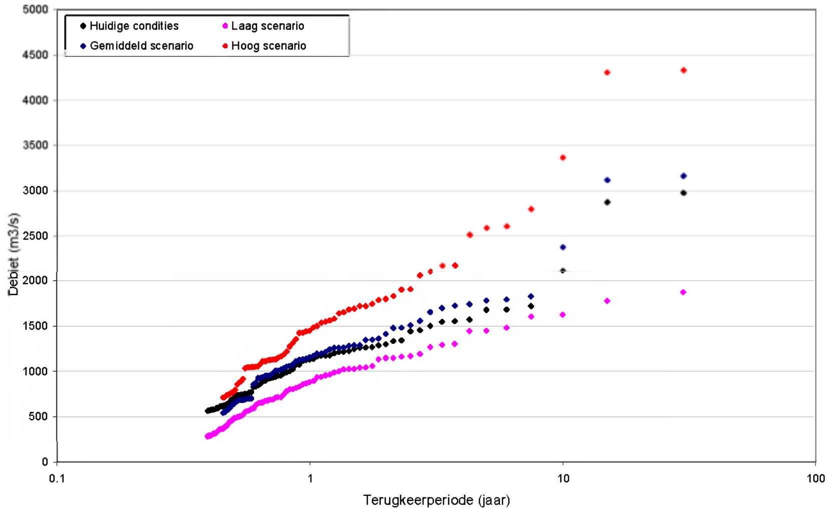

Figure 15 – extreme hourly high discharge per return period (Vansteenkiste et al., 2009)

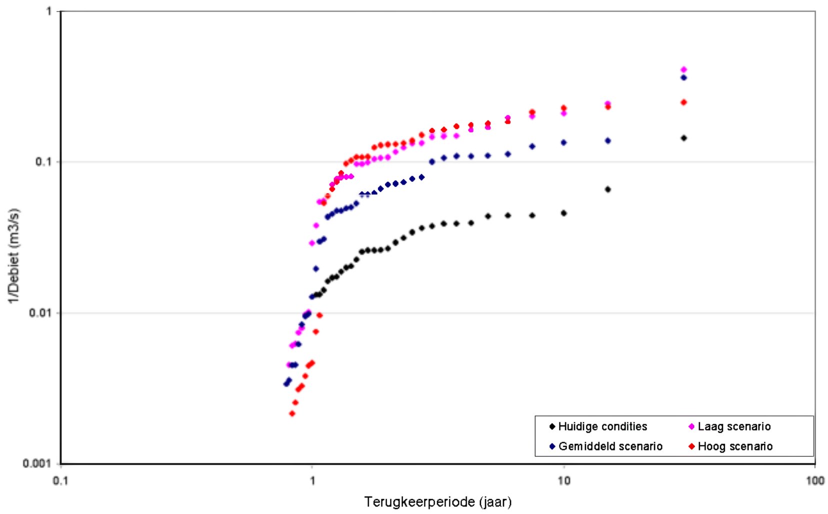

Figure 16 - extreme hourly low discharge per return period (Vansteenkiste et al., 2009)

Vansteenkiste et al. (2009) also presents **flooding maps** of the Border Meuse for several return periods. The results are depending on the scenario and the considered region. In general, inundations will be more extended in the high scenario and less extended in the low scenario, compared to the present situation. The mean scenario shows little impact.

The scale of **damage and risk** is similar. Table 9 shows the damage linked to the potential flooding areas in the Flemish Meuse basin. The damage maps were associated to each other to deduce the risk for the Flemish Meuse River basin. The absolute values are given for the present conditions, while the change in terms of percentage is given for the future scenarios (Vansteenkiste et al., 2009). More information about damage and risk calculations is written in paragraph 9.3.

Table 9 – Damage and risk calculations for the Flemish Meuse basin (Vansteenkiste et al., 2009)

	Present conditions	**Low scenario**	**Mean scenario**	**High scenario**
Damage caused by T1	2 019 000 euros/year	81%	111%	363%
Damage caused by T10	12 509 000 euros/year	69%	108%	142%
Damage caused by T50	17 092 000 euros/year	78%	106%	131%
Damage caused by T100	17 294 000 euros/year	78%	105%	131%
Risk	4 450 000 euros/year	75%	109%	219%

The MIRA 2009 research project describes the developments of the economical sectors and land use, and the consequences of these on the environmental pollution, the environmental quality and the biodiversity (Van Steertegem, 2009). The chapter of the consequences of climate change and land use change on hydrology and hydraulics in Flanders is based on the scientific report ‘Climate change and water management’ (Willems et al., 2009). The study uses the results of the CCI-HYDR scenario calculations to generate future flooding maps and the VITO land use scenarios to develop **damage and risk maps**.

An impact analyses for 67 river basins in Flanders was executed and gave following general conclusions (the Meuse River basin was not included) (Willems et al., 2009). The lowest river discharges in summer could decrease with 50% as a result of the strong decrease in summer precipitation and the increase in evaporation. The increase of number and magnitude of winter floods is rather limited due to the strong increase of evaporation compared to the increase of precipitation. However, the size of flooding areas can increase strongly. The increase of number and magnitude of summer floods will cause sewer system inundations.

The economical risk for 6 river basins in Flanders (IJzerbekken, Leiebekken, Bovenscheldebekken, Denderbekken, Benedenscheldebekken, Demerbekken) was calculated for the three CCI-HYDR climate scenarios for 2100 compared to the actual situation (Willems et al., 2009). The low scenario predicts a reduction of risk of 56% as a result of the smaller flooding areas. The mean scenario gives a small decrease of risk (-8%). A strong increase in risk (33%) results from the high scenario.

If land use change is also included in the risk calculations, the study concludes that the risk will increase with 5% if the present policy is remained. The increased risk is due to the increase of built-on area in flooding areas. However, if the policy includes measures to reach the European environmental objectives, the risk will only increase due to climate change (Willems et al., 2009).

6 Trend analysis

6.1 Historical data series

6.1.1 Precipitation

Throughout the year, the summer extreme precipitation depths can be as high as the winter extreme precipitation depths. Extreme floods in the Meuse basin mostly occur in the winter season and are associated with abundant precipitation and wet soils, while summer floods are influenced by thunderstorms and often observed only locally (Tu et al., 2005b).

Historical records in Europe demonstrate very different regional evolutions in **annual precipitation**. Indeed, between 1900 and 2000, precipitations have increased in the north of Europe by 10 to 40% while in the south of Europe they have decreased by 20% (De Groof et al., 2006). In the zone between 35° and 85° north latitude the average precipitation increased with 0.5% to 1% per decennia. This corresponds with 7% to 12% in a century, or an average of 62 mm (Brouwers et al., 2008). Annual precipitation amounts measured in Ukkel by the Royal Meteorological Institute of Belgium (RMI) since 1833 demonstrate a leap around 1910, characterised by an increase of 7% (Brouyaux et al., 2008). During the 20th century (1911-2002), the precipitation measurements in the Meuse basin show a significant increase of the annual precipitation amount around 1980 (Tu et al., 2005a).

Looking at the **half-year seasons precipitation amounts** in the Meuse basin, the amounts on rainy days in the winter (November to April), but also considering the whole winter period, have increased since 1980. No evolution is remarked for the summer half-year (May to October) (Tu et al., 2005a). For the **quarter-year seasons**, a wetter spring (mainly for March) from the late 1970s to the end of the 1980s and a slightly drier summer (mainly for August) since the late 1960s can be deduced (Tu, 2006). The RMI mentions twice an increase of 15% of precipitation amounts in the winter half-year, once around 1910 and once around 1965 (Brouyaux et al., 2008).

