climate changes spatial planning

Climate scenarios

From raindrop to high flow event

Modelling and reconstructing precipitation and flood frequency in the Maas catchment during the late Holocene

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KvR 043/12

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KvR report number KvR 043/12
ISBN ISBN/EAN 978-90-8815-035-7

This project (CS09; Modeling and reconstructing precipitation and flood frequency in the Meuse catchment during the late Holocene) was carried out in the framework of the Dutch National Research Programme Climate *changes* Spatial Planning. This research programme is co-financed by the Ministry of Infrastructure and the Environment.

Contents

Abstract

Abstract

This report forms a synthesis of the CS09-project carried out as part of the program Climate changes Spatial Planning (www.klimaatvoorruimte.nl), describing the most important results and outcomes. Main goal was to gain insight in interaction between water management in the Maas catchment, climate change and land use on decennial to millennial time scales, by the means of proxy reconstruction and numerical modelling.

Knowledge of the long-term (millennial scale) climatic fluctuations is crucial for the understanding and predicting capacities of future climate changes. Therefore, the CS09-project aims to compare present-day climate and future climate scenarios with palaeoclimatic fluctuations in the Maas basin. The focus is on precipitation characteristics, which tend to show a relatively high variability.
Since external factors like climate change and human impact influence the river system in such a way that they will have severe consequences for society, economy and public health, understanding of the cause-and-effect relations in the Maas basin appears to be of utmost importance. The study provides a baseline assessment of the 'natural' discharge conditions of the Maas river, against which the influence of intrinsic factors (natural evolution) and external factors (climate, human impact and tectonics) can be assessed. This provides a new long-term perspective in which the effects of future changes (natural and man-made) can be assessed. The project addresses the following key objectives:

- Providing a framework of semi-quantified, natural precipitation (mean annual precipitation, mean variability, amplitude and frequency of extreme precipitation events), functioning as a reference for possible future precipitation averages and extremes.
- Assessing the impact of past precipitation fluctuations on river flooding and discharge (frequency and periodicity), both under natural and anthropogenic conditions over different time scales.

Two of the four subprojects were testing the use of new proxies in the reconstruction of precipitation and discharge. The first one of these two subprojects was based on the use of hydrogen isotope fractionation in *Sphagnum* as a proxy for precipitation reconstruction. The second one used the oxygen and carbon isotope ratio in freshwater bivalves to reconstruct Holocene discharge and flooding.

Reconstruction of discharge by using freshwater bivalves as a proxy turns out to be complex, because isotope composition is more dependent on the surroundings than on discharge values; furthermore, the lifespan of the bivalves is quite short. However, when dealing with low discharge values, some quantification is possible.
Reconstruction of precipitation by means of hydrogen fractionation in Sphagnum is difficult, because temperature and species-specific factors appear to be the factors determining isotope fractionation.

It is difficult to reconstruct quantified discharge and precipitation based on proxies. In the third subproject, the traditional palaeobotanical and sedimentological proxies prove to be the most useful ones as they enable identification of former floods and might be used to improve the estimate of flood return periods. This has not been carried out in the present study.
In the fourth subproject, a coupled climate-hydrology model was developed to assess the impact of climate and land-use change on discharge and flood frequency.

The model simulations appoint changes in land use as the most important long-term (millennial scale) factor determining changes in discharge and the frequency of high-flows (fourth subproject). Over the last century, however, changes in precipitation and temperature became more and more important.

Whereas true quantitative reconstruction by the means of the developed proxies remains problematic, they serve as useful semi-quantitative or qualitative indicators of past climate and river conditions. Together with the simulations, which give a good overview of the trends in precipitation and discharge between 4000-3000 BP and 1000-2000 AD (as well as an outlook to the 21st century) the proxies help to gain insight in the long-term changes in climate and hydrology in the Maas basin.

1. Introduction

1.1 General background

Climatic changes have been occurring throughout earth history. Palaeoclimatologic studies show a long record of alternating colder and warmer periods. Around 11,500 years ago, the present warm (interglacial) period began. Over the past decades, however, the rate of change has increased at an unusual speed. Most climate scientists suspect that this acceleration is at least partly caused by human activity (IPCC, 2007).

To get a better understanding of the current and future changes in climate, many climatic models have been developed. The advantage of these models is their ability to provide quantitative and objective data. Prior patterns in precipitation and temperature can serve as a good indicator for future changes and therefore, most models are based on climate reconstructions. However, different models can display very different outcomes, partly because of the short timescales on which input data are often based. Records of meteorological measurements tend to provide a realistic input for near-future scenarios, but as the climate has a tendency to change on both the short term and long term scale, it is not enough to rely only on measurements from the last century. Knowledge of the long-term (centennial to millennial scale) climatic fluctuations is therefore needed to understand climate evolution and predict future climatic changes. In addition, long climatic evolution trends provide a wider range of climatic extremes than short-term climate changes (Vandenberghe, 2008).

1.2 Project outline and framework

The CS09-project is part of the Dutch National Research program Klimaat voor Ruimte (Climate changes Spatial Planning). This program focuses on the effects of climate change and possible methods to deal with climate change. It is developed to offer different stakeholders (including several Dutch governmental ministries and agencies, the private sector and non-governmental organisations) high quality and accessible knowledge on the interface of climate change and spatial planning. In addition, it is meant to engage a dialogue between stakeholders and scientists, thus facilitating the development of strategies that anticipate for climate change and contribute to safety and sustainability (Vandenberghe, 2008). This project is carried out under the theme Climate Scenarios (CS), focusing on the objective 'assessing the future by mining the past climate'.

For Western Europe, an increase in precipitation during wintertime is expected for the near future, while droughts might occur more frequently during summer time (Klein Tank and Lenderink, 2009). These expected changes have a direct impact on both river discharges and surface runoff, thus on societal and economic important processes like river flooding and soil erosion, especially in a densely populated and flood-susceptible country like the Netherlands. Therefore, the outcome of the CS09-project provides a valuable background for understanding the processes that drive changes in discharge regimes and flooding frequency. The focus of the program is on the downstream part of the basin of the rain-fed Maas River. Finally, it has to be stressed that the project aims to create a reference framework for understanding the evolution of flooding (frequency) and the impact of specific driving forces on flooding, rather than to provide precise predictive values of flood magnitude and frequency.

Furthermore, the CS09-project makes it possible to analyse not only the impact of climatic change, but also the impact of land-use change. Therefore, precipitation and discharge values are compared both before and after substantial human influence, thus assessing the impact of natural climatic variability versus land cover changes. The period 4000-3000 BP is chosen as natural reference, because the natural climatic forcings were broadly similar to the present-day ones and human influence was minimal (Goudie, 1992; Ward, 2008b) as opposed to the period 1000-2000 AD. Human influence is restricted here to land use, while man-made constructions (e.g. river dams and embankments; see for instance Lemin et al. (1987) and de Wit,(2009)) were not considered. For a longer framework of evolution of the Maas river system and a comparison with similar European river systems, we refer to studies by, for instance, Vandenberghe et al., (1994) and Huisink (1997).

This study is not only dealing with late Holocene precipitation and discharge, but also gives an outlook to the 21st century. Climatic fluctuations, especially concerning precipitation characteristics, tend to show a high variability. In order to get an accurate view of extreme weather frequency, a millennial timescale based on the Holocene is thought appropriate, as opposed to the ~150 year record of modern measurements (Cremer et al., 2010). This long-term approach is quite rare within climate modelling and is therefore considered to be of extra value.

1.3 Objectives and key questions

The overarching objective is to increase understanding of the interaction between climate (change) and human impact in the Maas basin. To reach this goal, the CS09-project aims to combine the strengths of modelling with those of proxy reconstruction.
The CS09-project consists of four subprojects, integrating novel proxies with a traditional sedimentological approach and with a coupled climate-hydrology model. The development of new proxies for precipitation and discharge reconstruction is important, while these proxies could be used for the fine-tuning of climate models and for the construction and evaluation of adaptation strategies. In addition, they are of morphological and ecological value: they have potential to be used as an environmental proxy, reconstructing past environmental and landscape changes.

