Effect of Climate Change on the Hydrology of the River Meuse

This project is carried out in the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change, Phase II (NOP-II)

M.J.M. de Wit[1,6](ed.), P.M.M. Warmerdam[1](co-ordinator), P.J.J.F. Torfs[1], R. Uijlenhoet[1], E. Roulin[2], A. Cheymol[2], W.P.A. van Deursen[3], P.E.V. van Walsum[4], M. Ververs[5], J.C.J. Kwadijk[5], H. Buiteveld[6]

[1] Wageningen University, Sub-department Water Resources
[2] Royal Meteorological Institute of Belgium
[3] Carthago Consultancy
[4] Alterra
[5] WL/Delft Hydraulics
[6] RIZA

Rapport 104

Sub-department Water Resources
Nieuwe Kanaal 11, 6709 PA Wageningen
The Netherlands
Internet: www.dow.wau.nl/whh

ISSN 0926-230X

FOREWORD

In 1995 the second phase of the Dutch National Research Programme on Global Air Pollution and Climate Change, NOP-II, commenced. The primary objective of the NOP as a strategic and long-term research programme is to meet the demand for information relevant for the development of national and international climate policy.

The project entitled 'Effect of climate change on the hydrology of the river Meuse' is part of the research theme focussing on impacts of climate change. The project was carried out in co-operation with a number of research institutes and resulted in this report. Model simulations of the impact of climate change on the hydrology of sub-catchments of the Meuse basin were performed at the Royal Meteorological Institute of Belgium (RMI), Alterra, and Carthago Consultancy. The effect of climate change on the water quality in the Meuse was analysed at Delft Hydraulics (WL). A statistical analysis of precipitation and discharge records was performed at the Sub-department Water Resources of the Wageningen University. This sub-department also co-ordinated the project and the finalisation of this report. RIZA provided support and a link between the research groups. Marcel de Wit moved from Wageningen University to RIZA, and part of the writing of this report has been performed at RIZA.

The data used in this project have many different sources. Detailed climate change scenarios were provided by the NOP office and by the RMI. Precipitation records were provided by RMI. The French streamflow data were provided by the Direction Régionale de l'Environnement (DIREN) de Lorraine. The streamflow data from Belgium were provided by the Ministère Wallon de l'Equipement et des Transports (MET) in Namur. The Dutch streamflow data were provided by Rijkswaterstaat Directie Limburg, and the Water Authority "de Dommel". All these sources are gratefully acknowledged.

Many people contributed to the project by attending the workshop held in Wageningen in December 2000. In particular we would like to thank Alexandra Jaskula-Joustra, Hans Middelkoop, Herman Crommelinck, Gaston Demarée, Lambert van Breemen, Lilian van Wijngaarden, Sander Bastings, Paul Dewil, Wilko Verweij, Cathelijne van Haselen, Reinder Feddes and Peter Troch for their contribution to this project.

CONTENTS page

ABSTRACT

This study describes historical observations and future estimates of the discharge regime of the river Meuse, with reference to climate change. It specially deals with low flows and integrates results obtained from analyses of observed records and simulations performed with hydrological models.

ABSTRACT

Deze studie beschrijft historische waarnemingen en toekomstschattingen van het afvoerregime van de Maas, met het oog op mogelijke klimaatsveranderingen. De studie richt zich met name op lage afvoeren en integreerd resultaten verkregen uit analyses van waargenomen reeksen en simulaties uitgevoerd met hydrologische modellen.

SUMMARY

Low flows and flooding are both natural phenomena. Therefore, the use of the river Meuse for water supply, navigation, and recreation, and the use of the Meuse floodplain for housing and agricultural production implies certain risks. There is a growing concern that these risks increase due to a global change of climate. The major aim of this study is to analyse whether or not this concern is justified. Below an answer will be given to the questions that are raised in this report.

- What is the predicted climate in the Meuse basin at the end of the 21th century?
- Has the precipitation regime in the Meuse basin changed over the last century?

The theory that greenhouse gas emissions are influencing the global climate is supported by the exceptional upward trend of the global temperature over the 20th century. How global warming will effect the climate in the Meuse basin is far more uncertain. The results of a number of global circulation models (GCMs) suggest that the average temperature will increase, the average winter precipitation will increase and the average summer precipitation will decrease in the Meuse basin. However, regional predictions derived from global experiments, should be interpreted with care. Another way to look at climate change is to analyse historical records. These records suggest a small increase of annual and seasonal average precipitation volumes, especially during the winter season. However, the natural variability of the climate is large and the data series used for the analyses described above are relatively short. Therefore, one cannot conclude that there is a significant upward trend in precipitation in the Meuse basin. Moreover, it remains to be seen whether the changes observed are due to global warming or not.

- Has the flow regime of the Meuse changed over the last century?

The natural variability of the discharge of the Meuse is large, and the differences over longer time intervals are small. This implies that one can not distinguish a significant trend.

- Does the winter precipitation affect the duration of the low flow period in the summer?
- Does the vulnerability to low flows and floods differ between different sub-catchments of the Meuse basin?

Low flows in the Meuse occur naturally during summer and early autumn. The analysis of precipitation and discharge records clearly showed that the duration of the low flow period not only depends on the summer precipitation, but also on the precipitation volume in the previous winter. This implies that in certain parts of the Meuse basin a substantial portion of the discharge originates from delayed (groundwater) flow. The statistical analysis of discharge time series measured at 23 gauging stations revealed large differences in the magnitude and rapidity of discharge fluctuations in the river Meuse network. Catchments with small and slow discharge fluctuations suggest a dominance of slow runoff components (groundwater flow), whereas catchments with large and fast discharge fluctuations suggest a dominance of fast runoff components. The latter are likely to be more vulnerable with respect to both floods and low flows. Vulnerable catchments seem to be located in the regions that consist of rocks from the Lias formation (southernmost part of the French Meuse basin, and eastern upper part of the Chiers and Semois), and in the Ardennes Massif (the upper Ourthe, Lesse, Vesdre and Amblève). Flood prevention at the source will be most effective in these regions. Less vulnerable catchments seem to be located in the Carboniferous limestones of the Condroz region and the Mesozoic limestones in the French part of the Meuse basin and the region north of the Ardennes. The groundwater reservoirs in these regions need to be protected in order to maintain a minimum water flow in the Meuse during dry periods.

- What will be the effect of climate change on the discharge regime of the Meuse?
- What will be the effect of other future changes on the discharge regime of the Meuse?

The discharge regime of the Meuse is determined by many factors (climate, land use, soil type, flow regulation etc.). In this study three different rainfall-runoff models have been used to analyse the combined effect of a number of these factors on the discharge regime of the Meuse and selected sub-catchments. The effect of climate change on the discharge regime of the Meuse depends very much on the climate change scenario chosen to perform the simulation. However, the two climate change scenarios used in this study result in similar patterns: an increase of the average discharge at the end of winter and at the beginning of spring and a decrease in average discharge in autumn.

The land use change scenarios were applied to three small sub-catchments of the Meuse basin. A simulation of a removal of drains and ditches and a stop of irrigation suggests that such a change of agricultural water management tempers the flow regime of streams in the Dutch part of the Meuse basin. This may result in lower flows during winter and larger baseflows during summer. Whether these drastic measures will also be effective in other parts of the Meuse basin needs further analysis. A simulation of a complete afforestation of two Belgian catchments suggests that this might reduce peak flows, but also increase low flow problems.

The topic of (human induced) changes of land use, and flow regulation on the hydrology of the Meuse was lively discussed at the workshop. During this discussion it was also argued that the use of (sub-surface and surface) reservoirs for both flood reduction and the augmentation of low flow rates is not easy. Reservoirs should be filled at the end of the winter in order to be used effictively during the summer. This implies that at the end of winter there is less capacity to store water, which might increase the risk of flooding.

- Will climate change affect the water quality of the Meuse?

Water quality problems in the Meuse are most severe during extremely dry and warm periods. However, a simulation of the effect of climate change on some general water quality variables suggests that these 'average' changes do not have a distinct impact on the 'average' water quality in the Meuse. A brief review of the literature suggests that other future changes, such as the reduction of emissions and changes in flow regulation, might have a greater impact on the quality of the water in the river Meuse than climate change.

This leaves the question whether the existing concern about the impact of climate change on the hydrology of the river Meuse is justified. To answer this question it should be noted that the model results presented in this report are based on average changes. The impact of global warming on the occurrence of extreme regional meteorological conditions, and as a result extreme hydrological conditions, is not (yet) known, and has therefore not been the focus of the research presented in this report. As long as the impact of global warming on the occurrence of extreme meteorological events in the Meuse basin is not known, there remains a reason for continuing concern about the impacts of global warming.

The floods of 1993 and 1995 have triggered the concern for floods in the river Meuse basin. However, the '*extreme low flow memory*' hasn't been refreshed since 1976. The discharge record of the Meuse at Monsin indicates that low flow periods of more than 100 days occur almost every ten years. The fact that such long lasting low flow period has not occurred during the last 25 years does not imply that it will not occur in the near future. Since 1976, navigation on the Meuse and the use of Meuse water for water supply in Belgium and the Netherlands have considerably increased. This means that a situation like 1976, may result in great economical loss.

So far only 'end of the pipe' measures have been taken to combat the negative effects of low flows in the Meuse (e.g. creation of buffer reservoirs). During the workshop it was stressed that also structural measures are needed to prevent long periods of low flows in the Meuse. The construction of surface water reservoirs in the Ardennes may be effective, but does not seem realistic due to lack of public support. Other more realistic measures to forcome problems caused by low flows are the reduction of pollution, further improvement of weirs and locks, good agreements on the distribution of water during periods of low flows, better predictions of low flows and, on the long term, the use of water from the Scheldt (Flandres) and the Rhine (the Netherlands) as an alternative for drinking water production.

Whatever the future of the Meuse basin will be, floods and long periods of low flows will continue to occur in the river Meuse. This implies that the benefits of the use of the river Meuse and its floodplains should be balanced against the risks associated with the use of the river Meuse and its floodplains. The results presented in this report may help to carry out these deliberations.

SAMENVATTING

In de rivier de Maas zijn zowel laagwater als overstromingen natuurlijke verschijnselen. Dit betekent dat het gebruik van de Maas voor (drink)watervoorziening, scheepvaart en recreatie en het gebruik van de overstromingsvlakte van de Maas voor bebouwing en agrarische productie bepaalde risico's met zich meebrengt. Er bestaat groeiende bezorgdheid dat deze risico's zullen toenemen als gevolg van de wereldwijde klimaatverandering. Het belangrijkste doel van dit onderzoek was te analyseren of deze bezorgdheid gerechtvaardigd is. Hieronder zal een antwoord gegeven worden op de vragen gesteld in de introductie van dit rapport.

- Welke verandering van het klimaat wordt voor de 21^{e} eeuw voorspeld voor het stroomgebied van de Maas?
- Is het neerslagregiem in het stroomgebied van de Maas veranderd gedurende de laatste honderd jaar?

De theorie dat de uitstoot van broeikasgassen het wereldklimaat beïnvloedt, wordt ondersteund door de buitengewoon sterke opwaartse trend van de mondiale temperatuur gedurende de 20^{e} eeuw. Hoe het klimaat in het stroomgebied van de Maas beïnvloed zal worden door een wereldwijde temperatuurstijging, is echter moeilijk te quantificeren. De resultaten van 'global circulation models' (GCM's) suggereren dat in het stroomgebied van de Maas de gemiddelde temperatuur zal stijgen, de gemiddelde neerslag gedurende de winter zal toenemen en de gemiddelde neerslag gedurende de zomer zal afnemen. Regionale voorspellingen afgeleid van wereldwijde experimenten, moeten echter met de nodige voorzichtheid geïnterpreteerd worden. Een andere manier om naar klimaatsverandering te kijken is het analyseren van historische reeksen. Neerslagreeksen over de 20^{e} eeuw suggereren een kleine toename van het jaarlijkse en seizoensgemiddelde neerslagvolume, met name gedurende de winter. De natuurlijke variatie van neerslag is echter groot en de gemeten meetreeksen zijn relatief kort. Derhalve kan niet worden geconcludeerd dat er sprake is van een significante trend in de neerslag. Bovendien valt nog te bezien of een eventuele opwaardse trend samenhangt met een wereldwijde temperatuurstijging.

- Is het afvoerregime van de Maas veranderd gedurende de afgelopen honderd jaar?

De natuurlijke verschillen in de afvoer van de Maas zijn groot en de verschillen over langere tijdsintervallen zijn gering. Dientengevolge kan er geen trend worden vastgesteld.

- Heeft de neerslaghoeveelheid in de voorafgaande winter invloed op de duur van de laagwaterperiode in de zomer?
- Zijn er verschillen tussen de deelstroomgebieden met betrekking tot de kwetsbaarheid voor het optreden van laagwater en overstromingen?

In de Maas zijn laagwaterperioden in de zomer een natuurlijk verschijnsel. De analyse van neerslag- en afvoergegevens toonde duidelijk aan dat de duur van een laagwater periode niet alleen afhangt van de neerslag in de zomer, maar ook van de hoeveelheid neerslag gedurende de voorafgaande winter. Dit komt doordat in bepaalde delen van het stroomgebied van de Maas een belangrijk deel van het neerslagoverschot vertraagd wordt afgevoerd. Statistische analyse van afvoerreeksen, gemeten op 23 verschillende locaties, toonde grote verschillen in de mate en snelheid van afvoerfluctuaties in het riviernetwerk. Deelstroomgebieden met kleine en langzame afvoerfluctuaties suggereren een dominantie van langzame afvoercomponenten (grondwaterstroming), terwijl deelstroomgebieden met grote en snelle afvoerfluctuaties een dominantie aangeven van snelle afvoercomponenten. De laatste zijn waarschijnlijk gevoeliger met betrekking tot het optreden van overstromingen en laagwater. Gevoelige deelstroomgebieden liggen in het zuidelijkste puntje van het Franse stroomgebied van de Maas, het oostelijke deel van de stroomgebieden van de Chiers en de Semois en in de Ardennen (de Boven-Ourthe, Lesse, Vesdre en Amblève). Minder kwetsbare deelstroomgebieden liggen in het kalksteengebied van de Condroz, het overgrote deel van het Franse stroomgebied van de Maas en het gebied ten noorden van de Ardennen. De grondwaterreservoirs in deze gebieden dienen beschermd te worden teneinde een minimum waterafvoer in de Maas te kunnen handhaven tijdens langdurige droge perioden.

- Wat zal het effect van klimaatveranderingen op het afvoerregiem van de Maas zijn?
- Wat zal het effect van andere toekomstige veranderingen op het afvoerregiem van de Maas zijn?

Het afvoerregiem van de Maas wordt bepaald door vele factoren (klimaat, landgebruik, bodemsoort, stroomregulering, enz.). In dit onderzoek zijn drie verschillende neerslag-afvoermodellen gebruikt om het gecombineerde effect van een aantal van deze factoren op het afvoerregiem van de Maas en enkele geselecteerde deelstroomgebieden te analyseren. Het berekende effect van klimaatverandering op het afvoerregiem van de Maas is sterk afhankelijk van het klimaatscenario dat wordt gekozen voor de berekening. De beide klimaatscenarios die voor dit onderzoek zijn gebruikt, resulteren echter in vergelijkbare patronen: een toename van de gemiddelde afvoer aan het einde van de winter en het begin van de lente en een afname van de gemiddelde afvoer in de herfst.

De scenario's voor verandering in landgebruik werden toegepast op drie kleine deelstroomgebieden. Een simulatie van het verwijderen van drainagebuizen en afwateringssloten en het stoppen van irrigatie suggereert dat een dergelijke verandering in watergebruik door de landbouw het afvoerregiem van beken in het Nederlandse deel van het stroomgebied zal temperen. Dit kan resulteren in lagere afvoeren gedurende de winter en een hogere basisafvoer gedurende de zomer. Of deze drastische maatregelen ook effectief zullen zijn in andere delen van het stroomgebied van de Maas dient nader onderzocht te worden. Simulatie van totale bebossing van twee gebieden in het Belgische stroomgebied suggereert dat dit de gemiddelde hoogwaterstanden zou kunnen reduceren, maar tevens de problemen met betrekking tot laagwater zou kunnen doen toenemen.

De invloed van de mens op het afvoerregime van de Maas was onderwerp van een levendige discussie tijdens de workshop. Gedurende deze discussie werd gesteld dat het gebruik van reservoirs (ondergronds en bovengronds) voor het verlagen van hoogwaterstanden en het verhogen van laagwaterstanden geen eenvoudige zaak is. Deze reservoirs zouden aan het einde van de winter gevuld dienen te worden om in de zomer effectief gebruikt te kunnen worden. Als gevolg daarvan is er aan het einde van de winter minder opslagcapaciteit beschikbaar, hetgeen het risico van overstromingen juist zou kunnen vergroten.

- Zal klimaatverandering de waterkwaliteit in de Maas beïnvloeden?

De problemen met de waterkwaliteit in de Maas zijn het grootst gedurende extreem droge en warme periodes. Echter, de simulatie van het effect van klimaatverandering op een aantal algemene waterkwaliteitsvariabelen suggereert dat deze 'gemiddelde' veranderingen geen duidelijke invloed hebben op de 'gemiddelde' waterkwaliteit van de Maas. Een kort overzicht van de literatuur geeft aan dat andere toekomstige veranderingen, zoals het reduceren van de uitstoot van afvalstoffen en veranderingen in de afvoerregulering, een grotere invloed zouden hebben op de kwaliteit van het water in de Maas dan klimaatverandering.

Dit laat de vraag open of de bezorgdheid over het effect van klimaatverandering op de waterhuishouding van de rivier de Maas gerechtvaardigd is. Voor de beantwoording van deze vraag dient men zich te realiseren dat de modelresultaten die in dit rapport worden gepresenteerd gebaseerd zijn op gemiddelde veranderingen. Het effect van temperatuurstijging op het voorkomen van extreme meteorologische gebeurtenissen – en hydrologische gebeurtenissen als gevolg daarvan – is (nog) niet bekend. Dit is daarom geen onderwerp van studie geweest in het hier gepresenteerde rapport. Zo lang de invloed van een mondiale temperatuurstijging op het voorkomen van extreme meteorologische verschijnselen in het stroomgebied van de Maas niet bekend is, blijft er reden voor voortdurende bezorgdheid over de mogelijke effecten ervan.

De overstromingen van 1993 en 1995 hebben het bewustzijn voor het gevaar van overstromingen in het stroomgebied van de Maas gewekt. De herinnering aan extreme lange laagwaterperioden is echter sinds 1976 niet meer opgefrist. De afvoerdata van de Maas bij Monsin geven aan dat laagwaterperioden van meer dan 100 dagen ongeveer een keer per tien jaar voorkomen. Het feit dat een dergelijke langdurige periode van laagwater in de Maas in de laatste 25 jaar niet is voorgekomen, wil niet zeggen dat dit niet in de nabije toekomst kan gebeuren. Sinds 1976 is de scheepvaart op de Maas en het gebruik van Maaswater voor de watervoorziening in België en Nederland belangrijk toegenomen. Dit betekent dat een situatie als die van 1976 grote economische schade zou veroorzaken.

Tot dusver zijn slechts ‘end of the pipe’ maatregelen getroffen om de negatieve effecten van laagwaterperioden in de Maas tegen te gaan (bijv. het inrichten van bufferreservoirs voor de watervoorziening). Tijdens de workshop werd benadrukt dat ook structurele maatregelen nodig zijn om lange perioden van laagwater in de Maas te voorkomen. De constructie van bovengrondse waterreservoirs in de Ardennen zou effectief kunnen zijn, maar deze optie lijkt niet realistisch als gevolg van het ontbreken van draagvlak bij het publiek. Andere meer realistische maatregelen zijn het terugdringen van de vervuiling, verdere verbetering van dammen en sluizen, goede overeenkomsten betreffende de verdeling van water gedurende laagwaterperioden, betere voorspelling van laagwaterperioden en, op de langere termijn, het gebruik van water uit de Schelde (Vlaanderen) en de Rijn (Nederland) als alternatieven voor de drinkwaterproductie.

Hoe de toekomst ook zal zijn, overstromingen en lange perioden van laagwater zullen in de Maas blijven voorkomen. Daarom zullen de voordelen van het gebruik van de rivier de Maas en de overstromingsvlakte van de Maas moeten worden afgewogen tegen de risico’s die met dit gebruik gepaard gaan. De resultaten die in dit rapport gepresenteerd worden kunnen een bijdrage leveren aan deze afwegingen.

1. INTRODUCTION

The rivers Rhine and Meuse are used for water supply for domestic and industrial uses, irrigation, hydropower generation, navigation, in-stream ecosystems, and water-based recreation. There is a growing concern that climate change will change the discharge regime of these rivers, which may hamper the functions of these rivers. Several studies have analysed the impact of climate change on the discharge regime of the Rhine (Middelkoop, 1999; Grabs et al., 1997). To date, the Meuse has received less attention.

The Meuse can be regarded as an almost purely rain-fed river, as opposed to the Rhine, for which snowmelt in the Alps plays an important role. The deviating characteristics of the Meuse justify an additional investigation towards the possible effects of climate change on the hydrology of the Meuse (Van Deursen, 1998). So far, most research on the hydrology of the Meuse focused on peak flows (e.g. Dijkman and Pedroli, 1994; WHM, 1998). The focus of the present study will be on the effects of climate change on low flows in the Meuse, but also aspects of climate change and high flows in the Meuse will be mentioned. The following questions will be addressed in this study:

- Has the precipitation regime in the Meuse basin changed over the last century?
- Has the discharge regime of the Meuse changed over the last century?
- Does winter precipitation affect the duration of the low flow period in the summer?
- Does the sensitivity to low flows and floods differ between different sub-catchments of the Meuse basin?
- What is the predicted climate change in the Meuse basin?
- What will be the effect of the predicted climate change on the discharge regime of the Meuse?
- What will be the effect of other future changes on the discharge regime of the Meuse?
- Will climate change affect the water quality of the Meuse?

The methodology used is a combination of data analysis and modelling studies. Precipitation and discharge are measured in the Meuse basin and one of the records dates back to the beginning of the 20th century. These records are analysed in order to find out whether precipitation and discharge in the Meuse basin have already changed over the last 90 years (section 4.1 and 4.2). The relation between precipitation in the Meuse basin and the occurrence of low flows in the river Meuse is addressed in section 4.3. Discharge records from 23 monitoring stations spread across the river Meuse network are used for statistical analysis of (low) flow characteristics in the different tributaries of the Meuse (section 4.4).

Section 5.1 describes how two climate change scenarios for the Meuse basin are derived from the results of Global Circulation Models. These two climate change scenarios are applied to three different rainfall-runoff models in order to simulate changes in discharge patterns in four different sub-catchments (section 5.2). Changes in land cover, irrigation, and drainage management are simulated in section 5.3, in order to get an impression of how climate change relates to other (autonomous or forced) changes in the Meuse basin.

The issue of low flows and water quality is addressed in section 5.4. Section 6 summarises the results of a workshop on climate change and low flows in the river Meuse. Conclusions and recommendations are given in chapter 7. First of all a description of the Meuse basin (chapter 2) and the data used (chapter 3) are given.

2. THE MEUSE

The river basin

The Meuse basin (figure 2.1) covers an area of approximately 33,000 km^2, including parts of France, Luxembourg, Belgium, Germany, and the Netherlands. The elevation of the Meuse basin is shown in figure 2.2. The differences in elevation are reflected in the average annual precipitation pattern (figure 2.3). The Meuse basin can be subdivided into three major geological zones: i) the Lotharingian Meuse. This part of the Meuse basin mainly consists of sedimentary Mesozoic rocks, ii) the Ardennes Meuse. Here the river transects the Paleozoic rock of the Ardennes Massif, and iii) the lower reaches of the Meuse. The Dutch and Flemish lowlands are formed by Cenozoic unconsolidated sedimentary rocks. According to Corine data about 34 % of the Meuse basin upstream of the Belgium/Dutch border is defined as agricultural land, 20% as pasture, 35 % as forested, and 9% as built-up area (figure 2.4).

Figure 2.1 The Meuse basin

Source: Aktieplan Hoogwater Maas (WHM/GTIM)

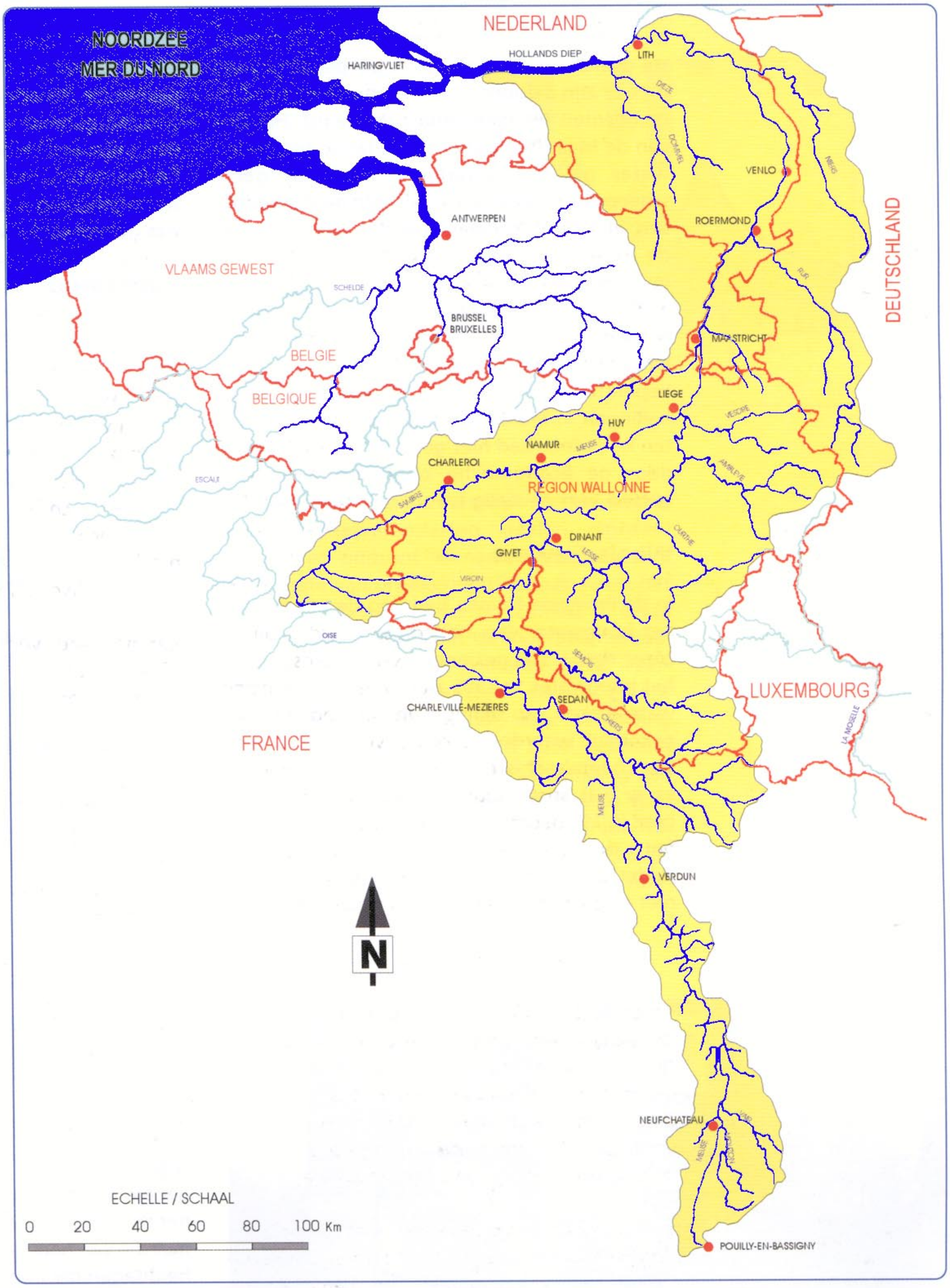


Figure 2.2 Elevation

Data derived from the USGS DEM, elaborated at the Joint Research Centre, Ispra

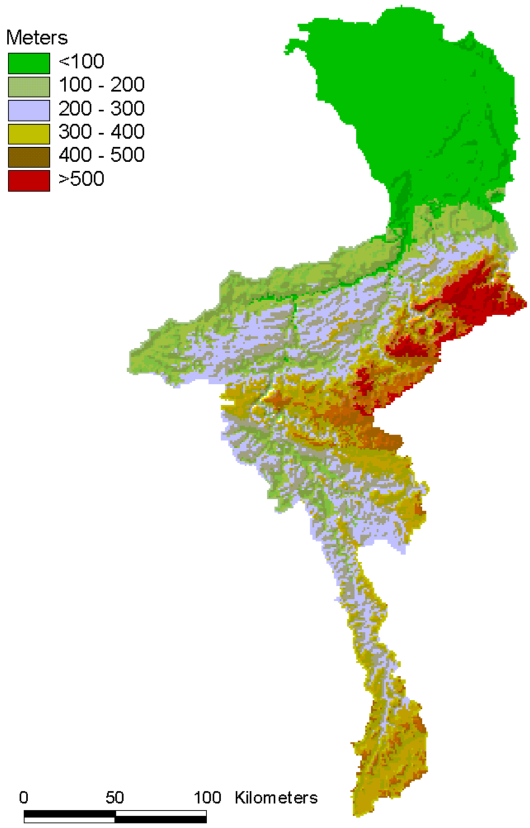


Figure 2.3 Average annual precipitation

Data elaborated at the Joint Research Centre, Ispra

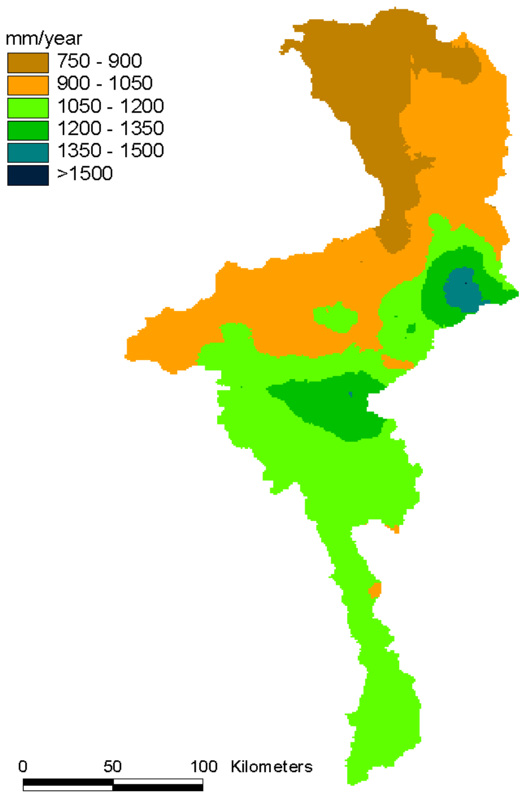
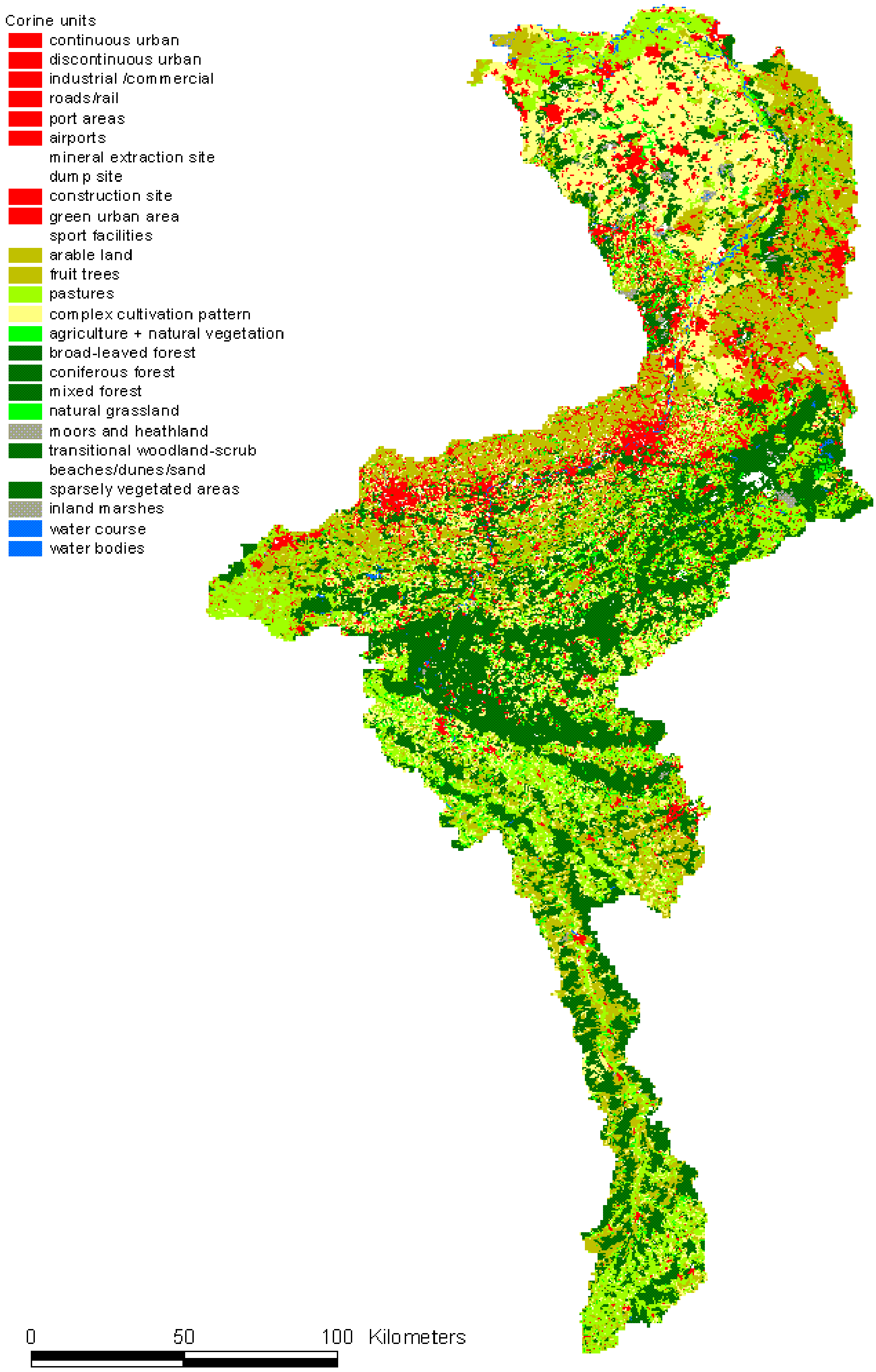


Figure 2.4 Land cover

Data derived from Corine, elaborated at the Joint Research Centre, Ispra



The river network and discharge regime

The river Meuse has a total length of almost 875 kilometres from its source in France to the Hollands Diep in the Netherlands. The most important tributaries of the Meuse are shown in figure 2.1. Low flows in the Meuse mainly occur between May and October. Precipitation is evenly distributed throughout the year, summer low flow coincides with the peak of evaporation during the summer months and high runoff values occur during the winter months when evaporation is small. Figure 2.5 shows the average monthly discharge of four monitoring stations along the Meuse. The flow regime of the Meuse is strongly influenced by the construction of weirs and locks, withdrawals of water, and canalisation (Berger, 1992). Downstream of Liège there are a number of canals that are fed by water from the Meuse. The most important are the Albertkanaal (16-22 m^3s^{-1}), the Zuid-Willemsvaart (approximately 16 m^3s^{-1}), and the Julianakanaal (approximately 16 m^3s^{-1}). These canals are not only used for navigation but also play an important role in the water supply in Flanders and the southern Netherlands. Reservoirs are found in the upper branches of the Rur (Germany), the Viroin, the Semois, the Sambre, the Ambleve, the Ourthe, and the Vesdre. These reservoirs are used for electricity production, drinking water supply, and flow regulation. Except for the Rur reservoir and the reservoir in the Eau d'Heure (Sambre), these reservoirs are too small to have a major effect on the discharge regime of the Meuse.