Since 1976, an increase in the number of very rainy days (> 20 mm/day) has already been observed in the north and centre of Europe (De Groof et al., 2006). Statistical analysis of long observation records (1911-2002) for the Meuse basin showed that the **annual number of wet days** (> 1 mm/day) has only slightly increased from 1972. The **annual very wet days** (> 10 mm/day) in the basin have considerably increased since 1980, roughly by 20% compared to the pre-1980 period (Tu et al., 2005a). The weather station in Ukkel shows no trend for the annual number of rainy days (> 1 mm/day) (Brouyaux et al., 2008).

When a year is divided into a **summer and winter half-year,** the **number of wet** (> 1 mm/day) **and very wet** (> 10 mm/day) **days** has shown no change for the summer (De Groof et al., 2006). For the winter half-year the number of very wet days (> 10 mm/day) has increased with 20% since 1980, while the number of wet days (> 1 mm/day) almost remains constant (Tu et al., 2005a). However, the months of spring also show an increase in number of wet days (Brouyaux et al., 2008).

Inspecting the snowfall, the RMI notices that the annual maximum thickness of the snow layer at the weather station of Saint-Hubert has decreased significantly (Brouyaux et al., 2008).

As a conclusion it seems that wet days have become wetter.

6.1.2 Evaporation

Potential evapotranspiration in the Meuse basin shows climate-induced fluctuations. The enhanced PET (mainly March to August) occurred roughly in the 1930s to the 1940s and the 1990s (Tu, 2006).

An important factor influencing evaporation is temperature. Between 1833 and 2007 the RMI remarks two abrupt leaps in the **annual temperature** diagram. The first one around 1910 from 9°C to 10°C and the second around 1980 from 10°C to 11°C (Brouyaux et al., 2008).

Precipitation anomaly is defined as evaporation minus precipitation. Figure 17 shows the **maximum annual precipitation anomalies** for the Netherlands. The average lies around 150 mm, but no trend can be deduced for the past century (Bresser et al., 2005).

Temperature and precipitation anomalies for successive seasons are not significantly related. There appears to be a weak but significant relationship between the temperature and precipitation anomalies within the same season. This relationship is positive for the winter half-year and negative for the summer half-year (De Wit et al., 2007a).

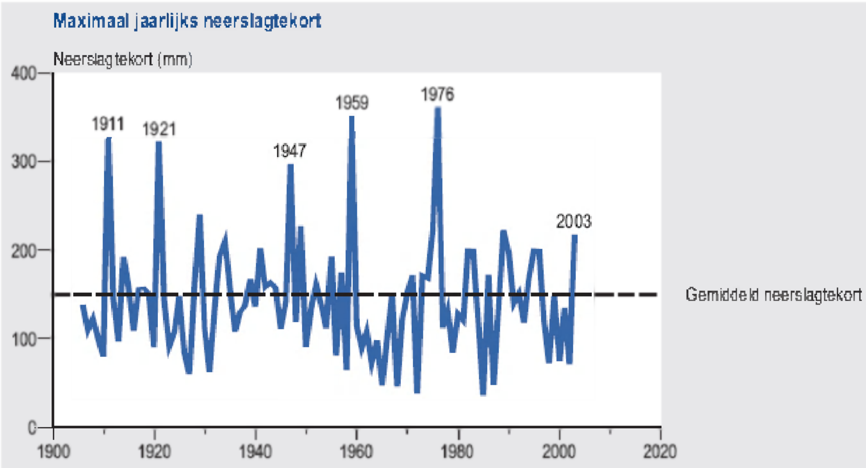

Figure 17 – Maximum annual precipitation anomalies in the Netherlands (Bresser et al., 2005)

6.1.3 Discharges

The Meuse basin is fed by rain and as a consequence, a **correlation** exists between variations in precipitation and variations in discharge. The variations in the discharge records are largely explained by meteorological factors. The land use changes have a marginal influence on the measured flow rates probably due to the size of the catchment and short time span (Ntegeka and Willems, 2008).

A large part of the variance of the average summer half-year discharge can be attributed to the variance of summer precipitation. The average summer half-year discharge also shows a weak but significant correlation with summer temperature, as well as with precipitation in the preceding winter half-year (De Wit et al., 2007a).

A broad **description of changes** in mean flows, high flows, peaks-over-threshold and low flows over the full measure period at Borgharen (since 1911) is given by Tu (2006). The observed change in annual average discharge since 1932 can be largely explained by water extractions between Liège and Borgharen. The average discharge in spring increases since 1978 and the average discharge in autumn decreases since 1933. The annual maximum day discharge and the winter maximum day discharge exhibited an increasing trend, with a significant change point around 1984. The timing of occurrence of winter maximum floods in the Meuse River has been significantly postponed since the early 1940s. No abrupt change in summer maximum day discharge is detected over the past century. There also exists evidence of more small floods (e.g. < 1200 m³/s) in the Meuse River in spring. The summer half-year (May-October) minimum consecutive 10-day moving average discharge shows a downward shift around 1933, with a decrease from 81 m³/s to 58 m³/s near Monsin.

In Figure 18, the second half of the 20th century is compared to the first half. One remarks that the averaged highest and lowest month discharges have not clearly changed. However, the discharge in spring is somewhat increased, while discharge in autumn is decreased (De Wit et al., 2007b).

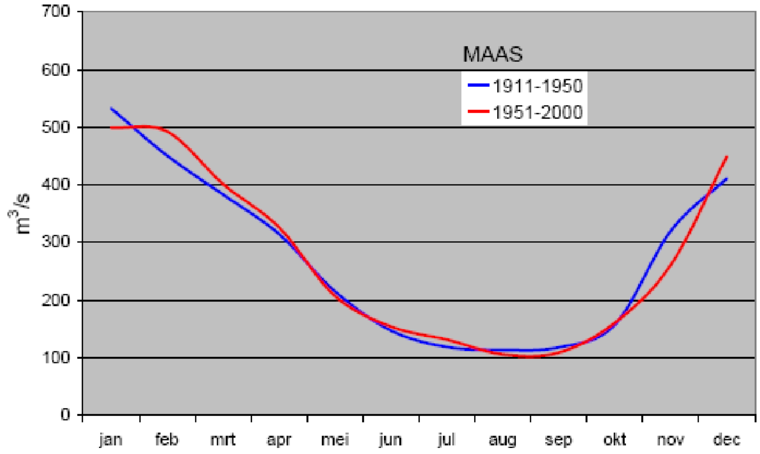

Figure 18 – Change in discharge regime at Borgharen (De Wit et al., 2007b)

During the 20th century, the annual rainfall-runoff ratio in the Meuse basin (upstream of Monsin) appears to have changed around 1932, with a significant decrease in the runoff proportion. This decrease cannot be explained by historical **land use changes** in the basin (Tu, 2006).

Five out of the seven largest floods recorded in the period 1911-2003 occurred during the last decade (Tu et al., 2005b). The relatively large magnitudes of (winter) floods in the Meuse in the last couple of decades are largely affected by the increased antecedent precipitation depths, and thus can broadly be ascribed to **climate variability**. Also fluctuations of summer low flows in the Meuse are in general in response to variations in the meteorological conditions. The downward shifts shown in summer low flow of the Meuse (after 1933) are very likely related to the quality of the discharge data analysed. The effects of historical land use changes on the discharge regimes of the Meuse River are marginal or statistically undetectable (Tu, 2006).

More pronounced are the effects of hydraulic works and management measures along the river systems of the tributaries. However, at the Meuse basin level, the attenuating effects of hydraulic works and management measures along the river network can not impact the occurrence of large floods in the downstream river (Tu, 2006).

