Strong increase in discharge and flood frequency of the River Meuse over the last four millennia: impact of climate variability and anthropogenic land-use changes

P.J. Ward[1], H. Renssen[1], J.C.J.H. Aerts[2], R.T. van Balen[1] and J. Vandenberghe[1]

[1] Department of Palaeoclimatology and Geomorphology, Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, The Netherlands

[2] Institute for Environmental Studies, Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, The Netherlands

E-mail: philip.ward@falw.vu.nl

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Introduction

In recent years the frequency and magnitude of high-flow events in the Meuse Basin (NW Europe, Fig. 1) has been relatively great, and flooding and flood risk mitigation have become issues of practical significance. However, as the discharge of the Meuse has only been measured accurately for about 100 years, it is difficult to delineate changes caused by human activities (land-use change and anthropogenic global warming) and natural fluctuations. Studies of palaeodischarge provide a means to overcome the lack of long-term observed discharge data.

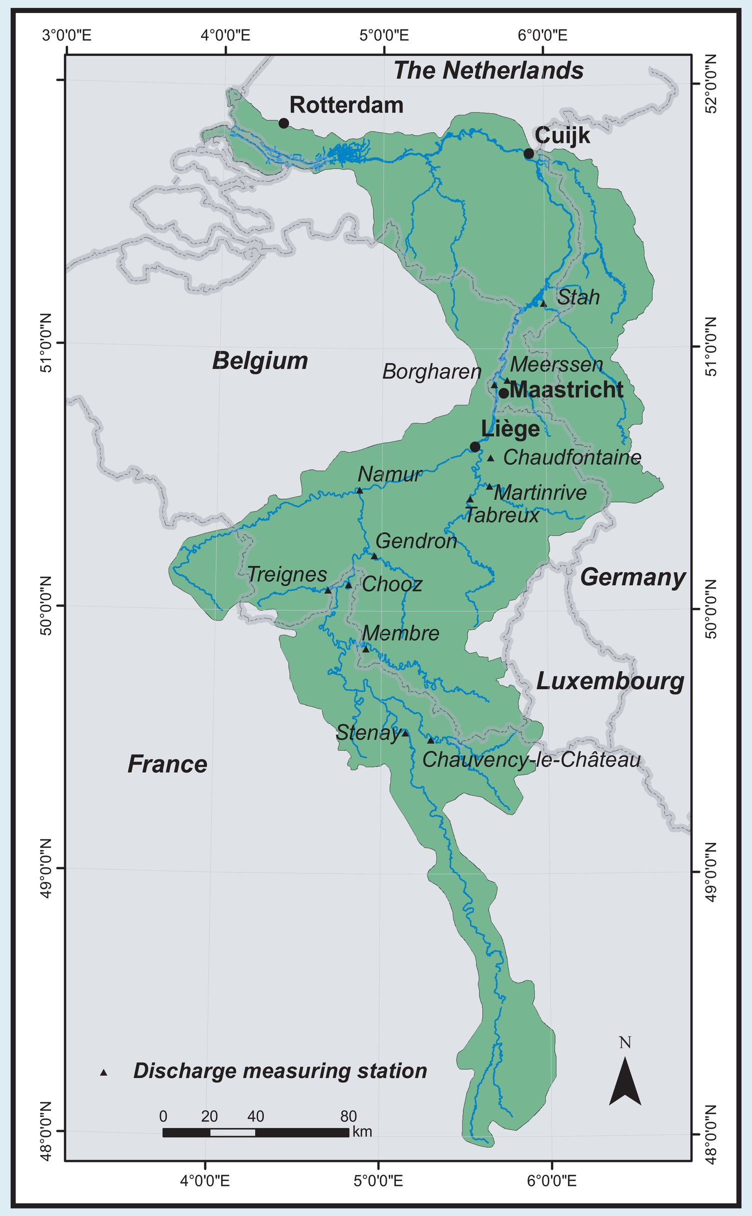


Fig. 1: The Meuse Basin

Methods and Research Approach

We have coupled a climate model (ECBilt-CLIO-VECODE)[1,2,3] with a hydrological model (STREAM)[4] to simulate the daily discharge of the Meuse in two time-slices: (a) 4000-3000 BP (natural situation); and (b) 1000-2000 AD (includes anthropogenic land-use and climate change). The climate model is forced by annually varying orbital parameters, greenhouse gas concentrations, volcanic aerosol concentrations, and solar activity. The research approach is shown in Fig. 2.