Figure 2.6 compares the discharge regime of the Meuse with the discharge regime of other rain-fed rivers of comparable size located in the vicinity of the Meuse basin. This figure shows that the average discharge regime of the Meuse, expressed as the ratio of monthly and annual averages, is more variable compared to that of the other rivers. This implies that the Meuse has a relatively fast response to precipitation and is therefore relatively sensitive to both flooding and drought. Figure 2.7 shows that the discharge of the Meuse also strongly varies over the years.

Low flows in the Meuse

During an average year there is sufficient water to fulfil the water supply, navigation and ecological functions of the Meuse. However, even under the 'current' climate there are many summers when the supply of water from the Meuse cannot meet the demands. Water stress occurs when the discharge rate at Monsin (near Liège) drops below 60 $m^3 \cdot s^{-1}$ (personal comment Rijkswaterstaat Directie Limburg). Figure 2.8 shows the number of days over the past century that this situation occurred.

During periods of low flows weirs are operated to maintain a minimum water level. This reduces the flow velocity and turbulence in the river, which in turn may lead to increased growth of algae (Ietswaart & van Dijk, 1996). Low flows also lead to water quality degradation, as the diluting and aerating capability of streams and rivers is reduced. Water from the Meuse is used for the water supply of about six million people in Belgium and the Netherlands (RIWA, 1995). The demand for water of good quality has increased with the advent of industrialisation and rapid population growth and is expected to increase further in the nearby future (WL, 1996). There is also a tendency to exploit more surface water instead of groundwater. All these factors explain the concern for the possible negative effects of climate change on the (drinking) water supply and shipping in the river Meuse (Van Deursen, 1998; Philips, 2000).

Figure 2.5 Average monthly discharges of the Meuse at Stenay (3904 km^2), Chooz (10120 km^2), Borgharen (21260 km^2), and Lith (29370 km^2).

The relatively low summer discharge at Borgharen reflects the water inlet to the canals upstream of Borgharen.

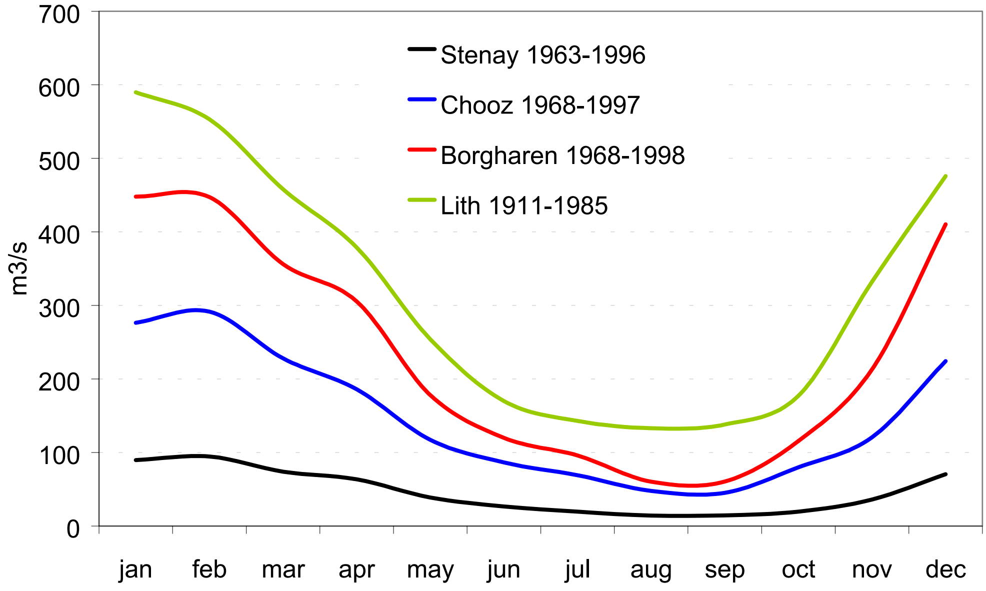


Figure 2.6 Normalised monthly discharge regimes of a number of Northwest European rivers.

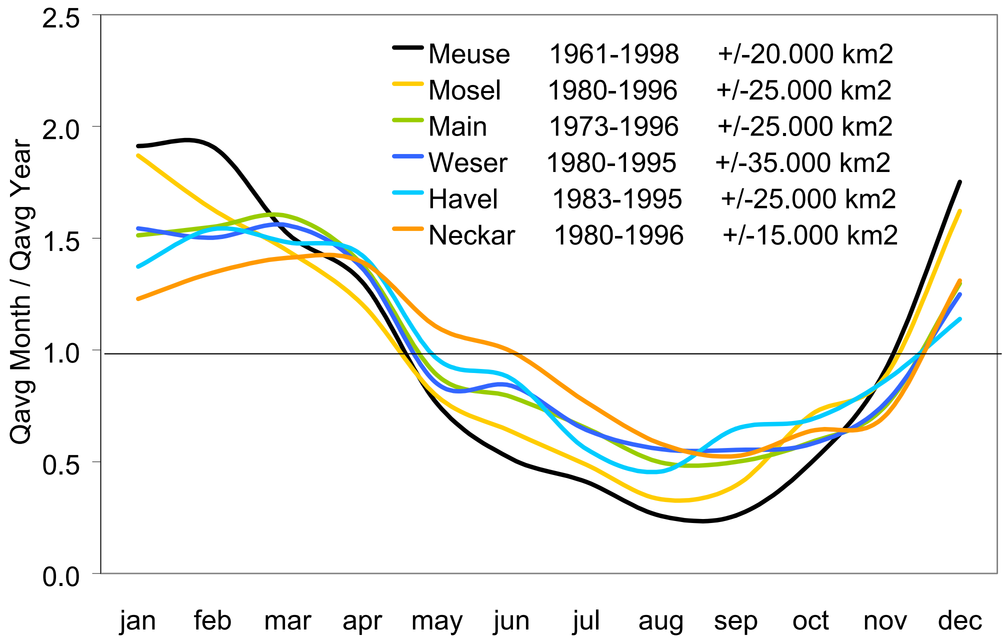
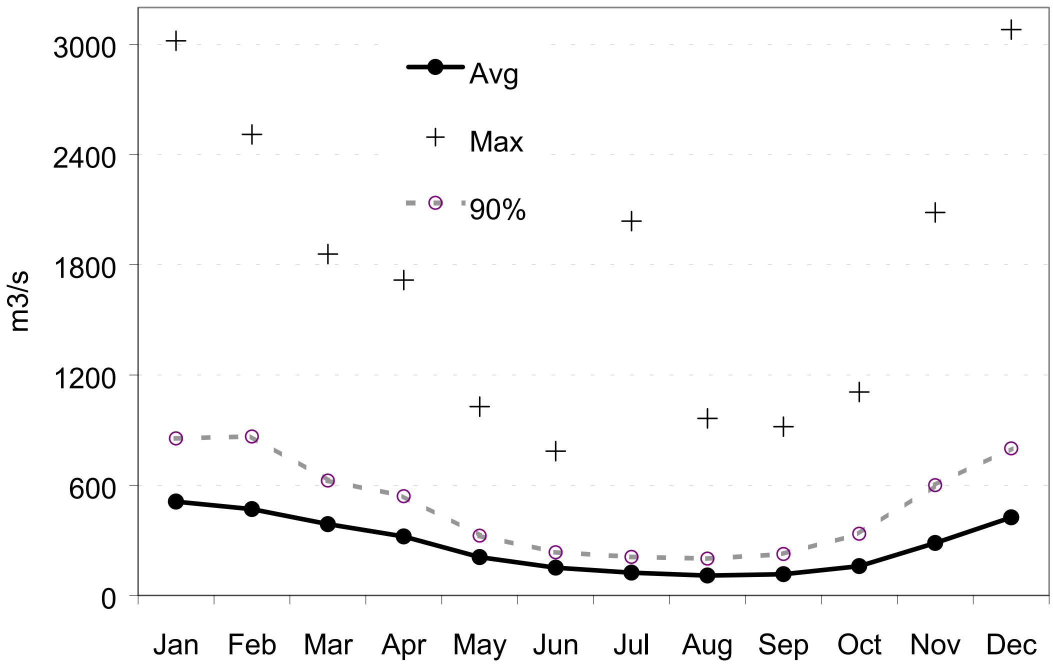


Figure 2.7 Average, minimum, maximum, and percentiles of the discharge at Meuse-Monsin (1911-1998)

In both boxes the black line shows the average monthly discharge (note that the two boxes have different scales for the y-axis). During 10% of the years the average monthly discharge exceeded the value given in the dotted line of the upper graph and during 10% of the years the average monthly discharge was less than the value given in the dotted line in the under graph. The + sign gives the maximum discharge that has been recorded in the specific month, whereas the - sign gives the minimum discharge that has been recorded in the specific month.



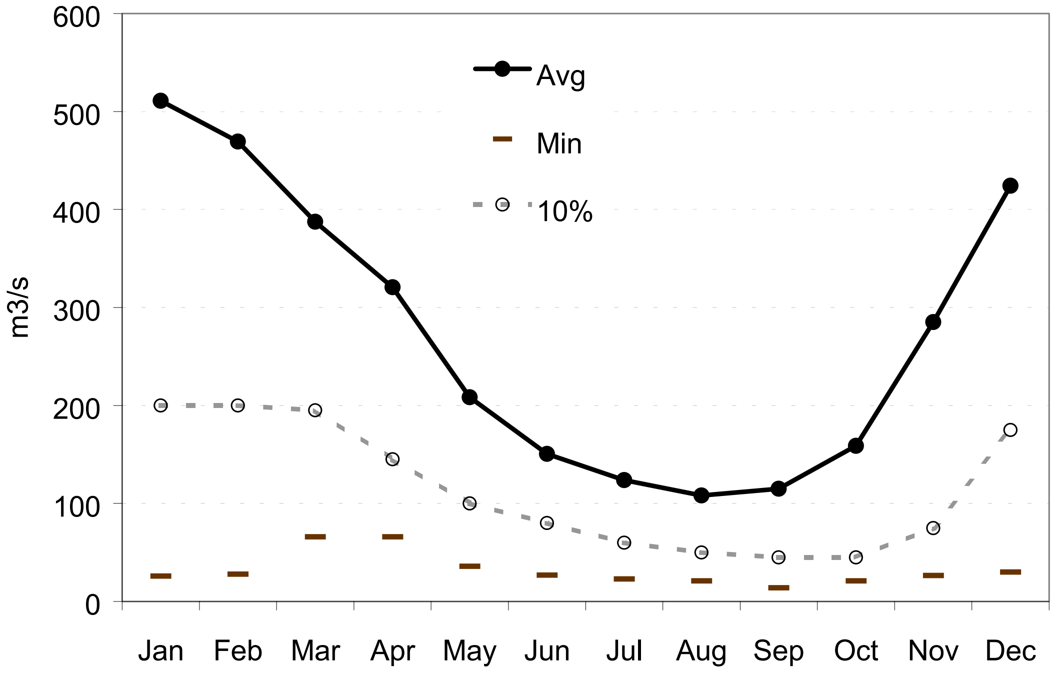
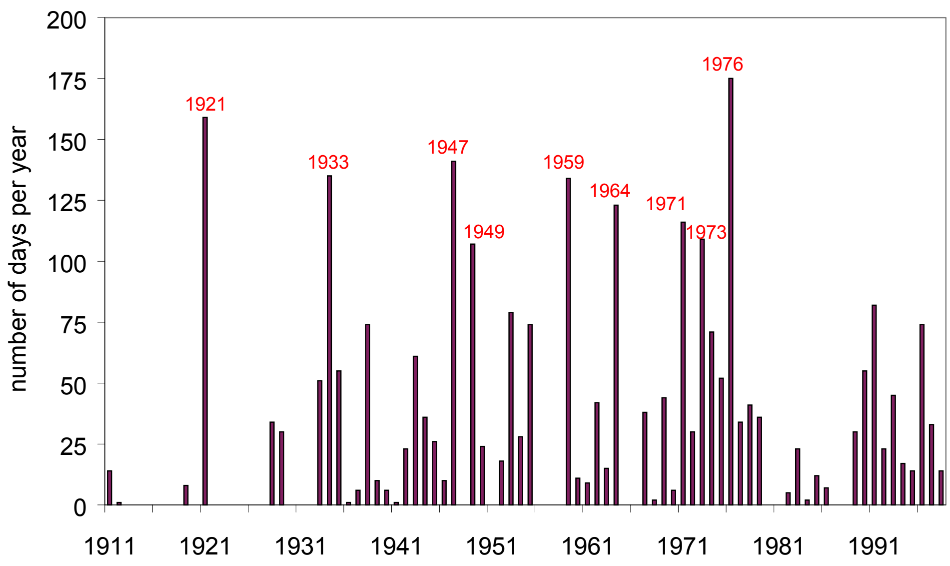


Figure 2.8 Annual number of days with a critical discharge rate of less than 60 m^3s^{-1} at Meuse-Monsin over the period 1911-1998



The Meuse fulfils an important link in the network of canals and rivers that connect the harbours of Antwerp and Rotterdam to the European hinterland. About 30,000 cargo-boats a year navigate the river Meuse. These numbers are expected to increase since the national authorities stimulate transport by water (personal comment Rijkswaterstaat Directie Limburg). Low flows (and floods) hamper the transport capacity of the waterways and lead to severe economical damage (e.g. RWS, 1983).

Meuse water is also used for the irrigation of agricultural land in Flanders and the southern part of the Netherlands. In general the need for irrigation water negatively corresponds with the discharge in the river Meuse. Long lasting low flows in the Meuse limit the water supply to agriculture. Another problem that is caused by low flows in the Meuse is the intrusion of seawater near the mouth of the Meuse (and Rhine). Finally, concern exists for the ecological functioning of the river Meuse during low flows, especially for the common Meuse (Flemish/Dutch border) (Salverda et al., 1998).

In 1995 the Flemish and Dutch authorities signed a treaty with respect to the water distribution between Meuse and the Dutch and Flemish canals. This treaty regulates an equal distribution of water and a shared responsibility for the common Meuse.

Floods in the Meuse

The flood of 1993 resulted in the largest peak discharge in the Meuse since 1926, and the flood of 1995 was of comparable size. The damage of the 1993 flood was estimated at more than 100 million Euro for the dutch province of Limburg alone (Dijkman & Pedroli, 1994). The damage of the 1995 flood was estimated at about 25 million Euro for the Belgium alone (KINT, 1999). The 1993 and 1995 floods have initiated several actions to combat flood problems in the Meuse (WHM, 1998). These actions include both measures to reduce the occurrence of peak flows (e.g. water retention and flow regulation) and measures to reduce the damage caused by floods (e.g. improved flood forecasting and improvements of embankments).

3. DATA

Daily discharge records

In some tributaries of the Meuse the discharge regime is strongly influenced by human impacts (e.g. the Sambre). Stations located at these tributaries were excluded from this study. This selection was based on expert judgements of the data providers. Also stations with a large number of missing data were not used. The remaining 24 stations used in this study are presented in figure 3.1 and table 3.1. The station Meuse-Monsin (code 24, near Liège) is an important record used in this study. This station represents the 'undivided Meuse'. Downstream of Monsin the 'Kempische' canals branch off. The discharge downstream of Monsin (e.g. at Borgharen) is influenced by the water flow in these canals. Discharge is not directly measured at Monsin. The record has been derived from discharge measurements at Borgharen, adjusted with information on water flows towards the canals between Monsin and Borgharen (personal comment, Rijkswaterstaat Directie Limburg).

Monthly precipitation records

The longest discharge record available (Meuse-Monsin/Borgharen) dates back to 1911. For precipitation even longer records exist, but here only data from 1911 to 1998 have been used. The analyses presented in this report are based on monthly average precipitation data measured at eight stations in Belgium (see figure 3.2). Information about the origin and quality of these data is given in Demarée et al. (1994). For comparison also monthly average precipitation data for De Bilt (Central Netherlands), Paris, and Strasbourg have been collected (KU, 2000). The total list of stations used is given in table 3.2. It should be noted that over the last century the methodology to measure precipitation has slightly changed. It is assumed that these changes do not have a major impact on the results of the analyses (see also Demarée et al., 1994).

Case studies

The impact of climate change on the hydrology of the Meuse is simulated with distributed rainfall-runoff models (section 5.2). These rainfall-runoff models are applied to four different sub-basins of the Meuse basin; the basin of the Ourthe Orientale upstream of Mabompre, the basin of the Mehaigne upstream of Moha, the basin of the Beerze, and the basin of the Meuse upstream of Borgharen. Section 5.4 presents a simulation of the water quality in the Belgian part of the Meuse. All these models have been calibrated with data for the period 1988-1992. For a description of the data underlying these case studies, the reader is referred to the separate reports, which are mentioned in chapter 5 and appendix 2.

Figure 3.1 Location of discharge stations

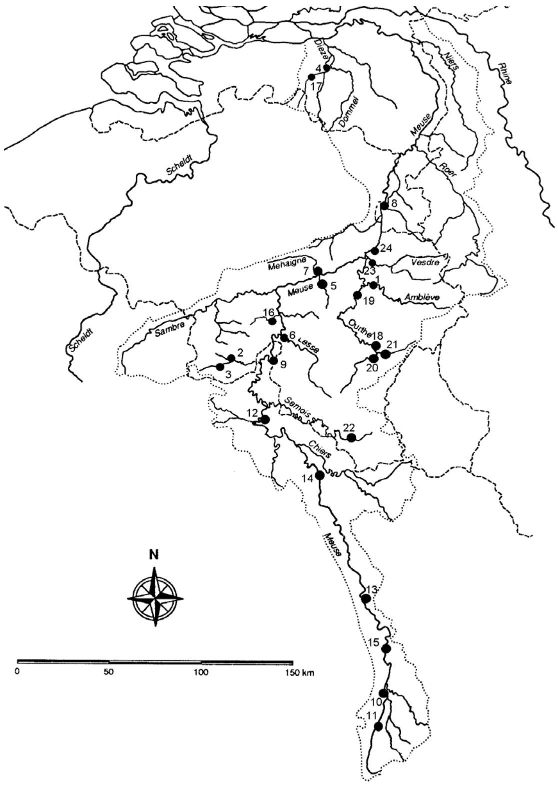


Table 3.1 Monitoring stations daily discharge

River	Station	Code (figure 3.1)	Basin km^2	First year used	Last year used	Origin Data
Amblève	Martinrive	1	1068	1968	1998	MET [a]
Eau Blanche	Nismes	2	254	1969	1990	MET
Eau Noire	Couvin	3	176	1986	1996	MET
Essche Stroom	Nemelaer	4	330	1973	1996	WSD [b]
Hoyoux	Modave	5	94	1973	1987	MET
Lesse	Gendron	6	1314	1968	1998	MET
Mehaigne	Moha	7	343	1969	1996	MET
Meuse	Borgharen	8	21260	1968	1998	RWS [c]
Meuse	Chooz	9	10120	1968	1997	DIREN [d]
Meuse	Domrémy-la-Pucelle	10	1031	1987	1996	DIREN
Meuse	Goncourt	11	364	1980	1996	DIREN
Meuse	Montcy-Notre-Dame	12	7724	1985	1992	DIREN
Meuse	Saint-Mihiel	13	2540	1985	1996	DIREN
Meuse	Stenay	14	3904	1985	1996	DIREN
Meuse	Vaucouleurs/Chalaines	15	1717	1986	1996	DIREN
Molignée	Warnant	16	125	1969	1996	MET
Nieuwe Leij	Goirle	17	115	1980	1994	WSD
Ourthe	Nisramont	18	737	1978	1996	MET
Ourthe	Tabreux	19	1616	1968	1998	MET
Ourthe Occidentale	Ortho	20	386	1978	1996	MET
Ourthe Orientale	Mabompré	21	317	1978	1996	MET
Semois	Ste. Marie	22	143	1978	1996	MET
Vesdre	Chaudfontaine	23	677	1968	1998	MET
Meuse	Monsin [e]	24	20000	1911	1998	RWS

[a] Ministère wallon de l'Equipement et des Transports, Belgium
[b] Waterschap de Dommel, The Netherlands
[c] Rijkswaterstaat Nederland, The Netherlands
[d] Direction Régionale de l'Environnement Lorraine, France
[e] The discharge record of Monsin has been composed from discharge data measured at Borgharen and information about the water inlet to the 'Kempische' canals (personal comment RWS).

Figure 3.2 Location of precipitation stations

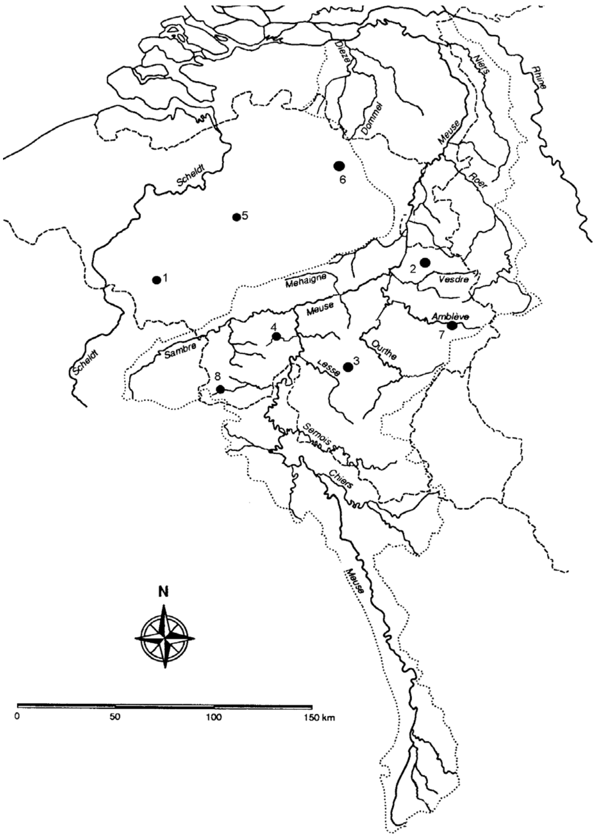


Table 3.2 Monitoring stations monthly precipitation

Station	Code (figure 3.2)	Elevation (m)	First Year	Last Year	Origin Data
Ath	1		1910	1982	RMI [a]
Chièvres			1983	1999	
Thimister	2		1910	1999	RMI
Rochefort	3		1910	1999	RMI
Denée Maredsous	4		1910	1981	RMI
Mettet			1982	1991	
Saint-Gérard			1992	1999	
Ukkel	5		1910	1999	RMI
Leopoldsburg	6		1910	1981	RMI
Koersel			1982	1999	
Stavelot	7		1910	1999	RMI
Chimay	8		1910	1999	RMI

[a] Royal Meteorological Institute of Belgium

Climate change scenarios

All climate change impact studies that are initiated by the Dutch National Programme on Climate Change and Air Pollution (NOP) are requested to use a climate change scenario that is based on the results of the HadCM2Gsa1 run. This global circulation model (GCM) has been developed at the Hadley Centre and its results are distributed by the Climate Research Unit of the University of East Anglia (Verweij & Viner, 2001). For comparison also the results of some other GCM runs were used in this study (table 3.3). The results of these GCMs were derived from the homepage of the Data Distribution Centre (DDC) of the Intergovernmental Panel on Climate Change (IPCC). This was done by the Royal Meteorological Institute of Belgium (RMI). The RMI uses these data for impact studies in Belgium (Roulin et al., in prep). GCMs are grid-based global models. A typical spatial resolution of these models is shown in figure 3.3. For a more detailed description of all GCM runs used in this study the reader is referred to the homepage of the DDC (http://ipcc-ddc.cru.uea.ac.uk/).

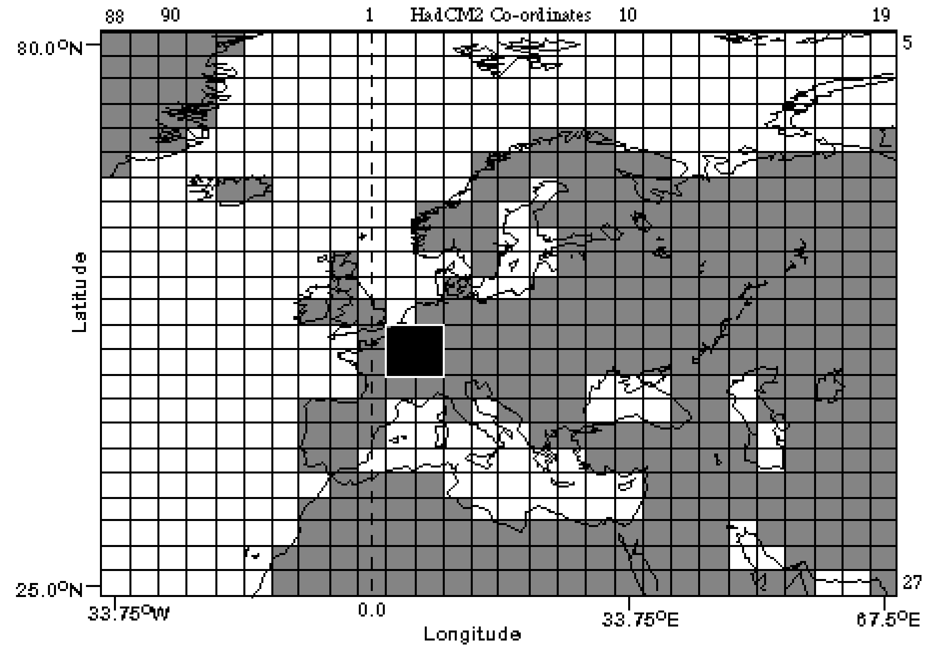
Table 3.3 GCM output used

GCMrun	Computation Centre	Elaborated by	Averaged at
HADCM2Gsa1	Hadley Centre, UK	Verweij & Viner (2001)	See figure 3.3
HADCM2Gga1	Hadley Centre, UK	RMI	50°5'N 5°E
HADCM2Gga2	Hadley Centre, UK	RMI	50°5'N 5°E
HADCM2Gga3	Hadley Centre, UK	RMI	50°5'N 5°E
HADCM2Gga4	Hadley Centre, UK	RMI	50°5'N 5°E
CGCM1	Canadian Centre for Climate Modelling and Analysis	RMI	50°5'N 5°E
CSIRO-MK2	Austalia's Commonwealth Scientific and Industrial Research Org.	RMI	50°5'N 5°E
CCSR-98	Center for Climate Research Studies, Japan	RMI	50°5'N 5°E
ECHAM4	Deutsches Klimarechenzentrum, Germany	RMI	50°5'N 5°E

Figure 3.3 Example of spatial resolution GCM output (cells HADCM2 runs)

For the HADCM2gsa1 run a weighted average of four cells was calculated to represent the Meuse basin:
The weight of each cell was roughly derived from the overlap of the cell with the Meuse basin
Cell (x;y;weight): 2;17;0.5 2;18;0.2 3;17;0.2 3;18;0.1

Source: Climate Research Unit, University of East Anglia, UK



4 ANALYSIS OF PRECIPITATION AND DISCHARGE RECORDS

4.1 Precipitation

Has the precipitation regime in the Meuse basin changed over the last century?

The prediction that global temperature increases as a result of greenhouse gas emissions is supported by the exceptional upward trend of the global temperature over the 20th century (IPCC, 2001). This upward trend has been derived from temperature measurements all over the world, and suggests that greenhouse gas emissions are already influencing global climate. This raises the question whether one can also observe changes in temperature and precipitation for Northwest Europe (including the Meuse basin) over the last century.

In the third assessment report of the state of the climate in the Netherlands the KNMI (1999) concludes; '*The average temperature in the Netherlands was 0.7 ^{o}C higher in the last twenty years than it was in the first twenty years of this century. There was also more precipitation in the second half of the century, which may be partially related to the warmer weather. The changes in temperature and precipitation levels, which were the greatest in winter, can be largely attributed to remarkable variations in atmospheric circulation'* (see also http://www.knmi.nl/onderzk/). Also Pfister et al. (2000) report a marked increase of the westerly air currents above (North-)Western Europe. They found that this change in atmospheric circulation corresponds with an increase in rainfall intensity and duration in Luxembourg since the 1950s. The variations of atmospheric circulation may primarily have natural causes, but are also consistent with some of the increasing CO_2 GCM experiments (Dai et al. (1997). An overview of the climate in the 20th century for Belgium is presented at: http://www.meteo.oma.be/IRM-RMI/century/xxeeuw.htm.

In addition, the monthly precipitation records for the eight Belgian stations presented in figure 3.2 (station codes 1 to 8) were analysed. The monthly values for all stations were simply averaged (not weighted), resulting in one value representing the Belgian part of the Meuse basin. This average record is here named 'record Ardennes'. The monthly values of the Ardennes record have been averaged for hydrological years (November to October), the winter period (November to April) and the summer period (May to October). The results are shown in figure 4.1. The differences between the average monthly precipitation values for

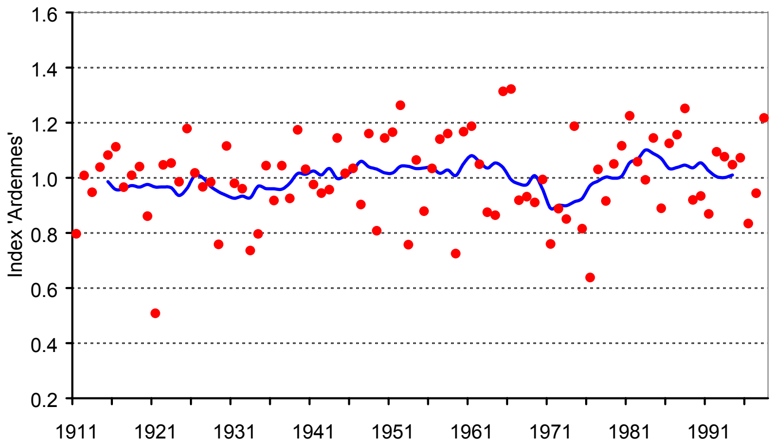
1910-1954 and the average monthly precipitation values for 1955-1998 (in terms of percentage) are plotted in figure 4.2. This graph compares the Ardennes record with the average of the values measured in De Bilt, Paris, and Strasbourg. This shows that the monthly pattern of change is rather consistent between the two records. In chapter 5 this graph (figure 4.2) will be compared with changes in the monthly discharge pattern of the Meuse.

Conformable the conclusions of the above studies, the records presented in figure 4.1 suggest a small increase of annual and seasonal average precipitation volumes, especially during the winter season. However, the natural variability of the climate is large and the data series used for the analyses described above are relatively short. Therefore, one cannot conclude that there is a significant upward trend in precipitation in the Meuse basin (see table 4.1). Moreover, it remains to be seen whether the changes observed are due to global warming or not.

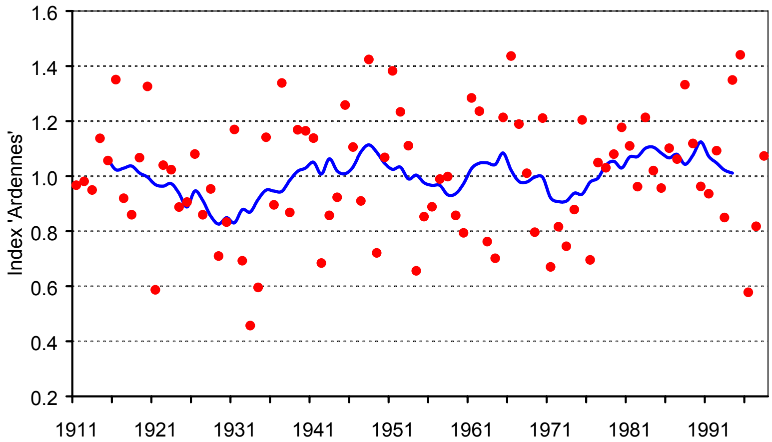
Figure 4.1 Precipitation record 'Ardennes'

Each dot represents a measured year/season. The line represents the moving average (window 10 years). The index value is calculated as the ratio of the value for the specific year and the average value for the period 1911-1998. So an index value of 1 represents an average year/season, an index value smaller than 1 represents a relatively dry year/season, and an index value large than 1 represents a relatively wet year/season.

a
Average hydrological year (November-October))



b
Average winter (November-April)



c
Average summer (May-October)

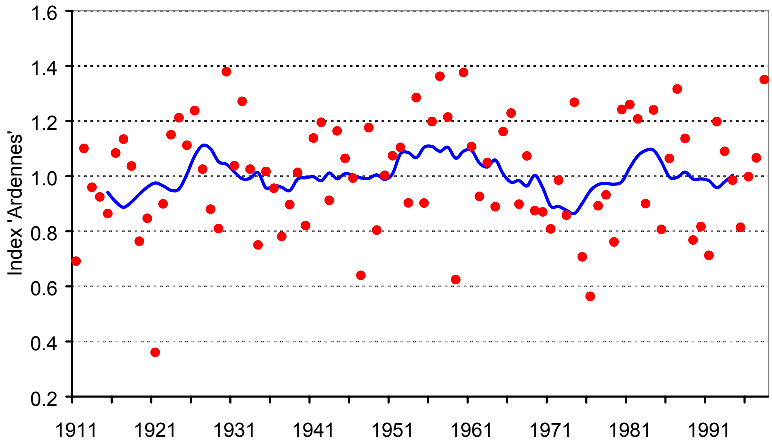


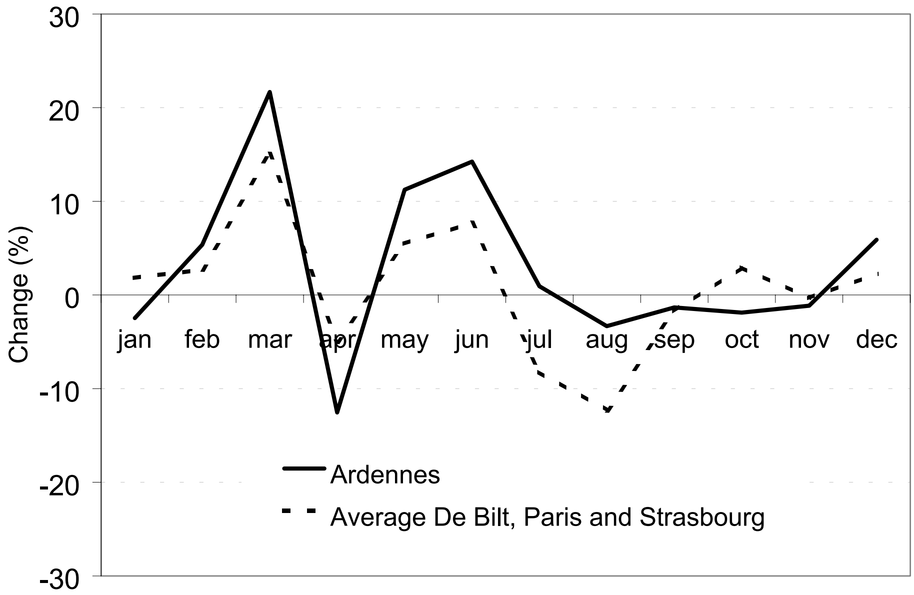
Table 4.1 Regression analysis of the precipitation record

This table shows the calculated value, standard error and 95% confidence intervals of the slopes of linear regressions applied to the records presented in figure 4.1. Positive slopes were calculated for all three records, suggesting an increase of precipitation. However, no trend (a slope of zero) falls within the confidence interval. The analysis presented in this table allows for a rough detection of trends. A more extended trend analysis, including a critical evaluation of the time series used falls beyond the scope of this study.