This is in contradiction with earlier thoughts, like in Baetens et al. (2004), which argue that the increase in peak discharges is due to the improvement of river infrastructure and the change in land use. During the 20th century the following changes took place: increasing urbanisation, intensifying of agriculture and guarding of mine collapsing areas. These changes required an enlargement and consolidating of dikes and by so, a bigger area from the river was taken away to provide dikes. As a result, the conveyance and the buffer capacity of the Meuse have decreased strongly and what's more, a continuous network of dikes was required to prevent floods at other places. The water of the Meuse is now forced to flow in a single channel. So the consequence is that for high discharges the power of the flowing water increases enormously and the danger for floods becomes very high (Baetens et al., 2004).

6.2 Future scenarios

6.2.1 Precipitation

The **annual precipitation amount** is expected to remain constant or increase slightly. The changes of summer and winter will compensate each other (Brouwers et al., 2008). Precipitation will be more clustered with more and longer periods of precipitation in winter and more and longer periods of drought in summer (Strubbe et al., 2005).

The expected **precipitation amount during winter** is dependent of the study. In Belgium studies are mainly executed by CCI-HYDR (Boukhris et al., 2007b), that combines more than 30 simulation runs from 10 Regional Climate models (RCM) into three climate scenarios (low, mean and high). Climate change predictions for the Netherlands are made by the Koninklijk Nederlands Meteorologisch Instituut (Van Den Hurk et al., 2006). A literature review is presented by Boukhris et al. (2007a). Towards 2100 an increase of 0%, 8% or 16%, respectively for the low, mean and high scenario is predicted (Boukhris et al., 2007b). The Koninklijk Nederlands Meteorologisch Instituut (KNMI) finds an average precipitation increase of 3.6% to 14.2% for 2050 (Boukhris et al., 2007a). The study of the KUL shows that the rainfall factors are time scale independent. In other words, the perturbation factors for precipitation amounts averaged over day, week, month or the whole season are all the same, i.e. the rainfall peaks will be affected similarly as the low storms (Boukhris et al., 2007b). Similar results can be deduced by the study of the KNMI, where the wet day frequency in winter will increase with 0.1%-1.9% and the precipitation on a wet day in winter will increase with 3.6%-12.1% (Boukhris et al., 2007a).

The expected **precipitation amount during summer** is time scale dependent. The number of wet days will decrease, but the amount of precipitation of the whole summer will decrease less, remains constant or increase, depending on the study. The study of the KUL gives perturbation factors of 0.84, 0.98 and 1.09 respectively for the low, mean and high scenario, but only for the day, week and month time scale. The seasonally perturbation factors are 0.77 (low), 0.86 (mean) and 0.95 (high). This means less rainy days, but if it rains, it will be heavier than in the past (Boukhris et al., 2007b). Similar results are obtained by the KNMI. The seasonally average precipitation amounts changes with -19% to +5.5%, the wet day frequency in summer changes with -1.6% to -19.3% and the precipitation on a wet day in summer changes with +0.1% to +9.1% (Boukhris et al., 2007a).

Another study shows that **extreme events** will become more extreme. The perturbation factor depends on the considered return period. For example, the precipitation of the storm with a return period of 1 year will increase with a factor 1.13, while the factor is 1.16 for the storm with a return period of 10 years (Boukhris et al., 2009).

A summary of the most recent results of the CCI-HYDR, INBO, KNMI, ADAPT and other projects on climate change can be found in the scientific report contributing to the MIRA 2009 research project, which examines the consequences of climate change and land use change on hydrology and hydraulics in Flanders (Willems et al., 2009).

6.2.2 Evapotranspiration

Evapotranspiration is influenced by several factors, e.g. temperature and moisture content. There is a duality as temperature will increase, but precipitation will decrease in summer time (De Groof et al., 2006).

The CCI-HYDR project predicts towards 2100 a perturbation factor for the **winter** potential evapotranspiration of 1.00 (low scenario), 1.13 (mean scenario), 1.27 (high scenario). The **summer** potential evapotranspiration will increase with a factor 1.10, 1.16 or 1.29, respectively for the low, mean and high scenario. These factors are time scale independent. In other words, they are almost the same for daily, weekly, monthly or seasonally averages (Boukhris et al., 2007b). Figure 19 gives the perturbation factors for each month.

The Koninklijk Nederlands Meteorologisch Instituut (KNMI) expects an increase of potential evapotranspiration in summer of +3.4% to +15.2% towards 2050 (Boukhris et al., 2007a).

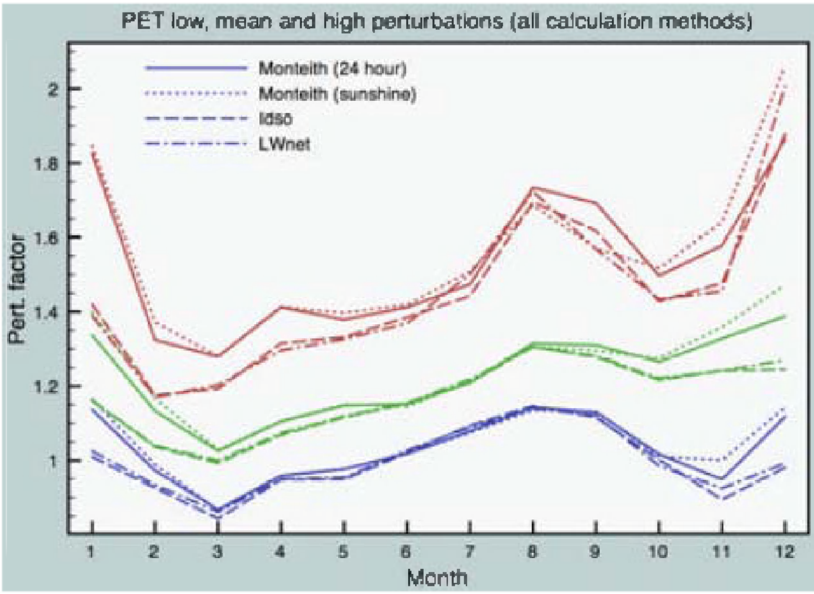

Figure 19 – Perturbations factors for 2100 for potential evapotranspiration for low (blue), mean (green) and high (red) scenarios using different calculation methods (Ntegeka et al., 2008)

6.2.3 Discharges

Changes in the discharge regime are found to be less pronounced than those in the precipitation regime. This **lower sensitivity** can be explained both by the increase in the evapotranspiration and by the natural storage capacity of the catchments (De Groof et al., 2006). However De Wit et al. (2007b) state as a general rule that the increase in terms of percentage of the annual average maximum of the 10-day winter precipitation sum in the Meuse basin leads to a similar increase of the discharged volume by the Meuse during high water.

The most important processes in the context of climate change impacts on river flooding were found to be precipitation, evapotranspiration, infiltration excess overland flow, saturation excess overland flow, subsurface storm flow, subsurface flow and river flow (Booij, 2005).

The increased precipitation amount in the winter will cause a rise in groundwater level. On the one hand this will increase the risk of inundations, but on the other hand it will decrease the risk of drought in the summer (De Wit, 2008). There is no indication that the occurrence of years with subsequent dry winters and dry summers will increase. Also, the correlation between summer precipitation and winter precipitation is not shown to clearly change under future greenhouse gas concentration conditions (De Wit et al., 2007a). Nevertheless, a study of the KUL shows more water shortages in summer towards 2100 (Brouwers et al., 2008).