The first subproject evaluates a new proxy for precipitation reconstruction, provided by the hydrogen isotopic signal in the leaves of *Sphagnum*, which is totally rain-fed (Brader, submitted). The second subproject examines the usability of another new proxy: isotopic mollusc shell composition. This proxy could possibly be used to reconstruct flooding events, as the shells of these organisms reflect water provenance and chemistry and thus varying river conditions (Versteegh et al., 2009). The third subproject uses a more traditional approach: sediment and palaeobotanical analyses are carried out to reconstruct and quantify precipitation forced discharge changes and land-use forced sedimentation changes. The fourth subproject uses a spatial modelling approach to be combined with the proxy-based reconstructions. Coupling a climate model (simulating precipitation evolution during the Holocene) with both a hydrologic model (simulating river discharge and flooding during the Holocene) and a soil erosion and sediment-delivery model (simulating sediment yield during the Holoence), this subproject describes the interactions between climate, discharge, and sediment yield at different time scales (Ward, 2008b).

The subprojects in this study have in common that they focus on palaeoprecipitation values and flooding events, thereby contributing to the two general objectives of the CS09-project. The first objective is to provide a framework of quantified, natural precipitation (mean annual precipitation, mean variability, amplitude and frequency of extreme precipitation events), functioning as a reference for possible future precipitation averages and extremes (objective 1).

With regard to this first objective, the following key questions are addressed:

- What was the mean annual precipitation in 4000-3000 BP?
- What was the amplitude and frequency of extreme precipitation events between 4000 and 3000 BP?
- In what way can hydrogen isotope fractionation in *Sphagnum* function as precipitation proxy?

Secondly, the impact of past precipitation fluctuations on river flooding and discharge (frequency and periodicity) is assessed, both under natural and anthropogenic conditions over different time scales (objective 2).

With regard to this second objective, the following key questions are addressed:

- What was the frequency of river flooding 4000-3000 BP?
- What is the degree of correspondence between mollusc-based reconstructions and modelling?
- How accurate are high river discharges as reflected in the input of clastic sediments and the accompanying reworked pollen?

Examining the link between precipitation and flooding, these objectives are integrated in the following key questions:

- How does periodicity of flooding correspond with periodicity of high precipitation events?
- How may precipitation events, river behaviour and human influence be linked in a numerical simulation model?
- How may such a model be useful to predict the impact of future precipitation variability on river hydrology and sediment transport in rivers?

Combined, the subprojects provide a multi-disciplinary approach focusing on ecological, geochemical, hydrological and modelling disciplines, thus enhancing the strength of the reconstructions. In chapter 2, the framework of intrinsic and external river system factors is provided, as well as a brief overview of the different subprojects. Subsequently, the main focus is on the overall results relating to the two key questions posed above, thereby integrating the results of the different subprojects.

1.4 Site description

The importance of research into the effects of climate change on river activity in The Netherlands has been acknowledged for several decades (Ward, 2008b; De Wit, 2009). Until now, most attention in The Netherlands was paid to the Rhine River (Pfister et al., 2004; Erkens, 2009), but the Maas River deserves also attention, because of its long trajectory on Dutch territory and its flooding history. In 1993 and 1995, the Maas and its tributaries overflowed their banks, causing considerable economical damage. Since then, numerous studies have been carried out, focusing on the hydrological changes in the catchment during the 20th century, showing an increasing discharge towards the end of the century (Stam, 2002). In 2003, on the other hand, the Maas catchment experienced a drought, i.e. a negative discharge extreme. The focus on the CS9-project on the Maas basin differs from other projects in its longer time scale, because it takes Holocene discharge fluctuations into account. Furthermore, it incorporates basin-wide soil erosion and sediment yield. It also provides an outlook to the future by simulating discharge and flooding during the 21^{st} century.

The Maas basin can be considered as a medium to large catchment, with an area of ca 33,000 km2. The river is predominantly rain-fed and originates in northeastern France, on the Langres Plateau. It stretches over approx. 900 km towards Rotterdam in the southern Netherlands, where it flows into the North Sea (Figure 1.1). Mean annual precipitation over the basin is approx 950 mm/a. This amount is mainly influenced by topographical factors as elevation and distance from the coast and is quite evenly distributed throughout the year. A remarkable difference can be seen between annual potential evapotranspiration during summer and winter, the prior contributing to over three quarters of the total. At Borgharen (near the Belgian-Dutch border), average discharge is 275 m^3/s and peak discharges of 3000m^3/s have been registered. Summer and winter half-year mean discharges are 146 m^3/s and 406 m^3/s respectively (Ward, 2008b).

The different subprojects focus on different parts of the Maas catchment. The *Sphagnum* calibration set is sampled throughout Europe and Holocene peat moss is cored in the NE part of the Hautes Fagnes (Brader, in prep.). As for the freshwater bivalves (subproject 2), both the Rhine and the Maas basin are taken into account. The research has been carried out in the Dutch part of both basins, i.e. the Rhine-Maas delta. The third subproject is located in palaeo-channels and scour hole lakes ('kolks') at different distances from the Maas. The fourth subproject focuses on the Maas basin upstream of Borgharen for three reasons. Firstly, this area provides the longest observed discharge time-series in the basin. Secondly, water management practice in the Netherlands uses daily discharge observations at Borgharen in the estimation of flood periodicity. Thirdly, downstream of Borgharen, the location of the Rhine-Maas confluence has changed during the Holocene.

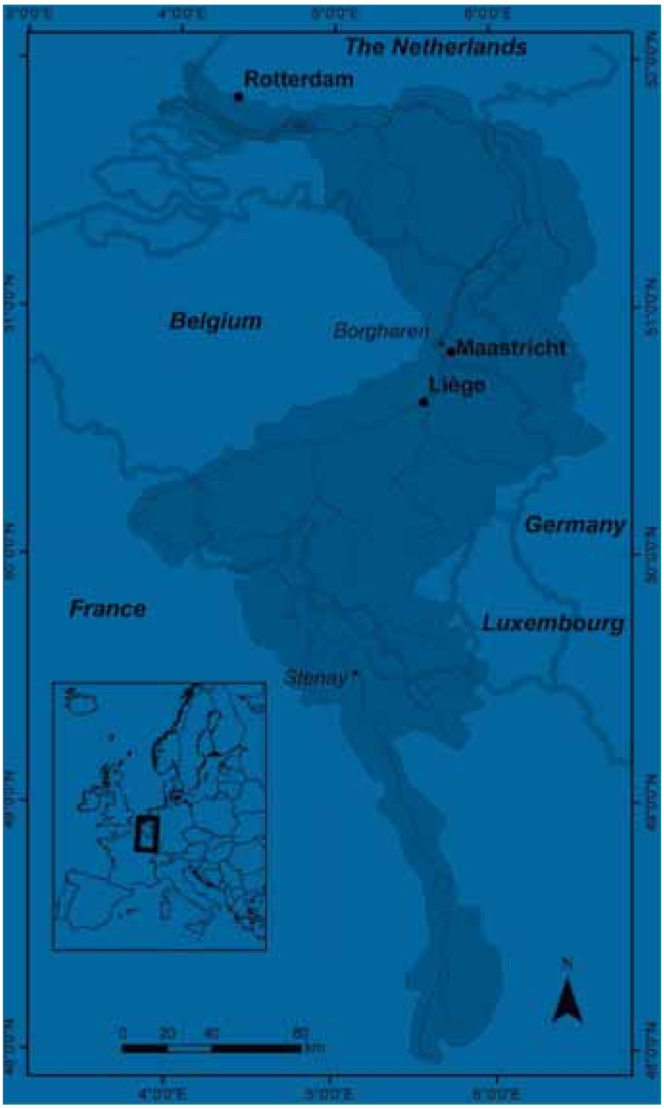

Figure 1.1.
Location of the Maas basin. The inset shows the location of the Maas basin in Europe (Ward, 2008b; after RWS Limburg, IWACO, 2000).