Variable	Slope of lineair regression	Standaar error	Lower bound	Upper bound
P year (mm/year)	0.699	0.577	-0.447	1.846
P winter (mm/month)	0.066	0.069	-0.071	0.203
P summer (mm/month)	0.045	0.066	-0.086	0.176

Figure 4.2 Relative change in monthly average precipitation values (%)

Change is P (1955-1998) minus P (1910-1954)



4.2 Discharge

Has the discharge regime of the Meuse changed over the last century?

The daily discharge record of the Meuse at Monsin (see chapter 3) was used to analyse changes in discharge rates for the period 1911 to 1998. The daily values of the Monsin record were averaged for hydrological years (November to October), the winter period (November to April) and the summer period (May to October). The results are given in figure 4.3. This figure also presents the minimum (for the summer period) and maximum (for the winter period) daily discharge values. Figure 4.3 shows that the average annual and seasonal discharge has hardly changed over the last century. However, the maximum measured daily winter discharge values seem to have increased (figure 4.3b), whereas the minimum summer discharges seem to have decreased (figure 4.3c). The natural variability of the discharge of the Meuse is large (see also figure 2.7), the differences over time are relatively small, and the discharge record is relatively short. Therefore, one cannot identify a significant trend from these discharge records (see table 4.2). One exception is the observed pattern for the minimum summer discharge (figure 4.3c). The upper bound of the 95% coinfidence interval is below zero. This suggests a downward trend for the minimum summer discharge.

The possible increase in maximum winter discharge (figure 4.3) is conformable to the possible increase in winter precipitation of the Ardennes record (figure 4.1b). The decrease of the minimum (and average) summer discharges (figure 4.3c) is not in accordance with the possible increase of the (summer) precipitation in the Ardennes (figure 4.1c). This might be due to an increase of water abstractions upstream, flow regulation, and/or changes in land use. Another possible explanation may be the increase of evaporation, caused by an increase in temperature (see chapter 4). Also systematic errors related to the indirect composition of the Monsin record (see chapter 3) may have caused a trend in the data.

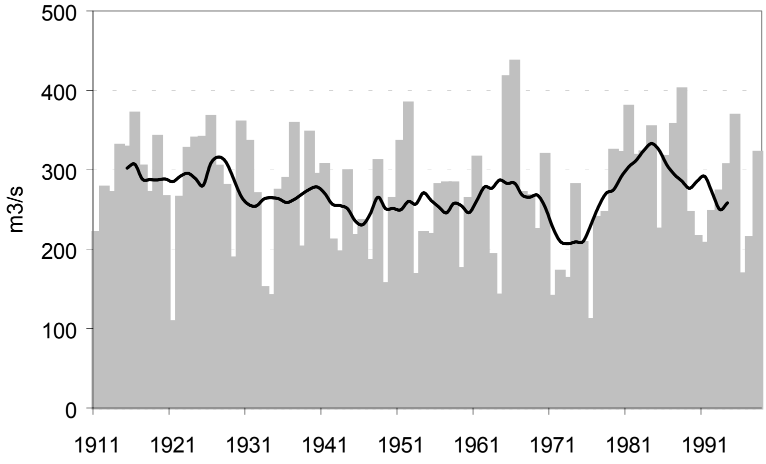
The differences between the average monthly discharge values for 1910-1954 and the average monthly discharge values for 1955-1998 (in terms of mm/month) are plotted in figure 4.4. This figure also includes the differences in average monthly precipitation values of the Ardennes record (see also figure 4.2). It appears that changes in the monthly average discharge regime of the Meuse are not simply a reflection of changes in the monthly average precipitation regime of the Ardennes record. This stresses the need for a more detailed analysis of rainfall-runoff processes in the Meuse basin (see chapter 5).

Figure 4.3 Discharge record Meuse-Monsin (Nov-Oct).

Each bar represents a year. The line shows the moving average (window 10 years)

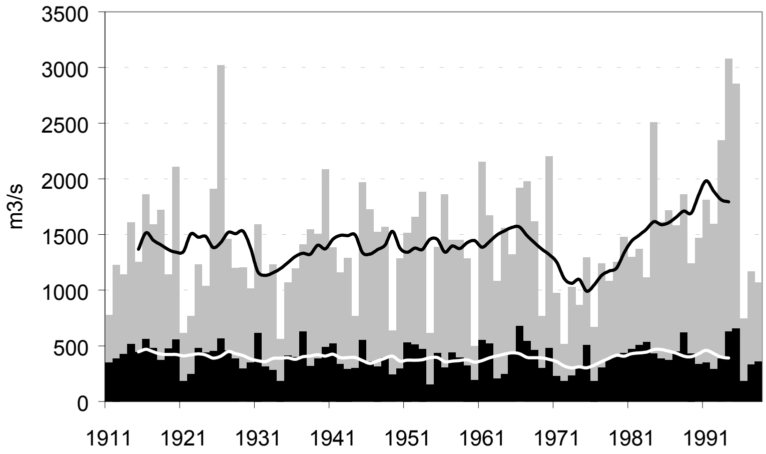
a

Annual average discharge (Nov-Oct)



b

Average winter discharge (Nov-Apr)
Black line for the maximum daily values, white line for the average values



c

Summer discharge Meuse-Monsin (May-Oct). Black line for the average values, white line for the minimum values

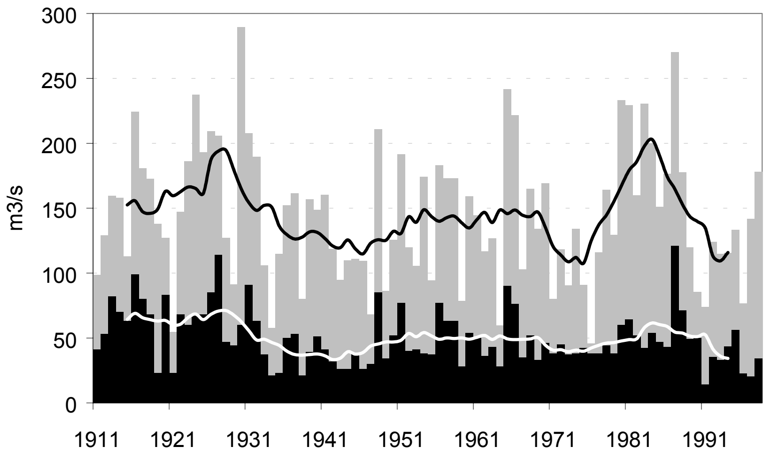


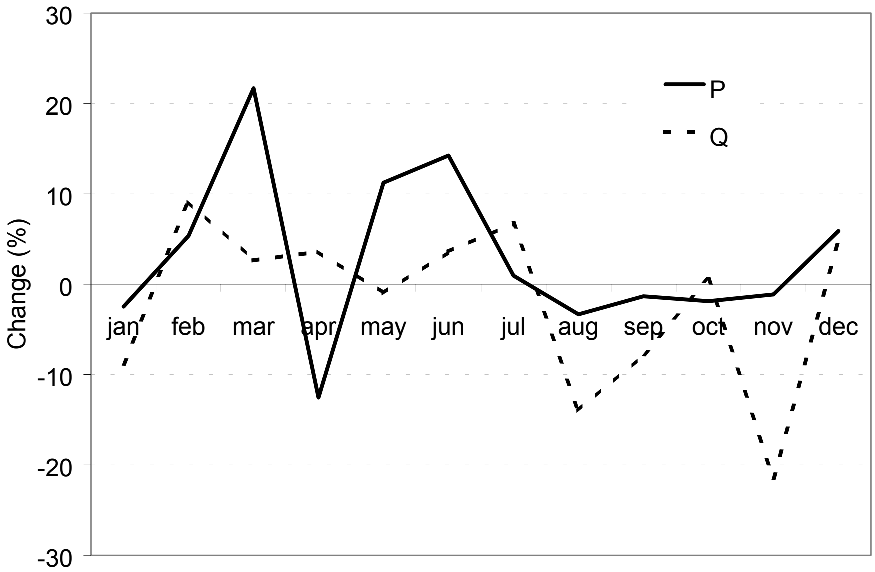
Table 4.2 Regression analysis of the discharge record

This table shows the calculated value, standard error and 95% confidence intervals of the slopes of linear regressions applied to the records presented in figure 4.3. Except for Q_{min} summer, no trend (a slope of zero) falls within the confidence interval of the regression analysis. The analysis presented in this table allows for a rough detection of trends. A more extended trend analysis, including a critical evaluation of the time series used falls beyond the scope of this study.

Variable	Slope of lineair regression	Standaar error	Lower bound	Upper bound
Q_{avg} year (m^3/s)	-0.142	0.308	-0.755	0.470
Q_{avg} winter (m^3/s)	-0.210	0.521	-1.247	0.826
Q_{max} winter (m^3/s)	3.027	2.177	-1.299	7.354
Q_{avg} summer (m^3/s)	-0.131	0.217	-0.563	0.301
Q_{min} summer (m^3/s)	-0.222	0.087	-0.395	-0.048

Figure 4.4 Relative change in monthly average precipitation (Ardennes record) and discharge values (Meuse-Monsin) (%)

Change is (1955-1998) versus (1910-1954)



4.3 Winter precipitation and summer discharge

Does winter precipitation affect the duration of the low flow period in the summer?

In chapter 2 the Meuse is characterised as a relatively fast responding river (see figures 2.6 & 2.7). This implies that compared to some other rivers the discharge of the Meuse will decrease relatively fast during a dry period. This raises the question; how fast? Is one dry summer enough to result in a long lasting low flow period in the river Meuse, or is the magnitude and duration of the low flow also influenced by the precipitation in the previous winter? To answer this question the average annual (November to October), winter (November to April), and summer (May to October) precipitation indices of the Ardennes record have been compared with the number of days (during one year) that the discharge of the Meuse at Monsin dropped below a critical discharge rate of 60 $m^3 \cdot s^{-1}$. The results are presented in figure 4.5. This figure can be used to analyse to what extent low flows correspond with low precipitation values in the summer and with low precipitation values in the (previous) winter. This visual analysis reveals the following:

The longest low flow periods in the Meuse were recorded in 1921 and 1976. In these years a dry winter was followed by a very dry summer. The winters of 1932/1933 and 1995/1996 are the driest winters in the Ardennes record, but no long lasting low flows were recorded in these years, because the summers of 1933 and 1996 were not dry. The summers of 1975 and 1991 were much drier than the summers of 1964, 1971, and 1973. However, the duration of the low flow period was longer in 1964, 1971, and 1973 than in 1975 and 1991. This can be explained by the fact that the winters of 1974/1975 and 1990/1991 were relatively wet, whereas the winters of 1964, 1971, and 1973 were relatively dry. Summarising, it can be said that long lasting low flow periods occur when a dry winter is followed by a dry summer. A dry winter followed by a wet summer or a wet winter followed by a dry summer does not result in a long lasting low flow period in the Meuse.

Between 1910 and 2000 there were nine years where the discharge at Monsin was below 60 m^3/s^{-1} for more than 100 days in one year (see also figure 2.8). The latest of these long lasting low flow periods was 25 years ago in 1976! The observation period is too short to conclude whether this is purely coincidental (no sequence of dry winter and dry summer) or a sign of climate change.

Figure 4.6 presents another way of looking at the contribution by winter precipitation to summer low flows. Winter precipitation, summer precipitation and summer baseflow are here presented as index values. The precipitation indices have been calculated from the 'Ardennes record', with the following formulas:

$I_{Pwinter,i} = P_{winter,i} / P_{winter,avg}$ and $I_{Psummer,i} = P_{summer,i} / P_{summer,avg}$

where $I_{Pwinter}$ is the index for the winter precipitation, $I_{Psummer}$ is the index for the summer precipitation, P_{winter} is the winter precipitation (November to April) , P_{summer} is the summer precipitation (May-October), i is the specific year (November-October), and avg is the average value for all years in the Ardennes record (1910-1998). So an index value smaller than 1 represents a dry season and an index value larger than 1 represents a wet season.

The summer baseflow is here calculated as the average value of the minimum discharge values for each of the six summer months (May-October):

$$BF_{summer} = [Qmin_{may} + Qmin_{june} + Qmin_{july} + Qmin_{august} + Qmin_{september} + Qmin_{october}) / 6$$

where BF_{summer} is the summer baseflow and $Qmin_{May..October}$ is the minimum measured discharge in May....October. The baseflow index of the summer is then calculated as:

$$I_{BFsummer,i}= BF_{summer,i} /BF_{summer,avg}$$

where $I_{BFsummer}$ is the index for the summer baseflow, BF_{summer} is the summer baseflow (may to october), i is the specific year, and avg is the average value for all years in the discharge record (for duration of the different records see table 3.1). An index value smaller than 1 represents a summer with a relatively low baseflow and an index value larger than 1 represents a summer with a relatively large baseflow.

Figure 4.6a shows that for some sub-basins the summer baseflow index correlates better with the winter precipitation index than with the summer precipitation index. This suggests basins with a relatively long memory. For other basins it is found that the summer baseflow index correlates better with the summer precipitation index than with the winter precipitation index. This suggests basins with a relatively short memory (figure 4.6b). Figure 4.6c suggests that the Meuse basin upstream of Monsin is a mixture of 'short memory' and 'long memory' basins. The summer baseflow index shows some correlation to both winter and summer precipitation indices. A more detailed characterisation of the 'hydrological response' of the different sub-catchments will be given in section 4.4.

The above mentioned analyses clearly show that the precipitation in the previous winter influences the length of the low flow period in the summer. This means that at the end of the winter (April) one can estimate the chance in a long lasting low flow period in the Meuse for the coming summer. Appendix 1 gives an example of what such a 'low flow forecasting' methodology could look like.

Figure 4.5 November-April precipitation index (top), and May-October (bottom) precipitation index 'Ardennes record' (black, 1st y-axis) versus the duration of the low flow period in the Meuse (grey, 2nd y-axis)

These two graphs are used to analyse the relation between seasonal precipitation volumes and the length of the low flow period

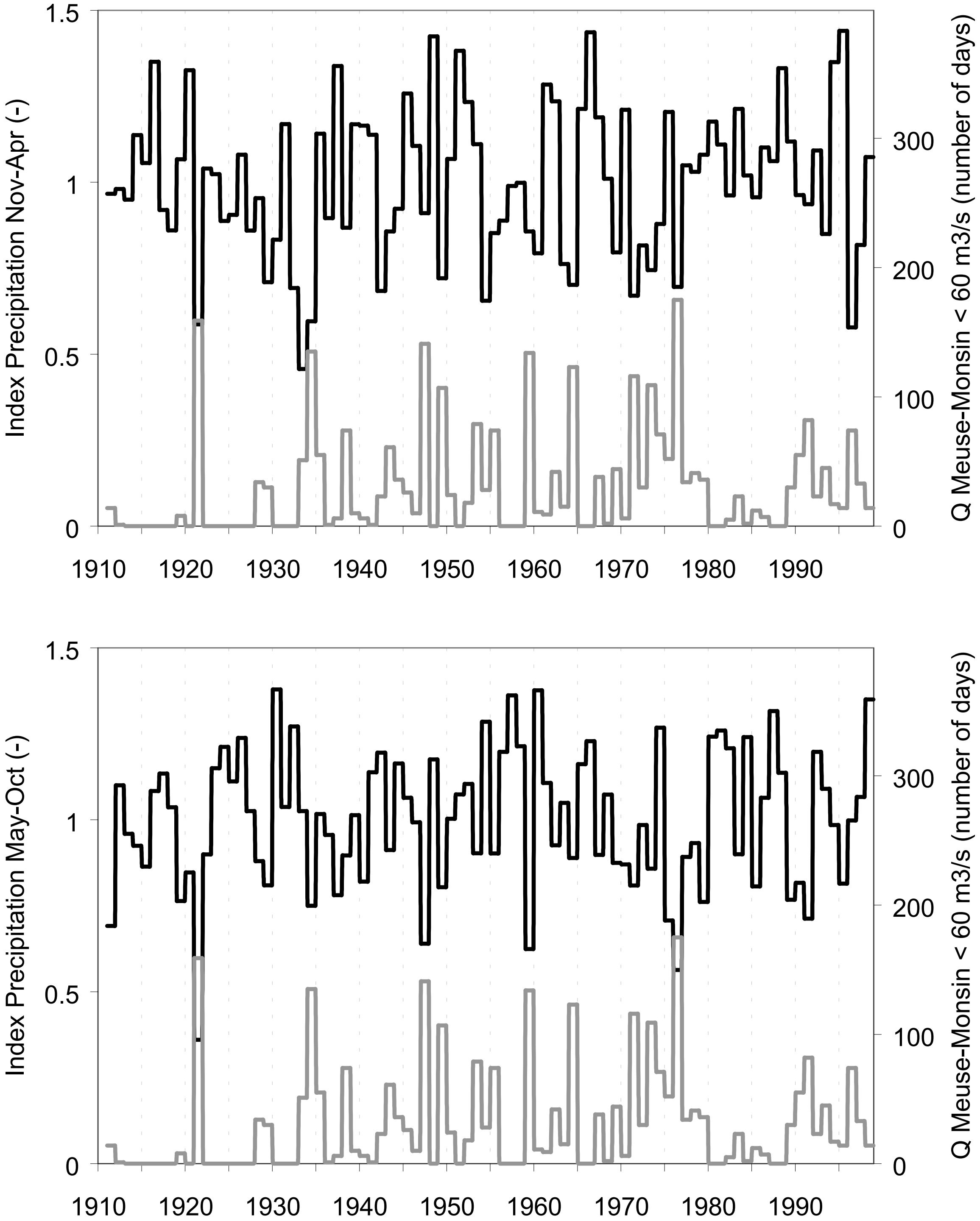
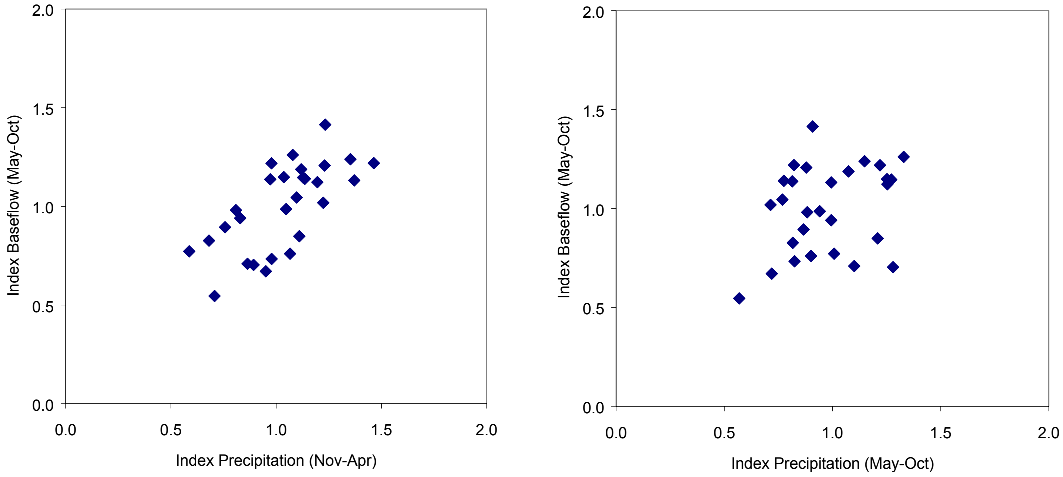
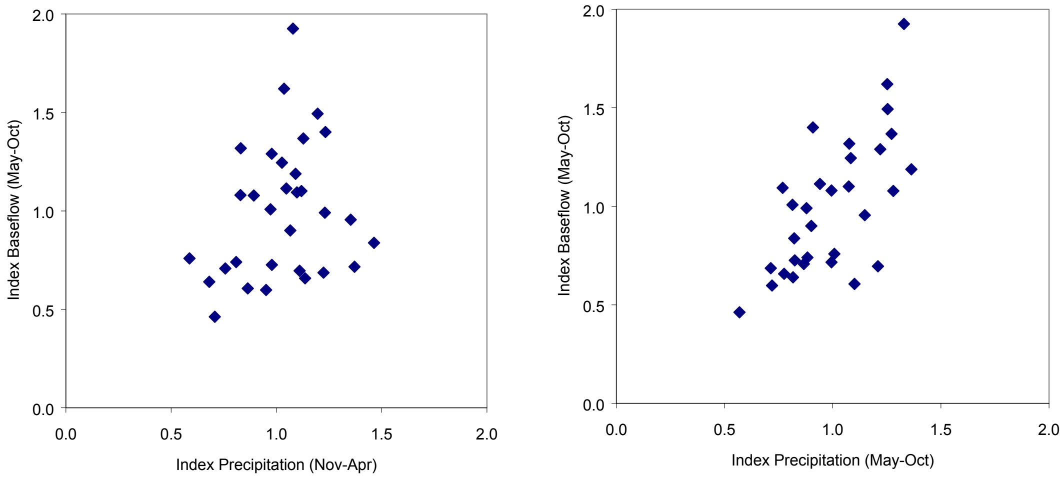


Figure 4.6 Scatterplot of precipitation (left graph November to April, and right graph May to October) and baseflow indices (May to October). Each point represents a year/season.

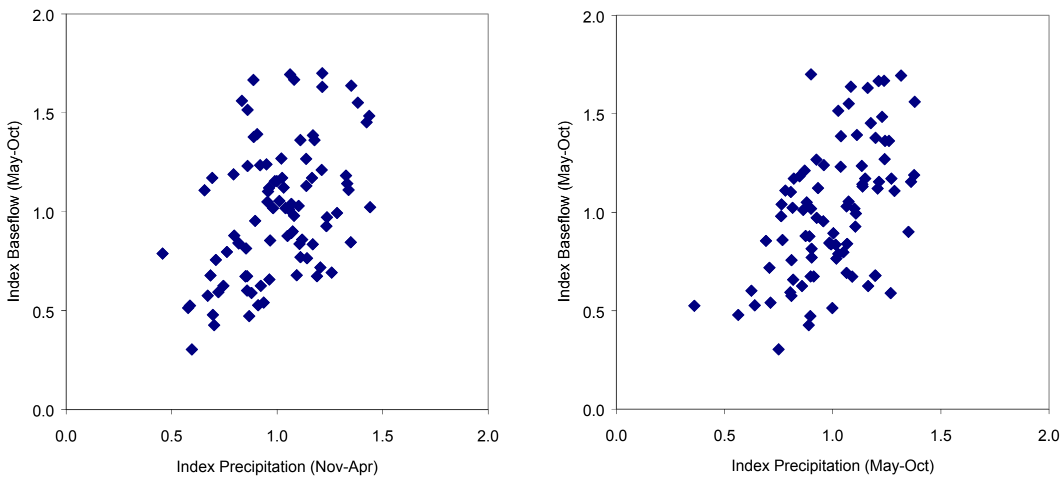
a *Sub-catchment with a relatively long memory (Molignée 1969-1998)*



b *Sub-catchment with a relatively short memory (Amblève 1968-1998)*



c *A mixture of different sub-catchments (Meuse basin upstream of Monsin 1911-1998)*



4.4 Statistical analysis of 23 discharge time series

Does the sensitivity to low flows and floods differ between sub-catchments of the Meuse basin?

The Meuse basin covers a wide range of landscapes (see chapter 2). These different landscapes have different hydrological characteristics. This implies that the sensitivity to both low flows and flooding differ between the geographical regions. In order to plan preventive measures and mitigate the impacts of drought, one needs to know which sub-catchments of the Meuse basin are most sensitive with regard to low flows and floods. This chapter presents the results of a statistical analysis of the discharge data, aiming at an identification of discharge characteristics of different sub-catchments of the Meuse basin. A complete description of the statistical analysis of the discharge data is given in Uijlenhoet et al. (2001), here only the major findings are presented. The analysis covers all stations listed in table 3.1, except for station Monsin (nr. 24).

Statistical analysis of the discharge data

If the discharge time series are regarded as realisations of stationary stochastic processes, two aspects of their variability need to be distinguished: the magnitude of their fluctuations and the speed of their fluctuations. In order to assess the sensitivity of the various sub-catchments to low flows and floods, both aspects require quantification.

The magnitude of the daily discharge fluctuation has been dealt with through identification of the mean daily discharges and the standard deviation. If the standard deviations are normalised by dividing them by the corresponding means, the coefficients of variation (CV) are obtained. The CV values are a measure of the magnitude of the variability. A small CV value indicates little fluctuation of the discharge, whereas a large CV value indicates a large fluctuation of the discharge. The mean daily discharge, standard deviation, and CV values for all 23 stations are presented in table 4.3.

Recession coefficients are a measure for the speed of flow recession. The calculation of the recession coefficients is based on exponentially decaying hydrograph tails (consistent with the linear reservoir model). The recession coefficients were only calculated for dry spells (see Uijlenhoet et al., 2001). The criteria used to calculate the recession coefficients were:

- the length of a recession period, defined as the length of the interval between the beginning of a dry spell and the day with the minimum discharge during a dry spell, has to be at least 60 days;
- the correlation coefficient between the logarithm of the discharges during the recession period and the corresponding day numbers has to be negative;
- the coefficient of determination of a linear regression between the logarithm of the discharges during the recession period and the corresponding day numbers (i.e. the square of the correlation coefficient) has to be at least 0.7.

Table 4.4 presents the estimated recession coefficients and the estimated coefficients of determination. Large recession coefficients indicate slow discharge recession, and small recession coefficients indicate fast discharge recession.

Table 4.3 Magnitude of discharge fluctuation: Coefficient of variation

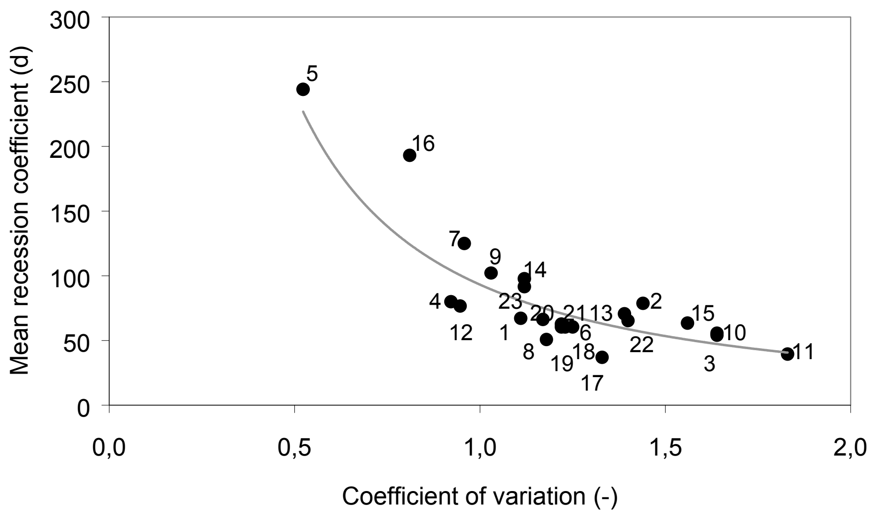
River	Station	Code (figure 3.1)	Basin km^2	Mean daily discharge (m^3s^{-1})	Standard deviation (m^3s^{-1})	Coefficient of variation (-)
Amblève	Martinrive	1	1068	18.6	20.7	1.11
Eau Blanche	Nismes	2	254	3.1	4.5	1.44
Eau Noire	Couvin	3	176	3.1	5.1	1.64
Essche Stroom	Nemelaer	4	330	3.1	2.8	0.92
Hoyoux	Modave	5	94	1.1	0.6	0.52
Lesse	Gendron	6	1314	17.4	21.8	1.25
Mehaigne	Moha	7	343	2.5	2.4	0.96
Meuse	Borgharen	8	21260	227	268	1.18
Meuse	Chooz	9	10120	147	151	1.03
Meuse	Domrémy-la-Pucelle	10	1031	11.1	18.1	1.64
Meuse	Goncourt	11	364	4.3	7.8	1.83
Meuse	Montcy-Notre-Dame	12	7724	100	94.7	0.95
Meuse	Saint-Mihiel	13	2540	29.7	41.2	1.39
Meuse	Stenay	14	3904	46.7	52.1	1.12
Meuse	Vaucouleurs/Chalaines	15	1717	21.4	33.3	1.56
Molignée	Warnant	16	125	1.4	1.1	0.81
Nieuwe Leij	Goirle	17	115	0.9	1.2	1.33
Ourthe	Nisramont	18	737	13.0	16.0	1.23
Ourthe	Tabreux	19	1616	22.2	27.0	1.22
Ourthe Occidentale	Ortho	20	386	6.9	8.1	1.17
Ourthe Orientale	Mabompré	21	317	5.3	6.5	1.22
Semois	Ste. Marie	22	143	2.4	3.4	1.40
Vesdre	Chaudfontaine	23	677	10.3	11.5	1.12

Table 4.4 Speed of discharge recession: recession analysis

River	Station	Code (figure 3.1)	Basin km^2	Mean recession coefficient (d)	Coefficient of determination (-)
Amblève	Martinrive	1	1068	67.2	0.79
Eau Blanche	Nismes	2	254	78.7	0.81
Eau Noire	Couvin	3	176	54.1	0.79
Essche Stroom	Nemelaer	4	330	79.9	0.78
Hoyoux	Modave	5	94	244	0.85
Lesse	Gendron	6	1314	60.4	0.84
Mehaigne	Moha	7	343	125	0.79
Meuse	Borgharen	8	21260	50.7	0.77
Meuse	Chooz	9	10120	102	0.81
Meuse	Domrémy-la-Pucelle	10	1031	55.6	0.84
Meuse	Goncourt	11	364	39.4	0.84
Meuse	Montcy-Notre-Dame	12	7724	76.6	0.82
Meuse	Saint-Mihiel	13	2540	70.6	0.86
Meuse	Stenay	14	3904	97.7	0.87
Meuse	Vaucouleurs/Chalaines	15	1717	63.4	0.81
Molignée	Warnant	16	125	193	0.83
Nieuwe Leij	Goirle	17	115	36.9	0.82
Ourthe	Nisramont	18	737	60.4	0.83
Ourthe	Tabreux	19	1616	60.4	0.82
Ourthe Occidentale	Ortho	20	386	66.2	0.83
Ourthe Orientale	Mabompré	21	317	62.7	0.83
Semois	Ste. Marie	22	143	65.2	0.80
Vesdre	Chaudfontaine	23	677	91.6	0.79

Figure 4.7 shows a scatterplot of the CVs and recession coefficients. Not surprisingly, these two derived variables do correlate. This implies that one can distinguish between sub-catchments with a relatively small discharge variability and a slow discharge recession, and sub-catchments with a relatively large discharge variability and a fast discharge recession.

Figure 4.7 Scatterplot of magnitude (Coefficient of Variation) and speed (Recession Coefficient) of discharge fluctuation. Numbers correspond to monitoring stations (table 3.1).



It appears that the magnitude and speed of the discharge fluctuations bare little or no correlation to the size of the upstream drainage areas (tables 4.3 and 4.4). This is somewhat surprising, one would expect that the fluctuations average out when moving to larger catchments. This implies that other catchment characteristics are also distinctive. Based on figure 4.7 the discharge stations were ordered from 'small and slow' discharge fluctuations to 'large and fast' discharge fluctuations. This ordering was done 'by eye' and the sequence is shown in table 4.5. This table also gives a rough characterisation of the lithology and geology in the upstream basins. This rough characterisation has been derived from BRGM (1996) and De Roeck and Tilmont (1963). It appears that some of the differences in the discharge fluctuations can be explained by the lithological/geological characteristics of the upstream basin.

The sub-catchments with small and slow discharge fluctuations are those catchments that mainly consist of calcareous rocks (catchments 5, 16, 7, 9, 12, 14). One would also expect relatively small and slow discharge fluctuations for catchments in the pleistocene sands (4 and

17). The relatively fast and large fluctuations of the catchment of the Nieuwe Leij (17), have most probably to be addressed to characteristics other than lithology. Striking are also the relatively large and fast fluctuations in the catchments located in the Lias formation (11, 10, 15, 22). A possible explaination may be that, compared to the Malm and Dogger formations (sub-catchments 9, 12-15), the Lias formation consists of less permeable rock types. Based on the rough lithological and geological characterisations presented in table 4.5, one cannot distinguish between the different sub-catchments in the Ardennes Massif.

Table 4.5 Rough characterisation of discharge fluctuation, lithology and geology of the sub-basins

Code	River	Station	Lithology	Geology
		relatively low and slow discharge fluctuations		
5	Hoyoux	Modave (B)	Limestone	Carboniferous
16	Molignée	Warnant (B)	Limestone	Carboniferous
7	Mehaigne	Moha (B)	Limestone, Sands	Tertiair, Cretaceous
4	Essche Stroom	Nemelaer (NL)	Sands	Pleistocene
9	Meuse	Chooz (F)	Limestone, Siltstone	Malm, Dogger
12	Meuse	Montcy-Notre-Dame (F)	Limestone, Siltstone	Malm, Dogger
14	Meuse	Stenay (F)	Limestone, Siltstone	Malm, Dogger
23	Vesdre	Chaudfontaine (B)	Phylitte, Quartzite, Limestone	Carboniferous, Devonian, Cambrian
1	Amblève	Martinrive (B)	Quartzite, Phylitte	Cambrian, Devonian
20	Ourthe Occidentale	Ortho (B)	Quartzite, Phylitte	Devonian
8	Meuse	Borgharen (NL)	Mixture	Mesozoic and Paleozoic
21	Ourthe Orientale	Mabompré (B)	Quartzite, Phylitte	Devonian
19	Ourthe	Tabreux (B)	Quartzite, Phylitte, Schists, Limestones	Devonian
18	Ourthe	Nisramont (B)	Quartzite, Phylitte	Devonian
6	Lesse	Gendron (B)	Quartzite, Phylitte, Shales, Limestones	Devonian
17	Nieuwe Leij	Goirle (NL)	Sands	Pleistocene
13	Meuse	Saint-Mihiel (F)	Limestone, Siltstone, Sandstone	Malm, Dogger, Lias
22	Semois	Ste. Marie (B)	Sandstone, Siltstone	Lias, Trias
2	Eau Blanche	Nismes (B)	Quartzite, Phylitte, Shales, Limestone	Devonian
15	Meuse	Vaucouleurs / Chalaines (F)	Limestone, Siltstone and Sandstone	Dogger, Lias
10	Meuse	Domrémy-la-Pucelle (F)	Sandstone, Siltstone, Limestone	Dogger, Lias
3	Eau Noire	Couvin (B)	Quartzite, Phylitte	Devonian, Cambrium
11	Meuse	Goncourt (F)	Sandstone, Siltstone	Lias
		relatively large and fast discharge fluctuations		

Catchments with small and slow discharge fluctuations suggest a dominance of slow runoff components (groundwater flow), whereas catchments with large and fast discharge fluctuations suggest a dominance of fast runoff components ('overland flow'). The latter are more vulnerable with respect to both floods and low flows. The analysis presented here can be used to get a rough picture of the vulnerability of the sub-catchments in the river Meuse basin.

Vulnerable catchments seem to be located in the regions that consist of rocks from the Lias formation (southern part of the French Meuse, and eastern upper part of the Chiers and Semois), and in the central part of the Ardennes (the upper Ourthe, Lesse, Vesdre and Amblève). Flood prevention at the source will be most effective in these regions.