Looking at the **change in discharge**, a specific study on the River Meuse upstream of Borgharen in Belgium and France predicts a small decrease of average discharge (~5%), but an increase in extreme discharge and variability (5-10%). It has been concluded that climate change would lead to an increase in the average discharge at the end of winter and at the beginning of spring, while a decrease of the average discharge is expected in autumn. However, natural variability of the Meuse discharge is large and differences over long time intervals are rather small, so it becomes hard to clearly quantify those long term changes (De Groof et al., 2006). Generally spoken, the winters become wetter and the summers become dryer.

Similar conclusions can be drawn by the simulations based on the KNMI and CCI-HYDR predictions.

The results of Figure 20 are calculated by applying the expected changes of the KNMI in a hydrological model of the Meuse (De Wit et al., 2007b). Moreover, it appears that the observed changes in the 20th century are smaller than the expected changes for the 21st century.

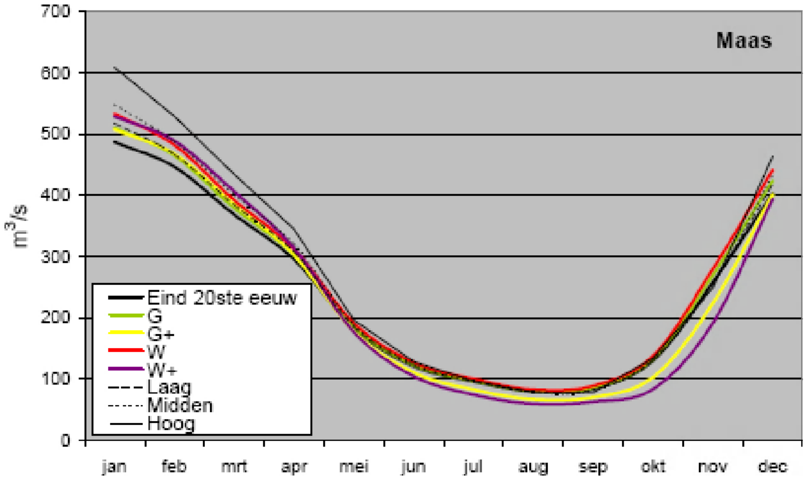

Figure 20 – Expected monthly average discharges for 2050 at Borgharen (De Wit et al., 2007b)

The simulations using the three climate scenarios developed by CCI-HYDR were executed with the hydrological model HBV-Maas and the hydraulic model SOBEK 1D (Boukhris et al., 2007b). The control period is 1969-1998 and the simulated period is 2070-2100. The results are presented by Vanneuville and Holvoet (2009).

The average yearly discharges are significantly lower for the low scenario and significantly higher for the high scenario compared to the actual situation (Table 10). The results for the average winter discharge in the high scenario are almost the double of the discharge in the control period. For future summer discharge, the three scenarios are all unambiguous. The average summer discharge will become lower than the half of the discharge in the control period. Maximum average yearly discharge is 1335 m³/sec in the control period and 1040 m³/sec, 1428 m³/sec and 1938 m³/sec in the low, mean and high scenario respectively (Vanneuville and Holvoet, 2009).

Table 10 – Average yearly and seasonal discharge for 2070-2100 at Borgharen [m³/s] (Vanneuville and Holvoet, 2009)

	Control period	**Scenario**		
		low	**mean**	**high**
Average yearly discharge	278	191	255	313
Average winter discharge (dec-feb)	445	270	465	701
Average summer discharge (jul-sep)	113	33	52	29
10%-percentile of daily values	50	14	21	12
90%-percentile of daily values	665	515	676	871

The monthly average discharge is shown in Figure 21. February has the highest monthly discharge, except for the low scenario where this occurs in March. A possible explanation is the higher influence of the base flow in the low, dryer, scenario. In all scenarios, September has the lowest discharge. The average is 15 m³/sec in the high and 18 m³/sec in the low scenario, in spite of a comparable reduction of rainfall during summer. The lower discharge in the high scenario is a result of the higher evapotranspiration which is a consequence of the higher temperature in the high scenario (Vanneuville and Holvoet, 2009).

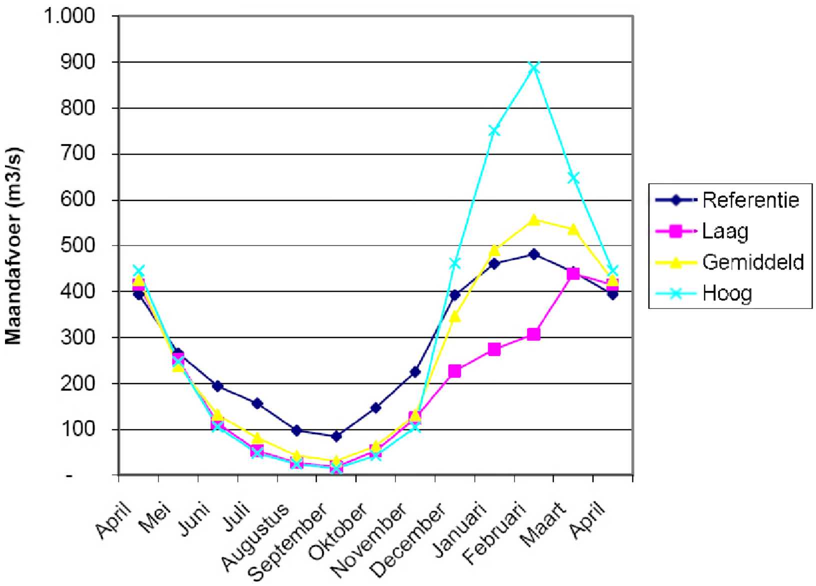

Figure 21 – Monthly average discharge for 2070-2100 at Borgharen (Vanneuville and Holvoet, 2009)

Table 11 indicates the maximum daily discharge during the highest high water in each series for the control period and the three scenarios with the HBV hydrological model and after simulation with SOBEK. The values clearly indicate the influence of river hydrodynamics which is realistically simulated with SOBEK (Vanneuville and Holvoet, 2009).

Table 11 – Maximum daily discharge during the highest high water at Borgharen (Vanneuville and Holvoet, 2009)

Scenario	HBV (m^3/sec)	SOBEK (m^3/sec)	Decrease (%)
Reference (1995)	2975	2660	10.6
Low	1872	1656	11.5
Mean	3164	2832	10.5
High	4335	3880	10.5

The general trend with climate change is a small decrease of the average discharge and a small increase of the standard deviation of the discharge (variability) and extreme discharges. The **cause** of the decrease of the average discharge lies within the slight increase of modelled average precipitation with climate change (about 5%) combined with the considerable increase of (potential) evapotranspiration (on average about 15%, see Table 4). The increase in discharge variability and extreme discharges is the result of the considerable increase of precipitation variability and extreme precipitation (10–20%), but is less than would be expected on the basis of the changes in precipitation behaviour. (Booij, 2005)

Climate change is one of the causes of floods and droughts, but also direct human interventions are disadvantageous: clearing of forest soils, straitening of rivers, suppressing of natural flooding areas, inadequate drainage, … (Brouwers et al., 2008). The increase in flood peaks in the Meuse River since the 1980s can be explained mainly by climate variability rather than by land-use changes. Nevertheless, in terms of future discharge regime in smaller rivers such as Ourthe or Mehaigne, the impact of changes other than climate induced ones (e.g. changes in land use…) may be as important as impacts resulting from climate change. This suggests that relevant adaptation measures (land use changes, water management, flow regulation, ...) could reduce peak discharges (De Groof et al., 2006).