2. Methodology and approach

One of the strengths of the CS09-project lies in its multiple-approach nature, coupling benefits of proxies and models. By combining the development of proxies for palaeoprecipitation and discharge with the creation of a numerical model that links these two parameters, a detailed, trustworthy outcome is attempted. Proxy records (e.g. hydrogen isotope ratios from palaeobotanical remains) form a high-resolution representation of the climatic past, thus giving insight on the frequency, intensity and periodicity of Holocene precipitation and river discharge. The model can be used to detect large-scale trends and to predict future changes.

In the next paragraph, an overview of the intrinsic and external factors influencing the basin is given. This overview can then function as a framework for the four different subprojects. The subsequent paragraphs provide an overview of the novel methodological aspects of each subproject.

2.1 Cause-and-effect framework of the Maas catchment

The Maas river system is constantly subject to change, both due to human influence and natural events. This change is inherent to a river system and forms a complicating factor when developing water management strategies; to determine the appropriate approach knowledge of the factors influencing the system is necessary.

Steering factors	**Variables**	**Parameters**	**Effects**	**Measurements**
Tectonics * Long term	Discharge	Vegetation	Socio-economic	Source
Climate * Decennial to millennial	Sediment	Land use	Health	Adaptation
Human impact * Decennial to millennial		Soil	Nature	
Natural evolution * Decennial to millennial				

Figure 2.1.
Relation between factors and effects in the Maas catchment.

The factors influencing a river system can be subdivided into intrinsic and external steering factors. The intrinsic factor is natural evolution: the balance between the transport capacity of a river (energy and discharge) and the sediment load (Schumm, 1977). Energy of the river is determined by its gradient (longitudinal slope), apart from the discharge. However, at the short time scale we are dealing with, the gradient may be considered as approximately constant. A relative sediment excess results in net sedimentation, a water excess results in net erosion. This equilibrium is dynamic; the river is constantly regulating itself to maintain an optimal balance. The external factors comprise tectonics, climate change and human impact (e.g. land use). Since the Maas basin is located in a tectonically stable environment, only climate change and human impact are considered relevant on a Holocene timescale.

These steering factors influence the discharge, energy and sediment load of a river system; parameters like soil type and vegetation determine the extent of the influence (figure 2.1). Concerning the effects, three main categories can be discerned: socio-economic effects, health effects and environmental effects. To avoid these negative effects, two types of water management related measures can be made: measures regulating the source factors (human influence and climate change) and adaptation strategies, cancelling out the negative effects of climate change and human impact. To make these measurements effective on the long run, analysing the interaction between water management, climate change and human influence is of utmost importance.

2.2 Precipitation reconstruction by hydrogen isotope signature in *Sphagnum*

Subproject 1 focuses on precipitation reconstruction by hydrogen isotope fractionation in *Sphagnum* leaves (thus representing objective 1). Peat moss (*Sphagnum*) forms the main constituent of raised bog ecosystems. These mosses are totally dependent on rainwater. As rainfall and humidity are the important factors in determining the hydrogen isotope signature of plants, the isotope fractionation of hydrogen is expected to reflect precipitation characteristics.

A number of external factors determine the isotope ratios in *Sphagnum* tissue: altitude, latitude, temperature, precipitation and relative humidity. Subsequently, metabolic and biosynthetic processes determine isotope fractionation within this plant. Before it is possible to analyse the effect of precipitation on fractionation, the influence of these internal factors must be examined.
The subproject started with a greenhouse pilot project. Three samples of *Sphagnum* (collected from Bargerveen in the NE part of the Netherlands) represent three genetically and ecologically distinct species, thus making it possible to examine the influence of *Sphagnum* species on the hydrogen isotope signature (Brader et al., submitted, 1). Hydrogen isotope fractionation is correlated with precipitation, while the lighter hydrogen isotopes become more depleted with increasing precipitation. Therefore, a relation between precipitation values and hydrogen isotope fractionation was expected.

Subsequently, a calibration set representing different areas and precipitation regimes was created. After harvesting the different species, the hydrogen isotope ratio was analysed using gas chromatography mass spectrometry. For each species, isotope fractionation was examined for three components: cellulose (principal cell wall component), bulk organic ratio and n-alkanes (chain lipids in the cell wall preventing water loss). Statistical analysis is done to determine mean and standard deviation of the isotopic values. Thus, the link between hydrogen isotope signature and precipitation is examined and evaluated against species dependency. The outcome is used to investigate the hydrogen isotope ratio of Late Holocene peat (Brader, submitted, 1). Finally, the knowledge on isotope fractionation described above is applied on the period 4000-3000 BP. In combination with palaeobotanical proxies, the Subboreal/Subatlantic boundary is documented, a transition related to a shift from continental to oceanic climate (Brader, in prep.).

2.3 Geochemistry of freshwater bivalves as a proxy for river dynamics

The potential of freshwater bivalve chemistry as a proxy for Holocene river conditions was examined by means of a monitoring experiment and shell analysis.
Subproject 2 (Versteegh, 2009) focuses on the use of freshwater mollusc shells to reconstruct river discharge and flooding, thus representing one of the key questions of objective 2. Freshwater molluscs are known to reflect the geochemistry of the ambient water in their shells, such as isotope ratios of stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$). Due to detailed analytical techniques, information on hydro-geochemistry can be obtained on a high temporal scale. The molluscs in this study are freshwater mussels, belonging to the bivalve family *Unionidae*. The $\delta^{18}O$ ratio of freshwater bivalves has proven to be a valuable proxy within palaeohydrology and has been used to detect changes in water source, discharge and rainfall patterns. In this study, $\delta^{18}O$ and $\delta^{13}C$ compositions are applied as environmental and palaeohydrological proxies. Possibilities and limitations of this method are examined.

In the first stage of subproject 2, special monitoring cages were developed in which the freshwater mussels could be observed. The cages consist of a partly sediment filled PVC box with a perforated stainless steel lid and a streamlined front. Three *Unionidae* species were collected, tagged and put in the cages: *Anodonta mollusk, Unio pictorum* and *Unio tumidus*. Subsequently, a number of shells was embedded in epoxy resin, thereby enabling drilling transverse sections of 300 μm perpendicular to the growth lines (Versteegh, 2009). The individual growth increments of these shell samples were then analysed for changes in $\delta^{18}O$ and $\delta^{13}C$ isotope ratios. Shells originated both from the monitoring cages and from shell archives representing selected 20th century time intervals. For all the periods, river water data were available. $\delta^{18}O$ and $\delta^{13}C$ isotope ratios were calculated with mass spectrometers for both river water and mollusc shells to establish the relation between water and shell isotope ratios (Versteegh et al., 2010a). Based on this relation, a growth model was constructed, exhibiting fast shell growth in June and growth cessation in winter. The model was used to analyse the dependence of shell isotope ratio on river water conditions and on possible additional environmental parameters. Finally, the use of freshwater bivalves as a proxy for quantification of past Maas records was tested.

2.4 Reconstruction of flood frequency by pollen, diatom and sedimentological proxies

In subproject 3, high river discharges have been reconstructed by means of several traditional palaeobotanical and sedimentological proxies. Pollen analysis of abandoned channel-infill shows that the Maas valley was completely covered by forests during the Late Holocene. As the forest zonation is highly dependent on groundwater levels, shifts in floodplain species composition probably indicate changes in river discharge. In addition, it can be expected that high and low discharges are reflected in changes in sediment accumulation rates, grain size and pollen concentration (Donders et al., 2008).

Therefore, both high-resolution sedimentological research and pollen and diatom analyses have been carried out on a decadal scale. Palaeo-channels at different distances from the river have been selected, while those in proximity to the river may suffer from erosion and those further away may not register flooding-related phenomena. Sediment and pollen have been acquired by coring. Age assessment of the drilled sediments is based on flood events registered by magnetic susceptibility features, volcanic ash layers and radiocesium activities in the upper layers (Cremer et al., 2010).