Less vulnerable catchments seem to be located in the Carboniferous limestones of the Condroz region and the Mesozoic limestones in the French part of the Meuse basin and north of the Ardennes. The groundwater reservoirs in these regions need to be protected in order to maintain a minimum water flow in the Meuse during dry periods.

Besides lithology and basin size there are many other characteristics that influence the discharge patterns, e.g. vegetation, relief, and human interference in the form of dams, weirs and/or sluices. A complete analysis of these characteristics and their influence on the discharge is beyond the scope of the analysis presented here.

5 MODEL SIMULATIONS

5.1 Climate change scenarios

What climate change is predicted for the Meuse basin?

Human activities are causing an increase in the atmospheric concentrations of greenhouse gases and aerosols. Together these changes are projected to change regional and global climate and climate-related parameters such as temperature, precipitation, and sea level (IPCC, 1995). Climate change will lead to an intensification of the global hydrological cycle and can have major impacts on regional water resources. Changes in total amount of precipitation and its frequency and intensity directly affect the magnitude and timing of runoff and the intensity of floods and droughts; however, at present specific regional effects are uncertain (IPCC, 1995). Global Climate Models also known as General Circulation Models (GCMs), are the tools used to perform climate change experiments from which climate scenarios (possible representations of how the climate will evolve) can be constructed. GCMs are the most complex of climate models, since they attempt to represent the main components of the climate system in three dimensions. It is widely acknowledged that the direct outputs of climate change simulations from GCMs are inadequate for assessing land-surface impacts on regional scale. This is primarily for two reasons: first, because the spatial resolution of GCMs (typically 50 000 km^2, see figure 3.3) is often larger than that required for input to impacts models; and second, because of doubts about the reliability of some GCM output variables (particularly those, like precipitation, that are critically dependent on sub-grid-scale processes such as those involving clouds) (Wilby and Wigley, 1999). This mismatch between what the climate impacts community requires and what the GCMs are able to supply, has been a confounding issue affecting the confidence placed in impacts scenarios at the basin scale (Hostetler, 1994). Unfortunately this mismatch also deeply affects the analysis presented in this study. The climate scenarios used for the Meuse basin are derived from GCM output. Here, the outputs of different GCMs are compared in order to get an idea of the uncertainties involved.

GCM outputs for the Meuse basin

Figures 5.1 and 5.2 give derived outputs for a number of GCMs (see table 3.3) for average precipitation and temperature changes in the Meuse basin. It should be noted that the scenarios used in this study do not cover the entire range of climate change scenarios. The scenarios presented in figures 5.1 and 5.2 all assume the same emission scenario (doubling of CO_2 emissions by the end of the 21th century). Various social, economic and technological developments have a strong impact on emission trends, and may lead to different emission scenarios. The emission scenario used as input for the GCM runs in figures 5.1 and 5.2 is more or less in the middle of the total range of emission scenarios reported by the IPCC (IPCC, 2001).

There are large differences in the GCM predictions for the Meuse basin (figures 5.1 and 5.2), but all GCMs simulate an increase of temperature, an increase of winter precipitation, and a decrease of summer precipitation.

Figure 5.1 Predicted relative change in precipitation for Belgium/Meuse basin (see table 3.3 and figure 3.3). Change is end 21th century minus end 20 th century.

Elaborated at the Royal Meteorological Institute of Belgium

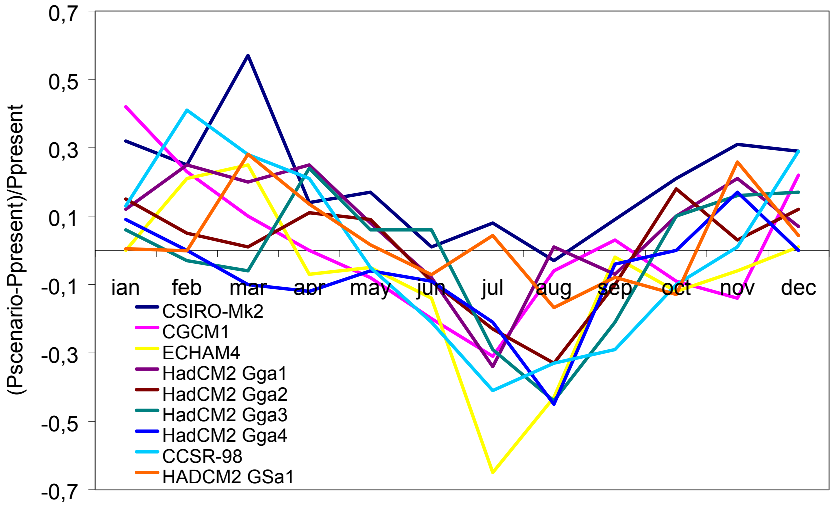
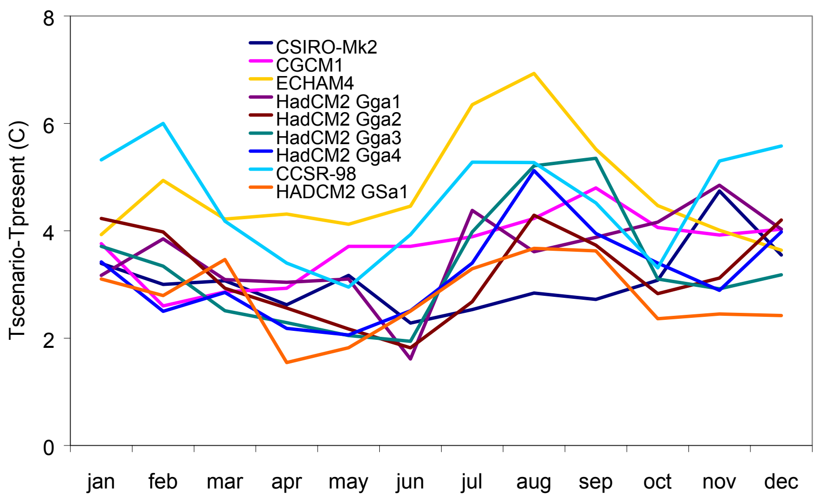


Figure 5.2 Predicted change in temperature for Belgium/Meuse basin (see table 3.3 and figure 3.3). Change is end 21th century minus end 20 th century.

Elaborated at the Royal Meteorological Institute of Belgium.



Implementation of GCM output

Global Circulation Models operate at relatively detailed temporal resolutions, which is necessary to simulate certain climatic processes (e.g. radiation). However, the results of GCMs should be interpreted at much more aggregated (coarser) temporal resolutions. GCMs are meant to simulate average changes in climatic conditions (e.g. average temperature at the end of the 21th century compared to the present average temperature), they are not meant to predict the weather for a specific day, month, or year. The same can be said about the spatial resolution of GCMs. GCMs operate at a spatial resolution of cells (typically 50 000 km^2) to simulate regional processes, but confidence is higher in the hemispheric-to-continental scale projections than in the regional projections.

It is possible to derive daily, weekly or monthly records for future climatic parameters (e.g. precipitation on March 13th, 2078) and use these for the hydrological simulation. However, given the considerations listed above it seems more reasonable to use average relative changes (e.g. a decrease of ten percent in the average July precipitation for the end of the 21th century compared to the end of the 20th century, see also figures 5.1 & 5.2) instead of absolute GCM output data.

In this study two change series are applied: i) a change series derived from the HadCM2Gsa1 run, and ii) a change series derived from a mixture of GCM runs. More than one scenario was run, in order to be able to illustrate differences between climate change scenarios. Running more than two climate change scenarios would have been interesting, but would have required more time than available within this project. Both change series consist of monthly values, and both series will be outlined below. The most important difference (for the analysis presented in this report) between these two scenarios is that the mixed scenario is somewhat 'drier' (especially in the summer) than the NOP scenario.

NOP scenario

This scenario is called NOP scenario, because it is based on the HadGM2Gsa1 run, which is used in all impact studies of the Dutch National Research Programme on Global Air Pollution and Climate Change (Verweij and Viner, 2001). The use of this scenario allows for a comparison with other NOP projects. Monthly climate predictions for the period 2070-2099 have been compared with the monthly values of the baseline run for the period 1961-1990. This results in average change series for the monthly precipitation, temperature, cloud cover, wind speed, and relative humidity (see table 5.1 and figure 5.3).

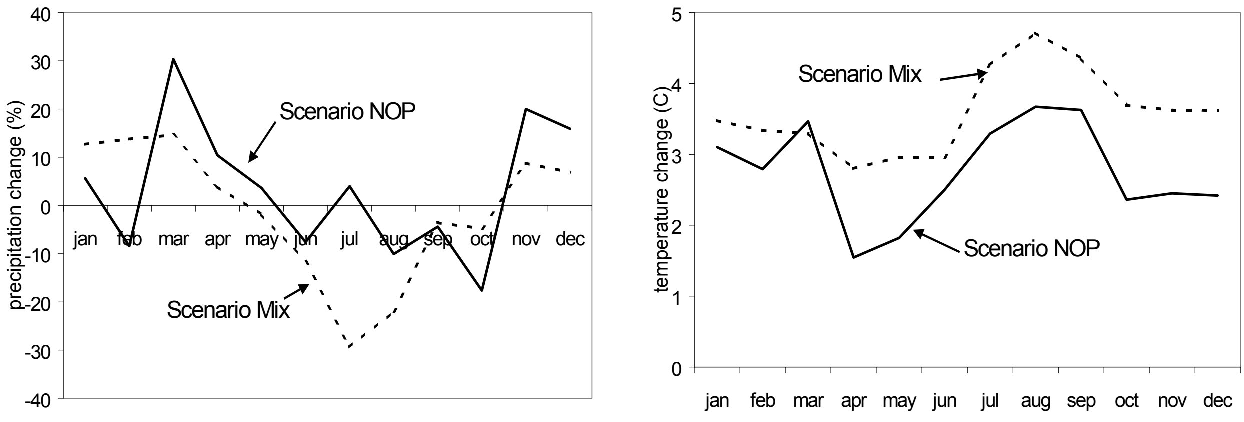
Mixed scenario

The second scenario has been derived from the output of five different GCMs. These GCMs were randomly selected. The changes (end of 20th century compared to end of 21th century) predicted with the HadCM2Gga1-, HadCM2Gga4-, HadCM2Gsa1-, CGCM1-, and ECHAM4 runs, were simply averaged. This resulted in one change serie (table 5.1). As shown in figures 5.1 and 5.2, the changes predicted by individual GCMs often fluctuate between months (one month it goes up, the next month it goes down etc.). Averaging the outputs of a number of GCMs results in a less erratic monthly change series (see table 5.1 and figure 5.3). Such a more smooth change serie will be more easy to interpret, when applied as input to a hydrological model (see section 5.2).

Table 5.1 Climate change series used; NOP scenario and Mixed scenario. Change is climate change run (end 21th century) minus baseline run (end 20th century)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NOP scenario												
Relative change in fractional cloud cover (%)	-0,47	1,18	2,84	-4,62	-1,68	-6,96	4,76	-10,90	-10,88	-12,63	-3,85	-0,45
Relative change in precipitation (%)	5,62	-8,41	30,35	10,41	3,64	-7,59	3,99	-10,07	-4,39	-17,63	19,99	15,90
Change in mean temperature at 1.5 m (Celsius)	3,10	2,79	3,47	1,55	1,82	2,50	3,29	3,67	3,63	2,36	2,45	2,42
Change in wind speed at 10 m (m/s)	0,08	0,09	-0,12	0,06	-0,07	-0,04	-0,30	-0,27	-0,12	-0,07	0,08	0,06
Relative change in relative humidity (%)	-0,97	-0,74	0,07	-0,32	-0,40	-0,44	-0,08	-11,37	-9,62	-4,45	-1,20	-0,49
Mixed scenario												
Relative change in fractional cloud cover (%)	-0,16	0,06	0,28	-3,21	-3,56	-3,65	-1,75	-7,63	-7,29	-6,54	-1,95	0,85
Change in diurnal temperature range at 1.5 m (Celsius)	0,09	-0,02	-0,06	0,13	0,17	0,13	0,73	0,94	0,65	0,45	0,19	0,08
Relative change in precipitation (%)	12,69	13,77	14,63	3,90	-1,88	-11,62	-29,33	-21,95	-3,58	-4,78	8,77	6,87
Change in radiation (W/m2)	-0,22	-1,24	-0,46	3,27	7,35	11,32	15,98	7,27	-0,02	4,28	2,46	0,68
Change in min temperature at 1.5 m (Celsius)	3,53	3,50	3,32	3,08	3,19	3,04	4,16	4,55	4,25	3,83	3,83	3,87
Change in mean temperature at 1.5 m (Celsius)	3,48	3,34	3,30	2,80	2,96	2,96	4,26	4,71	4,36	3,69	3,62	3,62
Change in max temperature at 1.5 m (Celsius)	3,61	3,48	3,26	3,20	3,36	3,17	4,89	5,48	4,90	4,27	4,02	3,95
Change in vapour pressure (hPa)	2,15	2,11	2,11	2,26	2,72	3,16	3,49	3,19	3,22	3,08	2,80	2,50
Change in wind speed at 10 m (m/s)	0,07	-0,03	-0,04	-0,06	-0,08	-0,10	-0,23	-0,24	-0,09	-0,07	-0,03	0,04
Relative change in relative humidity (%)	-0,97	-0,74	0,07	-0,32	-0,40	-0,44	-0,08	-11,37	-9,62	-4,45	-1,20	-0,49

Figure 5.3 Simulated change in monthly average precipitation and temperature. Change is climate change run (end 21th century) minus baseline run (end 20th century)



5.2 Simulation of climate change

What will be the effect of the predicted climate change on the discharge regime of the Meuse?

The discharge regime of the Meuse is not only a reflection of the precipitation regime in the Meuse basin, but it also reflects other climatic variables (e.g. temperature, radiation, evaporation...), landscape characteristics (e.g. hydrogeology, vegetation...), and human impacts (e.g. agricultural drainage, flow regulation). In order to account for all these different aspects, models are required. Rainfall-runoff models can be used to simulate the combined effect of changes in precipitation, changes in temperature, and changes in evapotranspiration. Moreover, physically-based rainfall-runoff models can be used to simulate other changes in the catchment, such as changes in land cover or changes in the operation of drainage systems. Rainfall-runoff models have frequently been applied in flood studies. To date their application in low flow studies has been relatively limited (Smakhtin, 2001). In this study distributed rainfall-runoff models have been used to simulate the effect of climate change (this section) and land use changes (section 5.3) on the discharge regime of the Meuse.

A number of earlier studies have already applied rainfall-runoff models to sub-catchments of the Meuse basin (Van Deursen, 2000; Gellens & Roulin, 1998; Van Walsum *et al*. 2001). In order to optimally use the experiences and data that have been derived from these studies, it was decided to use existing models instead of developing a new one. In this study three existing models have been applied to four different sub-catchments of the Meuse basin: SIMGRO (Veldhuizen et al., 1998), SCHEME (Roulin et al., 2000) and MEUSEFLOW (Van Deursen, 1999). The size of the sub-catchments studied varies between 220 and 22 000 km^2. This implies that also the resolution, available data, and model formulations used, vary for the different models. By using different models it will be possible to compare the output of different model structures and different sub-catchments. The relatively small sub-catchments are needed to analyse rainfall-runoff processes in somewhat more detail, whereas the MEUSEFLOW model is needed to derive predictions for the river Meuse. Moreover, a comparison of the results of the 'detailed' models with the MEUSEFLOW model will to a certain extent allow for a validation of the MEUSEFLOW model. A similar procedure was used for the analysis of the impact of climate change on the hydrology of the Rhine basin (Grabs et al., 1997).

Below a brief description of the three distributed rainfall-runoff models and the sub-catchments used is given. For a more detailed description the reader is referred to appendix 2.

SIMGRO

The SIMGRO (SIMulation of GROundwater flow and surface water levels) model was applied to the Beerze catchment. This flat catchment is located in the southern part of the Netherlands and covers an area of 223 km^2. Most of the catchment is used for agricultural production. The catchment mainly consists of unconsolidated (sandy) sediments. The Beerze catchment can be seen as a representative rural catchment for the Dutch and Flemish part of the Meuse basin.

The model SIMGRO simulates regional groundwater flow in relation to drainage, water supply, sprinkling, subsurface irrigation and water level control. The model simulates the flow of water in the saturated zone, the unsaturated zone and the surface water in an integrated manner. The model is physically-based and in principle suitable to be used in situations with changing hydrological conditions. The actual evapotranspiration is determined by the crop and the moisture content in the root zone. For these calculations, recorded values of precipitation and potential evapotranspiration of reference crops and woodland are used.

SCHEME

The SCHEME (SCHElde MEuse) model was here applied to two Belgian catchments: The Ourthe Orientale and the Mehaigne. The catchment of the Ourthe Orientale (317 km^2) mainly consists of Quartzite and Phylitte. It is a hilly catchment where forest is the major land cover type. The slightly sloping catchment of the Mehaigne (343 km^2) is mainly used for agricultural activities. It consists of loamy soils overlying Cretaceous limestone.

The SCHEME model is based on the IRMB (Integrated Runoff Model Franz Bultot) conceptual model (Bultot and Dupriez, 1976). The processes are lumped over grid cells of 50 km^2 and represented by a set of reservoirs. The parameters that determine the input to, storage in, and output from these reservoirs are optimised on a set of sub-catchments and regionalised over the whole basin. The model includes a module to route water to the outlet of the catchment. The potential evapotranspiration estimation is based on the Penman equation. Actual evapotranspiration is calculated as a function of interception and soil water content.

MEUSEFLOW

The MEUSEFLOW model was applied to the Meuse basin upstream of Borgharen (near Maastricht). It covers an area of about 21 000 km^2, embracing the Lotharingian and Ardennes Meuse (see chapter 2).

MEUSEFLOW is a distributed GIS-based water balance model developed on the methodology of the RHINEFLOW model (Kwadijk, 1993). MEUSEFLOW models the soil water balance for cells of 1 km^2, based on 10-day precipitation and temperature data, and geographical data such as land use and soil type. The discharge at the outlet of the basin is calculated as the sum of the runoff of all upstream cells. The reference evapotranspiration, crop factors and the moisture content in the soil determine the evapotranspiration. MEUSEFLOW uses a mathematical relation between temperature change and reference evapotranspiration change. This relation has been derived from Brandsma (1995).

Calibration 1988-1992

None of the three models listed above was especially designed for low flow studies. Therefore they have here been calibrated for a relatively dry period: 1988-1992. This five-year period includes three dry summers in a row (1989, 1990, and 1991, see also figure 4.5). For a more detailed description of the procedures used to calibrate the three rainfall-runoff models the reader is referred to appendix 2.

The measured and modelled monthly average discharge regimes for the 1988-1992 period are presented in figure 5.4. It should be noted that none of the models was calibrated specifically to fit the monthly average discharges regimes; the calibration of the SIMGRO model was mainly based on groundwater data, the calibration of SCHEME was based on daily discharge data and the calibration of MEUSEFLOW model was based on ten-day average discharge data. This means that extremes rather than average values were tuned. This implies that the results in figure 5.4 allow, to a certain extent, for a validation of the models.

For the Beerze catchment the modelled discharges are somewhat larger than the measured discharges, especially for the summer months (figure 5.4a). This may be partly due to the fact that the discharge measurements in the Beerze are not accurate at low flows since they were measured with a short-crested rectangular weir. The rectangular shape causes a high sensitivity for the zero level of the head gauge, which inevitably leads to inaccuracies. Such weirs also require a head difference of several dms between upstream and downstream water levels. This inevitably causes leakage below the construction.

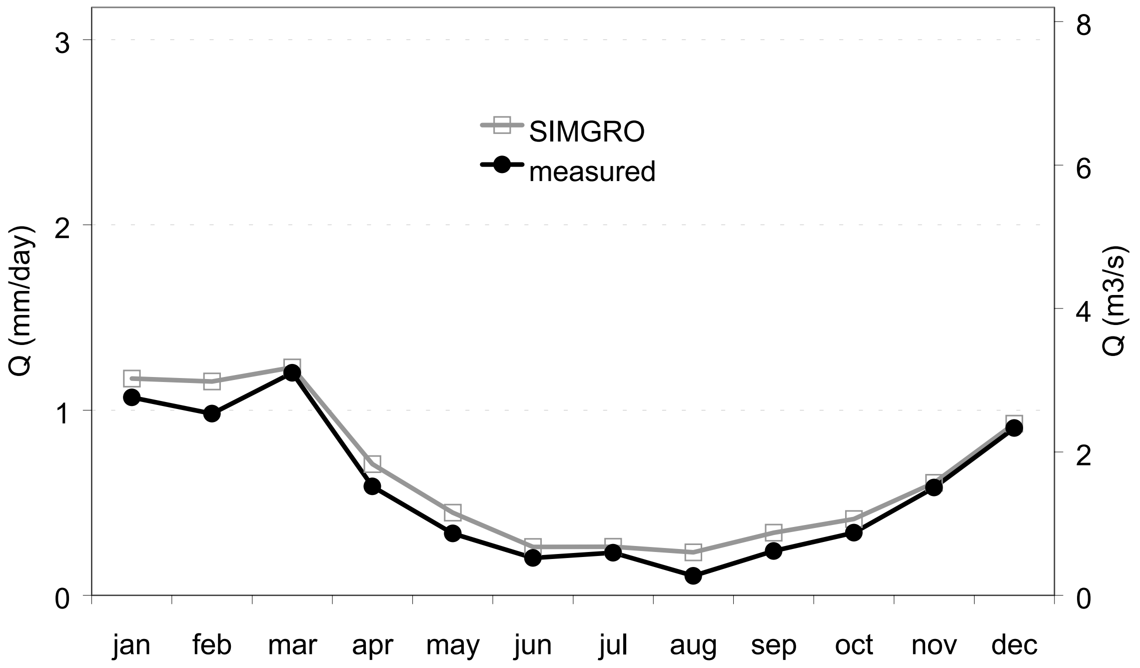
The Meuse basin upstream of Borgharen also covers the basins of the Mehaigne and Ourthe Orientale. This means that for these basins the results of MEUSEFLOW can be compared with the results of SCHEME. Figures 5.4b and 5.4c both present the results of MEUSEFLOW and SCHEME. It should be noted that SCHEME is tuned on the data for these two sub-catchments, whereas MEUSEFLOW has been designed for the entire Meuse basin upstream of Borgharen. Also the input data (e.g. precipitation maps) for SCHEME are more detailed than those used for MEUSEFLOW. This may explain why SCHEME fits the observed discharge regime for the Mehaigne and Ourthe Orientale better than MEUSEFLOW. However, the results of MEUSEFLOW are in the correct order of magnitude and are in good agreement with the observed flow regime at Monsin (figure 5.4d).

Figure 5.4 shows that the discharge regime in the different sub-basins differs considerably (note that the scale of the first y-axis is the same for all catchments). These differences are reasonably well reproduced by the different models. The limited amount of time and data available for this study did not allow for a more extensive validation of the models used. However, the decision to use the presented models for climate change simulations was also motivated by the fact that these models have already been tested and applied in a number of earlier studies. RHINEFLOW (the model from which MEUSEFLOW has evolved) was applied to assess the impact of climate change on the discharge of the river Rhine (Kwadijk, 1993). Gellens & Roulin (1998) used the IRMB model (the model from which the SCHEME model has evolved) to assess streamflow response of eight Belgian catchments to IPCC climate change scenarios. SIMGRO was used to analyse the effects of climate and land-use change on dutch lowland stream ecosystems by van Walsum et al. (2001).

Figure 5.4 Observed and modelled monthly average discharge regime (1988-1992)

Note that the scale of the first y-axis is the same for all catchments.

a) Beerze



b) Mehaigne

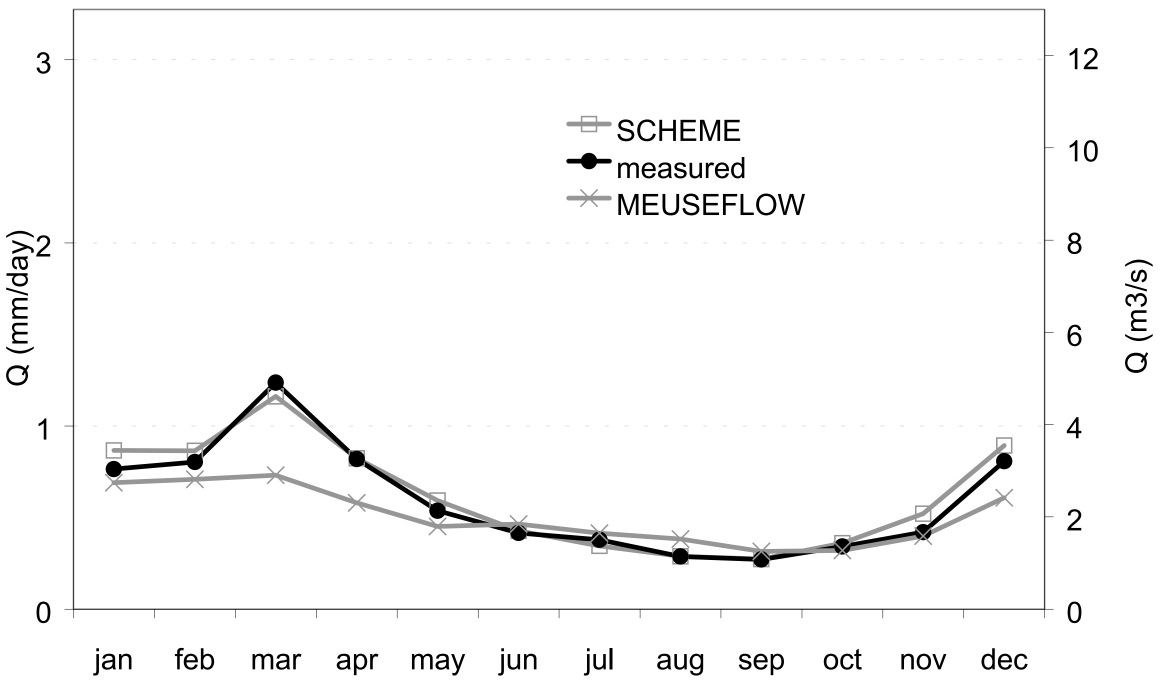
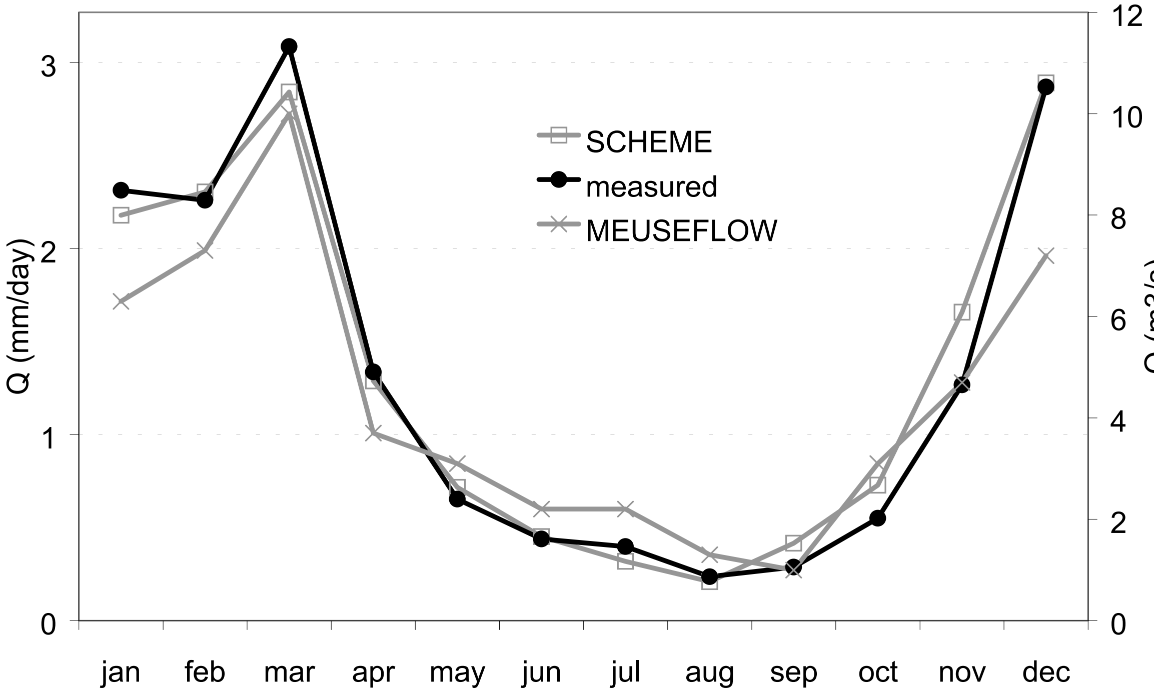


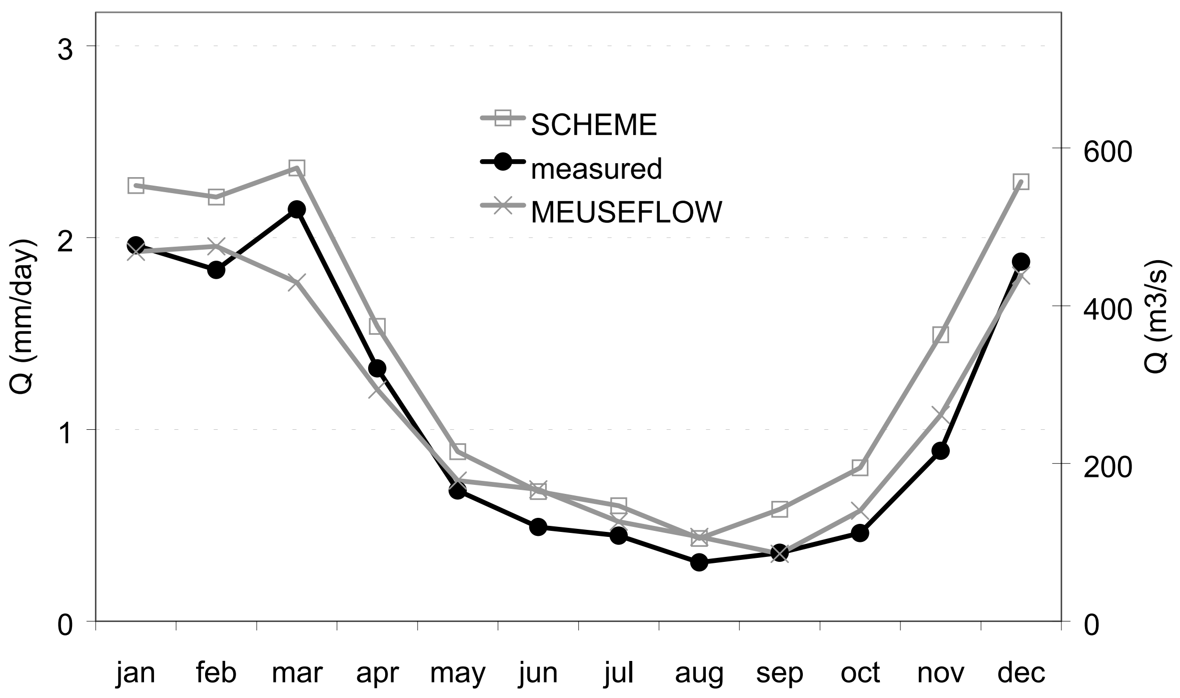
figure 5.4 Observed and modelled monthly average discharge regime (1988-1992) (continued)

Note that the scale of the first y-axis is the same for all catchments.

c) Ourthe Orientale



d) Meuse-Monsin (Meuseflow)



Simulation of climate change

The climate change series (NOP and Mixed scenario) presented in table 5.1 were superimposed on the climate record of 1988-1992, which results in two modified five-year climate records. These two modified climate records have been used as input for the models described above. A similar procedure has been used in many other climate impact studies (e.g. Mimikou et al., 2000; Sefton & Boorman, 1996; Gellens & Roulin, 1998). This simple scaling of the 1988-1992 climate record assumes no changes in the temporal distribution of rainfall (e.g. length of dry periods, or rainfall intensities), whereas in practice this too is likely to change. However, to date it has not been possible to firmly establish a clear connection between changes in regional extremes and human-induced climate change (IPCC, 1995, see also section 5.1).

Both the NOP scenario and the Mixed scenario were run for the Meuse basin upstream of Borgharen, the Mehaigne, and the Ourthe Orientale. For the Beerze catchment two versions of the NOP scenario were applied. This was done to simulate the possible effect of a doubling of the atmospheric CO_2 concentration on the transpiration of plants. SIMGRO calculates evapotranspiration as the product of the reference evaporation and crop factors. An enrichment of the atmospheric CO_2 concentrations increases the stomatal resistance of crops and thus decreases the stomatal opening which may result in a decrease of the transpiration per unit leaf area (Rozema et al., 1991). To simulate this process, the crop factors were reduced based on the values reported in Haasnoot et al. (1999). They argue that a doubling of atmospheric CO_2 concentrations may result in a 10-35% decrease of the crop factors. SIMGRO was run with and without a change of the crop factors.

Although MEUSEFLOW operates at a temporal resolution of 10 days and SIMGRO and SCHEME operate at a temporal resolution of 1 day, the results of the simulations are here presented as changes in the monthly average values. A more detailed presentation of the results is meaningless, since the climate change series are also given as monthly average values (see table 5.1).

Results

Figure 5.5 shows the differences in precipitation, actual evapotranspiration, and discharge between the baseline run (1988-1992), the NOP scenario run, and the Mixed scenario run for all sub-catchments. The results for the individual catchments are presented in appendix 3. Below an interpretation of the results is given.

The absolute difference in precipitation (P) results directly from the use of the relative change series for the two climate change scenarios (see table 5.1). The absolute differences in precipitation (mm day^{-1}) may slightly differ between the sub-catchments, because the relative changes have been superimposed on the climate records (1988-1992) available for each specific catchment.

All, except one, runs simulate an overall increase of the actual evapotranspiration (E). This is mainly a reflection of the increase of the potential evapotranspiration due to the increase of the temperature. However, during a part of the summer the actual evapotranspiration may decrease due to a decrease in soil moisture content (caused by a decrease in precipitation). A completely different result for the simulated actual evapotranspiration is obtained if crop factors are reduced due to an increase in atmospheric CO_2 concentration. This is illustrated by the results of the Beerze runs. The NOP run with reduced crop factors results in a decrease in the simulated evapotranspiration in the Beerze catchment, whereas the NOP run without reduced crop factors results in an increase in the simulated evapotranspiration in the Beerze catchment.

The changes in the simulated discharge regime are less pronounced than the changes in the simulated precipitation regime. This is partly due to changes (increase) in the actual evapotranspiration and partly due to the (natural) storage capacity of the catchments. The overall picture that evolves is that climate change may lead to an increase in the average discharge in late winter and early spring, and a decrease in the average discharge in autumn. Figure 5.5a shows that the different climate change series result in different results. Figure 5.5a also shows that the changes simulated by MEUSEFLOW are in the same order of magnitude as the changes simulated by results obtained from SIMGRO and SCHEME. This suggests that MEUSEFLOW can be used to quantify the possible impact of climate change on the average discharge regime of the Meuse.

Roulin et al. (in press) apply the SCHEME model to analyse the impact of climate change on the hydrology of Belgian rivers. Figure 5.5b presents the preliminary results for the Meuse and compares these results with those of the MEUSEFLOW simulation. Figure 5.5b suggests that the difference in the predicted change of the average monthly discharge regime that results from using different hydrological models (MEUSEFLOW versus SCHEME) is smaller than the difference in the predicted change of the average monthly discharge regime that results from using different climate change scenarios (NOP scenario versus Mixed scenario).