7 Water uses

In the past century, the global water use has increased with a factor 8. This is due to a growing world population, but also to an increase in water use per world citizen. The water of the Meuse is being used for inland navigation, drinking water, electricity production, process water in industries, irrigation in agriculture and water tourism. By so, the Meuse has an economical value of hundreds million euros a year. In case of a dry and warm summer, the water shortage of the Meuse can cause cost tens of millions of euros for damage and losses of income (De Wit, 2008). The balance of water uses for the Meuse is presented in Figure 22.

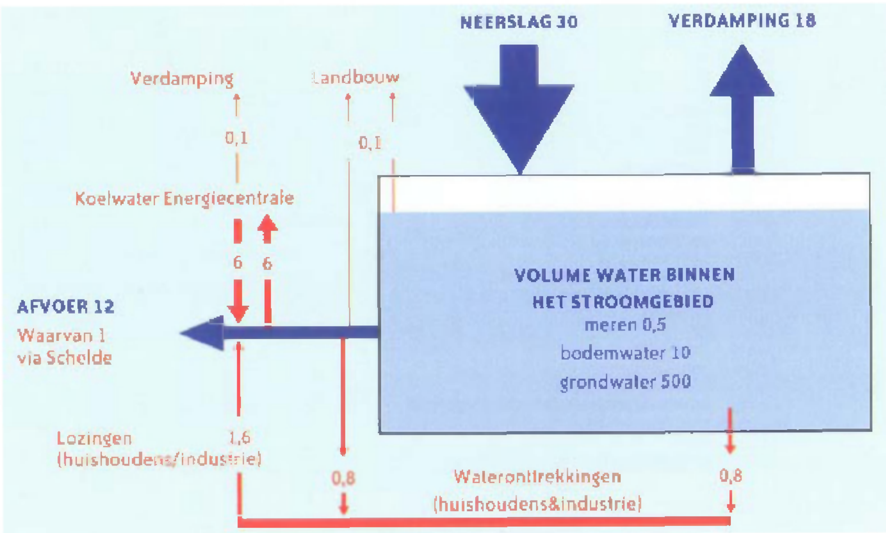

Figure 22 – Water balance Meuse basin [km³/year] (De Wit, 2008)

The extraction of water can be divided into on the one hand extraction from surface water and on the other hand extraction from groundwater (CIW, 2008). The Albertkanaal is an important provider concerning the extraction from surface water. In the year 2005, the water companies extracted 58 million m³, the -mainly chemical- industry used 23 million m³ from an extraction of 37 million m³ and 7 million m³ from an extraction of 151 million m³ was lost by energy production. Concerning the extraction from groundwater, 111 million m³ was permitted to extract in the Flemish part of the Meuse basin. An overview of permitted and real extracted amounts per sector is given in Table 12. A description of several sectors (households, industry, trade & services, agriculture, transport, tourism & recreation) is made by CIW (2008).

Table 12 – Permitted and real extraction amounts in the Flemish part of the Meuse basin (2005) (CIW, 2008)

Sector	Permitted extraction [m³/year]	Percentage real extraction	Real extraction [m³/year]
Trade & Services	1 361 208	21%	285 854
Industry	10 878 404	44%	4 786 498
Agriculture	12 024 284	25%	3 006 071
Utility companies	85 336 410	65%	55 468 667
Undefined	1 636 900	100%	1 636 900
TOTAL	111 237 206		65 183 989

An analysis of the tax database on waste water gives a total water use in the Flemish Meuse basin of 327.77 million m³/year. When analysing the permission database of groundwater extractions, 77.6 million m³ groundwater is pumped up each year. The water used by sectors can be groundwater, rainwater, surface water, other water (second circuit) or tap water. Remark that the latter is originating from surface or groundwater. According to the tax database for large-scale consumers, 88.9% of the used water comes from surface water, 7.3% from groundwater, 2.7% from tap water, 0.7% from other water and 0.4% from rain water (CIW, 2009).

Important to notice is that Meuse water is being used outside the Meuse River Basin via the canals of the Kempen. The Antwerpse Waterwerken (AWW) is responsible for the production and distribution of water for the inhabitants and industry of the Antwerp region and for other drink water companies in Flanders (Pidpa, TMVW, VMW) (AWW, 2009). Table 12 only mentions water amounts used in the Flemish part of the Meuse basin. Real water uses originating from the Meuse River are higher. For 2008, AWW supplied a total water amount of 140 454 619 m³, of which 37 700 976 m³ for private consumption (27%), 63 024 707 m³ for industrial use (45%) and 39 728 936 m³ for delivery to other water companies (28%) (AWW, 2009).

7.1 Drinking water

The water in the Meuse basin is being used by 6 million people for drinking water purpose. If one counts 125 litre of water each person a day, the total amount reaches 0.25 km³ water a year (De Wit, 2008).

The Flemish part of the Meuse basin contains a population of 416 000 inhabitants, which use each about 121 l water a day (CIW, 2008). This means a water use of 0.018 km³/year. The Flemish water companies taken together (Bree, Maaseik, Eisden, Meeswijk, As, Neerharen en Tongeren) are pumping up 111 700 m³ a day, or 0.04 km³ a year (Baetens et al., 2004). The Bekkenbeheerplan Maas (CIW, 2009) mentions a water use of 26.9 million m³ water each year in the housing sector, based on an analysis of the tax database on waste water. The permission database of groundwater extractions gives an amount of 56.6 million m³/year pumped up by the water companies.

In periods of low discharge, the amounts used for drinking water are reduced. The level of the groundwater table is monitored closely to prevent depletion (De Wit, 2008). There also exists a risk of increasing prices for drinking water in periods with low water availability (De Groof et al., 2006).

7.2 Fluvial navigation

At the moment, no shipping occurs at the Border Meuse as there are no weirs in this part of the Meuse. The weir of Linne makes it possible that navigation for transport of gravel can take place in a small part downstream Maaseik and that the Border Meuse is navigable for ships of 600 ton from kilometre 57 on, this is 4.5 km downstream Maaseik (Baetens et al., 2004).

As there is no navigation possible at the Border Meuse, shipping occurs via the parallel channels Zuid-Willemsvaart on Flemish side and Julianakanaal on Dutch side (www.gemeenschappelijkemaas.be, 2009). The Meuse supplies a whole network of channels that connect the ports of Antwerp and Rotterdam and the European inland (Baetens et al., 2004).

The most important canals in Limburg and Antwerp are the Albertkanaal (class VI), the Zuid-Willemsvaart (class II) and the Canal Bocholt-Herentals (class II). However, as the Albertkanaal lies for the major part in the Scheldt basin, the water body is assigned to that basin (CIW, 2008).

The water use of the canals consists of the loose of water during lockages. Raadgever (2004) gives day average water losses for several locks in Flanders.

7.3 Agriculture

Agriculture uses water for irrigation. Most farmers extract water from the groundwater reservoir, which causes a drop in groundwater level. A better solution is to supply water via a system of channels. The water used by agriculture does not flow back to the river. For the entire Meuse basin, about 0.1 km³ is used by agriculture. The need is not equally distributed over the year, but peaks in the summer, at the same time when the Meuse has low flows (De Wit, 2008).

The Bekkenbeheerplan Maas (CIW, 2009) mentions a water use of 0.045 km³ water each year by the agricultural sector for the Flemish part of the Meuse basin, based on an analysis of the tax database on waste water. The permission database of groundwater extractions gives an amount of 6.2 million m³/year pumped up by the farms.