2.5 Simulating discharge and sediment yield characteristics in the Maas basin

For subproject 4, a coupled climate-hydrological model for simulating Holocene discharge was developed. The model is a combination of two existing models: the ECBilt-CLIO-VECODE (a 3D climate model describing atmosphere, ocean and vegetation) and the STREAM model (a grid-based spatially distributed water balance model).

The first step was spatial downscaling from the 5.6°x5.6° climate model grid to the 0.5°x0.5° run-off model grid. While this spatially downscaled model was still too coarse, a second (statistical) downscaling step was applied. Precipitation values were simulated by running the ECBilt-CLIO-VECODE climate model, both for 4000-3000 BP and 1000-2000 AD. The run was transient, reflecting annual fluctuations in orbital parameters, atmospheric greenhouse gas concentrations, atmospheric volcanic aerosol content and solar activity. The use of four ensemble members (representing the same climatic parameters, but with slightly different initial conditions to simulate chaotic atmospheric behaviour) ensured natural variability. Next to these climate data, the STREAM model also used discharge data and data on soil and hydrography as input data.

The coupled model was validated against Holocene palaeohydrological records of 19 rivers for Early Holocene (9000-8650 BP), Mid Holocene (6200-5850 BP) and recent (1750-2000 AD). Model results were compared with palaeodischarge estimates from multi-proxy records (Aerts et al., 2006; Ward et al., 2007).

The coupled model was then used to simulate daily Maas discharge during 4000-3000 BP (natural situation) and 1000-2000 AD (anthropogenic influence) (Ward et al., 2008). Both climate and land use data were used as input data.

Subsequently, the model was used to simulate discharge in the 21st century under SRES emission scenarios A2 and B1 (IPCC, 2007; Ward et al., 2011). Scenario A2 (high CO_2-emission) depicts the world in regions striving for self-sufficiency. The B1 scenario (low emission) depicts good international cooperation on reducing the emission of greenhouse gases. In addition, use is made of the WATEM/SEDEM model to simulate sediment yield during 4000-3000 BP, 1000-2000 AD and the 21st century (Ward et al., 2009).

3. Results

In this chapter, the results of the different subprojects focusing on the amount of precipitation and river discharge are presented, as well as results concerning the influence of climatic and anthropogenic changes on flooding and fluvial sediment transport. Together, the results facilitate comparison of climate scenarios with palaeoclimatic fluctuation. Although a first step is made towards a framework of quantified, natural precipitation variability (objective 1), exact proxy data cannot be provided yet. Some parts of the proxies are more complex than expected and the investigation of their palaeoclimatic significance is still continuing.

3.1 Precipitation: proxy and model results

A greenhouse pilot study carried out in subproject 1 shows that a special kind of n-alkanes (the cell wall lipids) have a strong influence on the isotope fractionation (Brader et al., 2010, submitted 2). While the composition of this C23 n-alkane differs for different species, the isotope fractionation also differs in between species, creating a unique fractionation signature. Atmospheric isotope ratios are reflected both in cellulose and in lipids of *Sphagnum*, but δD from C23 n-alkanes is a more precise proxy for isotopes in precipitation than $\delta^{18}O$ from cellulose. This outcome was used in the production of a calibration set: for various species throughout Europe it was analysed how isotope ratio is altered by internal fractionation (figure 3.1).

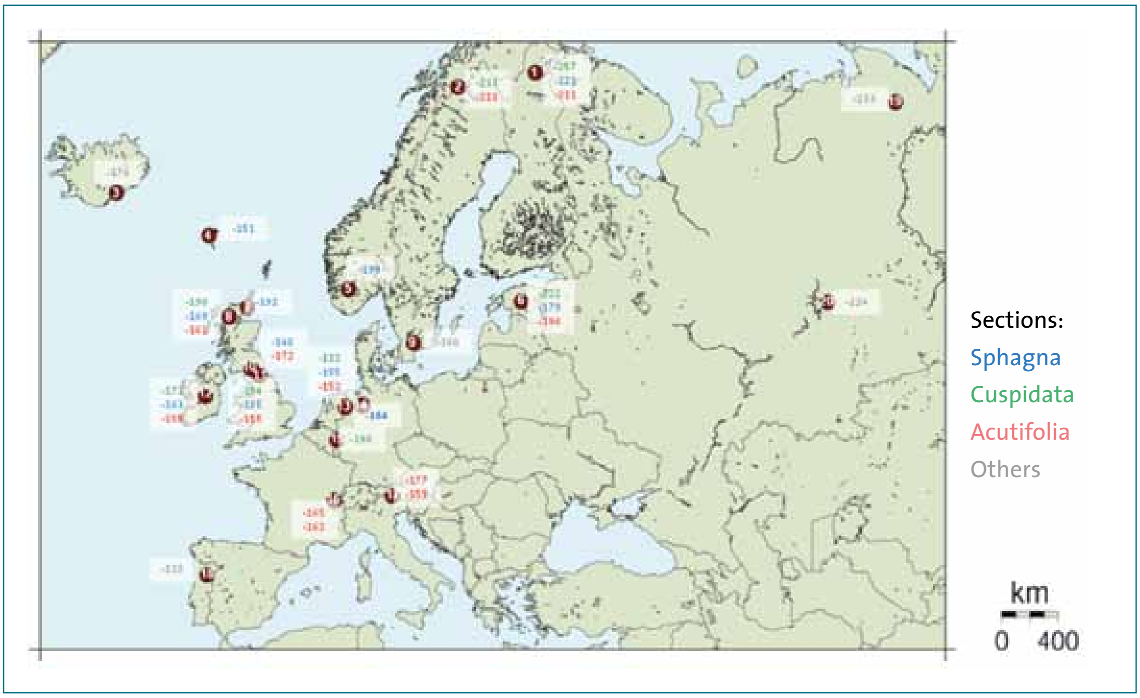

Figure 3.1.
δD of C23n-alkanes (Brader, 2010).

Figure 3.2 shows a clear SW-NE trend, both for atmospheric isotope ratio (more depleted towards the north) and temperature. However, the amount of precipitation does not follow such a clear SW-NE trend; the precipitation amount tends to vary considerably from one place to another.

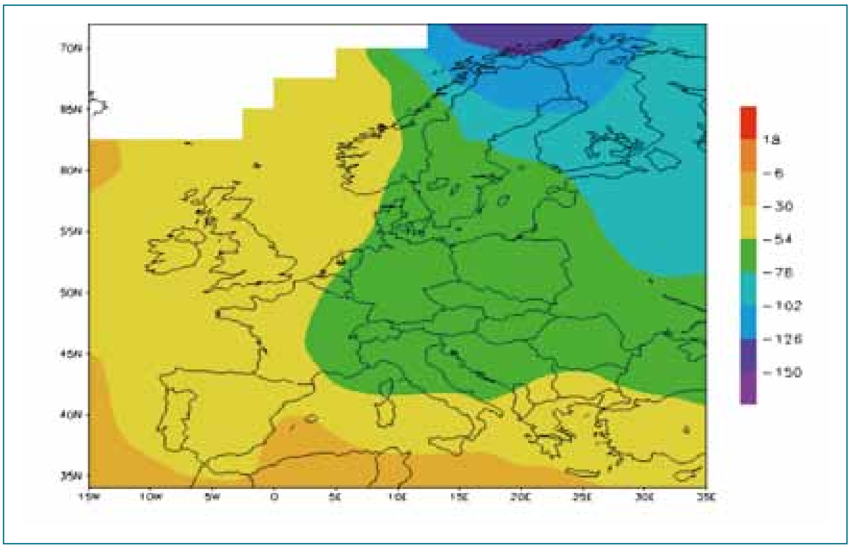

Figure 3.2(a).
Observed weighted annual ∂²H atmospheric isotope ratio, (IAEA/GNIP monitoring program) (Brader, 2010).