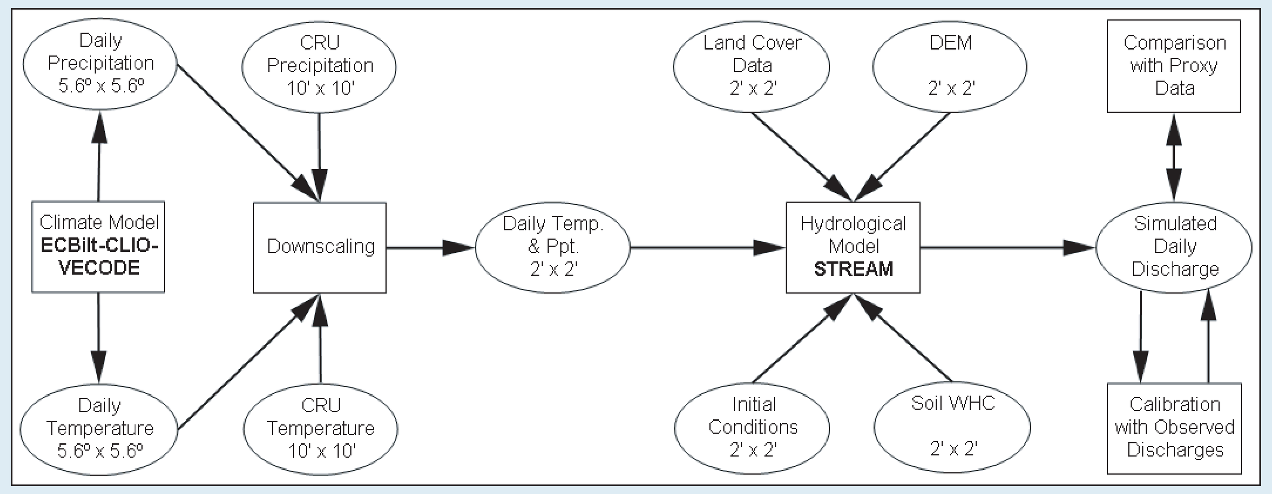
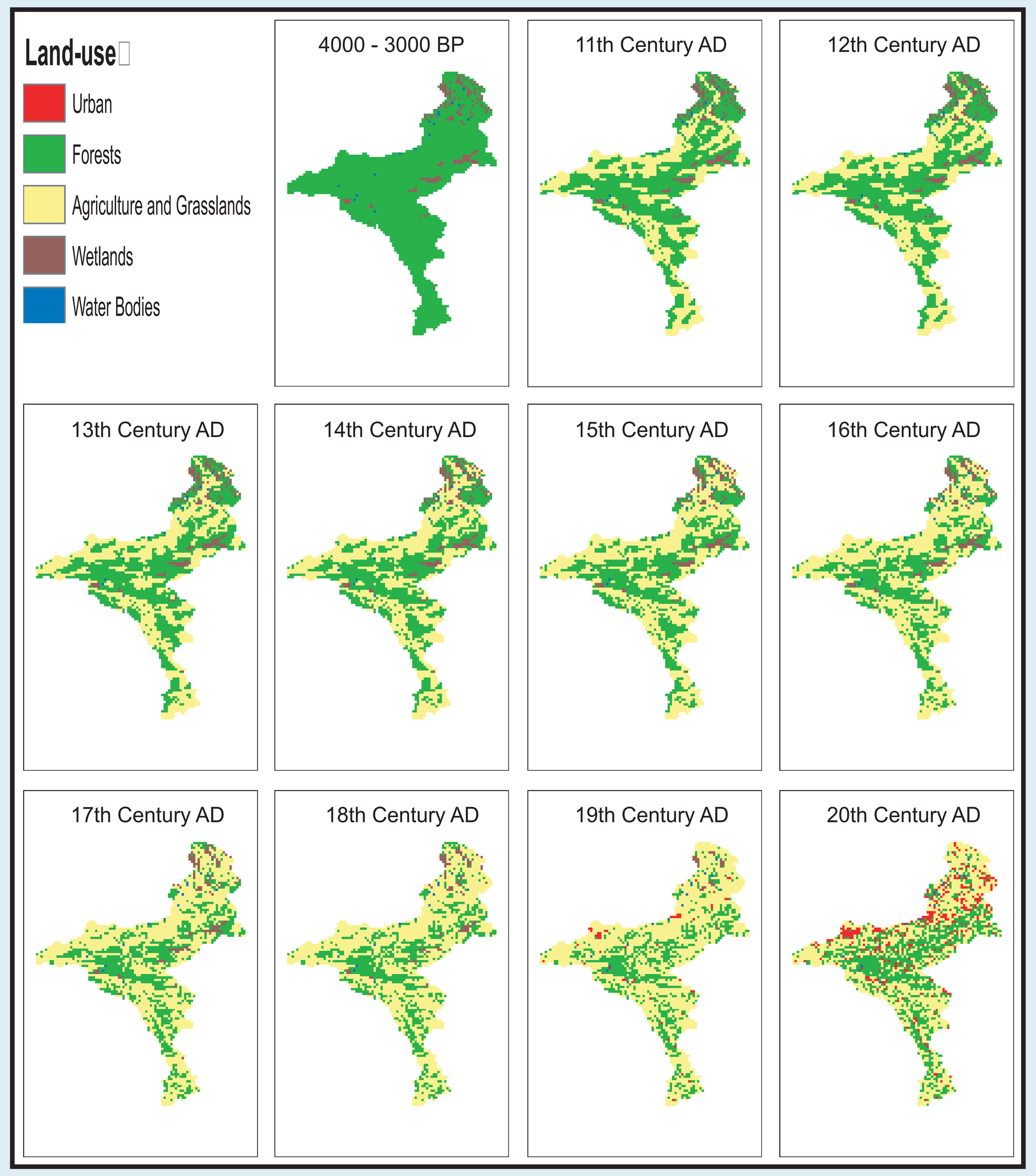