Climate change has a great influence on agriculture. A critical factor is the availability of water in dry periods, because more water resources are drawn on in such periods. For example, the extreme temperatures experienced in 2006 in European countries have had tangible effects on yield. Compared to 2005, the main crops affected were: soft wheat (-4%), winter barley (-2%), grain-maize (-5,1%), potatoes (-4,3%) and sugar beet (-3%). In total, cereal production should be much less - around 9 million tons (-3,6%) - than what it was in 2005, which was considered to be a year of lesser yield (De Groof et al., 2006).

Possible measures of adaptation are (Bates et al., 2008):

- adoption of varieties/species with increased resistance to heat shock and drought
- modification of irrigation techniques, including amount, timing or technology
- adoption of water-efficient technologies to 'harvest' water, conserve soil moisture (e.g. crop residue retention), and reduce siltation and saltwater intrusion
- improved water management to prevent water logging, erosion and leaching
- modification of crop calendars, i.e., timing or location of cropping activities

Not only drought will cause problems, also the increase in intensity and frequency of precipitation (Bates et al., 2008).

7.4 Hydropower, nuclear plant

Along the Meuse several electricity generating stations use the water of the Meuse as cooling water. After use, the water is discharged into the Meuse again. However, the water has a higher temperature and a part of it is evaporated. The total installed potential of all thermal and nuclear power stations along the Meuse reaches 12 033 MegaWatt. Averaged over a year, 6 km³ Meuse water is used as cooling water, or 190 m³/s, of which 1.5% (2.8 m³/s) evaporates (De Wit, 2008).

For the Flemish part of the Meuse basin, the Bekkenbeheerplan Maas (CIW, 2009) mentions a water use by the energy sector of 226.9 million m³ each year, based on an analysis of the tax database on waste water. Of this amount, 97% (0.22 km³) is discharged back as cooling water. Raadgever (2004) gives information for two Electrabel power plants. In Genk, 6 m³/s is extracted, of which 5.7 m³/s is discharges again. In Mol, 3.6 m³/s is extracted, of which 3.5 m³/s is discharges again.

In periods of low flows or high temperature, restrictions are being established for the thermal pollution by the power stations (De Wit, 2008). These periods occur in summer, while the highest electricity use is in winter time (Baetens et al., 2004). Nevertheless, these restrictions can suffer the electricity production (De Wit, 2008). In the Walloon Region, two criteria counts for water used as cooling water. First, the discharged water is not allowed to be warmer than 28°C. Second, the difference in temperature between the extracted and discharged water has to be less than 3°C. In other words, problems appear on days with a surface water temperature above 25°C. The temperature rise due to climate change will cause an increase of number of such days (De Groof et al., 2006). It is expected that prices of electricity will increase, because warmer surface water means a loss in efficiency as cooling water, and electricity demand will increase in warm periods (De Groof et al., 2006).

The total installed potential of all hydro-electric power stations along the Meuse, counts to 140 MegaWatt, and projects exist to build more hydropower plants (De Wit, 2008). For low flows, the frequently switching on and off of the turbines causes unnatural variation in water level and water velocities. This demands a better regulation of discharge, like the weir of Borgharen that flattens the variations of the hydropower plant of Lixhe. The Border Meuse encounters the consequences of this station (Baetens et al., 2004).

Water reservoirs do not supply net energy, but form a buffer in periods of high electricity demand (De Wit, 2008).

7.5 Industries

There are no industrial companies on the Flemish side of the Border Meuse which are tapping water directly from the Meuse. On the contrary, some companies use water from the Albertkanaal, from water pipes, or extracted from the groundwater reservoir (Baetens et al., 2004). For the Flemish part of the Meuse basin, the Bekkenbeheerplan Maas (CIW, 2009) mentions a water use of 52.6 million m^3/year used by the industry and trade sector, based on an analysis of the tax database on waste water. Of this amount, 42% (0.022 km^3) is meant as cooling water. The permission database of groundwater extractions gives an amount of 11.64 million m^3/year pumped up by the sector industry and trade.

The expected extreme events caused by climate change will also have an impact on the production and the distribution of goods and products. And so, harmful weather conditions may bring about a failure in the supply of raw materials. In the same way, the transport of commuters to their place of work will also be hit by the weather (De Groof et al., 2006).

Finally, the Meuse gives profit to the tourist sector. Here as well, climate change can produce negative effects. For example, low flow hampers kayaking and low discharges cause an increase in concentration of pollutants and pathogenic elements (De Groof et al., 2006).

8 Water hazard mitigation

8.1 Flood control

The website www.gemeenschappelijkemaas.be offers a time line of protection works and other aspects along the Meuse between 1771 and 2005.

The high water levels on the Meuse in 1980 and 1984 have lead to the establishment of the Maasdijkenplan. The purpose was to make all the existing winter dikes in Limburg property of the Flemish Government and to build new dikes if necessary. Finally, a completely closed dike system without buildings in the winter bed has to be arisen. The dikes should protect the hinterland against a discharge of 3000 m^3/s, with an additional height of 0.5 m (WL, 2003a).

In 2003, the summer bed of the Meuse is being enlarged at Berg-Meeswijk over a zone of 700 meter, together with the construction of a new winter dike (www.gemeenschappelijkemaas.be). Before, the winter dike came near to the summer bed at Flemish side and the ground sloped up fast at Dutch side. This bottle neck caused damming up of the water (WL, 2003a).

The brooks which formerly flow out into the Meuse, now have to pass the winter dikes. For this reason, outlet sluices with valves were build. Together with the latest dike works, the outlet structures of the Kikbeek and Ziepbeek were renewed in 2003 (www.gemeenschappelijkemaas.be).

Since 2004, all dikes between Lanaken en Maaseik (45 km) have been adapted to the protection goals of the Maasdijkenplan (www.gemeenschappelijkemaas.be).

The project “Levende Grensmaas” aims to restore the contact between the river and the winter bed. It has been approved in 1995 and will realize a large-scale nature area over a river distance of 50 km (Baetens et al., 2004). The project includes river bank lowering, realisation of side ditches, reestablishment of contact with discharging brooks and integration of old gravel pools in the landscape in an ecological sensible way. The exploitation of gravel along the Meuse has finished since 2006 (De Coster, s.d.). For example, the locations Negenoord and Maasbeempter Greend will be rearranged (WL, 2003a).
Figure 23 gives an overview of locations arranged in the project “Levende Grensmaas”.

In The Netherlands, a study is executed on calamity control of floods from Rhine and Meuse (Ministerie van Verkeer en Waterstaat, 2006). It considers the remainder risk to flooding after the execution of the Planologische Kernbeslissing Ruimte voor de Rivier, the Maaswerken and the Hoogwaterbeschermingsprogramma. Climate change is not included in the research. Five options are examined:

- International concordance
- Organizational measures
- Emergency overflow areas
- Construction of compartmentalization dikes
- Sharpen of safety norms

The options are checked against the following criterions: safety, effects on other policies, public support, feasibility and costs.