For 4000-3000 BP, simulated mean annual precipitation is 882 mm/a; for 1000-2000 AD, the precipitation amount is slightly higher (895 mm/a). Mean summer half-year precipitation increases significantly between the two periods, mean winter half-year precipitation decreases significantly (Ward et al., 2008).

There is no significant monotonic trend to be found for mean 50-year precipitation, neither over the 4000-3000 BP period nor over the 1000-2000 AD period. During the 20th century, mean simulated annual precipitation is 912 mm/a; this is the largest mean centennial precipitation of all of the centuries studied . Precipitation amounts on very wet days (95th and 99th percentiles) are greatest during 4000-3000 BP. Over 1000-2000 AD, there is an increase in precipitation depths during the 20th century.

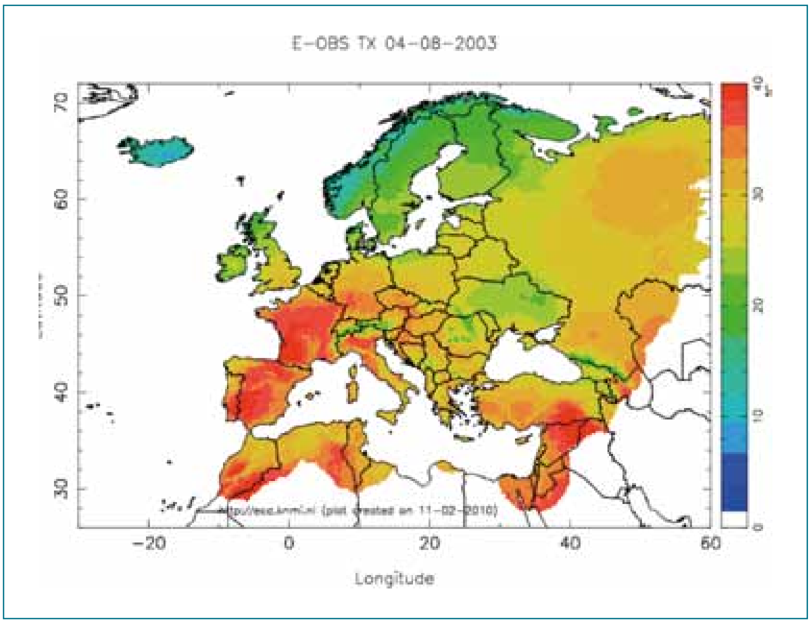

Figure 3.2(b).
Temperature isotherms (European Climate Assessment & Dataset) (Brader, 2010).

For the 21st century, significant positive trends are simulated for mean annual precipitation, both under scenario A2 and B1. This increase is especially expected in winter, spring and autumn. In the first half of the 21st century, hardly any difference in mean annual precipitation is expected between the scenarios; A2 will experience a stronger increase during the second half of the century (Ward et al., 2011).

3.2 Discharge

3.2.1 Mean discharge

In subproject 2, the relationship between oxygen and carbon isotope composition in freshwater mollusc shells was used to develop an intraseasonal growth rate model. Monitoring shows that shell $\delta^{18}O$ match the predicted growth value based on water $\delta^{18}O$ and water temperature. The same holds for the seasonal range of $\delta^{18}O$ values, except for the winter, when the molluscs do not grow. Onset and cessation of growth are mainly influenced by water temperature. In summer, water$\delta^{18}O$values in the Maas are higher than in winter, due to evaporation and enriched summer rainfall (fig. 3.3). Shell $\delta^{18}O$ shows an opposite trend, with sharp upward peaks in $\delta^{18}O$ representing winter growth cessation and lower values in summer.

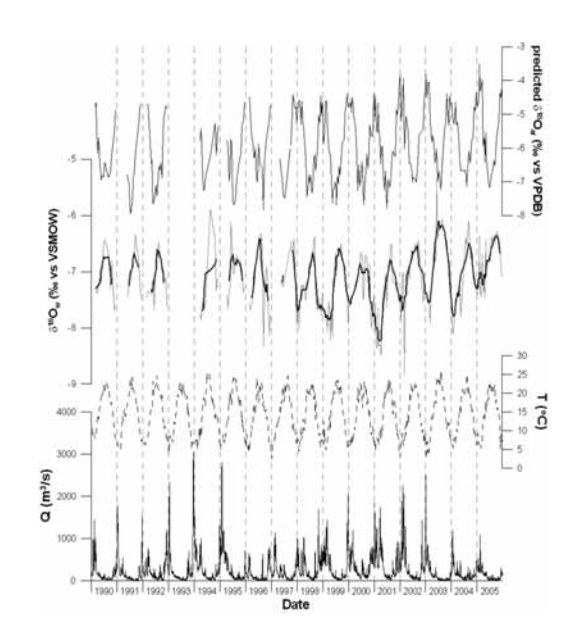

Figure 3.3.
Discharge (Q) plotted with water δ18O values, water temperature (T) and predicted shell δ18O values. The Maas has high discharge and low water δ18O values in winter (Versteegh, 2009).

The model simulations from subproject 4 show that mean discharge and flood frequency of the Maas are significantly higher during the period 1000-2000 AD than during 4000-3000 BP (Ward et al., 2008). The increase in mean summer half-year discharge was much larger than for mean winter half-year discharge (+21.6% compared to +2.3%). Discharge in the 20th century was higher than during the preceding period, while there was no significant difference in interannual variability. Over all, discharge shows an increasing monotonic trend during the period 1000-2000 AD. Long-term changes in mean 50-year discharge are shown in figure 3.5.

Within the 21st century, mean 50-year discharge is simulated to increase more than during the entire period stretching from 4000-3000 BP to 1000-2000 AD (to more than 300 m^3/sec), especially due to strongly increasing winter season discharge (Ward et al., 2011). For the second half of the 21st century, an increase in summer discharge is simulated both under scenario A2 and scenario B1, despite a summer precipitation decrease and a relatively stable actual evapotranspiration (AE). However, the modelled increase in precipitation during autumn, winter and spring leads to an increased ground water storage and thus to an increase in summer discharge.

3.2.2 Flooding events

Peak discharges cannot be reconstructed from the bivalve-proxy data because of the logarithmic relation between the Maas discharge and water δ18O. This logarithmic relation means that water δ18O values will only differ slightly between normal and extremely high summer discharge situations; therefore, it is difficult to interpret past flooding events. In contrast, summer drought (negative extreme discharge) may be reconstructed in particular; low discharge events up to 6 m^3/sec during the 20th century can be detected (Versteegh et al, 2010b).

In subproject 3, a 400-year sediment record from a scour hole lake near the Maas River has been investigated for flooding frequency and landscape change by means of sedimentological and palaeobotanical analysis. Flooding events are recognized by coarse-grained layers in the otherwise fine-grained sediment while peaks of Pinus pollen are indicative for river transport from the hinterland. Furthermore, the aquatic plant pollen diversity is high, while the overall decreased pollen influx points to a sediment rich river influx into the lake. In figure 3.4, both the historically known events and the ones inferred from the multi-proxy data are shown.