Fig. 2: Overview of the general research approach

(1) Opsteegh et al. 1998, Tellus 50A, 348-367
(2) Goosse & Fichefet 1999, JGR 104, 23,337-23,355
(3) Brovkin et al. 2002, GBC 16, 1139
(4) Aerts et al. 1999, Phys. Chem. Earth, B24, 591-595



Land-use change

We created land-use maps for each century (Fig. 3) based on CORINE data, census data, historical records, and pollen analyses.

The most striking change in land-use is the huge reduction in forest cover between the natural situation (98%) and the situation at 1000 AD (53%) (at the expense of agriculture). This reduction continued until the 19th Century AD (29%); in the 20th Century AD forest and urban area expanded at the expense of agriculture.

Fig. 3 (left): Land-use maps for 4000-3000 BP and 1000-2000 AD, showing the large decrease in forested area between 4000-3000 BP and 1000-2000 AD. In the 20th Century AD some reforestation has occurred.

Climate development

In 1000-2000 AD annual precipitation was higher than in 4000-3000 BP (Fig. 4). However, intense precipitation events were more common in the latter period. Over the last 1000 years precipitation shows no trend, but 20th Century precipitation was higher than in any other century. Mean temperature decreased over the Late Holocene, but increased significantly in the last 100 years (especially in winter).

Fig. 4 (right): Average basin precipitation (pre) and temperature (tmp) over the periods 4000-3000 BP and 1000-2000 AD (50-yr means).