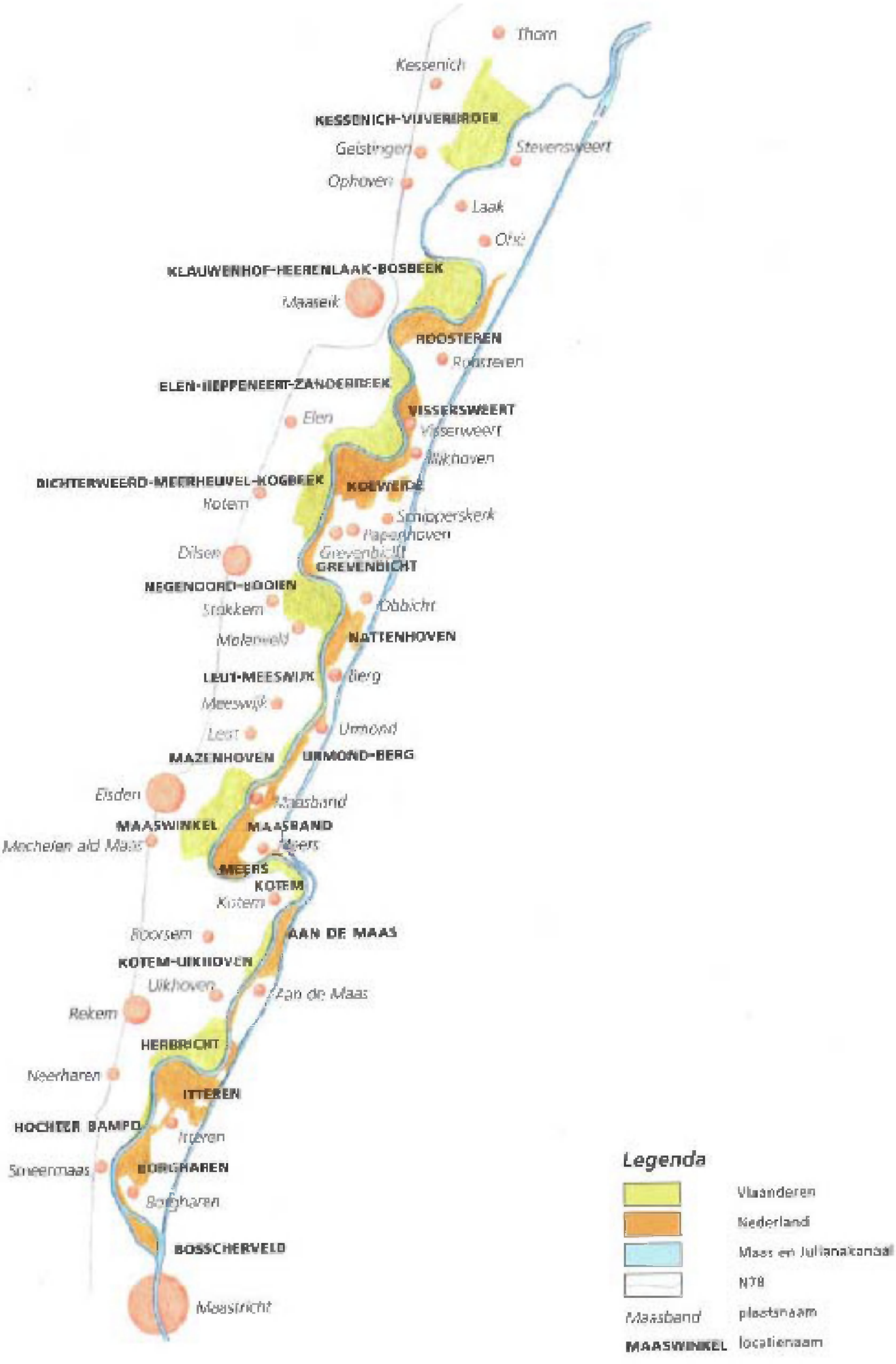

Figure 23 – Locations of the project “Levende Grensmaas” (De Coster, s.d.)

8.2 Low water supply

In case of low water, supply to the Flemish canals, Dutch canals and the Border Meuse is arranged by the Meuse discharge agreement of 1995. The water saving measures of this agreement comes into force when the discharge at Monsin is lower than 130 m³/s. Basically, the water is distributed equally between Flanders and the Netherlands, in such way that a minimum discharge of 10 m³/s on the Border Meuse is guaranteed to prevent irremediable damage to the vulnerable nature. The distribution of the water between the Meuse and the Flemish and Dutch canals is shown in Table 13 (De Wit, 2008). More information about low flows is written under paragraph 5.2.

Table 13 – Low flow Agreement between the Flemish Region and the Netherlands (De Wit, 2008)

Discharge in Liège	**Border Meuse**	**Flemish canals**	**Dutch canals**	**Underspending [days in a year]**		
				1911-2003	**2003**	***1976***
130 m³/s	60 m³/s	35 m³/s	35 m³/s	126	210	*264*
100 m³/s	50 m³/s	25 m³/s	25 m³/s	90	172	*237*
60 m³/s	10 m³/s	25 m³/s	25 m³/s	31	96	*190*
30 m³/s	10 m³/s	10 m³/s	10 m³/s	2	0	*92*
20 m³/s	6.7 m³/s	6.7 m³/s	6.7 m³/s	0.4	0	12

8.3 Impacted economic activities

Raadgever (2004) has developed a damage model for low water at the Meuse. The report also contains a description of the affected sectors, which is similar to the paragraphs under 7 Water uses. Low discharges could increase the costs of transport by inland navigation in two manners. First, by restrictions in lading ratio at low water levels; second, by longer waiting times at locks. The Vlaamse Besparingsscenario mentions a ‘request to save water’ to the industry. However, this measure cannot be enforced. It is clear that the economical importance is quite high and production cannot continue without water supply from the Meuse. If water supply to crops is not optimal, yields will decrease. However, farmers can have the possibility to switch to groundwater use instead of surface water use. The Antwerpse Waterwerken disposes of reservoirs with a total capacity of 7 million m³. By so, the water extraction can be interrupted for 2 weeks without damaging the water supply to the consumers. Low water can cause damage to electricity production in two manners. Increasing water temperatures give lower efficiency and discharging is normally forbidden for temperatures higher than 30°C.

Climate change will have an impact on water quality, which is amongst others important for the tourist sector. Water quality is most critical during hydrological extremes and high water temperatures. The increase in frequency and intensity of droughts, high waters and heat waves resulting from climate change could lead to a deterioration of chemical water quality (Van Vliet et al., 2008).

9 Water management system

9.1 Flood forecasting

Flanders Hydraulics Research has an online forecast system of the Border Meuse in the floodwatch software from DHI (Soresma, DHI Water & Environment, 2005). It is possible to process and validate telemetry data, execute forecasts and visualize and distribute results in a centralized and automatic way. The forecasts are made for a period of 2 days.

The Flemish Environment Agency (Vlaamse Milieumaatschappij - VMM) also has a forecast system for the unnavigable waterways in Flanders. They distribute forecasts for two days in advance on the website www.overstromingsvoorspeller.be.

9.2 Low flow forecasting

The Hydrological Information Centre (Hydrologisch Informatiecentrum - HIC), part of Flanders Hydraulics Research (Waterbouwkundig Laboratorium - WL), is responsible for low water reporting from April to October. The monthly messages contain information about precipitation, river discharges and groundwater levels starting from recent hydro-meteorological data, completed with forecasts for the coming decades of days. The low water messages can be found on http://www.lin.vlaanderen.be/awz/waterstanden/hydra/laagwbericht/index.htm.

9.3 Design flood

A research to the estimation of extreme floods of the River Meuse was executed by Leander et al. (2005). A stochastic weather generator for the Meuse basin based on nearest-neighbour resampling has been developed. The generated daily sequences of area rainfall and temperature sequences were used to perform 3000-year simulations of the daily discharge at Borgharen with the HBV rainfall–runoff model.

For certain return periods, Table 14 gives discharges on the Border Meuse at Borgharen. The normative discharge in the Netherlands for the Meuse is determined at 4000 m³/s. The dikes in the Netherlands have to stand up against this discharge. Based on statistics, the 4000 m³/s discharge will happen once in 1250 year (De Wit, 2008).