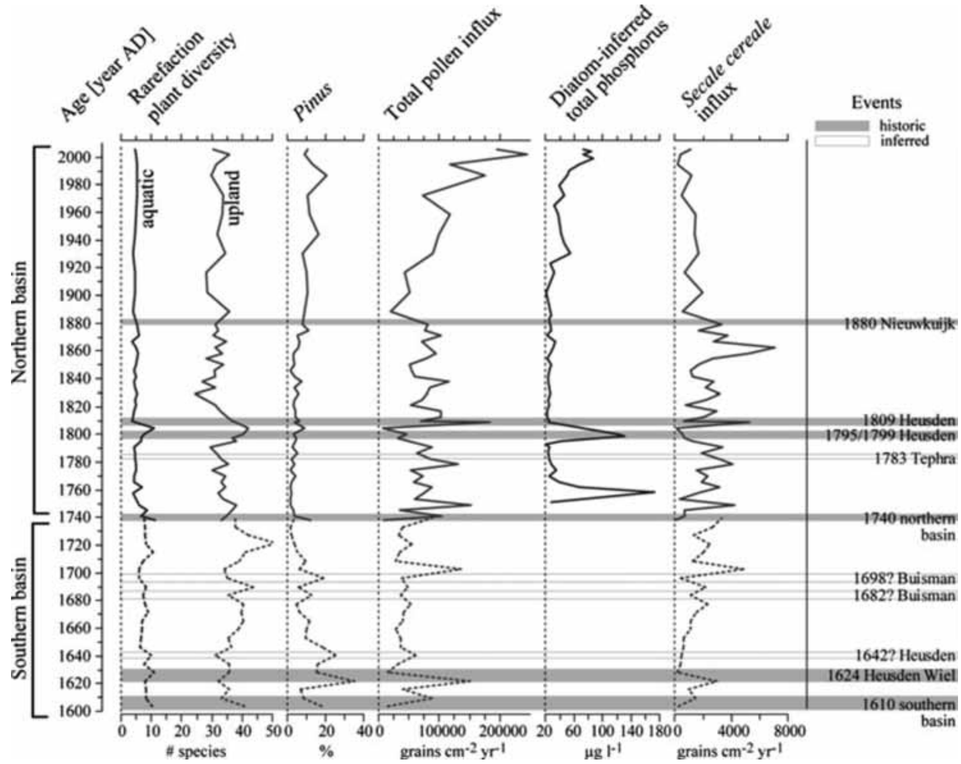

Figure 3.4.
Compilation of several individual proxy records (pollen diversity, total phosphorus (TP), and polleninflux) demonstrating a response to the basin flooding events since AD 1610. Grey lines represent historic events; white lines inferred events (Cremer et al., 2010).

Based on the coupled climate-model simulations, it can be seen that the frequency of high-flow events increased between 4000-3000 BP and 1000-2000 AD. The results show that this is especially the case for very high discharge in excess of 3000 m^3/s (Ward et al., 2008); the recurrence time decreased from 77 years in the period 4000-3000 BP to 65 years in the period 1000-2000AD.

In the 20th century, high-flow events occurred even more frequently than in the rest of the millennium. The recurrence time of high flow events with a discharge in excess of 3000 m^3/s decreased further still to 40 years; this is almost twice as often as was the case under natural conditions (i.e. 77 years, 4000-3000 BP) (Ward et al., 2011). However, although the frequency of these large high-flow events was particularly great during the 20th century, there are other 100-year periods in the simulation results in which the flood frequency was similar, and hence it does not exceed the bounds of natural variability.

For the 21st century, an increase in the frequency of high flow events can be seen both for scenario A2 and B1, for different flood magnitudes. (Ward et al., 2011). For example, high flows with a discharge over 3000 m^3/s are simulated once per expected 20 years (A2) or 25 years (B1). The main causal mechanism for the increase in the frequency of extreme floods (return period 1250 years) is the projected increase in winter precipitation.

3.3 Human influence

It is possible to study the effect of land use change by analysing the pollen composition from different time periods (Cremer et al., 2010). Figure 3.5 shows a decrease in cereal pollen and an increase in grass pollen after 1875 in the Haarsteegse Wiel, because of overseas import and conversion to pasture lands. Until around 1870, (buck)wheat and hemp cultivation was dominant. Afterwards, the pollen amount of these species decreased and the amount of Poaceae pollen (indicating pasture land) strongly increased (Cremer et al., 2010). The pollen assemblages also indicate changes in lake water quality. In the 18th and 19th century, the scour hole lake has an intermediate nutrient content (i.e. mesotrophic), which is rather unexpected in a nutrient-rich downstream river floodplain (Cremer et al., 2010). This relatively nutrient-poor state might be due to the fact that flooding was sporadic. The lake is mostly fed by rainwater and nutrient-poor groundwater. From the late 19th century onward, the lake became eutrophic due to increased flooding and subsequent intensified land use and use of artificial fertilizers (Cremer et al., 2010).

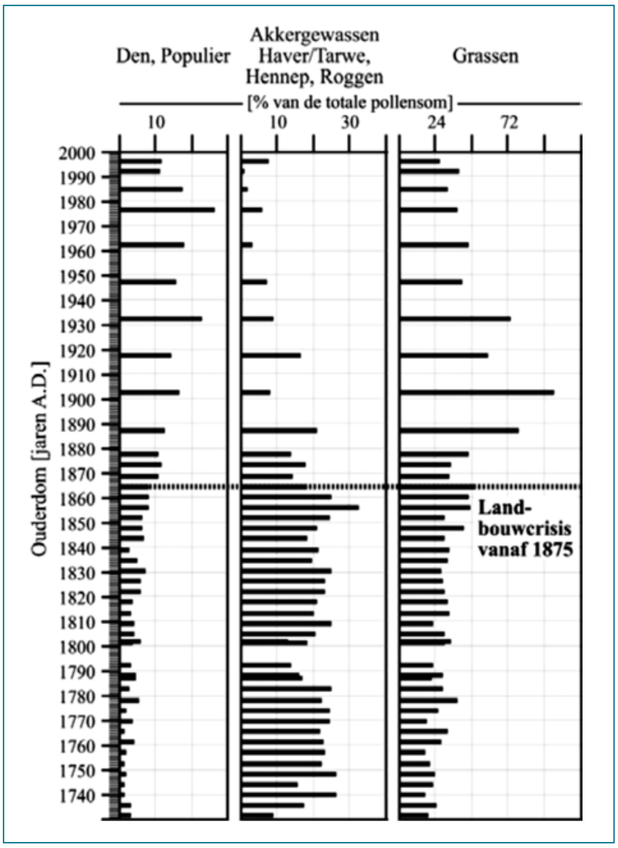

Figure 3.5.
After 1875, the amount of cereal pollen decreased and the amount of grass pollen increased (Cremer et al., 2009).

Further model experiments were carried out to quantify the separate and combined influences of long-term change in both climate and land use on discharge and flood frequency. This was achieved by carrying out the experiments for the periods 4000-3000BP and 1000-2100AD, but only allowing one parameter (climate or land use) to vary at a time, whilst holding the other parameter constant. The model experiments show that the increase in mean discharge (especially during summer) and flood frequency between 4000-3000 BP and 1000-2000 AD (and especially between 4000-3000 BP and the 20th century) is caused primarily by large-scale changes in land use (deforestation) during this period. These changes led to a decrease in evapotranspiration, and thus increasing discharge. Over the 20th century, reforestation took place, but discharge increased further compared to the 19th century. The simulation results show that on this timescale, changes in climate (specifically a strong increase in simulated annual and winter precipitation) were the main causal mechanism of this increase; the effects of the former overwhelmed the influence of land use change on this timescale (see 3.4.4; Ward, 2008b).

In the 21st century, the change in simulated land use is very dependent on the scenario used. For this study, the 'Continental Market' and 'Global Cooperation' scenarios of EURURALIS were used, which correspond to the storylines of the climate emission (SRES) scenarios A2 and B1 respectively. Under A2, total changes in land use are small, due to urbanisation and agriculture. In the Maas basin, agriculture plays the main role. Under the B1 scenario, forested area increases by 2%; agriculture decreases by 2% (Ward, 2011). Over the 21st century (compared to the 20th century), climate change dominates the influence on the discharge and flood frequency of the Maas, whilst the impact of land use change is small (for both land use change scenarios). Other studies on the effects of land use change on peak-flows show mixed results (see Ward et al., 2011, and references therein). Cosandey et al. (2005) state that the effects of deforestation on flood generation are less severe during large-scale, low intensity (frontal) rainfall events; most of the high flows on the Meuse occur during such events. According to the model results, under the minor land use change projected for the 21st century, changes in forest cover will have a small influence on flood frequency in the near future.

3.4 Sediment yield

Knowledge about sediment yield (SY) is important since sediment delivery into rivers is responsible for supply of nutrients, pesticides and heavy metal contaminants to the water. Moreover, soil erosion can cause many environmental problems and economic problems. To simulate the sediment yield, the WATEM/SEDEM model has been used (Verstraeten et al., 2002); the required input data are: digital elevation (influencing gradient), soil erodibility factor (soil susceptibility to rainfall erosion), rainfall erosivity (erosional impact of rain based on amount and intensity of precipitation) and crop factor (susceptibility to water erosion).