Figure 5.6 translates the results of the MEUSEFLOW simulation into the average discharge regime of the Meuse at Monsin. The discharge regime measured for 1955-1998 is regarded as the baseline run. This graph clearly shows that the climate change runs simulate an increase of the average discharge at the end of winter and at the beginning of spring and a decrease of the average discharge in autumn. These changes are more pronounced for the Mixed scenario run than for the NOP scenario run. The Mixed scenario run results in lower 'lowest monthly averaged' discharge values, whereas the NOP scenario run does not result in a change of the 'lowest monthly averaged' discharge values. Both scenarios do not simulate a large change of the 'largest monthly averaged' discharge values. For comparison also the average discharge regime for the period 1911-1954 has been plotted. Although the changes between 1911-1954 to 1955-1998 are too small to be statistically relevant, they show the same direction of change as the results of the climate change analysis.

Figure 5.5a   Simulated change in precipitation, evaporation and discharge.

The blue lines represent the difference between the baseline run and the NOP run. The red lines represent the difference between the baseline run and the Mixed run. Note that the y-axis is the same for all graphs.

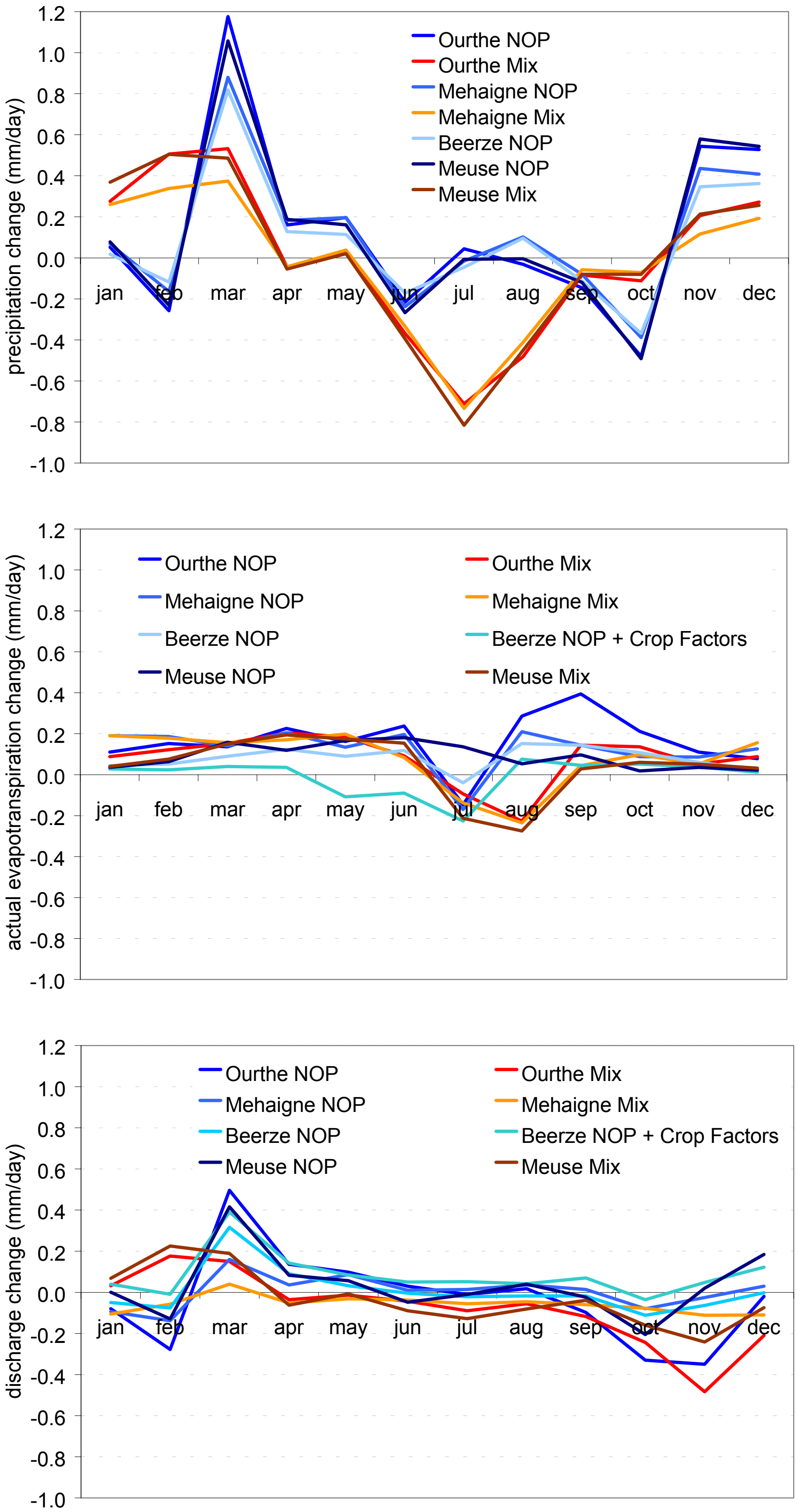


Figure 5.5b Comparison of the simulated impact of climate change on the discharge regime of the Meuse (near Belgian/Dutch border) as modelled with Meuseflow and Scheme (preliminary results by Roulin et al., in press).

It should be noted that the Meuseflow model was calibrated for the period 1988-1992, whereas the Scheme model was calibrated for the period 1981-1988. The blue lines represent the difference between the baseline run and the NOP run. The red lines represent the difference between the baseline run and the Mixed run. Note that the y-axis is the same as in the graphs presented in figure 5.5a.

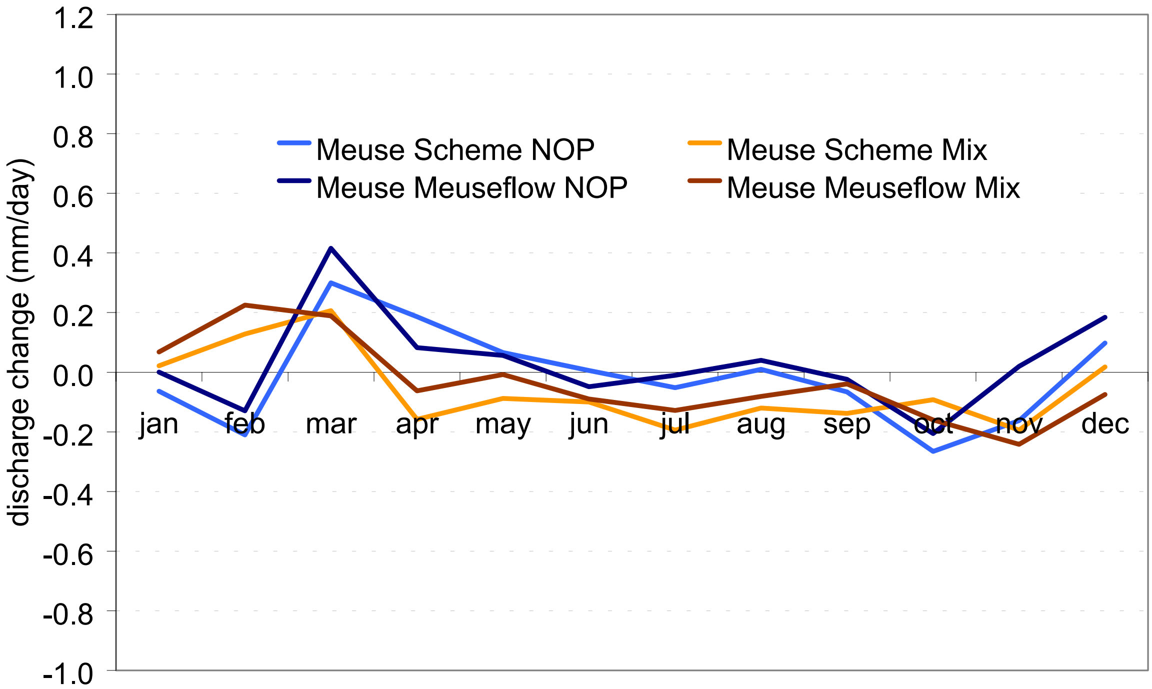
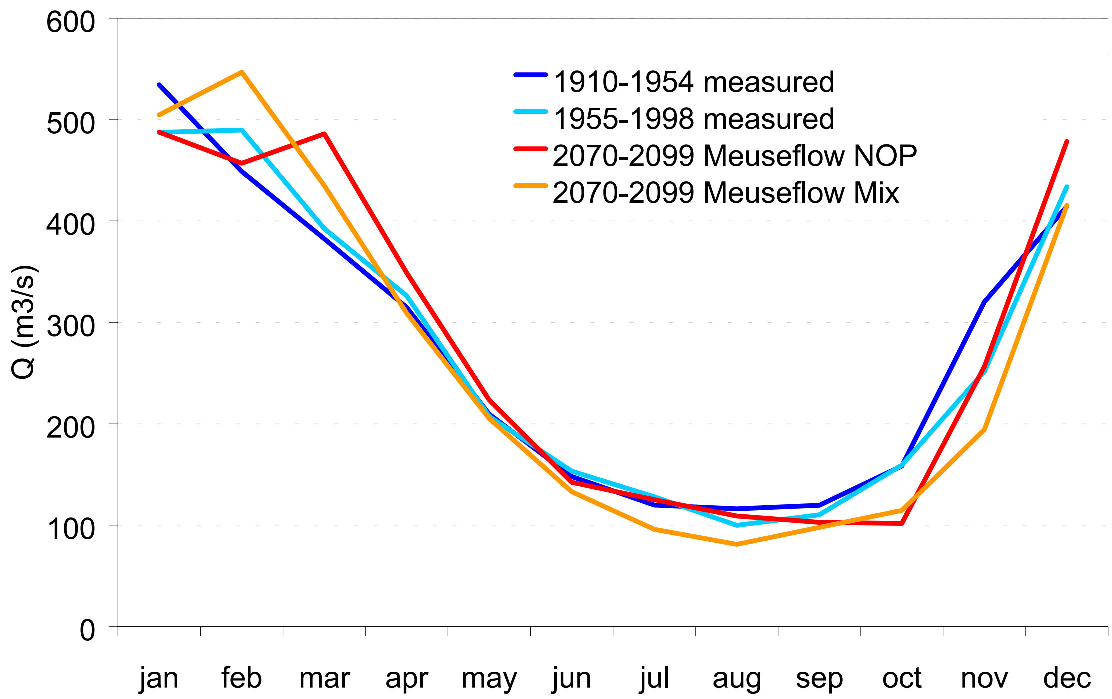


Figure 5.6 Observed and simulated changes in the average discharge regime of the Meuse at Monsin



5.3 Simulation of other changes

What will be the effect of other future changes on the discharge regime of the Meuse?

Changes in urbanisation, forestry, drainage of agricultural soils, irrigation and flow regulation have, to a certain extent, influenced the discharge regime of the Meuse over the past and will most probably influence the discharge regime of the Meuse in the future. Human activity frequently leads to an accelerated runoff of precipitation. Urbanisation tends to increase downstream flood peaks and volumes (Massing et al, 1990). Deforestation may intensify river flooding, but the effects are low where initial storage values are low, for example at steep slopes with shallow soils, which produce rapid quick flow whether forested or not (Hewlett, 1982b). Ward and Robinson (2000) argue that the drainage of heavy clay soils generally results in a lowering of large and medium flood peaks, whereas on more permeable soils, the effect of drainage usually tends to increase flood flows. Over the last century there has been an increase in the forested area in the Ardennes region (Dijkman & Pedroli, 1994). Especially in the Dutch and Flemish part of the Meuse basin there has been a substantial growth in the area of drained agricultural land over the last century. Also the urbanised area has increased, especially in the Charleroi-Namur-Liège region (Dijkman & Pedroli, 1994). The canalisation of the river Meuse dates back to the 17th century and has been expanded in the 20th century (Berger, 1992). In general the canalisation has resulted in an accelerated discharge during periods of peak flows and a delayed discharge, due to the operation of weirs and locks, during periods of low flows.

A quantification of the combined effect of all these changes in the Meuse basin is beyond the scope of this study. The models described in section 5.2 are here used to simulate the impact of a few of the changes described above on the average discharge regime of three small sub-catchments of the Meuse basin. Nature development, drainage, and irrigation simulation experiments are applied to the Beerze catchment with the SIMGRO model. A simulation of land cover changes (afforestation) is applied to the Ourthe Orientale and Mehaigne catchments, using the SCHEME model. The land use scenarios used here may not be realistic sensitivity analyses. Moreover, they do not cover the complete range of possible changes that may occur in the 21th century. They are meant to trigger the discussion on how (autonomous or forced) human impacts in the Meuse basin, may affect the discharge regime of the river Meuse. All scenarios were run with the climate data from the 1988-1992 baseline run.

The Beerze experiments

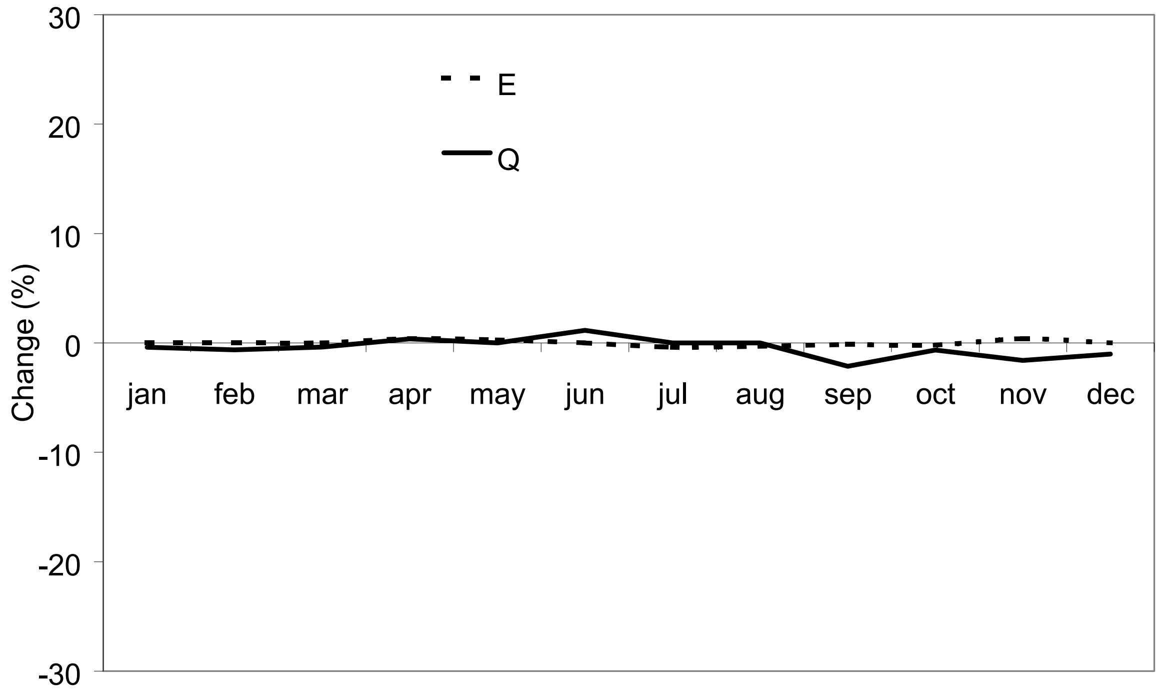
Scenario 'Nature Development'

The sandy deposits of Brabant are intersected by South-North orientated valleys. Human impacts have strongly influenced the characteristics of these -originally wet- valleys. Due to their potential for nature development there are plans to restore the hydrology and vegetation of these valleys. These plans fit in the construction of a nationwide network of connected ecological zones in the Netherlands, the so-called National Ecological Network (EHS) (Ministry of Agriculture, Nature and Fisheries, 2000). This development may also have an impact on the discharge regime of the Beerze. The SIMGRO model was used to simulate the implementation of the EHS (Van Walsum et al., 2001). The EHS is simulated by removing the field drains and ditches, the sprinkling, and by changing agricultural land into natural grasslands. Since the EHS is mainly situated along the main streams, these measures cause a rising of watertables in the stream valleys. The streams remain untouched in the simulated scenario.

The SIMGRO simulation suggests that the implementation of the EHS has hardly any effect on the average evapotranspiration and discharge in the Beerze catchment as a whole (figure 5.7). This is mainly due to the fact that the implementation of the EHS will only affect a small percentage of the total area of the Beerze catchment. The change in the morphology of the streams has not been simulated and this explains why the implementation of the EHS hardly affects the peak discharges.

Figure 5.7 Impact of the implementation of 'Nature Development' (EHS) on the actual evapotranspiration (E) and discharges (Q) in the Beerze catchment

Change represents the relative difference (%) between the baseline run and the scenario run
Note that the scale of y-axis is the same as the scale of the y-axis in figures 5.8, 5.9 and 5.10

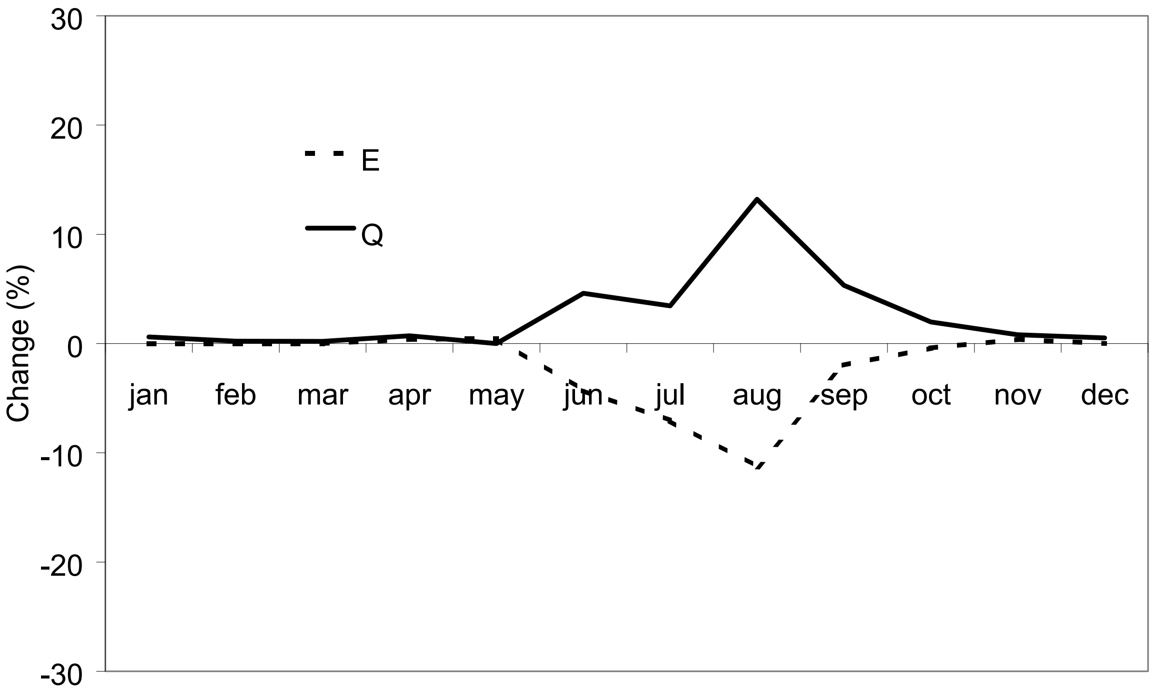


Scenario 'No more irrigation and drainage of agricultural land'

The agricultural land in the Beerze catchment is mainly used for grazing and the growth of fodder crops (especially maize). The sandy texture of the soils in the region explains the need for irrigation during summer, whereas the lack of relief explains the need for agricultural drainage during winter. Irrigation leads to an increase of the actual evapotranspiration. Moreover, it reduces the discharge, since the water used for irrigation is taken from groundwater within the catchment. At present (baseline run) SIMGRO simulates a sprinkling rate of 0.67 mm day^{-1}. This rate has been calibrated on the basis of the sprinkling amounts for the region as a whole (Van Walsum *et al.* 2001). SIMGRO was used to simulate how a stop on irrigation may affect the evapotranspiration and discharge regime of the Beerze. This was done by simply turning off the sprinkling. Figure 5.8 shows that this measure may result in a substantial increase (5 to 10%) in the average summer discharge.

Figure 5.8 Impact of a stop on irrigation on the actual evapotranspiration (E) and discharges (Q) in the Beerze catchment.

Change represents the relative difference (%) between the baseline run and the scenario run
Note that the scale of y-axis is the same as the scale of the y-axis in figures 5.7, 5.9 and 5.10

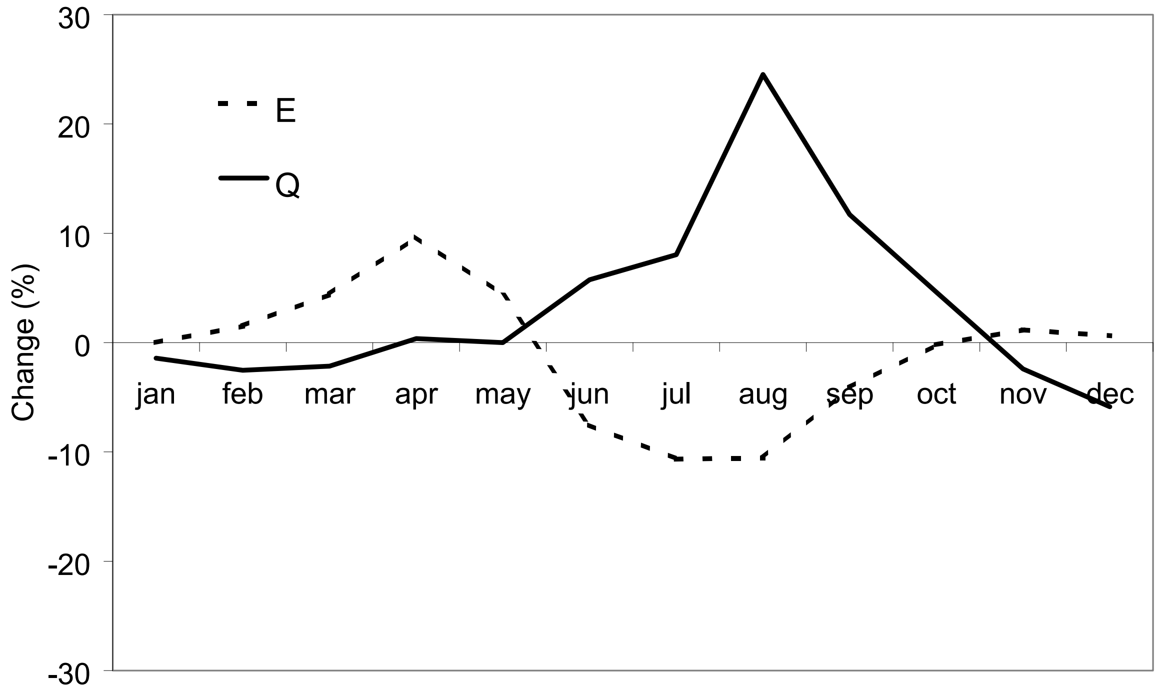


As a next step also the impact of agricultural drainage was simulated with SIMGRO. At present about 5% of the agricultural land in the Beerze catchment is drained by field drains. Besides, most agricultural land is drained by ditches with an average distance of 180 meter. In the 'no drainage' scenario all field drains and field ditches have been removed from the model.

The effect of drainage on the hydrology is twofold; on the one hand drainage may lead to an accelerated runoff of precipitation, which may result in an increase in the discharge. On the other hand drainage may lower the groundwater level, which increases the storage capacity of the soil and reduces groundwater outflow. Both aspects are reflected by the SIMGRO simulation. In the Beerze catchment the removing of drains leads to a decrease in winter discharge (less accelerated runoff), and an increase in summer discharge (increase in groundwater flow). Figure 5.9 shows the difference in the monthly average evapotranspiration and discharge values in the Beerze catchment when agricultural soils in the Beerze catchment are no longer irrigated or drained. The model simulation suggests that these changes might lead to an increase in average summer discharge and a decrease in average winter discharge. For the analysis of the impact of above mentioned land use changes on peak discharges in dutch lowland streams the reader is referred to Van Walsum et al. (2001) and van Bakel et al. (2001).

Figure. 5.9 Impact of a stop on irrigation and drainage on the actual evapotranspiration (E) and discharges (Q) in the Beerze catchment.

Change represents the relative difference (%) between the baseline run and the scenario run
Note that the scale of y-axis is the same as the scale of the y-axis in figures 5.7, 5.8 and 5.10



The Ourthe and Mehaigne experiments

Scenario 'Afforestation'

Forest is the natural vegetation in large parts of the Meuse basin. At present about 35% of the Meuse basin is forested. There is a general perception that the afforestation of (parts of) the Meuse basin will temper the flow regime of the river Meuse. At present about 49% of the Ourthe Orientale and 7% of the Mehaigne catchments are forested. The SCHEME model uses vegetation type specific factors to calculate evapotranspiration in these catchments. Therefore the model can be used to simulate the effects of afforestation on the evapotranspiration and discharge (Bultot et al, 1989).

Figure 5.10 shows the simulated effect on the evapotranspiration and discharge if the catchments of the Ourthe Orientale and the Mehaigne would be completely covered with decidious forest. On an annual basis the evapotranspiration from forests is larger than the evapotranspiration from agricultural crops. From May to July when most agricultural crops are growing, this difference is smaller. This explains the difference between the simulated evapotranspiration for the baseline run and the afforestation run. The differences are larger for the Mehaigne catchment than for the Ourthe Orientale catchment, since at present (the baseline run) the Mehaigne has less forested area than the Ourthe Orientale. Not suprisingly the increase in evapotranspiration results in a decrease of the discharge. This analysis suggests that afforestation might reduce the risk of flood flows, but increases the risk of low flows (figure 5.10c).

Figure 5.10a Impact of complete aforrestation (decidious forest) on the actual evapotranspiration (E) and discharges (Q) in the Ourthe Orientale catchment.

Change represents the relative difference (%) between the baseline run and the scenario run
Note that the scale of y-axis is the same as the scale of the y-axis in figures 5.7, 5.8 and 5.9

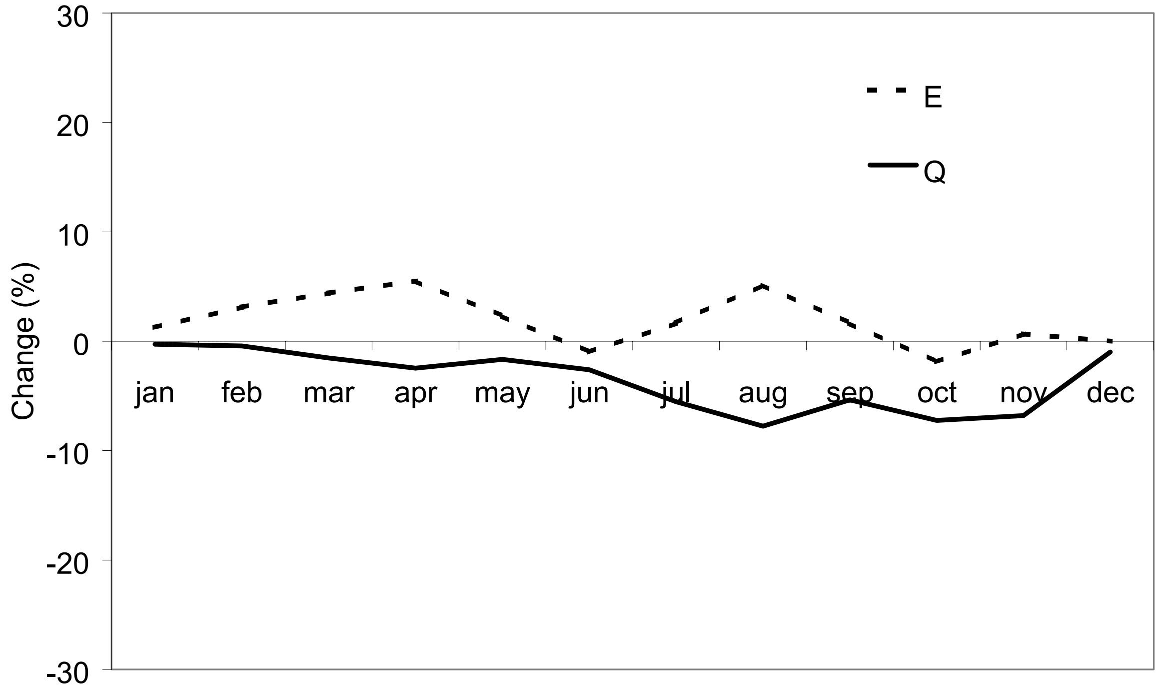


Figure 5.10b Impact of a complete aforrestation (decidious forest) on the actual evapotranspiration (E) and discharges (Q) in the Mehaigne catchment.

Note that the scale of y-axis is the same as the scale of the y-axis in figures 5.7, 5.8 and 5.9
Change represents the relative difference (%) between the baseline run and the scenario run

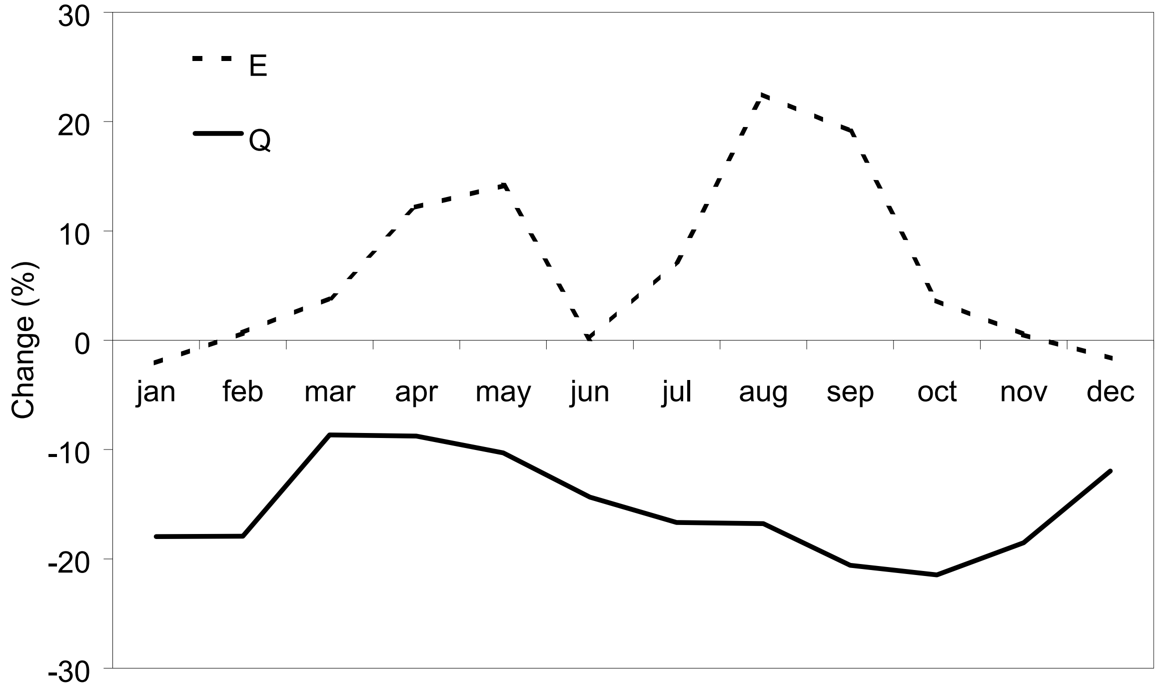
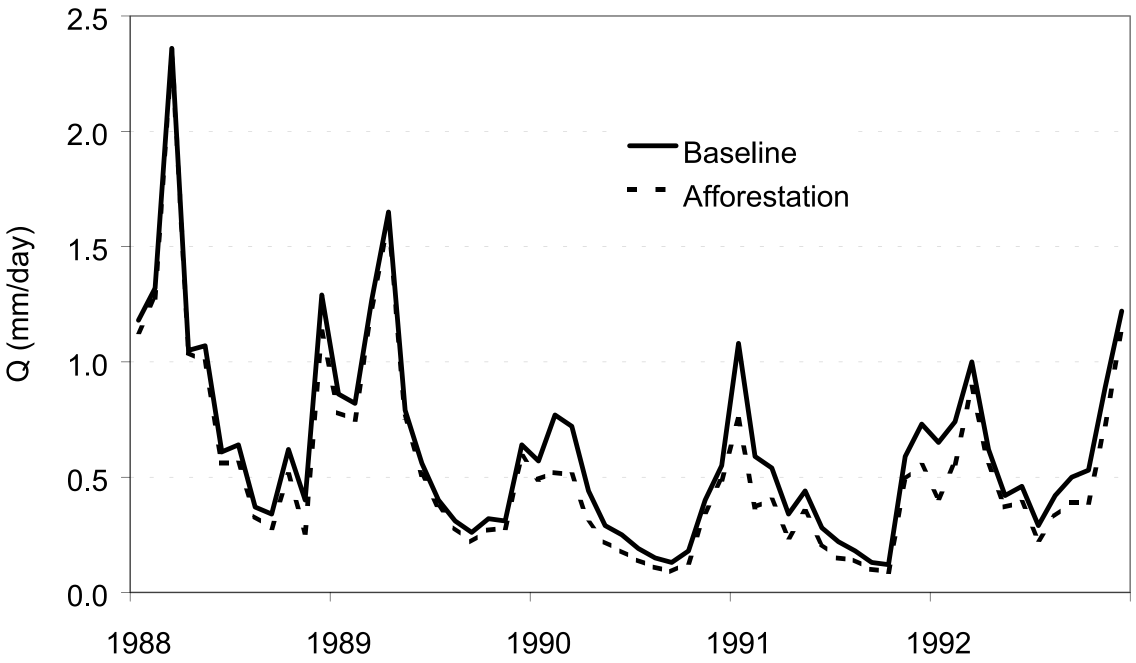


Figure 5.10c Impact of complete aforrestation (decidious forest) on the monthly average discharges (Q) in the Mehaigne catchment.

Note that the scale of y-axis is the same as the scale of the y-axis in figures 5.7, 5.8 and 5.9
Change represents the relative difference (%) between the baseline run and the scenario run



The scenarios presented above illustrate that changes other than climate change may be as important as climate change, when analysing the future discharge regimes in the river Meuse network. This raises the question whether land use changes, changes in water management, and flow regulation can reduce peak flows and the risk of long periods of low flows in the Meuse? To answer this question, more detailed research is needed. The issue of measures to combat flooding and low flow problems in the Meuse were also discussed at the workshop. A summary of this discussion is presented in chapter 6.

5.4 Simulation of water quality

Will climate change affect the water quality of the Meuse?

A large volume of wastewater from industry and households is discharged into the river network of the Meuse. These so called point source emissions are not related to meteorological events. This means that the emission loads from point sources are the same during low flows and during peak flows, which implies that the concentrations of pollutants emitted from point sources are largest during periods of low flows. Low flows also lead to a reduction in flow velocity and in water turbulence. Moreover, low flows in the Meuse generally correspond with warm periods. All these conditions have a negative effect on water quality. A change in climate towards summers with lower discharges and higher temperatures may therefore hamper the use of the Meuse for the production of drinking water. Not only climate changes, also changes in flow regulation and changes in wastewater emissions will affect the water quality of the Meuse in the coming century. Here we will simulate the impact of different future scenarios on some aspects of the water quality in the Meuse. More specifically we apply scenarios for changes in climate, weir management, and nutrient emissions to simulate possible changes in the average chlorophyll concentrations, average nutrient (nitrogen and phosphorus) concentrations, and average oxygen concentrations in the Belgian part of the river Meuse by the end of the 21^{th} century.