Table 14 – Discharges on the Border Meuse (Baetens et al., 2004; De Wit, 2008)

Return period	Discharge on the Border Meuse
40-50 days a year	500 m³/s
8 days a year	1000 m³/s
2 years	1500 m³/s
10 years	2260 m³/s
50 years	2865 m³/s
100 years	3110 m³/s
250 years	3430 m³/s
1250 years	4000 m³/s

The policy in Flanders is different from the Netherlands. Protection works are not based on a maximum discharge, but are determined using a risk methodology approach.

The Hydrological Information Centre (Hydrologisch Informatiecentrum - HIC) of Flanders Hydraulics Research (Waterbouwkundig Laboratorium - WL) has developed a method to calculate objectively the damage of flooding (WL, 2003b). The purpose is not to prevent floods, but to let them take place where they damage the least.

The analysis of risk occurs in three steps (Figure 24):

- First, flood maps are calculated for certain return periods. There exist two kinds of flood maps, maximum water level as well as maximum rate of water rise.
- In a second stage, damage maps are designed. Considering the land use (built-on, industry, agriculture, …) and socio-economic data (market value buildings, crops, cars, … and possible number of victims) the maximum damage in case of loss is calculated. However, the damage in reality is not equal to the maximum damage calculated, as it depends on the water depths and rate of water rise of the flood. For this reason, the flood maps are combined with the maximum damage maps to real damage maps.
- At last, the flooding risk is determined with the formula damage x frequency, which is summed over all return periods. The result is one risk map [€/m².year].

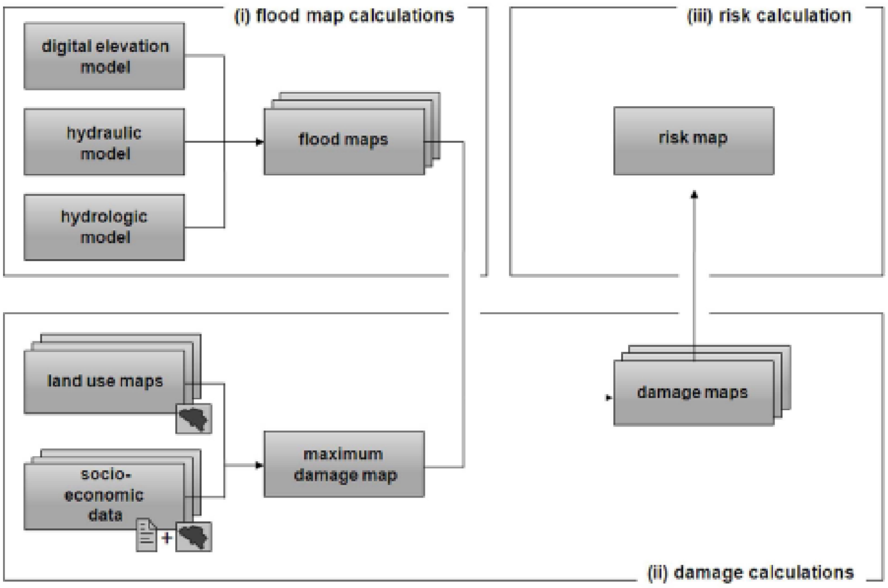

Figure 24 – Schematic representation of risk methodology (Kellens et al., 2008)

9.4 Water management services

The authorized public service for water management of the Border Meuse is nv De Scheepvaart. The principal tasks of nv De Scheepvaart are the maintenance, exploitation, management and commercialization of the Albertkanaal, the canals of the Kempen, the Scheldt-Rhine connection and the Border Meuse (www.descheepvaart.be).

In case of an emergency situation, distinction is made between internal and external emergency (IBZ, s.d.). In case of an internal emergency situation, the public safety is not endangered and the waterway manager, in this case nv De Scheepvaart, is responsible for the intervention. If the public safety is endangered, the emergency situation becomes external and the authority shifts to the government. Three levels are distinguished:

- Municipal alert (mayor is responsible)
- Provincial alert (governor is responsible)
- Federal alert (minister of internal affairs is responsible)

9.5 Models inventory

The inventory of existing hydrological, hydraulic and groundwater models made by Baetens et al. (2004) can be found in Table 15.

Table 15 – Inventory of models (Baetens et al.,2004)

Hydrological models	• MEUSEFLOW 1.0: water balance model on a monthly basis (RIZA WL Delft Hydraulics) • MEUSEFLOW 2.0: water balance model on a 10-day basis (RIZA WL Delft Hydraulics) • MEUSEFLOW 2.1: version with special attention to low water and climate change (RIZA WL Delft Hydraulics) • MEUSEFLOW-LIGHT: aggregated version (RIZA WL Delft Hydraulics) • Hydrological (HBV) models of Vesdre, Lesse and Amblève (RIZA WL Delft Hydraulics)
Hydraulic models	• ZWENDL: 1D model (RWS) • SOBEK: 1D model in substitution for ZWENDL (RWS) • WAQUA: 2D model (RWS) • MIKE 11: quasi 2D model (Flanders Hydraulics Research) • RHASIM: effects of low water on ecological development • INFOWORKS hydrological – hydraulic models of different watercourses (Voer, Itterbeek, Jeker, Bosbeek, Abeek, Berwinne, …) (VMM)
Groundwater models	• IWACO Zandmaas/Maasroute: groundwater supply towards the Meuse (RWS) • DHV grondwatermodel Grensmaasproject: regional groundwater model as part of the MER Grensmaas (Royal Haskoning) • Vlaams Grondwater Model (VMM)

Flanders Hydraulics Research disposes of a mathematical model of the Border Meuse. It concerns a quasi two dimensional hydraulic model, built in DHI MIKE11 version 2000B - module HD (Maeghe et al., 2002). The base model was made in 2002, followed by an actualisation in 2006 (Pannemans et al., 2006) and an extension in 2009 (Bogman et al., 2009).

The base model contains the Border Meuse between Lanaken and Maaseik. The modelled length is 34.4 km. The influences of the relative small brooks discharging in the Border Meuse (Geul, Ziepbeek, Kikbeek, Langbroekbeek, …) are neglected. The area of the sub basin of the Border Meuse is not considered too, as this is negligible compared to the basin area of the upstream Meuse. In this model, the effects of the project “Levende Grensmaas” are examined (Maeghe et al., 2002).

The realisation of the “Levende Grensmaas” project and the Maasdijkenplan, and the exploitation of gravel pools made it necessary to actualise the hydraulic model. In addition, new bathymetrical data for the summer bed, a new digital level model and adapted boundary conditions (discharge from weir at Borgharen instead of measuring point at Lanaken) were introduced. This actualisation was realised in Mike11 version 2005, SP3 (Pannemans et al., 2006).

The model was extended from Maaseik to the weir at Linne. By this extension of 10 km, the entire Meuse on Flemish territory is modelled. Additionally, an actualisation of the model to include the adaptations resulting from the project “Levende Grensmaas” was executed. For this model, the Mike11 version 2007 SP2 was used. Finally, the influence of two tributary brooks, the Geul and the Geleenbeek, was examined. In previous versions of the model, brooks were not included. Contrary to what was thought, the influence is not negligible. The influence on the water level of the Meuse upstream from the discharge of the Geul is limited, but can be 2 to 10 cm downstream this point (Bogman et al., 2009).

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Waterbouwkundig Laboratorium

Flanders Hydraulics Research

Berchemlei 115
B-2140 Antwerpen
Tel. +32 (0)3 224 60 35
Fax +32 (0)3 224 60 36
E-mail: waterbouwkundiglabo@vlaanderen.be
www.watlab.be