Long-term simulation shows an increase in sediment yield between 4000-3000 BP (92000 Mg/a) and 1000-2000 AD (306000 Mg/a). While rainfall erosivity has been fairly constant over the last millennia, the majority of the increase in simulated SY is caused by changes in land use change. Due to foreign imports, crop cultivation decreased regionally from the end of the 19th century (Cremer et al., 2010). The reforestation and urbanisation in the 20th century lead to a slight decrease in SY (281000 MG/a), as forests tend to decrease rainfall erosivity and soil erosion (Ward et al., 2009). However, as the total amount of deforested land increases, sensitivity to rainfall erosion increases.

For the 21st century, changes in SY are highly dependent on land use change. For both scenarios, climate change only will lead to an increase in SY (due to rainfall erosivity), but this is overwhelmed by a decrease in sediment yield due to reforestation, especially in the B1 scenario, thus leading to a net decrease. (Ward et al., 2009).

4. Discussion

In this chapter, the results obtained by the different subprojects are discussed. Firstly, the use of novel methodologies is discussed. Secondly, the focus is on precipitation and discharge quantification during the late Holocene.

4.1 The use of hydrogen isotope fractionation in *Sphagnum*

It is important to know in what way internal fractionation processes could play a role in the isotope signature of *Sphagnum* before its significance as a proxy for palaeoclimatic reconstruction can be evaluated. It appears that the difference between actual isotope signature and the expected internal fractionation signature in a known *Sphagnum* species is caused by external fractionation, for instance by evaporation. Thus, fractionation of oxygen and hydrogen isotopes as recorded in *Sphagnum* is a function of temperature and not of precipitation and no quantification of past or present precipitation values is possible by means of this proxy (Brader et al., submitted 2). However, this result can be used to interpret certain climatic changes in a qualitative way: the obtained knowledge has been used analysing a Late Holocene peat core with known species composition, showing shifts between wetter and drier periods that cannot be seen by analysing macro plant remains (Brader, in prep.). When making these reconstructions, it is important to use *Sphagnum* samples with a known species composition. (Brader, submitted 1 and 2).

4.2 The use of isotope ratio in freshwater bivalves

Although quantification of discharge remains problematic, some discharge trends can be recognized, especially spring-summer river discharge conditions (Versteegh et al., 2010a). The Maas displays a logarithmic relationship between river discharge and water $\delta^{18}O$ values, which allows reconstruction of low discharge episodes. The studied species normally reach an age of ca. 15 years, thus living long enough to analyse decadal and seasonal changes. But, due to their short lifespan and the large interannual environmental variation, mollusc shells cannot be used to record long term climatic variation. A side-discovery from this study is the fact that the difference in water $\delta^{18}O$ values from different sources (rainwater/meltwater vs rainwater) is reflected in the bivalve shells, thus enabling reconstruction of river water sources in ancient river channels.

While water temperature and water $\delta^{18}O$ tend to be more variable in freshwater than in marine environments, freshwater bivalves tend to be more difficult to interpret. To minimise these problems, it is necessary to analyse a sufficient number of shells (>10) from a given climate interval in order to capture the full range of interannual variability (Versteegh, 2009). It is also necessary to cover a sufficiently long period for reliable comparisons over a long timescale.

4.3 Reconstruction of flood frequency by pollen, diatom and sedimentological proxies

This multi-proxy approach enables detection of unknown flood events in sedimentary archives. Although quantification of discharge and flood magnitude cannot be achieved by such reconstructions, it appears possible to qualitatively discern floods and estimate their return times at a millennium sale (Cremer et al., 2010).

The flooding signal in the scour hole lake along the Maas River represents a few centuries, but it is possible to go back in time even further when using long-term records of river dynamics from natural archives such as oxbow lakes and abandoned river channels.

4.4 The use of a coupled climatic-hydrologic model to assess palaeodischarge

A model coupling climate and hydrology had never been used to examine changes in palaeodischarge, and thus the approach chosen in this subproject is novel. The application of the model shows that it forms a useful tool to assess long-term changes in palaeodischarge, especially when combined with multi proxy data. Although this model could not be combined directly with the proxies developed in the other subprojects, it did use all available proxy data from literature. The model was not only useful in linking precipitation and discharge, but also in analysing human influence on land use change. Simulations were made for both a natural reference period (4000-3000 BP) and the past millennium. As the model proved to be accurate simulating palaeodata, it was also used to project future (21^{st} century) precipitation and discharge values under two climate scenarios.

4.5 Effect of actual evapotranspiration on mean and peak discharges

Water surplus, leading to high discharge and flooding, is dependent on both precipitation and actual evapotranspiration (AE). Therefore, long-term changes in discharge are not simply the result of changes in precipitation. No monotonic trend of increased annual precipitation was simulated over the periods 4000-3000 and 1000-2000 AD, in contrast to mean annual discharge, which increased significantly during the period 1000-2000 AD (Ward, 2008a). During summer, precipitation increased only by 5.6 % between 4000-3000 BP and 1000-2000 AD, while discharge increased by 21.6 % (Ward, 2008a). Winter precipitation experienced a slight decrease between 4000-3000 BP and 1000-2000, while winter discharge experienced an increase. These increases in summer and winter discharge were accompanied by AE decrease. For the 20^{th} century, a significant increase is seen for mean annual discharge and AE, as well as a weak increase in precipitation.

4.6 Effects of climate change and human activity on discharge and sediment yield

The influence of land use change depends largely on the type of change. If forested land is converted into arable land, its vulnerability in terms of rainfall erosivity is higher compared to a conversion to pasture (Ward et al., 2009). The effects of land-use change in this study only pertain to the coverage of each land-use type, and not to changes in factors such as land-use intensity (e.g. changes in crop types, irrigation etc.) or water management (e.g. water retention basins). These factors may have a greater influence on discharge. However, the results are indicative of long-term changes in discharge due to the effect of land-use conversion on AE, soil water storage, and soil erodibility (Ward, 2008b). In future, selected scenarios should accommodate the influence of changes in land-use intensity and water management on discharge and sediment yield.

5. Conclusions and recommendations

In order to develop reliable numerical models simulating future climatic and hydrologic changes, it is important to be aware of the long-term trends in precipitation and discharge characteristics. Therefore, the CS09-project was aiming to determine precipitation and flood frequency in the Maas catchment during the late Holocene by means of reconstruction and modelling and to derive the relative impact of changes in climate and land use on river activity. Recommendations and future prospects are mainly derived from Ward (2008b).

5.1 Reconstruction by palaeo-ecological methods

One of the goals of the CS09-project was to develop and evaluate new proxies for reconstruction and quantification of precipitation and flooding. Both methods (*Sphagnum* hydrogen isotope fractionation and bivalve oxygen isotope ratio) prove to be very complex, because more parameters than just precipitation and flooding influence the proxy signal. Although quantification of palaeoprecipitation and palaeodischarge by means of proxies remains problematic, use of these newly developed proxies improves insight in climatic and hydrologic conditions during the Holocene. As each *Sphagnum* species shows a unique internal hydrogen and carbon fractionation signature, these signatures can be used to determine the composition of Holocene peat cores, thus giving insight in the vegetation type and related landscape and climatic settings. Precipitation quantification might not be possible, but the proxy might be able to discern wetter and drier shifts, enabling the derivation of precipitation periodicity (Brader, submitted 1 and in prep.). The study of freshwater bivalves has shown that three mollusc species faithfully record the oxygen and carbon isotope ratios in their environment, making them a useful tool in palaeoclimate research. Preliminary models for interannual and intraseasonal growth rate have been constructed, which could function in future studies to relate growth increments with corresponding time frames, thus making interpretation of palaeorecords possible. A better knowledge of growth strategies of different species in different reservoirs would be desirable. In addition, using a multi-proxy approach within one organism will improve accuracy of river dynamics reconstructions (Versteegh, 2009). Because molluscs have a life span of circa 15 years, their interpretative value is limited for the reconstruction of long-term evolution patterns. For such reconstructions a large amount of individual molluscs should be collected. However, this methodology offers good perspectives for reconstructions at episodic snap-shots.