The chlorophyll concentration can be used as an indicator for the total algae biomass. Algae hamper the production of drinking water, since they may produce toxins, affect the taste and odour of the water, and block filter systems. The growth of algae depends on many physical, chemical and biological conditions in the aquatic system. The most limiting factor for algae growth determines their growth rate. Human activities such as agricultural fertilisation and discharge of wastewater have increased the nitrogen and phosphorus levels in many European rivers to such levels that these nutrients are no longer limiting for the growth of algae (Stanners & Bourdeau, 1995). Also the regulation of rivers to fulfil navigational requirements and the construction of reservoirs have accelerated the growth of algae in river systems. On the other hand, the discharge of toxic substances is a human impact that may limit the growth of algae (Ietswaart & van Dijk, 1996).

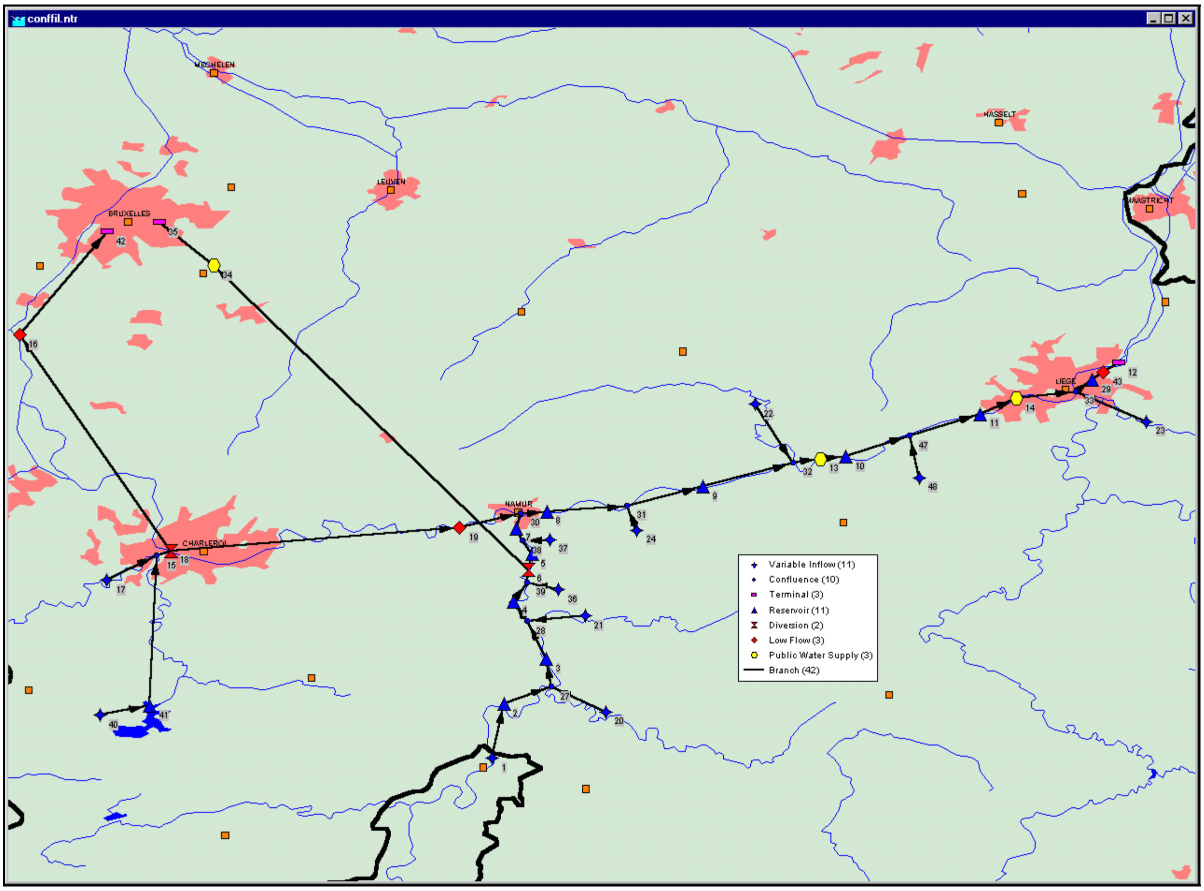
Observed temporal and spatial patterns

Baggelaar and Baggelaar (1995) performed a trend analysis on a large number of water quality parameters in the Meuse for the period between the 1970s and the 1990s. They found an increase over time for the chlorophyll concentrations between Namur and Liège. For the stations downstream of Liège they didn't find a significant trend over time in the chlorophyll concentrations. The highest chlorophyll concentrations are measured in the Belgian part of the river Meuse, especially around Namur (RIWA, various years). Baggelaar and Baggelaar (1995) did not find a trend over time in the N and P concentrations in the Meuse between the early 1970s and the early 1990s. N and (especially) P concentrations increase between Namur and the Belgian/Dutch border (RIWA, various years), due to the emission of large volumes of wastewater. Oxygen concentrations drop downstream from Namur (RIWA, various years). No pronounced trend over time has been observed for the oxygen concentration in the Meuse between the 1970s and the 1990s (Baggelaar and Baggelaar (1995).

Simulation of water volume and water quality in the Belgian part of the river Meuse

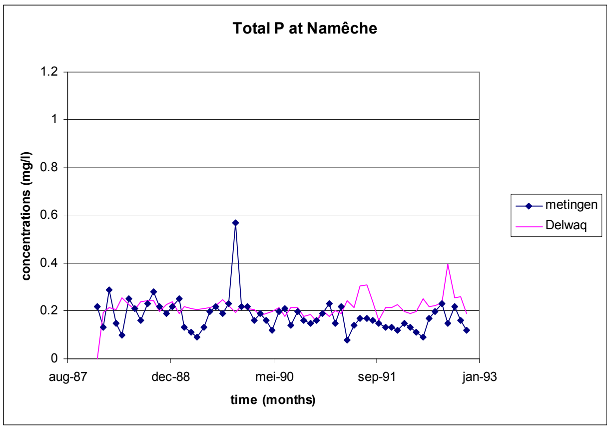
A water balance model called RIBASIM (river basin simulation) was used to schematize the river network in the Belgian part of the river Meuse. RIBASIM is a generic, fully graphically-oriented, model package for simulating the time-varying characteristics of river basins under varying hydrological conditions (http://www.wldelft.nl/soft/ribasim/index.html). RIBASIM permits the evaluation of a variety of measures related to infrastructure, operations and demand management. RIBASIM is built up of nodes and links between nodes. The nodes represent confluences, water extractions etc., whereas the links represent the river segments between two nodes. In all 43 nodes were used to schematize the river Meuse between the French/Belgian border and the Dutch/Belgian border. Seven different types of nodes were used; reservoir nodes, public water supply nodes, inflow nodes, low flow nodes, diversion nodes, terminal nodes, and confluence nodes (see figure 5.11). A timestep of 10 days was used to run RIBASIM. For a detailed description of the operation of the RIBASIM model in the Belgian part of the Meuse, the reader is referred to WL (Ververs et al., in prep). The output of MEUSEFLOW (see chapter 5.2) is used as input to the RIBASIM model. This allows for a simulation of the water volumes for the period 1988-1992, and the two climate change scenarios.

Figure 5.11 The schematization of the Meuse in RIBASIM



RIBASIM was linked to the generic water quality model DELWAQ. DELWAQ simulates the water quality in a water body of a given geometry and volume, taking into account flow characteristics, pollution loads and meteorological conditions. It can be applied to different types of water quality problems, such as microbiological pollution, dissolved oxygen problems, eutrophication and toxic substances. For a detailed description of the operation of the DELWAQ model in the Belgian part of the Meuse, the reader is refered to (Ververs et al., in prep). A baseline run for the period 1988-1992 has been used to tune the RIBASIM/DELWAQ model. Only a limited number of the parameters was adjusted. Figure 5.12 shows the observed and simulated chlorophyll-a, N, P, and O concentrations for 1988-1992. The spatial (Namèche versus Eijsden) and temporal (1988 to 1992) patterns of the modelled N, P, and O concentrations show a reasonable agreement with the observed concentrations (figure 5.12a,b,c). Chlorophyll-a concentrations appear to be more difficult to simulate (figure 5.12d). The limited amount of time and data available for this study did not allow for an additional validation of the model.

Figure 5.12a Simulated and observed phosphorus (P) concentrations (1988-1992) in the Meuse at Nameche and Eijsden



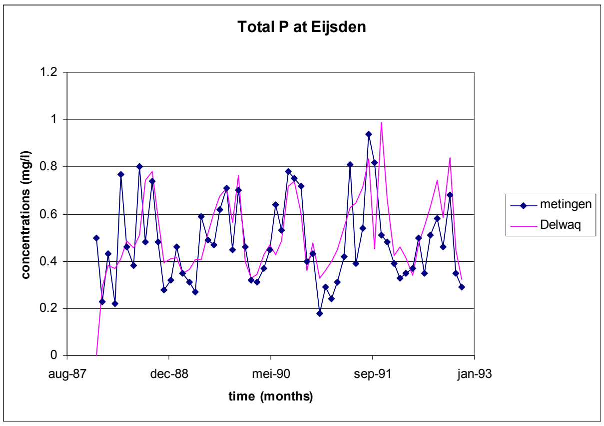
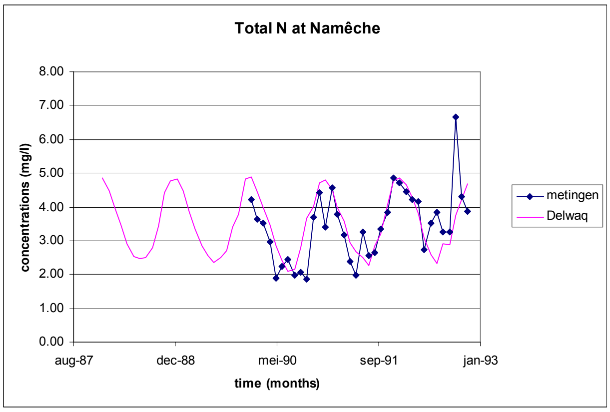


Figure 5.12b Simulated and observed nitrogen (N) concentrations (1988-1992) in the Meuse at Nameche and Eijsden



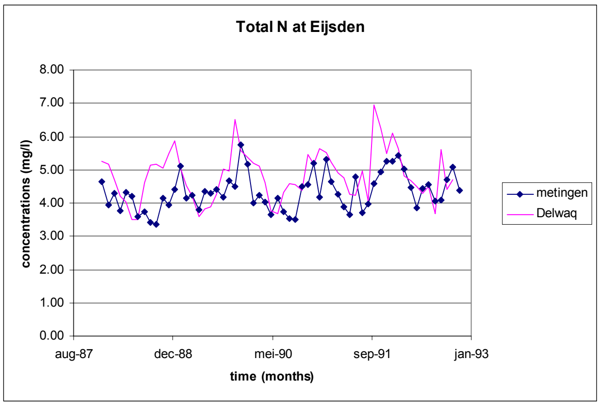
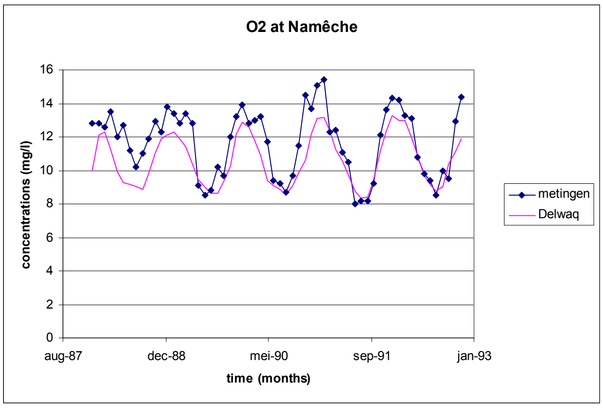


Figure 5.12c Simulated and observed oxygen (O) concentrations (1988-1992) in the Meuse at Nameche and Eijsden



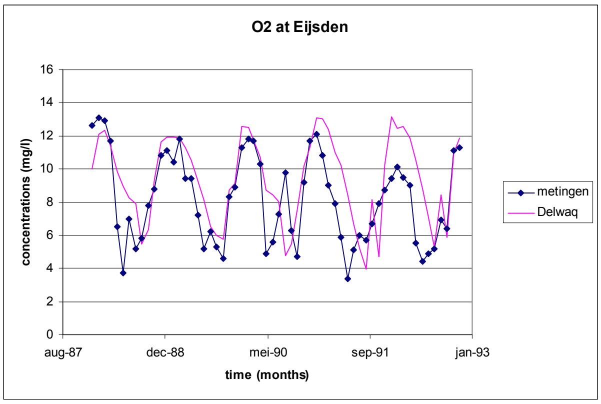
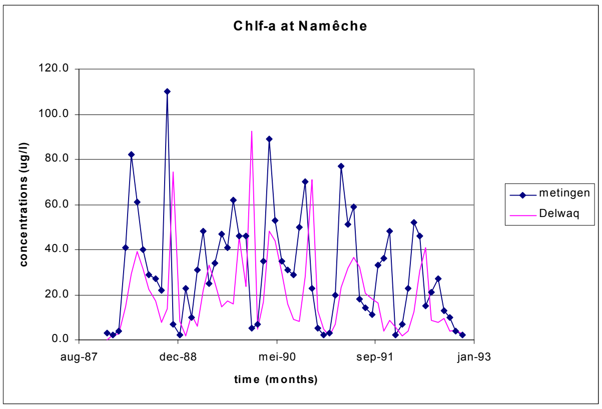
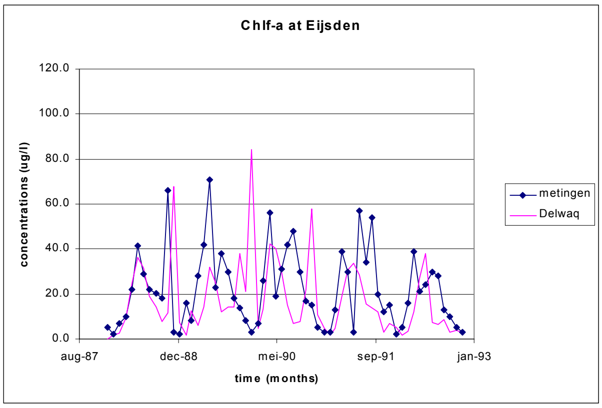


Figure 5.12d Simulated and observed chlorophyll-a concentrations (1988-1992) in the Meuse at Nameche and Eijsden





Scenario analysis

The RIBASIM/DELWAQ model was used to simulate chlorophyll, nutrient, and oxygen concentrations for five different runs:

Climate scenarios
1 NOP climate change series
2 Mixed climate change series
Flow regulation scenarios
3 Weirs opened
4 Weirs closed
Emission scenario
5 Reduced nitrogen (-50%) and phosphorus (-75%) emissions

For the climate scenarios both water inflow (as derived from the Meuseflow scenario runs) and water temperature have been adapted. It was assumed that the water temperature increases with the same rate as the change of the air temperature (see table 5.1). The emission reduction rates applied in the emission scenario are based on emission scenarios for the Rhine and Elbe basins presented in de Wit (1999). The reduction rates used in this scenarios may be realised if 95% of the population are connected to wastewater treatment plants that remove 90% of the nutrient loads from the effluent, and all farmers succeed in limiting the surplus on agricultural soils (fertiliser + manure –yield) to 25 kg N $year^{-1}$ $hectare^{-1}$ and 5 kg P $year^{-1}$ $hectare^{-1}$. A more extended explanation of the N and P emission scenario is given in (Ververs et al. , in prep).

Results

The results of the different runs are presented in table 5.2. The concentration values in table 5.2 are the average over all river segments in the Belgian part of the Meuse. A comparison of the results of the baseline run and the scenario runs suggests that none of the scenarios has a distinct effect on the chlorophyll concentrations and oxygen concentrations. This result suggests that nutrients are not limiting for algal growth even after drastic reductions of the nutrient emissions. Also the (average) changes in discharge and temperature (climate change) are too small to result in a distinct effect on the (average) water quality. The emission reduction scenario leads (self-evidently) to a reduction of N and P concentrations.

Table 5.2 Results of the RIBASIM/DELWAQ simulations

Annual average water fluxes (m3/s)

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Inflows	254.71	262.29	247.04	254.71	254.71	254.71
Outflows	254.49	262.10	246.97	254.54	254.30	254.49

Annual average nitrogen fluxes (kT/year)

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Inflows	40.38	41.55	39.61	40.38	40.38	20.43
Outflows	39.28	40.29	38.30	39.33	38.62	19.81

Annual average phosphorus fluxes (kT/year)

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Inflows	3.32	3.39	3.17	3.32	3.32	0.87
Outflows	3.30	3.38	3.16	3.30	3.30	0.86

Summer average water fluxes (m3/s)

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Inflows	152.36	156.29	136.87	152.36	152.36	152.36
Outflows	150.72	154.68	135.27	153.35	152.88	150.72

Summer average nitrogen fluxes (kT/year)

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Inflows	20.98	21.47	19.41	20.99	20.99	10.69
Outflows	19.78	20.06	17.93	20.10	19.33	10.07

Summer average phosphorus fluxes (kT/year)

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Inflows	2.42	2.45	2.21	2.42	2.42	0.64
Outflows	2.39	2.43	2.19	2.42	2.40	0.63

Annual average concentrations

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
DO (mg/l)	10.44	10.22	10.08	10.43	10.39	10.55
Chlf(ug/l)	21.39	20.45	19.83	22.27	18.80	20.98
TotN(mg/l)	3.51	3.48	3.46	3.56	3.47	1.78
TotP(mg/l)	0.21	0.21	0.21	0.21	0.21	0.06
Vol (Mm3)	4.57	4.57	4.59	4.25	8.02	4.57

Summer average concentrations

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
DO (mg/l)	9.45	9.24	9.10	9.43	9.33	9.56
Chlf(ug/l)	24.43	23.72	23.00	24.13	20.23	23.88
TotN(mg/l)	3.05	3.02	3.00	3.07	2.98	1.56
TotP(mg/l)	0.22	0.22	0.21	0.22	0.21	0.06
Vol (Mm3)	3.62	3.66	3.63	4.36	8.16	3.62

Statistics

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
DO(mg/l) 10% percentile	8.42	8.09	7.87	8.46	8.33	8.70
Chlf(ug/l) 90% percentile	42.11	40.83	40.65	42.24	33.88	41.35

Discussion

The modelling analysis suggests that the predicted changes in climate and nutrient emissions will not have a major impact on the algae growth in the river Meuse. It should, however, be noted that enhanced biological production and other associated effects of eutrophication are generally more apparent in lakes, reservoirs, and coastal areas than in flowing rivers. Reduced summer discharges, the increase in temperature, and reduced nutrient emissions may have a limited effect on the algae growth in the Meuse, but these changes may have a far greater impact on non-flowing water bodies that receive water from the Meuse, such as drinking water reservoirs.

The closure of the weirs (scenario 4) results in a reduction of the flow velocity, a deepening of the water column and sedimentation of suspended material. This leads to an increase in water temperature, less aeration, and increased light penetration. Under the conditions in the baseline run, DELWAQ simulates not only an increased growth of algae, but also an even larger increase in algae mortality. The net effect is that DELWAQ predicts lower chlorophyll concentrations for the run with closed weirs than for the run with open weirs (table 5.2). This result is contradictory to the general opinion that algae growth increases due to the operation of weirs. However, also for the period 1988-1992 the chlorophyll concentrations decrease in downstream direction (between Namur and Dutch/Belgian border), despite the fact that this stretch of the river is completely canalised.

Several studies have shown that longer residence times (e.g. due to a closure of the weirs), may lead to a shift in the algae population from less harmful species (diatoms) towards toxic species (cyanobacteries) (Ietswaart & van Dijk, 1996; Köhler, 1994). Here, only total chlorophyll-a concentrations were simulated, without consideration of the composition of the algae population. Another important aspect of algae growth that has not been taken into account in this study is the influence of toxins on algae growth. Toxins hamper the growth of algae, which might explain the reduction of the chlorophyll concentration between Namur and the Dutch/Belgian border. This implies that a reduction of the emissions of toxic substances may result in increased algae growth.

Finally it should be mentioned that this study is based on estimated annual emissions, and on average monthly hydrological and meteorological data. Some water quality phenomena, e.g.

algae blooms, are governed by events that cannot be described through average annual and average monthly data. This might also explain the small difference between the simulated annual values and the simulated summer values. For chlorophyll-a the model predicts a 10 to 15 % difference between annual average values and summer average values (table 5.2), whereas the observed values show a difference of about 30% (RIWA various years). This suggests that the results of the RIBASIM/DELWAQ model are too much averaged.

Other water quality problems such as accidental spills of toxins, and emissions of heavy metals and pesticides are less influenced by climate change, but are mostly related to the technical and financial means available. For the near future we may expect an improvement of the overall water quality in the Meuse, since technical and financial efforts are being made to reduce pollution in the Meuse basin (ICWS, 1995; Ietswaart & van Dijk, 1996). These efforts have already proved to be effective in the river Rhine (van Dijk & Marteijn, 1993; Van Dijk, 1995).

In the coming years there will be many changes in the Dutch part of the river Meuse (Grensmaas and Zandmaas). The river bed will be widened and deepened. These construction works (De Maaswerken, see also http://www.maaswerken.nl/) aim at a reduction of peak discharges, nature development, and the mining of sand and gravel. These constructions may result in a decrease in the flow velocity during low flows and an increase in the area of non-flowing water bodies. There is a concern that these changes will lead to an increase in the algae population in the river Meuse (RIWA, 2000).

A far more extended review on algae growth in the river Meuse is given in Ietswaart & van Dijk (1996). They conclude that with the current knowledge it is not yet possible to accurately describe the influence of the different conditions on the algae growth and composition in the river Meuse. They recommend that further research should consist of a combination of monitoring, experiments and mathematical modelling.

Conclusion

It is beyond doubt that water quality problems in the Meuse are most severe during extremely dry and warm periods, such as the summer of 1976. Here we have simulated 'average' changes in climate (change series in table 5.1), and the RIBASIM/DELWAQ model used suggests that these 'average' changes do not have a distinct impact on the 'average' water quality in the Meuse. A brief review of the literature suggests that other factors, such as the reduction of emissions and changes in flow regulation, might have more impact on the quality of the water in the river Meuse than climate change.

6 WORKSHOP REPORTAGE

Forty people attended the workshop on low flows in the river Meuse in Wageningen on December 15th, 2000. Aim of the workshop was to get feedback and to exchange experiences with policy makers, stakeholders and other scientists. During the morning session three speakers gave presentations. The first speaker gave an overview of the research activities in the Netherlands with respect to climate change and hydrology. The second presentation dealt with river management and low flows. The third speaker demonstrated how drinking water companies and navigation deal with low flow problems. The abstracts of these presentations are given in the first part of this chapter. In the afternoon two discussion groups were formed. Possible measures to combat low flows in the Meuse were the main topic of discussion. The outcome of the discussion groups is presented in the second part of in this chapter.

6.1 Presentations

Towards integrated assessment of the implications of global change for water management - The Rhine experience

Hans Middelkoop *Utrecht University*

The rivers Rhine and Meuse fulfil important socio-economic and environmental functions for their riparian states and, in particular, for the Netherlands. The water demands of the user functions, such as safety, ecology, inland navigation, hydropower, water availability for agriculture, industry and drinking water are high already under present-day conditions. Climate change is expected to enhance the discrepancies between water supply and demand in the Rhine and Meuse rivers. This issue has been investigated in a sequence of climate-impact studies in the Rhine and Meuse basins.

To assess the impact of climate change on the discharge of the river Rhine, the International Commission for the Hydrology of the Rhine basin (CHR) initiated a research project in 1989 for the development of a water management model for the entire Rhine basin. The climate impacts for sub-catchments in different parts of the Rhine basin were evaluated using detailed models. Using the coarse-scale water balance model, RHINEFLOW the implications for the entire Rhine basin were assessed. In general terms, due to climate change the river Rhine will shift from a combined rainfall-snowmelt regime to a more rainfall dominated regime. This coincides with a seasonal change in the discharge regime: winter discharge will increase, and summer discharge reduces. Extreme discharges (both peaks and low flows) will be amplified.

In a subsequent study, carried out in the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (NOP), the effects of climate change on the Rhine discharge and sediment transport were investigated. In addition a detailed impact assessment regarding the demands and vulnerability of the user functions of the water systems in the Netherlands (rivers, inland lake, terrestrial areas) was carried out. For each of these sub-systems models have been developed to simulate the hydrological changes. Subsequently, tools have been developed to evaluate the consequences for the functions considered in each sub-system (i.e. safety, nature, navigation, agriculture, industry, and drinking water production). The study demonstrated to what extent the user functions of the Rhine and water systems in the Netherlands may be affected by climate change. Extreme flows on the Rhine will occur more frequently, which increases the demand for an adequate discharge capacity of the high-water bed. Using a DSS, the resilience of the river system and the other functions within the high-water channel have been evaluated for different landscape planning alternatives. Inland navigation may be hampered by more frequent low flows; however, the inland navigation sector seems highly resilient and adaptive to changing environmental (and economic) boundary conditions. Current lake levels in the IJsselmeer cannot be maintained if the sea level rises. This reduces the capacity for the surrounding polders to release excess water into the lake. Agriculture will suffer more damage due to both droughts and periods of excess water.

The impact evaluations are surrounded by major uncertainties concerning socio-economic and agro-economic developments, resulting in changes in the conditions of the water systems and changes in water demand, as well as climate change and the inherent hydrologic response that affect water availability. In an ongoing project we will establish a set of integrated scenarios for the Rhine and Meuse basins, representing different world-views, based on the so-called Perspectives method. Using these scenarios we attempt to define strategies for future water management that are robust under uncertainty.

River management and low flows in the river Meuse

A. Jaskula-Joustra *Rijkswaterstaat Directie Limburg*

The Meuse has different functions, for example for nature, shipping, drinking water supply, industry, agriculture, etc. In summer and autumn there is often not enough water to fulfil the demand for water by these functions. Due to economic development and climate change we expect this problem to grow in the future. According to the Meuse Treaty in dry periods the Netherlands and Flanders share water equally. To avoid conflicts between different functions priorities are given: during a period of water shortage the water supply is first cut for the functions with a lower priority. Different users take measures to decrease their demand for water, for example by applying alternative solutions (using cooling towers instead of cooling with water), creating a buffer (drinking water companies, industry), using rain water (horticulture,household), storing water in the ground (agriculture). Shipping uses much water for locking through. In order to decrease this quantity Rijkswaterstaat takes different measures: pumping water back at locks, applying saving reservoirs or siphoning lockage and decreasing the frequency of locking. These measures are either expensive or inconvenient for shipping or bad for the environment. A very durable measure seams to stimulate the infiltration in the catchment area of the Meuse, so that the base flow can increase. The possibility of taking this measure and its effectiveness should be studied.

Flanders Water Supply and low flows on the river Meuse.
A new challenge for the near future due to Global Climate Change

H. Crommelinck *Antwerpse Waterwerken*
C. Danckaerts *Dienst voor de Scheepvaart (België)*

A brief analysis of the hydrological basin of the river Meuse in Belgium makes us aware of its importance for the feeding of the Albertcanal and the Campine Channel Network in Flanders. The historical treaty between Flanders and the Netherlands deals with the water transport by the river Meuse and the raw water distribution to the member states. It emphasises the possible use of the raw water by the partners, especially in case of low flows on the main river Meuse. The drinking water supply of the Antwerp region, including the Port of Antwerp, and an important part of Flanders, is carried out by AWW, the Antwerp Water Works. The only raw water source for AWW however, is the Albertcanal. The intake of the raw water from the Albertcanal at low flows on the river Meuse is not only linked to the total quantity of the flow, it is also a qualitative problem. This is illustrated by the evolution of the measured salt-parameters. Measures have been taken at low flow, due to the imposed economy on water use in Flanders. Research has been done in finding solutions in order to assure the continuity of the drinking water supply for the future. The storage of raw water in large open safety-reservoirs and the infiltration of filtered raw water in available soils, seem to be the only alternatives. These scenarios are illustrated. Finally a long term vision is the only strategy to meet the predicted Global Change, and in particular, to counter the effects of a possible climate change on drinking water supplies.

6.2 Workshop discussion

group 1

A scenario.....

It is September 2002, the driest summer since 1920. There is hardly any water left in the Meuse and navigation is no longer possible. The drinking water supply of 6 million people is threatened. Dead fish are floating in the river. Agricultural crops are withering. Dry weather is forecasted for the coming week. The situation has created a media-hype. You are involved in water management and you are being interviewed. You are asked the following questions:

Is this the result of climate change?

> You cannot tell! Some participants argued that it doesn't matter, whether it is climate change or not, because extremes will also occur without climate change. Others argued that this is an important question, because it determines which water management strategy we should choose. By the time we are sure that it is the result of climate change it will be too late to act, because the implementation of measures takes time.

Is this the result of human impacts on the hydrology of the Meuse basin?

> We all agreed that the hydrology of the Meuse is strongly influenced by human impacts. During a low flow situation the operation of weirs, locks, and pumps results in increased water levels and a slowed down runoff of freshwater to the sea. We also discussed to what extent the accelerated drainage of urban and agricultural land influences the filling of the groundwater reservoir and as a result the baseflow during low flows. Some were convinced that the accelerated drainage has resulted in lower baseflows, others argued that extreme low flows are simply the result of a long lasting lack of precipitation.

A similar situation also occurred in 1976. What structural measures have you taken to prevent water stress?

> Only 'end of the pipe' measures have been taken. Drinking water companies and industries have enlarged their buffer capacity and the operation of weirs, pumps, and locks has been improved. Two new reservoirs have been built after 1976 in the Ardennes, but they were already planned in the 1960s. No structural measures have

been taken to increase the baseflow in the river network. So far measures to reduce water stress have been taken independently by the different stakeholders (navigation, agriculture, drinking water). In the future more integrated solutions should be developed.

Should we build new reservoirs in the river Meuse basin, or what other measures could we take in the near future?

The construction of new reservoirs in the Ardennes would be an efficient tool to assure a minimum discharge for all functions during dry periods. This is, however, a very drastic measure for which there is limited public support. The discussion about the construction of new reservoirs should be renewed. We might also think about many small reservoirs instead of a few large reservoirs. Also the infiltration of water in (man-made) caves (e.g. Sint Pietersberg) was mentioned as a possible measure. One can also think about waterways to conduct water during dry periods from the river Rhine network to the river Meuse network. Also a further improvement of the water quality in the Meuse (Scheldt and Rhine) will help to solve problems during low flows.

Should we no longer depend on the Meuse for our drinking water supply, and look for alternatives?

Yes, especially for the long term we should consider these alternatives.

Do you think this is a realistic scenario?

We all agreed that the above mentioned scenario may occur in the near future *group 2*

Extreme low flows and water stress occur along the river Meuse even 'without' climate change (e.g. 1976). The floods in the early 1990s have turned the attention to measures that aim to reduce the risk of flooding along the river Meuse. In this group it was discussed whether we should also pay more attention to measures that aim to combat long periods of low flow in the Meuse. Moreover, it was discussed how measures to prevent floods may affect low flow conditions in the Meuse. Three statements were formulated to trigger the discussion:

The economic damage that results from low flows is even larger than the economic damage that results from flooding. This implies that the problem of low flows should get a more prominent place in the water management of the Meuse basin

Climate change or not, everyone agreed that low flows deserve more attention.

Low flows lead to large economic damage, but it is hard to compare this damage with the damage that results from flooding. Moreover, there is more than just economical damage. The 'psychological' impact of floods is much greater than the 'psychological' impact of low flows. The technical measures to sustain navigation during low flows cost a lot of energy and money. The economic damage of low flows on the drinking water production is less easy to quantify. Current policies stimulate the use of shipping for transport and the use of surface water for the production of drinking water. This implies that the risk for economic damage resulting from low flows may increase. These risks need to be quantified.

Measures for the reduction of floods have not been evaluated for their impact on low flows. Some of these flood reduction measures might even enlarge low flow problems

&

Water retention is the key to success. It will both reduce the risk of flooding and the risk of low flows

These two statements have been discussed jointly.

Both groundwater reservoirs and surface water reservoirs have been addressed. From the discussion it became clear that the use of reservoirs for both flood reduction and the prevention of low flows is not easy. Reservoirs should be filled at the end of the winter in order to be efficiently used during the summer. This implies that at the end of the winter there is less capacity to store water, which might even increase the risk of flooding. These conflicting goals may hamper the management of such reservoirs.

Also the question was raised whether we should take measures to prevent low flows or whether we should adapt to low flow situations. It was concluded that well-considered preventive measures are needed to combat urgent problems, but we should also 'learn to live' with accidental periods of low flows.

Moreover, it was stressed that low flow problems should be dealt with from a European perspective, especially in relation to developments in neighbouring river basins.

Both groups stressed that low flows in the Meuse have occurred in the past and will occur in the future. Integrated measures and strategies to deal with low flows should urgently be developed in close co-operation between all parties involved.

7 CONCLUSIONS AND RECOMMENDATIONS

Simulations performed with a number of different Global Circulation Models (GCMs) suggest an increase in temperature, an increase in winter precipitation and a decrease in summer precipitation in the Meuse basin by the end of the 21th century.

The modelling exercise suggests that climate change may result in a decrease of *average* discharge during the low flow season (especially during autumn) due to an increase of temperature and a decrease of the average summer precipitation volume. However, the statistical analysis shows that the occurrence of *extreme* low flow periods in the Meuse (such as 1976) also depends on the winter precipitation volume, which is (on average) expected to increase due to climate change.

The comparison of simulation runs performed with different climate change scenarios and different rainfall-runoff models suggests that the difference in the predicted change in average monthly discharge regime that results from using different rainfall-runoff models is smaller than the difference in the predicted change in average monthly discharge regime that results from using different climate change scenarios.

The possible change of crop factors due to the increase in atmospheric CO_2 concentration, may have a major impact on the evapotranspiration and discharge regime. This strikes the need for a better understanding of this aspect of climate change.

The conclusions given above refer to average patterns. The impact of global warming on the occurrence of extreme regional meteorological conditions, and as a result extreme hydrological conditions, is not (yet) known. This implies that there remains a reason to be continuously concerned about the possible effects of climate change on the occurrence of long periods of low flows and floods in the Meuse. Further research on the effects of climate change on the hydrology of the Meuse, requires a better understanding of the possible effects of global warming on regional extreme meteorological conditions.

During the period between 1910 and 2000 there were nine years when the discharge rate of the Meuse was below a critical level for more than 100 days. The latest of these long lasting low flow periods was in 1976. The use of the Meuse for (drinking) water supply and shipping has considerably increased over the last 25 years. This implies that even 'without' climate change there is a reason to be concerned about the occurrence of long periods of low flows in the Meuse.

Catchments that are especially sensitive to both low flows and floods are located in the regions that consist of rocks from the Lias formation (southernmost part of the French Meuse basin, and eastern upper part of the Chiers and Semois), and in the Ardennes Massif (the upper Ourthe, Lesse, Vesdre and Amblève). Less sensitive catchments are located in the Carboniferous limestones of the Condroz region and the Mesozoic limestones in the French part of the Meuse basin and the region north of the Ardennes.

The case studies performed in this study show that autonomous or forced land use changes, flow regulation and water management may substantially change the discharge regime of the Meuse in the coming century. A quantification of the impact of these changes on the discharge regime of the Meuse requires further research.

The model simulation and the brief review of the literature suggest that other factors, such as the reduction of emissions and changes in flow regulation, will have more impact on the quality of the water in the river Meuse than climate change.

During the workshop it was concluded that integrated measures and strategies to deal with low flows in the Meuse should urgently be developed in close co-operation between all parties involved.