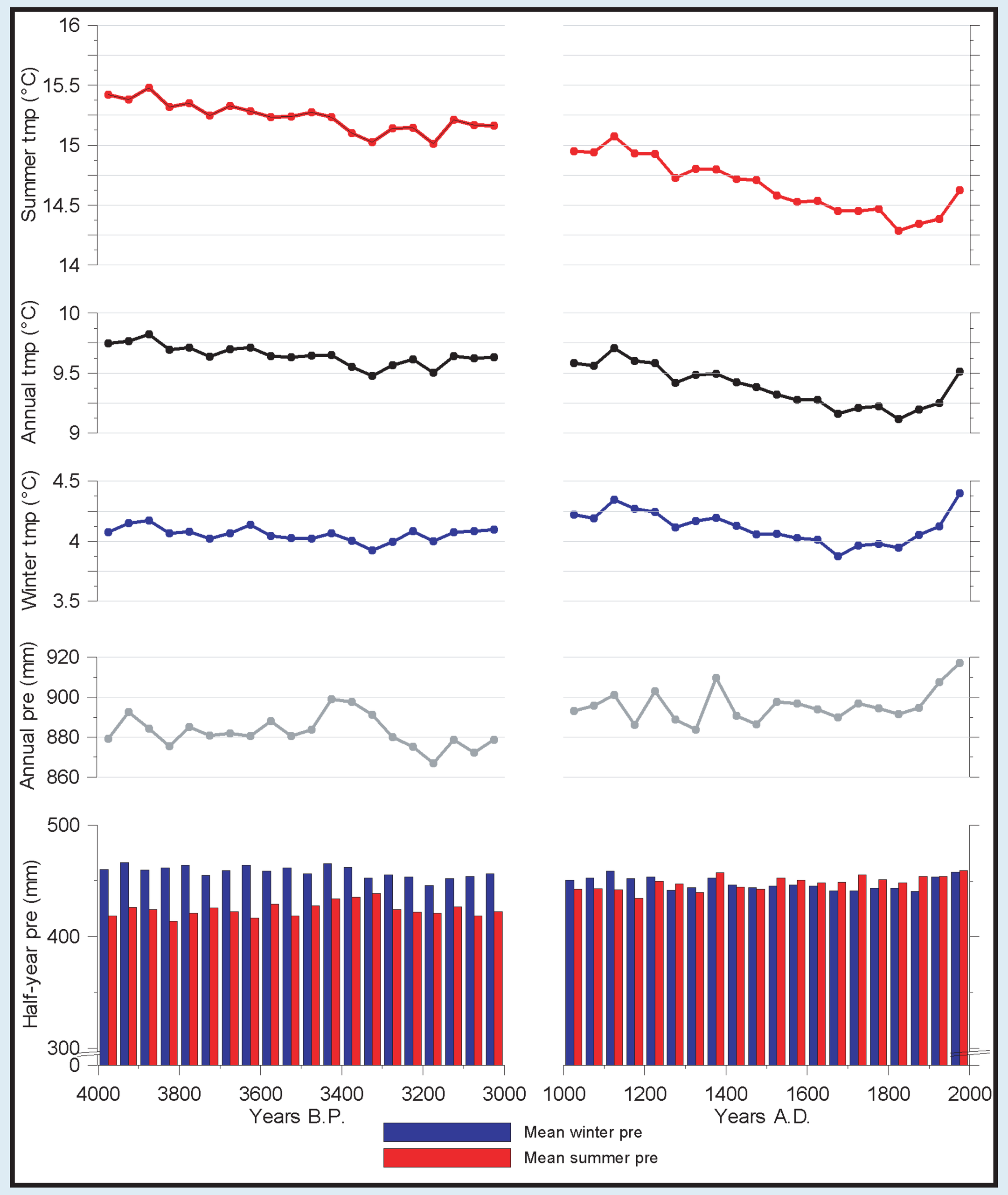
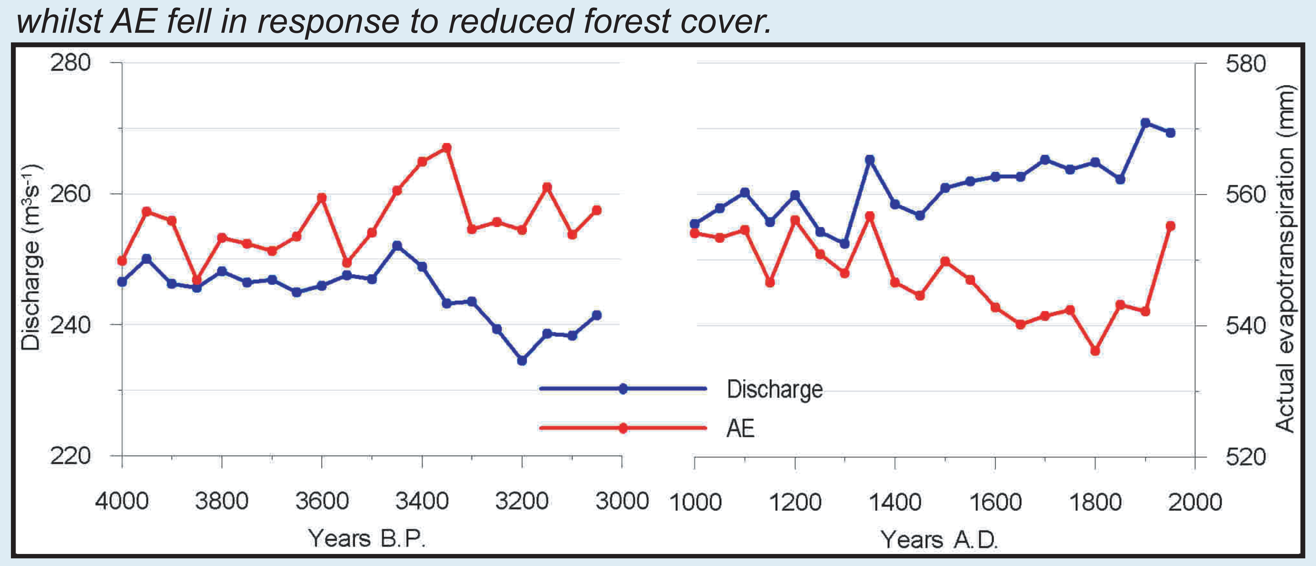
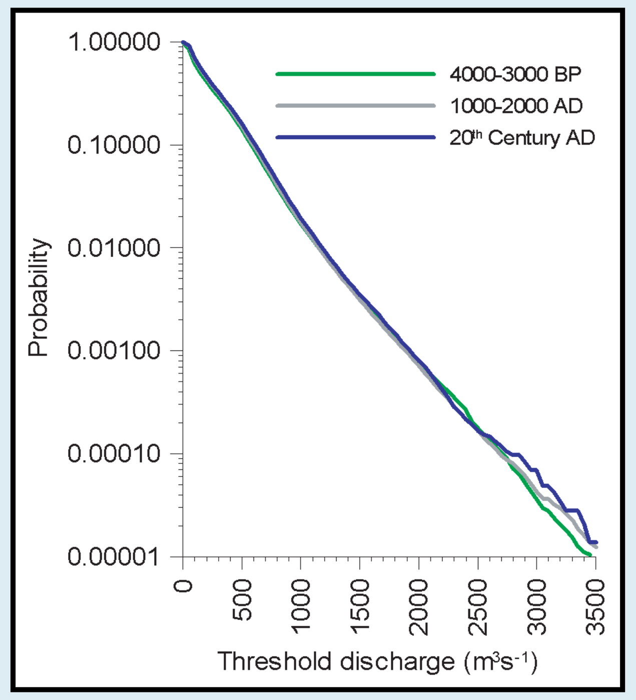