The use of sedimentological and palaeobotanical data as a proxy provides relatively good data on high discharges in the past, albeit rather on a relative than a quantitative scale. This proxy enables more accurate estimation of past recurrence periods, however (Cremer et al., 2010). Similar conclusions appear from the study of the Geul River, a main tributary of the Maas River on Dutch territory (Stam, 2002; de Moor and Verstraeten, 2008; de Moor et al., 2006). Especially the results of that river point to the continuous tendency of rivers to keep a dynamic equilibrium in order to adapt to external changes of natural (e.g. climate) or artificial origin (e.g. canalisation, channel stabilisation, changes in channel dimensions) (Schumm, 1977; Vandenberghe et al., 2011).

5.2 Modelling

Quantified results on precipitation and discharge are mainly derived from the outcome of the coupled climatic-hydrologic model. As this model has been verified using multiproxy data (Ward et al., 2007), the confidence in this model to simulate past and future changes in precipitation, discharge and flood frequency is high. In addition, the climate model was combined with a model to simulate sediment delivery from the slopes to the river and thus to calculate river sediment yield (De Moor and Verstraeten, 2008; Ward et al., 2009).

On a millennial time scale, land use change (namely deforestation) was found to be the main causal mechanism of simulated changes in mean and peak discharges and sediment yield. However, the frequency of the most extreme floods (return period of 1250 years) was not affected by land use change on this timescale. The simulated increases in discharge and flood frequency between the 19th and 20th century were mainly controlled by increased precipitation, while reforestation and urbanisation led to a reduction in the mean annual sediment yield in the Maas. The latter conclusion, however, is in contrast to Belgian results that report an increase in sediment yield, possibly due to endikement of the Maas that prevented deposition on the natural floodplain (Lemin et al., 1987).
It appears that long-term model simulations of both water and sediment budgets can only been reliably achieved in combination with proxy reconstructions.

5.3 Projected changes in discharge and flood frequency of the Maas River in the 21st century

The different factors (land use and climate change) that have been of influence on the Maas discharge and sediment budget throughout the Holocene will continue to cause a variety of effects, ranging from flooding to erosion or sedimentation. Projected changes were calculated for the A2 and B1 emission scenarios. The model results suggest that increased precipitation will have a stronger influence than land use change on river discharge and flood frequency in the 21st century. The frequency of high-flow events is projected to increase, mainly as a result of increased winter precipitation. Since the projected increase of forest cover in the 21st century is rather modest, its influence on discharge will be minor on this timescale. However, land use will continue to be the dominant factor in controlling changes in sediment yield. Sediment yield will decrease slightly because of the replacement of arable land by pasture, although this effect will be counteracted by increased rainfall erosivity.

5.4 Implications for river management

1. Although large changes in forest cover of the Maas basin would significantly affect discharge, flood frequency, and sediment yield, such a scenario is not expected in the 21st century (WUR/MNP, 2007). Largest effects of land-use change are predicted for sediment yield, which is not an unimportant element when dealing with dredging requirements. Reforestation and the change from arable land to grassland are options to decrease soil erosion.
2. Even under relatively optimistic scenarios of future emissions, simulated increases in discharge and flood frequency are large which stress the need for adaptation strategies. These may include multi-functional land-use planning with the purpose of increasing flood capacity and flood water retention in times of high flows. For instance, selected floodplain areas may be intermittently inundated providing accompanying benefits for nature conservation, tourism and even extraction of sediment resources. The design of such measures should keep pace

with the natural tendency of the river to strive to dynamic equilibrium (Venhuizen and Vandenberghe, 2011; Vandenberghe et al., 2011).

3. The estimation of design discharges could be better determined from multi-model simulations using large ensembles of model runs under a range of future climate and land-use scenarios than from a statistical derivation from observed low-frequency peak discharges in the past..
4. Scenario approaches as applied by the coupled model by Ward (2008b) appear to be most valuable in identifying the causal mechanisms for changes in discharge, flood frequency and sediment yield over the last 4000 years. In particular, this approach enables us to verify the discharge models against multi-proxy evidence for periods in which environmental conditions were different from those of the present day. Therefore, the applied methodology is very promising for validating the performance of models outside the bounds of measured data, and hence their applicability under scenarios of possible future change.

5.5 Future research

1. In general, long-term effects of land use and climate change on high-flow frequencies have to be investigated by a combined model-proxy approach. In particular, this research has assessed the effects of reforestation and the change from arable land to grassland should be calculated. In future research, the influence of urbanisation on discharge and sediment budget over the past millennia should be analysed more precisely.
2. Effects of other kinds of human interference in the hydrologic system other than land use (for instance the construction of dams and embankments, canalisation, deepening and widening of river channels, creation of side channels and retention basins) on mean and extreme discharges, floods and sediment yield should be introduced in future model studies. This requires more complex model structures than used in this study, which are currently computationally prohibitive for use in a millennial-scale ensemble study. However, as computational efficiency increases, this should become feasible.
3. This study shows that precipitation will have a considerable impact on future discharge and flooding frequency: even with a climate scenario that involves little CO_2-emission mean and extreme precipitation values will increase. Moreover, the increases in flood frequency projected for the 21st century are much greater than the flood frequencies seen over the last four millennia. This highlights the importance of ongoing research into climate adaptation options and strategies, serving as a reminder for the importance of increased knowledge in this field.
4. For practical reasons, a climate model of intermediate complexity was used in this project (ECBilt-CLIO-VECODE). When computational efficiency will increase, the future use of an RCM (Regional Circulation Model) nested in a GCM (General Circulation Model) may obtain a more realistic series of spatial and temporal precipitation. Moreover, the downscaling of precipitation data was carried out using a simple approach. The study of Leander and Buishand (2007) found it to be advantageous to correct also for the variability of 10-day precipitation amounts; such an approach could be considered in future studies.
5. Online coupling of the ECBilt-CLIO-VECODE and WATEM/SEDEM models will provide a more integrated tool for basin analysis.
6. Until now, the palaeodischarge proxy data are of a qualitative nature. Quantification of the signal changes in discharge and sediment yield provide an interesting scientific challenge.
7. It would be beneficial to apply the methods used in this project to other catchments in order to assess regional effects of climate and land use change on long timescales. This would allow for more generalised statements on their relative influence, and may show regional similarities and differences in causal mechanisms of long-term change.

6. Acknowledgements

Comments by the 'Programmaraad', anonymous reviewers, J. Veraart and Ph. Ward are gratefully acknowledged.

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Appendix:

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www.klimaatonderzoeknederland.nl.

Climate changes Spatial Planning

Climate change is one of the major environmental issues of this century. The Netherlands are expected to face climate change impacts on all land- and water related sectors. Therefore water management and spatial planning have to take climate change into account. The research programme 'Climate changes Spatial Planning', that ran from 2004 to 2011, aimed to create applied knowledge to support society to take the right decisions and measures to reduce the adverse impacts of climate change. It focused on enhancing joint learning between scientists and practitioners in the fields of spatial planning, nature, agriculture, and water- and flood risk management. Under the programme five themes were developed: climate scenarios; mitigation; adaptation; integration and communication. Of all scientific research projects synthesis reports were produced. This report is part of the Climate scenarios series.

Climate scenarios

The projects in this field are designed to obtain high quality climate information and scenarios relevant for the Netherlands. The projects both focus on an improved monitoring and modelling of regional climate variability, and at the construction of tailored climate change scenarios suitable for exploring spatial adaptation options, such as flood retention areas or coastal defense. In all fields special attention is devoted to extreme climate conditions. The climate scenarios are designed and developed jointly with a number of key stakeholders.

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