REFERENCES

Baggelaar, P. K. & Baggelaar, D. H. (1995). Trends in de oppervlaktewaterkwaliteit van Rijn en Maas. RIWA, Amsterdam

Bakel, van P., Hoogendoorn, J., Luijendijk, J. & Peerboom, J. (2001). Hoogwaterreductie vanuit regionale stroomgebieden: samenhang of tegenstellingen. H_20 3, p. 27-29.

Berger, H.E.J. (1992). Flow forecasting for the river Meuse. PhD Thesis. Delft University, Faculty of Civil Engineering. Delft, The Netherlands.

Brandsma, T. (1995). Hydrological Impact of Climate Change. A sensitivity study for the Netherlands. PhD Thesis. Delft University, Faculty of Civil Engineering. Delft, The Netherlands.

BRGM (1996). Carte Géologique de la France au millionième. Editions BRGM. Service Géologique National. France.

Bultot, F. and G.L. Dupriez (1976). Conceptual hydrological model for an average-sized catchment area. Journal of Hydrology, 29, 251-292.

Bultot, F., A. Coppens and G.L. Dupriez (1983). Estimation de l'évapotranspiration potentielle en Belgique (Procédure révisée). Inst. Roy. Mét. Pub., Série A, n° 112, Uccle-Bruxelles, 28 pp.

Dai, A., Fung, I., Del Genio, A. (1997). Surface observed global land precipitation variations during 1900-88. Journal of Climate 10, p. 2943-2962.

DDC. (2000). The Data Distribution Centre (DCC) of the Intergovernmental Panel on Climate Change (IPCC). http//www.ipcc.ch/

Démaree, G., Derasse, S. & Gellens, D. (1994). Hoogwaterstanden en wateroverlast van de Belgische Maas te Visé. Deelrapport in opdracht van het WL voor de Tweede Commissie Boertien. Koninklijk Meteorologisch Instituut (RMI). Brussel, België.

De Roeck, M. & Tilmont, J. (1963). Algemene Atlas. Wesmael-Charlier, Namen, België.

Deursen, W.P.A., van (1998). Vulnerability water supply of the Netherlands through the river Meuse. NOP report 410200010. Dutch National Research Programme on Global Air Pollution and Climate Change. De Bilt, The Netherlands

Deursen, W.P.A., van 2000. MEUSEFLOW 2.1, Laagwaterstudies Maasstroomgebied, RIZA project RI-2988A. RIZA, Arnhem.

Dijk, van. G.M., Marteijn, E.C. & Schulte-Wülwer-Leidig, A. (1995). Ecological rehabilitation of the river Rhine: plans, progress and perspectives. Regulated Rivers 11, pp. 377-388.

Dijkman, J.P.M. & Pedroli, G.B.M. (1994). Onderzoek Watersnood Maas. Hoofdrapport De Maas Meester. WL, Delft.

Gellens, D. & Roulin, E. (1998). Streamflow response of Belgian catchments to IPCC climate change scenarios. Journal of Hydrology 210, p. 242-258.

Grabs, W., Daamen, K., Gellens, D., Kwadijk, J., Lang, H., Middelkoop, H., Parmet, B., Stadler, B., Schulla, J. & Wilke, K. (1997). Impact of climate change on hydrological regimes and water resources management in the Rhine basin. International Commission for the Hydrology of the Rhine Basin. CHR report no. I-16.

Haasnoot, M., Vermulst, J. & Middelkoop, H. (1999). Impact of climate change and land subsidence on the water systems in the Netherlands: Terrestrial Areas. NOP Project 952210. RIZA Report 99.049. RIZA, The Netherlands.

Hewlett, J.D. (1982). Principles of Forest Hydrology. University of Georgia Press. Athens, USA.

Hostetler, S.W. (1994). Hydrologic and atmospheric models: the (continuing) problem of discordant scales. Climate Change 27, p. 345-350.

Ietswaart, Th., & van Dijk, G.M. (1996). Effecten van eutrofiëring en hydrologische omstandigheden op fytoplankton in de Maas. Consequenties voor de drinkwaterbereiding. RIVM report 733008002. De Bilt, The Netherlands

IPCC (1995). IPCC Second Assessment Climate Change 1995. A report of the Intergovernmental Panel on Climate Change (IPCC). http//www.ipcc.ch/

IPCC (2000). IPCC Special report. Emission Scenarios. Summary for Policymakers. A special report of the Intergovernmental Panel on Climate Change (IPCC) working group III. http//www.ipcc.ch/

IPCC (2001). Summary for Policymakers. A report of Working Group I of the Intergovernmental Panel on climate Change. http//www.ipcc.ch/

KINT (1999). Hoogwaterstanden en overstromingen in België. Evaluatie van de tastbare kosten veroorzaakt door de overstromingen van januari 1995. KINT/IRGT rapport nummer 4. Brussel

Können, G.P. (editor) (1999). De toestand van het klimaat in Nederland 1999. KNMI. http//www.knmi.nl/voorl/nader/klim/klimaatrapportage.html

Köhler, J. (1994). Origin and succession of phytoplankton in a river-lake system (Spree, Germany). Hydrobiologia 289, p. 73-84.

KU (2000). Wetterzentrale: Klimadaten. Karlsruhe University (KU). http//www.-imk.physik.uni-karlsruhe.de/%7Egmueller/klima/

Kwadijk, J.C.J., 1993. The impact of climate change on the discharge of the river Rhine. PhD-thesis Utrecht. University, department of Physical Geography, The Netherlands. KNAG/NGS publication 171.

Massing, H., Packman, J., Zuidema, F.C. (editors) (1990). Hydrological Processes and Water Management in Urban Areas. IAHS Publication No. 198, p. 175-181.

Middelkoop, H. (editor) 1999. The impact of climate change on the river Rhine and the implications for water management in the Netherlands. NOP Project 952210. RIZA Report 2000.010. RIZA, The Netherlands.

Mimikou, M.A., Baltas, E., Varanou, E. & Pantazis, K. (2000). Regional impacts of climate change on water resources quantity and quality indicators. Journal of Hydrology 234, p. 95-109.

Ministry of Agriculture, Nature and Fisheries (2000). Natur voor mensen, mensen voor natuur. Nota natuur, bos, en landschap. Ministerie van LNV, Den Haag, The Netherlands

Pfister, L., Humbert, J., Hoffmann, L. (2000). Recent trends in rainfall-runoff characteristics in the Alzette river basin, Luxembourg. Climatic Change 45, p. 323-337.

RIWA (various years). Jaarverslag Deel B: De Maas. RIWA, Amsterdam

RIWA (2000). De impact van de hydrologische ingrepen in de Maas. RIWA, Amsterdam.

Roulin, E., A. Cheymol, and D. Gellens, 2000. Impact of climate changes on the water resources in the river Meuse basin. In Proceedings of the International Conference on Integrated Water Resources Management for Sustainable Development, 19-21 December, 2000, New Delhi, India, Mehrota. R., B. Soni and K.K.S. Bhatia Eds., National Institute of Hydrology, Roorkee, India, 1045-1054.

Roulin, E., A. Cheymol, & D. Gellens (2001). Integrated modelling of the hydrological cycle in relation to global climate change. Contribution to the final Report of the project GC/DD/08 in the framework of the « Global change and sustainable development » program of the Belgian Federal Services of Scientific, Technical and Cultural Affairs. Royal Meteorological Institute of Belgium.

Rozema, J., Lambers, H., van de Geijn, S.C., Cambridge, M.L. (editors) (1993). CO_2 and biosphere. Kluwer Academic Publishers. Dordrecht, The Netherlands.

Rijkswaterstaat (1983). Verdeling van Maaswater bij watertekorten. Rijkswaterstaat Directie Limburg, Maastricht.

Salverda, A.P., Klein, J.D. & Schulze, F.H. (1998). Vaststelling ecologisch verantwoorde afvoerfluctuatienorm voor de Grensmaas. Report 31 of the project: Ecological

Rehabilitation of the River Meuse. Witteveen + Bos Consulting engineers. The Netherlands.

Sefton, C.E.M. & Boorman, D.B. (1996). A regional investigation of climate change impacts on UK streamflows. Journal of Hydrology 195, p. 26-44.

Smakhtin, V.U. (2001). Low Flow Hydrology: a review. Journal of Hydrology 240, p. 147-186.

Stanners, D. & Bourdeau, P. (1995). Europe's Environment. The Dobris Assessment. European Environmental Agency (EEA). Copenhagen, Denmark.

Uijlenhoet, R., Warmerdam, P., Torfs, P. & de Wit, M.J.M. (2001). Statistical Analysis of Daily Discharge Data of the River Meuse and its Tributaries (1968 – 1998): Assessment of Drought Sensitivity. Wageningen University. Water Resources department. Report nr. 100. Wageningen, The Netherlands.

Veldhuizen, A.A., A. Poelman, L.C.P.M. Stuyt and E.P. Querner, 1998. Software documentation for SIMGRO V3.0; Regional Water Management Simulator; Wageningen, DLO-Staring Centrum. rapport 104-def.doc. 289 p. 37 Fig.; 49 ref.

Ververs, M. Kwadijk, J., and van Gils, J. (in prep). Effect of climate change on water quality of the river Meuse. Report WL Delft, The Netherlands

Verweij, W. & Viner, D. (2001). Description of the default climate scenario for impact projects in NOP -II. NOP report 410200058. Dutch National Research Programme on Global Air Pollution and Climate Change. De Bilt, The Netherlands

Van Walsum, P.E.V., Verdonschot, P.F.M., and Runhaar, J. (eds.) (2001). Effects of climate and land-use change on lowland stream ecosystems. NOP Report 410 200 067.Dutch National Research Programme on Global Air Pollution and Climate Change. RIVM, Bilthoven, The Netherlands.

Ward, R.C. & Robinson, M. (2000). Principles of Hydrology. McGraw-Hill Publishing Company. London.

WHM (1998). Actieplan Hoogwater Maas. Werkgroep Hoogwater Maas (WHM). Namur, Belgium.

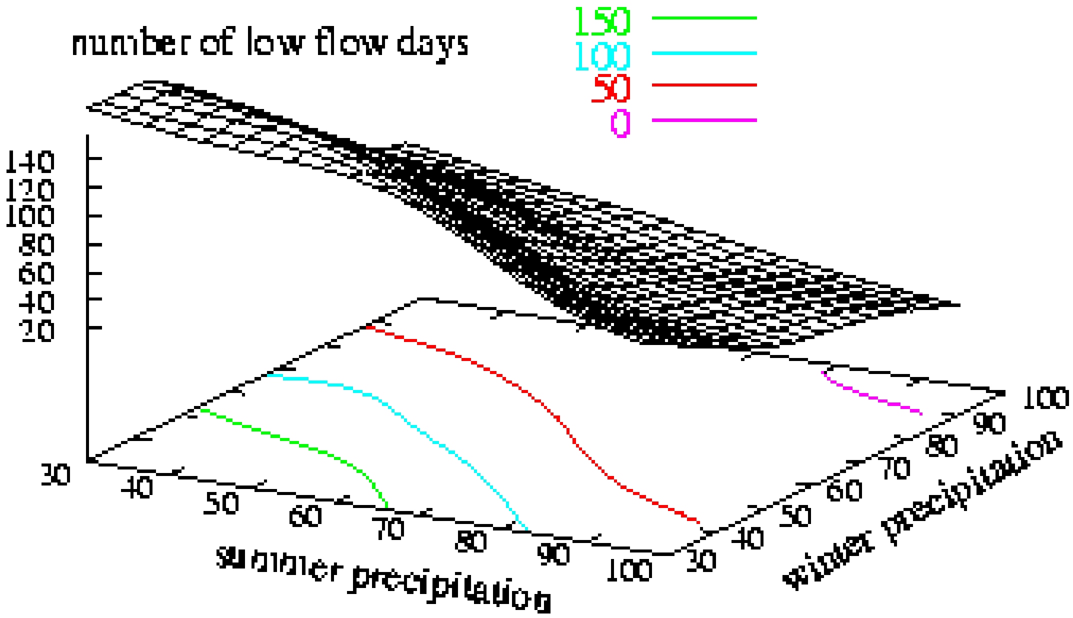
Wilby, R.L. & Wigley, T.M.L. (2000). Precipitation predictors for downscaling: Observed and general circulation model relationships. International Journal of Climatology 20, p. 641-661.

Wit, M.J.M. de (1999). Nutrient fluxes in the Rhine and Elbe basins. PhD-thesis Utrecht. University, department of Physical Geography, The Netherlands. KNAG/NGS publication 259.

WL (1996). Van zorgen om de Maas naar zorgen voor de Maas. Rapport ten behoeve van de 2[de] parlementaire Maasconferentie. WL Delft, The Netherlands.

APPENDIX 1 LOW FLOW FORECASTING

The figure below shows a 3D plot of a function that describes how the number of low flow days relates to the precipitation in the summer and the foregoing winter. This function can be used to estimate (at the end of the winter) probability functions for the duration of the low flow period in the coming summer.



APPENDIX 2A DESCRIPTION OF THE RAINFALL-RUNOFF MODELS: *SIMGRO*

Operated at

ALTERRA

short model description

The model SIMGRO (SIMulation of GROundwater flow and surface water levels) simulates regional groundwater flow in relation to drainage, water supply, sprinkling, subsurface irrigation and water level control. The model simulates the flow of water in the saturated zone, the unsaturated zone and the surface water in an integrated manner. The model is physically-based and therefore suitable to be used in situations with changing hydrological conditions.

To model regional hydrological processes, as in SIMGRO, the modelling domain has to be schematized geographically, both in horizontal as well as in the vertical direction. In horizontal direction the groundwater system is schematised as a network of nodes. The soil water system uses nodal sub-domains (polygons around nodes) for its calculations. The surface water system is schematized as a number of catchments, which are formed by a network of sub-catchments. Each sub-catchment is modelled as one surface water reservoir. In vertical direction the groundwater system is subdivided into a number of geohydrological layers (aquifers and aquitards). The soil water system consists of a root zone reservoir and a subsoil reservoir.

Groundwater
The groundwater module uses the quasi 3-dimensional approach in groundwater modelling. Therefore aquifers and aquitards are to be specified. Horizontal groundwater flow (in aquifers) is modelled using the finite element technique. This technique allows a user to follow natural boundaries and make refinements without introducing a great number of irrelevant nodes.

Unsaturated zone
The unsaturated zone is modelled as vertically oriented, 1-D models or 'columns', using the steady-state approach. Each type of land use, within any nodal sub-domain, is modelled separately. The 1-D column model consists of two reservoirs, one for the root zone and one for the subsoil. If the equilibrium moisture storage for the root zone is exceeded, excess water will percolate to the saturated zone. If the moisture storage is smaller than the equilibrium moisture storage, upward flow from the saturated zone is simulated through capillary rise. The height of the phreatic surface is calculated from the water balance of the subsoil, using a storage coefficient which is dependent on the depth of the groundwater table. Special processes are included in the unsaturated zone model, such as surface runoff and hysteresis.

Evapotranspiration
Evapotranspiration is determined by the crop and the moisture content in the root zone. For these calculations, recorded values of precipitation and potential evapotranspiration of a reference crop and woodland must be available. The potential evapotranspiration for other crops or vegetation types are derived from the values for the reference crop by conversion. Potential evapotranspiration for pine-forest is calculated as the sum of transpiration and interception.

Surface waters
A typical surface water system consists of a dense network of water courses, yet it is impossible to explicitly account for all individual water courses in a regional hydrological model like SIMGRO. Surface water levels are important for flood routing and for the assessment of drainage and subsurface

irrigation. Therefore the major water courses are modelled as a network (i.e. a cascade) of reservoirs. The exchange between groundwater and surface water is calculated using a drainage resistance concept in conjunction with head differences between groundwater and surface water.

Exchange between groundwater and surface water
The dynamics of the movement of surface waters through open watercourses evolve much faster than those of groundwater motion. Hence, the associated sub-models have their own time step for numerical approximation. The result is that the surface water sub-model performs several time steps during a single time step of the groundwater sub-model. Groundwater levels are assumed to remain unchanged during any time step, whereas the interaction between groundwater and surface waters is accumulated using the continuously updated surface water levels. At any call of the groundwater module, all water balance components associated with the unsaturated zone and the surface water sub-models, like drainage and sprinkler irrigation volumes, accumulated since the previous call, are used to update the groundwater level.

temporal resolution

The groundwater and surface water submodels of SIMGRO each run with a time step that is tuned to the type of dynamic behaviour. The groundwater submodel has a time-step of 0.25 day and the surface water submodel a time step of 0.025 day. Model output of the surface discharges and water levels are however integrated and averaged over the time period of one whole day, in order to smooth out variations that are caused by the computation algorithm.

spatial resolution

The SIMGRO model makes use of triangular finite elements for the spatial discretisation. There are 12000 nodes that form together 25000 of these elements for a model that covers an area of roughly 60000 ha. For judging the spatial resolution the area per node is the most suitable. The cross-sections of the nodal domains vary between 100 m in the stream valleys to several hundred meters in the high areas. This variation has been applied in order to provide maximum resolution in areas that are of the most interest. Also for modelling purposes it is judicious to have a high resolution in the stream valleys, because then the simulation of inundation conditions is the most accurate. This is especially important when simulating peak flows.

model flow charts

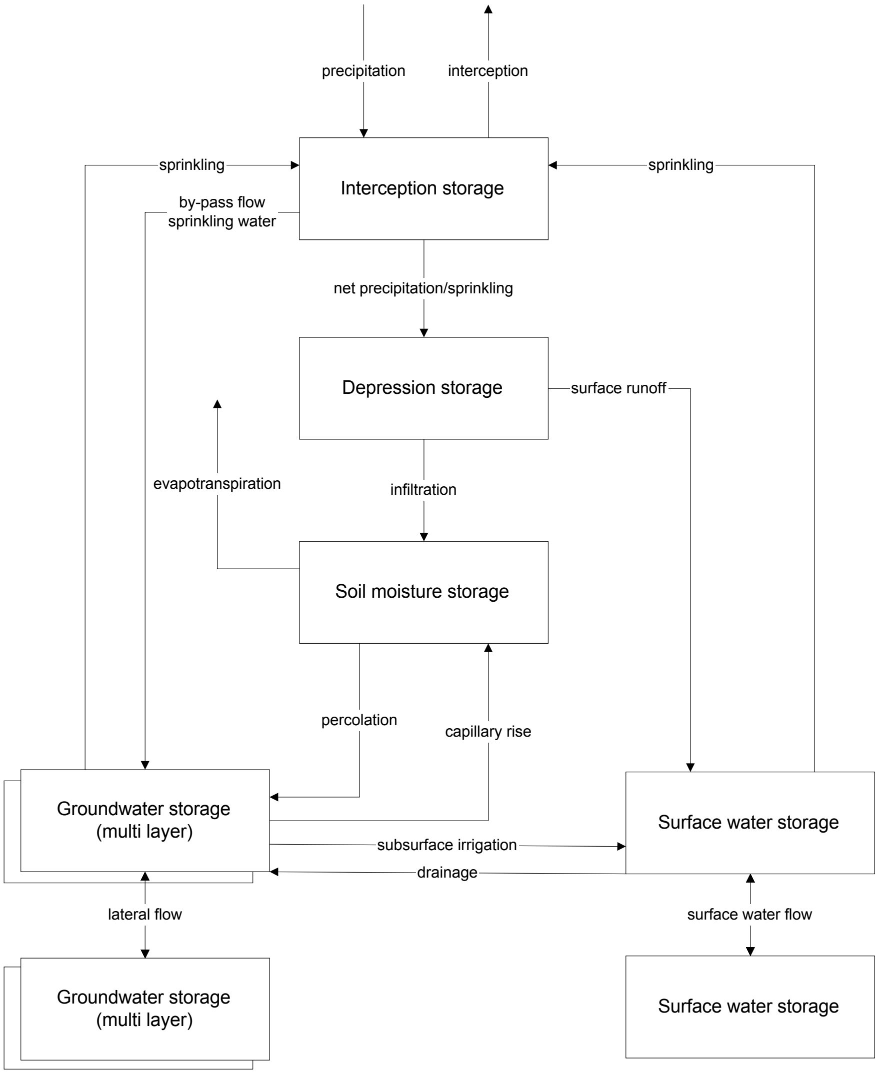


Fig. 1
Schematization of water flows in SIMGRO, by means of transmission links and storage elements.

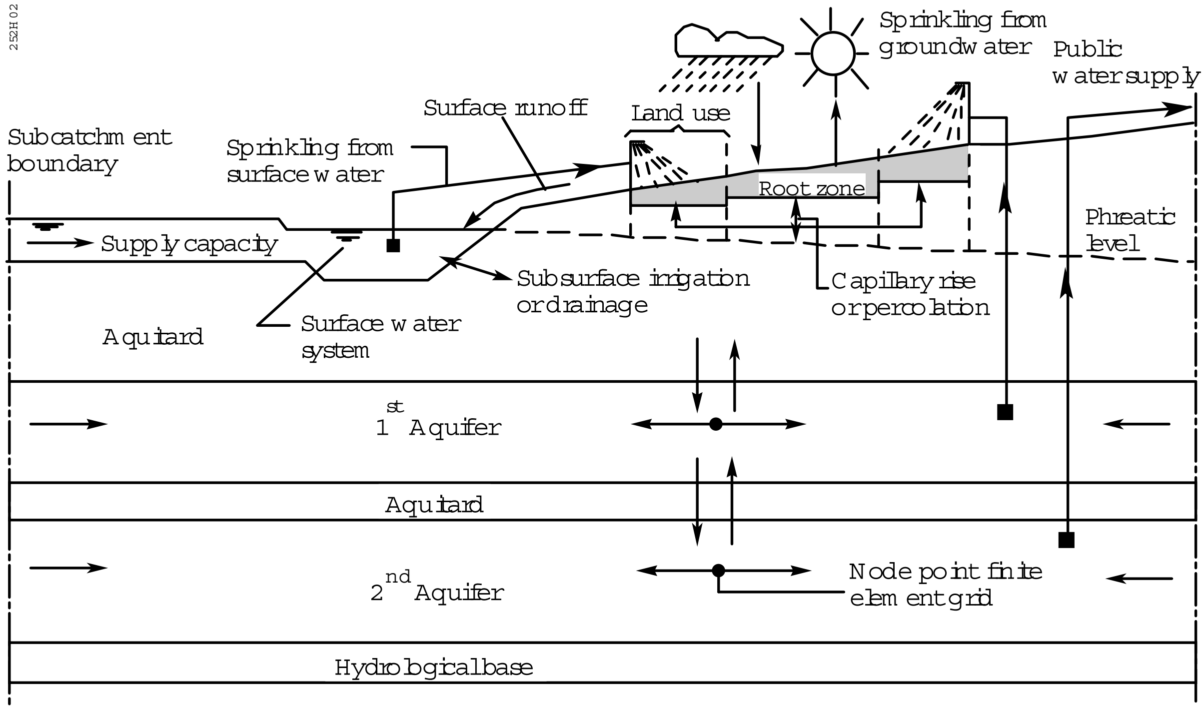
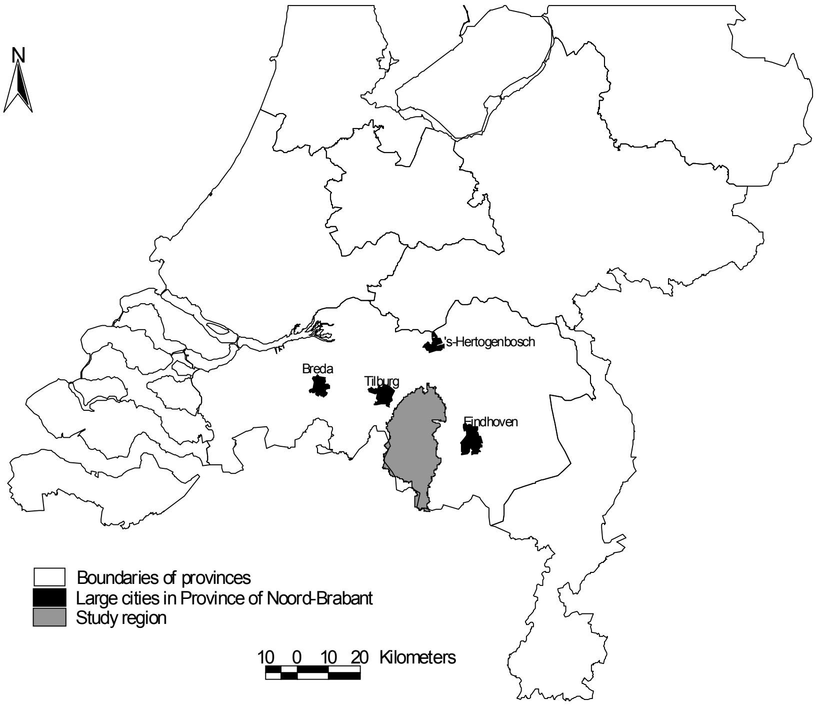


Fig. 2
Schematisation in SIMGRO of the hydrological system within a nodal sub-domain by means of an integration of saturated zone, unsaturated zone and surface water (Querner & van Bakel, 1989).

modelled sub-basin

The modelled part of the basin of the Beerze covers an area of 23227 hectares.

figure 3 *Location of Beerze catchment*



1988-1992 calibration

The calibration of SIMGRO was based on the following sources of information:

- a groundwater map of the so-called Mean Highest Groundwater level, revised in 1990
- a groundwater map of the so-called Mean Lowest Groundwater level, made in 1960 (only used for verification purposes, because it is 30 years old)
- measurements of groundwater levels, for diverse depths
- the measurements of the discharge between 1984 and 1998

The first phase of the calibration involved adjustment of the conductivity of the subsoil, mainly based on the fairly recent map of the Highest Mean Groundwater level of 1990. In order to get a reasonable fit, the conductivity had to be lowered substantially. Other groundwater information was mainly used to check the calibration.

A systematic sensitivity analysis was performed for the drainage resistance of the main waterways, the streams. On the basis of visual inspection of the simulated groundwater maps a choice was made for the so-called entrance resistance, which is the most uncertain factor in the initial data set.

Then, by comparing the simulated map of the Mean Highest Watertable to the measured one conclusions were drawn with respect to the drainage resistance at field level. In this way the presence of agricultural drainage was calibrated into the model. For the part of the area for which this method could be verified (areas with the known presence of agricultural drainage) the verification was quite satisfactory.

In the final phase of the calibration a systematic sensitivity analysis was done for the drainage resistance of the small trenches. This calibration was done on the basis of the frequency distribution for the high flows.

Exact ' fitting' of the model to the measured discharge data was hampered by the bounds given to the input parameters describing the groundwater flow: a better fit would have been obtained by further lowering the conductivities. But that was considered out of bounds by the institute NITG-TNO who supplied the data from their REGIS database.

References

Veldhuizen, A.A., A. Poelman, L.C.P.M. Stuyt and E.P. Querner, 1998. *Software documentation for SIMGRO V3.0; Regional Water Management Simulator;* Wageningen, DLO-Staring Centrum. rapport 104-def.doc. 289 p. 37 Fig.; 49 ref.

APPENDIX 2B DESCRIPTION OF THE RAINFALL-RUNOFF MODELS: *SCHEME*

Operated at

RMI

short model description

The SCHEME model is based on the IRMB conceptual model (Bultot and Dupriez, 1976). The IRMB model has been designed to study medium scale catchments. It has been successfully applied to catchments with areas ranging from 100 to more than 1000 km^2 in Belgium and other countries. In the IRMB model, the parameters are lumped over the catchment area and represented by a set of reservoirs. The SCHEME model has been developed in order to study river basins with a surface area up to 10^4 km^2 like the Scheldt and the Meuse river basins. The conceptual approach of the IRMB model has been applied on grid cells of 50 km^2 (Figure 1). The parameters are optimised on a set of sub-basins and regionalised over all grids. The model is completed with a module to route the runoff of each grid cell to the outlet. The time step is one day and surface processes are computed separately for each of nine different land covers. The potential evapotranspiration is estimated with the Bultot et al. (1983) method based on the Penman equation. Actual evapotranspiration is calculated by depleting first the water intercepted by vegetation and then the water content of the two soil buckets to meet the potential evapotranspiration. Both soil layers are supposed to dry at a rate proportional to the ratio of the current water depth of their corresponding soil bucket and their content when saturated. A detailed description of the model can be found in Roulin et al. (2000, 2001).

For the present study, the model parameters were optimised on the data of the selected sub-catchments. The parameter values have been used for the impact of climate change study without regionalisation. The routing module adapted for large river networks has not been applied in these small catchments. The λ parameter allows a fraction of the baseflow to be seeped or abstracted towards or from adjacent basins or reaches.

temporal resolution

day

spatial resolution

50 km^2

a flow chart of the model

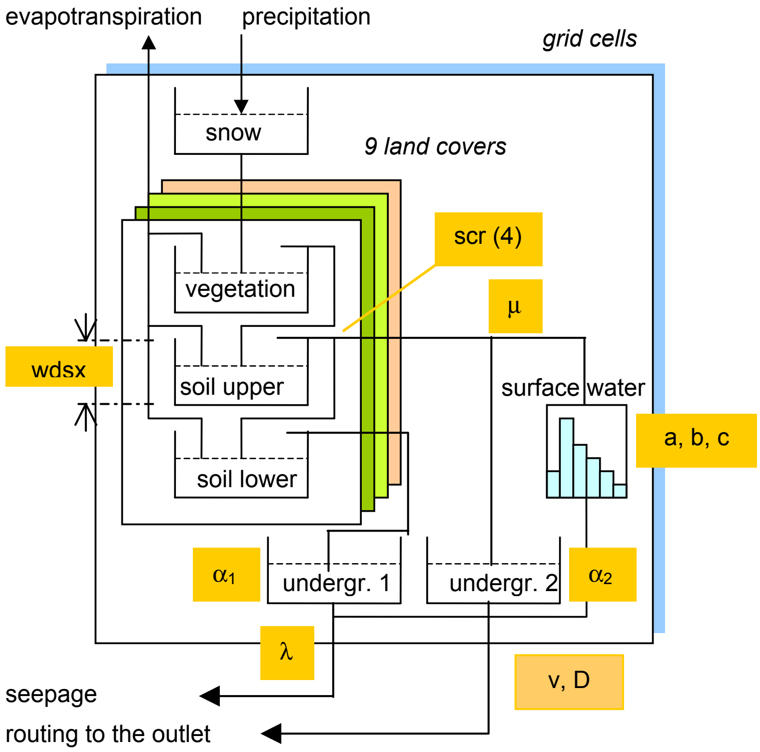
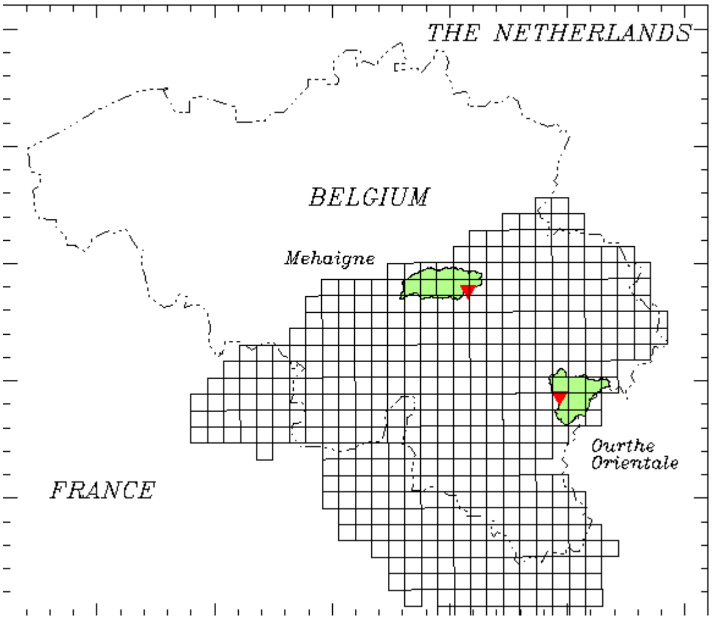


Figure 1 Conceptual representation of the processes within a grid cell of the SCHEME model. In yellow, parameters to be optimised: wdsx is the water capacity of the upper soil reservoir, scr are the seasonal surface runoff coefficients, μ is a parameter redirecting part of the surface flow towards a second underground reservoir, a,b and c describe the shape of the unit hydrograph (high a and b and low c correspond to a hydrograph concentrated in a few days) , α_1 and α_2 are the recession coefficients of the underground reservoirs, λ is the fraction of the baseflow for seepage or abstraction and v and D are respectively the wave celerity and the diffusion coefficients in the routing module

modelled sub-basin

Two contrasting Belgian sub-catchments (Figure 2) have been chosen to test the sensitivity to droughts using the SCHEME model. These sub-catchments are the Ourthe Orientale at Mabompré (317 km^2) and the Mehaigne at Moha (343 km^2). The first is characterized by a fast response to the occurrence of storms and is situated in the Ardennes and the second is characterized by a large limestone aquifer that allows the base flow to be sustained during summer.



1988-1992 calibration

The values of the parameters optimised for the two sub-catchment are presented in Table 1. The differences between both sub-catchments are:

- Greater values of the seasonal surface runoff coefficients (scr) for the Ourthe;
- Shorter unit hydrogram of the surface water for the Mehaigne
- Greater values of the recession coefficients of both underground reservoirs of the Ourthe;
- An important fraction of the underground flow is seeped from the Mehaigne sub-catchment whereas the Ourthe watershed matches closely to the contour of its corresponding hydrogeological basin.

The validation statistics are presented in Table 2.

Table 1 Parameter values optimised on the observed streamflow

parameter	Mehaigne	Ourthe
Wdsx (mm)	34	21
Scr winter	0.161	0.478
Scr spring	0.279	0.374
Scr summer	0.102	0.097
Scr autumn	0.120	0.204
a	0.481	0.333
b	0.340	0.166
c	-1.066	-0.283
μ	2.215	1.843
α_1	0.021	0.185
α_2	0.006	0.019
λ	0.484	0.000

Table 2 Difference between observed and simulated daily values of the total streamflow. Rms is the root mean square, r2 is the correlation coefficient and ntd is the efficiency (Nash) coefficient

	Mehaigne	Ourthe
rms	.251	.739
bias	.009	.011
r^2	.812	.839
ntd	.811	.839

references to more detailed descriptions of the model

Bultot, F. and G.L. Dupriez, 1976. Conceptual hydrological model for an average-sized catchment area. J. Hydrol., 29, 251-292.

Bultot, F., A. Coppens and G.L. Dupriez, 1983. Estimation de l'évapotranspiration potentielle en Belgique (Procédure révisée). Inst. Roy. Mét. Pub., Série A, n° 112, Uccle-Bruxelles, 28 pp.

Bultot, F., G.L. Dupriez and D. Gellens, 1990. Simulation of land use changes and impacts on the water bance – a case study for Belgium.

Roulin, E., A. Cheymol, and D. Gellens, 2000. Impact of climate changes on the water resources in the river Meuse basin. In Proceedings of the International Conference on Integrated Water Resources Management for Sustainable Development, 19-21 December, 2000, New Delhi, India, Mehrota. R., B. Soni and K.K.S. Bhatia Eds., National Institute of Hydrology, Roorkee, India, 1045-1054.

Roulin, E., A. Cheymol, and D. Gellens, to be published in 2001. Integrated modelling of the hydrological cycle in relation to global climate change. Final Report of the project GC/DD/08 in the framework of the « Global change and sustainable development » program of the Belgian Federal Services of Scientific, Technical and Cultural Affairs.

APPENDIX 2C DESCRIPTION OF THE RAINFALL-RUNOFF MODELS: *MEUSEFLOW*

Operated at

Carthago Consultancy

short model description

The hydrological cycle of a drainage basin can be viewed as a series of storage reservoirs and flows. A water balance approach is used as a framework to describe the transformation of input (precipitation) through this cycle. The 'water budget' for each of the compartments of this cycle can be described as a simple mass balance:

Change in compartment = Influx – Outflux.

For larger catchments this water balance can be described as seven compartments and variables:

- The distribution of precipitation in time and space. Precipitation is the most important influx of water into the catchment.
- The distribution of temperature in time and space. Temperature is the most important controlling factor for snow storage, snow melt and potential evapotranspiration.
- Glacier and snow storage which gains water from precipitation and loses water to snow melt.
- Soil moisture storage/ shallow ground water reservoir, which gains water from the surplus of precipitation and looses water through evapotranspiration, through seepage to the deeper groundwater and to direct runoff.
- A deeper groundwater reservoir that gains water from the soil moisture storage and looses water to river baseflow.
- The spatial distribution of land use and soil characteristics. These parameters are important for a proper analysis of soil storage capacity and evapotranspiration estimates.
- Components for estimating baseflow and quickflow as a function of soil moisture and deeper groundwater. Discharge produced in a certain region follows the drainage pattern towards the outlet of the catchment.

MEUSEFLOW-2 is a water balance model for the river Meuse based on these components. MEUSEFLOW-2 is a further extension of the MEUSEFLOW-1 and RHINEFLOW-1 models. These models are water balance models with a timestep of 1 month and 3x3 km^2. MEUSEFLOW-2.1 uses a timestep of 10 days, and a spatial resolution of 1x1 km^2.

MEUSEFLOW recognises 3 compartments as storages or reservoirs: the snow compartment, the soil compartment and the deep groundwater compartment. Each of these compartments is implemented as a raster GIS-layer, thus allowing for simulation of spatial characteristics of the compartments. PCRaster is used as the GIS environment for development of the model. For each of the timesteps in a model run, these reservoirs are updated, representing the temporal behaviour of these storages.

The following dataset is available for the MEUSEFLOW model:

- temperature data — stations with min, max and mean 10-day station temperature
- precipitation data — stations with 10-day areal (sub-basin) precipitation
- evaporation data — stations with reference station evapotranspiration data (10-day estimates)
- runoff data — stations with 10-day discharge data

Although the spatial resolution of the model is 1x1 km^2 and thus individual cells can be evaluated at this level, the calibration and validation of the larger sub-basins of the Meuse basin do not assure a correct estimate for individual cells. Although the scale at which data is stored in the GIS is 1x1 km2 and the results can be made available on the same scale one should be careful to use this scale as an evaluation scale of the model. It is impossible to calibrate and validate the model for this spatial resolution, and thus local assessments can not be made based on a regional model. However, the model is calibrated and validated for larger sub-catchments, and the results should be applicable to this scale. For the level of sub-catchments of tributaries of the Meuse the model should produce reliable results.

For each timestep of 10 days, MEUSEFLOW reads from its database gridvalues for temperature, precipitation and reference evapotranspiration. For each timestep, cell precipitation and temperature are evaluated to determine whether precipitation is in the form of snow or rain, and snowmelt is determined. The Snowcover layer is adjusted accordingly. The available water (rain and snowmelt) is further processed in the soil module, where Direct Runoff, evapotranspiration and seepage to deeper groundwater is determined. Deeper groundwater releases water for runoff in two processes: Quickflow and Slowflow. Combined with the Direct Runoff, these components yield the total runoff component.

Simulating processes in the Snow compartment

Within the snow compartment the following processes are simulated:

- Snowfall
- Snowmelt
- SnowStorage.

There are various solid forms of precipitation which, before being drained from the catchment, remain at the surface for some time. For this study, snow is the most important one. In most alpine regions, snowmelt runoff is responsible for the annual maximum instantaneous discharge and most of the annual flow. Due to their steep, variable topography, alpine catchments are characterised by a large degree of heterogeneity in the important properties controlling snow accumulation, snowmelt and meltwater runoff.

Snow accumulates at the surface, storing a certain amount of water, and releases its contents when melting. This might occur in one specific event or as a series of melting and re-freezing of water.

For MEUSEFLOW-2 a snow module is developed with the following characteristics.

- Simulation of snowfall and snowmelt based on both minimum and maximum temperature for each timestep. Snowfall will be triggered by minimum temperature, and the fraction of precipitation falling as snow equals the fraction of the temperature-interval between minimum and maximum temperature that is below this 'snowfall trigger temperature'.
- Simulation of snowmelt based on both minimum and maximum temperature for each timestep. Snowmelt is triggered by the maximum temperature. Snowmelt is decreased for the fraction of the temperature interval that is below this 'snowmelt trigger temperature'.

Soil compartment

Within the soil compartment the following processes are simulated:

- Rapid overland flow (‘Direct runoff’)
- Actual and potential evapotranspiration
- Partition of excess water in a slow flow and a quick flow component
- Budget of the soil moisture

Inputfluxes for this compartment are the SnowMelt and Rainfall terms calculated in the snow compartment module. OutputFluxes for this module are the Direct Runoff, Quickflow and Slowflow terms.

The RHINEFLOW-1 and MEUSEFLOW-1 models simulate this soil compartment and its major terms with a Thornthwaite-Mather formulation for potential evapotranspiration. This potential evapotranspiration approach is limited for its applications in Climate Change studies. The main reasons for this limited applicability are:

- The Thornthwaite-Mather approach uses a empirical model, with as its main independent variable temperature. The use of this type of formulae for Climate Change studies results in an overestimation of potential evapotranspiration.
- The Thornthwaite-Mather formulae are developed for the use in the United States. Applying these formulae in other areas is not without considerable potential problems.

Better estimates of potential evapotranspiration in the Meuse catchment under current climate conditions are available from the meteorological institutes in the catchment. The task for MEUSEFLOW-2 is to estimate changes in evapotranspiration as a result of changes in climate, its task is not to estimate evapotranspiration under present day conditions. MEUSEFLOW-2 uses an approach in which the available reference evapotranspiration data for the current situation is used. For Climate Change scenarios a mathematical relation between temperature change and reference evapotranspiration change is used. This relation for the Dutch situation is derived by Brandsma [1995], and can be established for other areas using Penman (for a very detailed estimation) or Blaney-Criddle (for a good and more robust estimate). This relation becomes external to the MEUSEFLOW-2 model, and is implemented as a tabular relation between temperature change and evapotranspiration change.

Groundwater compartment

The groundwater compartment is responsible for the production of baseflow (or the 'SloFlo' component of the overview scheme of Meuseflow). This compartment is implemented as a large reservoir, gaining water flow the Soil Compartment, and releasing water to the baseflow component. The amount of water gained is determined by the Soil compartment, and MEUSEFLOW uses a simple linear reservoir approach to determine baseflow with a fixed recession constant rc. The governing formulaes are:

$$S_{groundwater} = S_{groundwater}(t-1) + \text{Inflow}$$
$$\text{Baseflow} = S_{groundwater}/rc$$
$$S_{groundwater} = S_{groundwater} - \text{Baseflow}$$

temporal resolution

10 days

spatial resolution

1 km^2

modelled sub-basin

Totale stroomgebied boven Borgharen: 21260 km2

references to more detailed descriptions of the model

Kwadijk, J.C.J., 1993. The impact of climate change on the discharge of the river Rhine. PhD-thesis Utrecht. University, department of Physical Geography, The Netherlands. KNAG/NGS publication 171.

Van Deursen, W.P.A., 1995. Geographical Information Systems and Dynamic Models. Development and application of a prototype spatial modelling language. PhD-thesis. Utrecht University, department of Physical Geography, The Netherlands. KNAG/NGS publication 190.

Van Deursen, W.P.A., 1997. Voorbereidingen MEUSEFLOW 2, Verdamping en meteostations, Rapportage aan RIZA, November 1997.

Van Deursen, W.P.A., 1998a. Tussenrapportage Meuseflow 2, rapportage fase 1. Rapportage aan RIZA, November 1998.

Van Deursen, W.P.A., 1998b. Design of the Rhineflow-2 model. Report of the NOP project 952210. Rapportage voor NOP.

Van Deursen, W.P.A., 1998c. Vulnerability water supply of the Netherlands through the river Meuse. Programming study. Report of the NOP project 952251. Rapportage voor NOP.

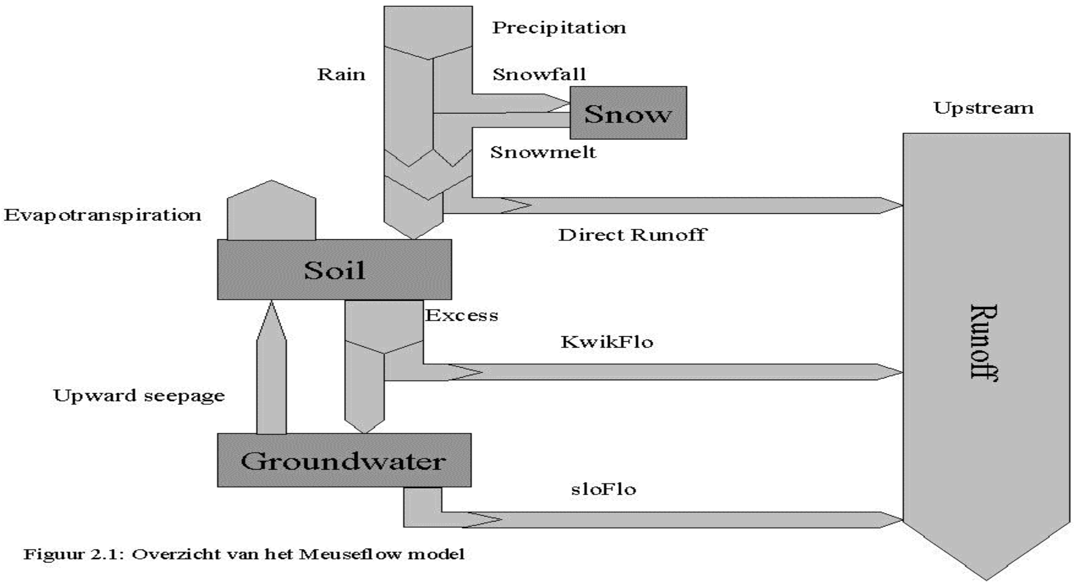
Van Deursen, W.P.A., 1999. Rapportage Meuseflow 2.0, eindrapportage ontwikkeling MEUSEFLOW 2.0. Rapportage aan RIZA, December 1999.

Van Deursen, W.P.A., 2000. Tussenrapportage Meuseflow 2.1, rapportage fase 1 ontwikkeling MEUSEFLOW 2.1. Rapportage aan RIZA, Augustus 2000.

Van Deursen, W.P.A., 2000. MEUSEFLOW 2.1, LaagwaterstudiesMaasstroomgebied, RIZA project RI-2988A, Oktober 2000

Middelkoop, H. (editor) 2000. The impact of climate change on the river Rhine and the implications for water management in the Netherlands, NOP -project 952210, RIZA Report 2000.010. June 2000.

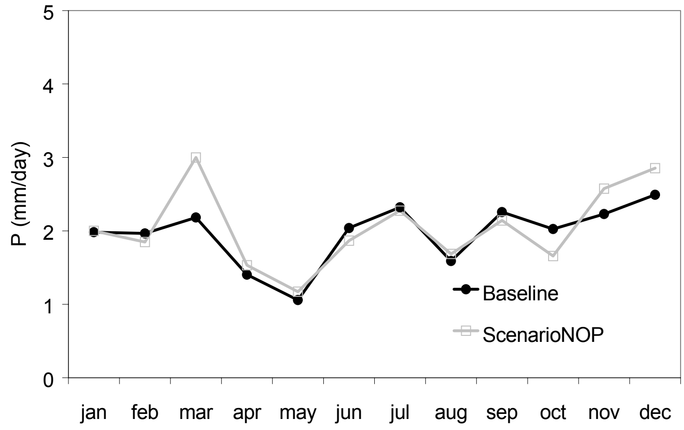
Figure 1. Flowchart MEUSEFLOW

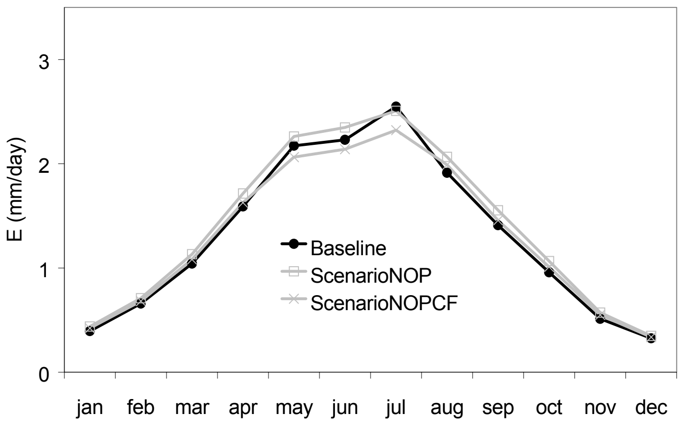


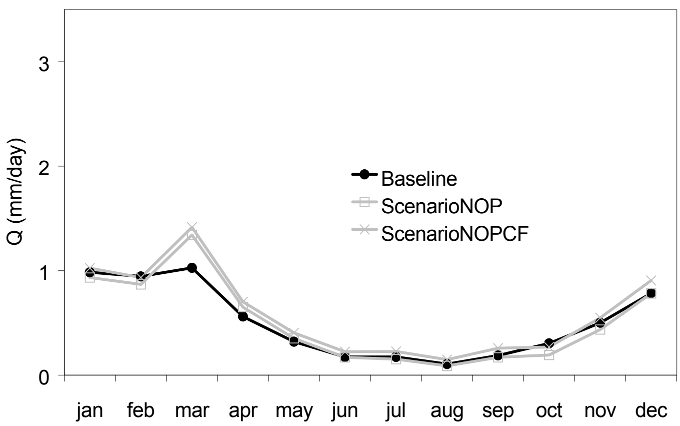
Figuur 2.1: Overzicht van het Meuseflow model

APPENDIX 3 RESULTS OF THE SCENARIO RUNS

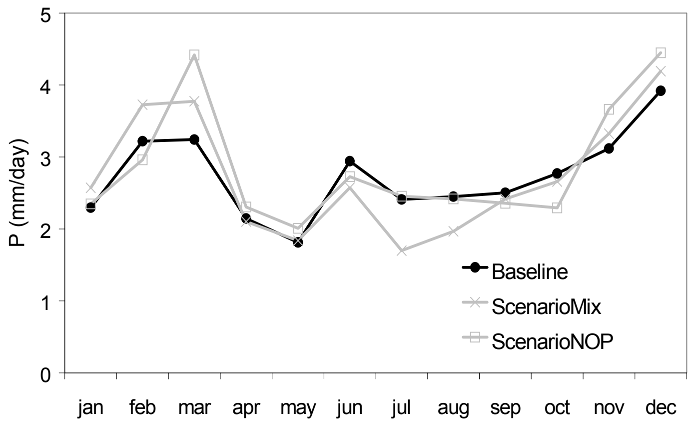
Beerze

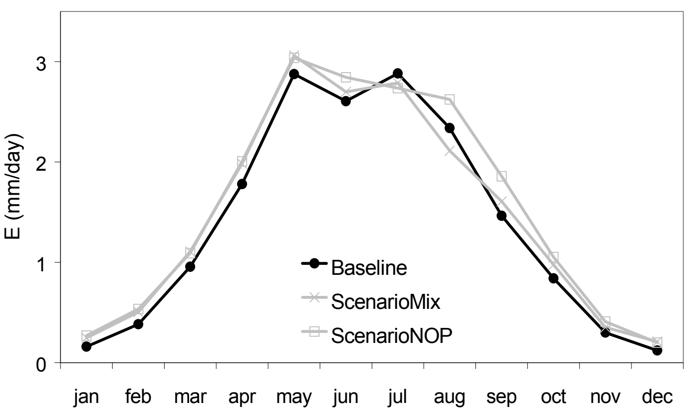


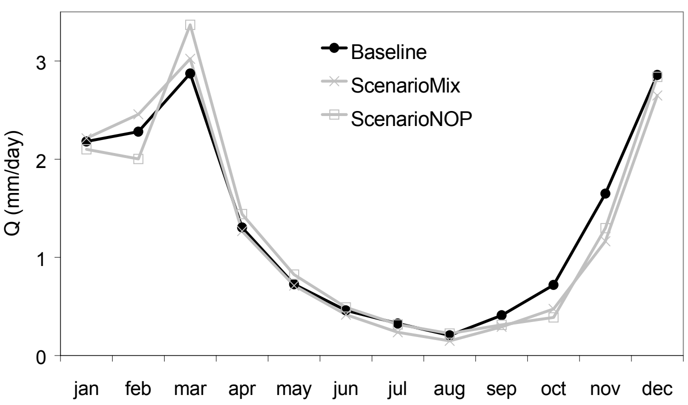


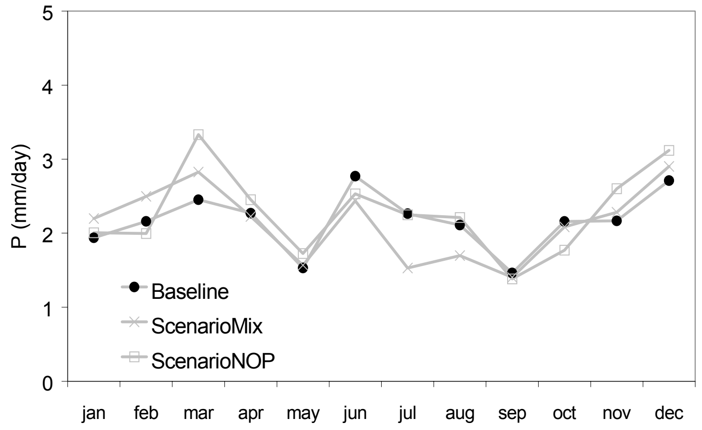


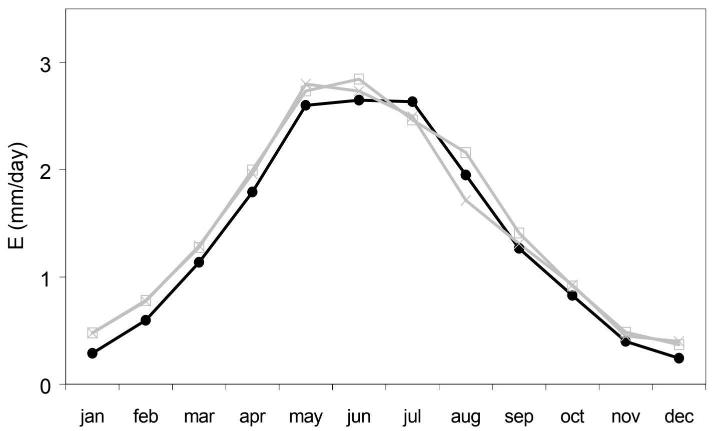
Ourthe Orientale

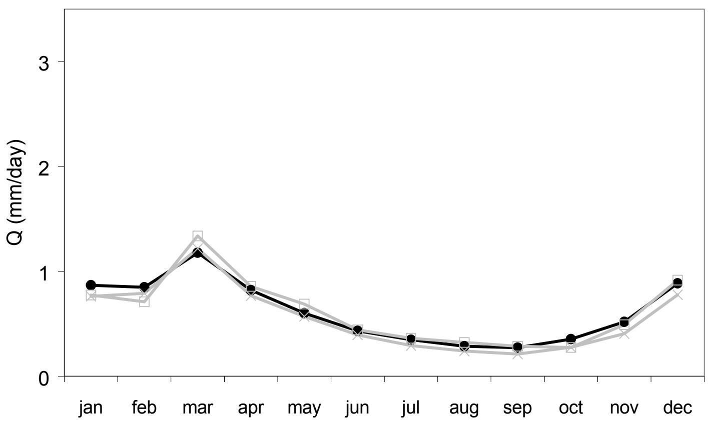




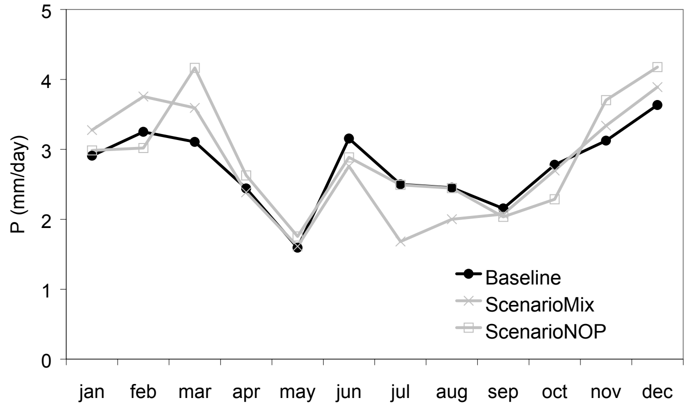


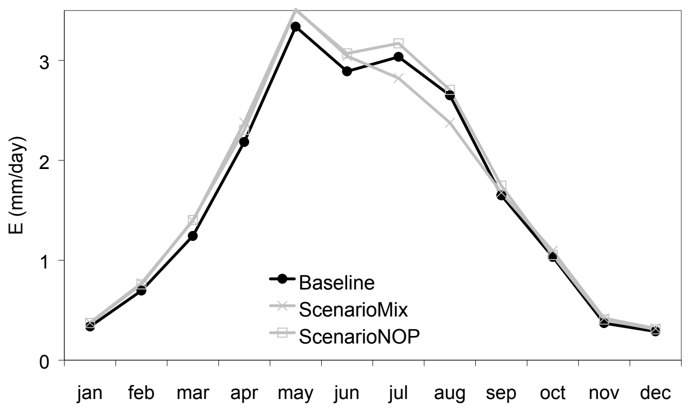

5
4
3
2
1
0
P (mm/day)
Baseline
ScenarioMix
ScenarioNOP
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec

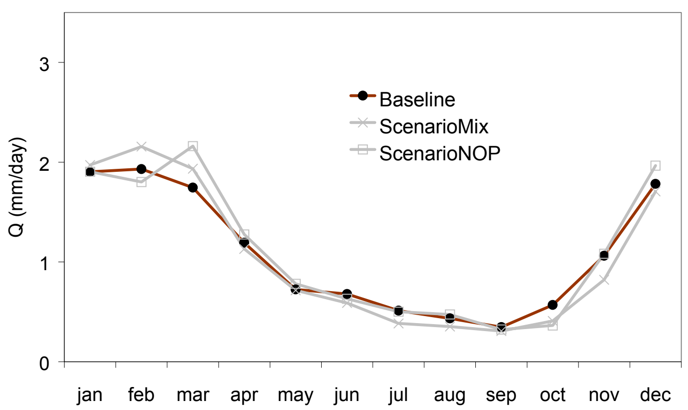

3
2
1
0
E (mm/day)
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec


3
2
1
0
Q (mm/day)
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec

Meuse (Borgharen)







APPENDIX 4 WORKSHOP PARTICIPANTS

Name	Institute
Dhr. Van Bakel	Alterra
Dhr. A. v.d. Oever	Koninklijke Schippersvereniging Schuttevaer
R. Eijsink	Vewin
Dhr. H. Crommelinck	Antwerpse Waterwerken
Ir.A. Jaskula-Joustra	Rijkswaterstaat Directie Limburg
Paul van Walsum	Alterra
Emmanuel Roulin	Royal Meteorological Institute of Belgium
Anne Cheymol	Royal Meteorological Institute of Belgium
Gaston Demaree	Royal Meteorological Institute of Belgium
Wilko Verweij	NOP
Jaap Kwadijk	WL
Mauk Burgdorffer	RIZA
Hans Middelkoop	Universiteit Utrecht
Marcel Ververs	WL
Willem van Deursen	Carthago Consultancy
Drs. L.W.C.A. van Breemen	N.V. Waterwinningbedrijf Brabantse Biesbosch
E. van Wijngaarden	Waterschap de Dommel
Marcel de Wit	Universiteit Wageningen
Paul Torfs	Universiteit Wageningen
Emiel van Loon	Universiteit Wageningen
Piet Warmerdam	Universiteit Wageningen
Hanneke Ooms	Rijkswaterstaat Directie Zuid-Holland
Ubo Pakes	RIZA
Sander Bastings	Rijkswaterstaat Directie Limburg
Pieter Valkering	ICIS Universiteit Maastricht
Willem Overmars	St. Ark/Buro Stroming
Alphons van Winden	St. Ark/Buro Stroming
Ir. Peter Viaene	Min. v/d Vlaamse Gemmenschap
Marc Hoffmann	Universiteit Wageningen
Annemiek Verhallen	Universiteit Wageningen
Claudio Paniconi	Universiteit Wageningen
M. Thunus	Ministere Wallon de l'Equipement et des Transports (MET)
R. Jilderda	KNMI
Cathelijne van Haselen	HasKoning
Martijn Booij	Universiteit Twente Waterhuishouding en Milieu

Inlichtingen zijn verkrijgbaar bij het secretariaat:
Wageningen Universiteit
Departement Omgevingswetenschappen
Sectie Waterhuishouding
Nieuwe Kanaal 11
6709 PA Wageningen
telefoon : 0317 - 482778
telefax : 0317 - 484885

For information please contact the secretariat:
Wageningen University
Department of Environmental Sciences
Sub-department Water Resources
Nieuwe Kanaal 11
6709 PA Wageningen
The Netherlands
telephone : +31 - (317) – 482778
telefax : +31 - (317) - 484885

Internet: www.dow.wau.nl/whh

EERDER VERSCHENEN RAPPORTEN/PREVIOUS REPORTS

Nr	Auteur(s) + titel/author(s) + title	Prijs/Price (Hfl)
51.	Boiten, W., A. Dommerholt en M. Soet, 1995. Handboek debietmeten in open waterlopen.	*
52.	Boiten, W., 1995. Het opstellen van de afvoerkrommen van klep-stuwen.	17,50
53.	Boiten, W., 1995. Afvoerrelaties klepstuwen op de samenvloeiing van de Veengoot en de Van Heeckerenbeek.	*
54.	Benning, R.G., 1995. Towards a new lumped parameterization at catchment scale.	24,00
55.	Bastiaansen, C.J.M., 1995. Lui River Valley Model, and some of its applications.	22,00
56.	He, Q., K.D.W. Nandalal, J.J.K.M. Bogardi and D. Milutin, 1995. Application of stochastic dynamic programming models in optimization of reservoir operations: A study of algorithmic aspects.	33,00
57.	Lanen, H.A.J. van, B. van de Weerd, R. Dijksma, H.J. ten Dam en G. Bier, 1995. Hydrogeologie van het stroomgebied van de Noor en de effecten van grondwateronttrekkingen aan de westrand van het Plateau van Margraten. Basisrapport.	*
58.	Lanen, H.A.J. van, R. Dijksma en B. van de Weerd, 1995. De effecten van grondwateronttrekkingen aan de westrand van het Plateau van Margraten op de hydrogeologie van het Noordal. Samenvattend rapport.	*
59.	Bogardi, J.J.K.M., B.A.H.V. Brorens, M.D.U.P. Kularathna, D. Milutin en K.D.W. Nandalal, 1995. Long-term assessment of a multi-unit reservoir system operation: the *ShellDP* programme package manual.	56,50
60.	Dommerholt, A., 1995. Afvoerrelatie meetoverlaat Stemerdinkbrug.	*

* niet te koop bij de sectie, alleen ter inzage/not for sale at the department, for inspection only.

Nr	Auteur(s) + titel/author(s) + title	Prijs/Price (Hfl)
61.	Dijksma, R., J.H. Bouma en H.F. Gertsen, 1995. Proefproject verdroging Duurswouderheide. Hoe effectief zijn de beheersmaatregelen?	*
62.	Verburg, P.H., 1995. De relatie tussen de vochttoestand van de bodem en de vochtindicatie van de vegetatie. Een nadere bepaling van de grens tussen 'vochtig' en 'droog' binnen het ecotopensysteem.	26,00
63.	Denecke, H.W., 1995. Voorlopige evaluatie drainagesysteem militaire oefenterrein Marnewaard.	*
64.	Arts, M.P.T. en W. Boiten, 1995. Meetnet voor afvoermetingen in de Renkumse Beken.	*
65.	Arts, M.P.T. en R. Dijksma, 1995. Morra park, voorlopige resultaten grond- en oppervlaktewater meetnet.	*
66.	Akker, M.F.A. van den en B.J.H. van de Wiel, 1996. Hoogwatervoorspellingen voor de Rijn bij Lobith met hybride methoden. De hydrologische Muskingum methode uitgebreid met lineaire en niet-lineaire updatingstechnieken.	39,00
67.	Soet, M., P. Petrovic, J.N.M. Stricker, W. Meijninger, A. van Schaik en T. Lapsansky, 1996. Water budget of maize on heavy clay in a continental climate: field experiment and model simulation. Final report of the project "Evaporation estimation comparison".	*
68.	Torfs, P.J.J.F. en H. Middelkoop, 1996. Analysis of discharge series from the Rhine basin at different levels of aggregation.	*
69.	Dijksma, R. (ed.), 1996. International excursion Hydrogeology - SLOVAKIA, september 8-15, 1996. Excursion report.	-,-
70.	Oevelen, P.J. van and I.H. Woodhouse, 1996. NOPEX/FOREST-DYNAMO ground data collection and data analysis report.	25,00
71.	Dam, J.C. van, J. Huygen, J.G. Wesseling, R.A. Feddes, P. Kabat, P.E.V. van Walsum, P. Groenendijk and C.A. van Diepen, 1997. Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment.	45,00
72.	Warmerdam, P.M.M. (ed.) en M. Quist (ed.), 1997. Verslag van de buitenlandse excursie Hydrologie naar België, 1 t/m 5 september 1997.	-,-
73.	Moors, E.J., J.N.M. Stricker and G.D. van den Abeele, 1998. Evapotranspiration of cut over bog covered by *Molinia Caerulea*.	18,50
74.	Eertwegh, G.A.P.H. van den en C.R. Meinardi, 1998. Water- en nutriëntenhuishouding van het stroomgebied van de Hupselse beek.	*
75.	Eertwegh, G.A.P.H. van den, J.R. Hoekstra en C.R. Meinardi, 1998. Praktijkproef nutriëntenbalans: nutriëntenbelasting in oppervlaktewater via drainage van akkerbouwpercelen op zeeklei.	*

Nr	Auteur(s) + titel/author(s) + title	Prijs/Price (Hfl)
76.	Boiten, W. 1998. Levering drie Rossum-stuwen Schouwen West.	*
77.	Oevelen, P.J. van, M.A.M. Vissers and I.H. Woodhouse, 1998. RESMEDES Spain 1996. Ground data collection and analysis report.	27,50
78.	Dijksma, R., H.A.J. van Lanen, W.J. Ackerman en H.F. Gertsen, 1998. De afvoer van de Noor (Zuid-Limburg). Periode 1992 - 1997.	*
79.	Soet, M., J.N.M. Stricker, P. Droogers and J. Esenbrink, 1998. EFEDA-Spain and HAPEX-Sahel. A further analysis of data.	*
80.	Wojcik, R., P.J.J.F. Torfs and S. Ignar, 1998. Sensitivity of output covariance to non-second order properties of the input in the case of unsaturated zone models.	25,00
81.	Kroes, J.G., J.C. van Dam, J. Huygen en R.W. Vervoort, 1998. Users Guide of SWAP 2.0. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment.	35,00
82.	Boiten, W., 1998. Levering Rossum-stuw. Polder de Noordplas.	*
83.	Boiten, W., 1998. IJking Friese spuisluizen. Friese Sluis te Zoutkamp, Suatiesluis Nes, Ameland.	*
84.	Dijksma, R. en J.F. Borsje, 1999. Het Morra Park. Water als lust of last.	*
85.	Klok, E.J. and K.P. Roelofsma, 1999. Modelling of glacier and snow melt processes within the hydrological catchment model WaSiM-ETH.	27,50
86.	Boiten, W., 1999. Ontwerp Hobrad-overlaat. Project Evertsekoog, Texel.	*
87.	Warmerdam, P.M.M. en P.J.J.F. Torfs, 1998. Verslag van de buitenlandse excursie Hydrologie naar de landendriehoek Frankrijk, Duitsland en Luxemburg. 30 augustus tot 5 september 1998.	-,-
88.	Wójcik, R., 1999. Non-linear stochastic methods for discharge prediction.	60,00
89.	Kalma, J.D., R.A. Feddes, G. Boulet, M.F. McCabe and S.W. Franks, 1999. Towards effective land surface parameters for use with SVAT models: the use of similarity scaling and inversion techniques.	14,00
90.	Kalma, J.D., S.W. Franks, B.J.J.M. van den Hurk, M.F. McCabe and R.A. Feddes, 1999. Estimating large scale land surface fluxes: the use of remote sensing data with SVAT and NWP models	15,00
91.	Ovaa, B.P.S.A., 1999. Gebiedscontracten. Een nieuwe kijk op sturing van regionaal landgebruik en waterbeheer.	25,00
92.	Boiten, W., 2000. Report Overseas Study Tour Rhine Basin, 7-21 November 1999. Hydrology Project India.	*
93.	Boiten, W., 2000. Debietmeetstations in het gebied Halkenbroek.	*

Nr	Auteur(s) + titel/author(s) + title	Prijs/Price (Hfl)
94.	Schaaf, S. van der en P.M.M. Warmerdam, 2000. Herstel van het watersysteem in het bebouwde gebied van Wageningen. Haalbaarheidsonderzoek.	30,00
95.	Dommerholt, A., 2000. Meetopstelling voor aan- en afvoer van water in de Vlietpolder bij Hoogmade. Onderdeel project "Water- en Nutriëntenhuishouding Veenweideproject".	*
96.	Boiten, W. 2000. Debietmeetstations op de Schipbeek; Kloosterstuw te Deventer, inlaatgemaal Twentekanaal te Markelo.	*
97.	Dijksma, R. (ed.), 2000. International excursion Hydrogeology – Poland. 3-10 September 2000.	-,-
98.	Dijksma, R. en H.A.J. van Lanen, 2001. De afvoer van de Noor (Zuid-Limburg). Periode 1992-2000.	*
99.	Boiten, W., 2001. Rehabilitation of the Busongo Reservoir near Sirigu, Bolgatanga, Ghana.	17,50
100.	Uijlenhoet, R., M.J.M. de Wit, P.M.M. Warmerdam and P.J.J.F. Torfs, 2001. Statistical Analysis of Daily Discharge Data of the River Meuse and its Tributaries (1968-1998): Assessment of Drought Sensitivity.	15,00
101.	Loon, E.E. van and P.A. Troch, 2001. Book of Abstracts. International Workshop on Catchment scale Hydrologic Modeling and Data Assimilation. Wageningen, September 3-5, 2001.	30,00
102.	Boiten, W., 2001. Inrichting debietmeetnet Vallei en Eem. Vooronderzoek, richtingsadvies en ontwerp van een lange overlaat achter de Grebbesluis.	*
103.	Dommerholt, A., W. Boiten en M.R. Hoffmann, 2001. Meetopstelling voor hoogwater peilregistratie. Afwijking tussen gemeten en werkelijke waterhoogte.	*
104.	Wit, M.J.M. de (ed.), P. Warmerdam, P. Torfs, R. Uijlenhoet, E. Roulin, A. Cheymol, W. van Deursen, P. van Walsum, M. Ververs, J. Kwadijk and H. Buiteveld, 2001. Effect of climate change on the hydrology of the river Meuse.	40,00