Fig. 5 (below): Discharge (blue) and actual evapotraspiration (red) over the periods 4000-3000 BP and 1000-2000 AD (50-yr means). Discharge increased significantly between the natural situation and 1000-2000 AD, whilst AE fell in response to reduced forest cover.



Changes in discharge and evapotranspiration

Mean discharge in 1000-2000 AD (blue line, Fig. 5) was significantly higher than in 4000-3000 BP, and shows an increasing trend over the last 1000 years. Actual evapotranspiration (AE) (red line, Fig. 5) was higher in 4000-3000 BP than in the last millennium, and decreased over the last millennium, following the reduction in forested area. In the last 100 years both discharge and AE increased significantly compared to the preceding century.



Changes in flood frequency

Fig. 6 shows that large floods are now more common than under natural conditions. The recurrence time of very large floods (> 3000m^3s^{-1}) has almost halved from 77 years (natural situation) to 40 years (20th Century AD).

Fig. 6: Probability of daily discharge above a given threshold. The frequency of high flow-events has increased in relation to the natural situation (4000-3000 BP).

Causal mechanisms of increased discharge

The increase in discharge and flood frequency between the natural situation and the 20th Century AD can be almost fully attributed to changes in land-use (reduced AE due to deforestation) (Table 1). However, the increase between the 19th and 20th Centuries AD is driven by increased annual and winter precipitation.

	Q_{ann}	Q_{90}	Q_{95}	Q_{99}	$Q_{99.99}$
4000-3000 BP to 20th Century AD					
Climate and land-use	+12.5	+7.1	+5.6	+4.1	+10.1
Climate only	-	+0.6	+0.1	-0.6	+3.6
Land-use only	+12.4	+6.6	+5.5	+4.8	+6.5
19th Century AD - 20th Century AD					
Climate and land-use	+3.5	+2.9	+3.2	+4.0	+9.7
Climate only	+4.5	+3.7	+3.7	+4.5	+9.9
Land-use only	-1.0	-0.8	-0.5	-0.5	-0.2

Table 1: Percentage change in mean discharge (Q_{ann}) and various high-flow percentiles between 4000-3000 BP and the 20th Century AD (above), and between the 19th and 20th Centuries AD (below).

Conclusions

Mean discharge and flood frequency were significantly higher in the last millennium than in the natural situation (4000-3000 BP).

On the millennial timescale these increases can be almost fully attributed to the large-scale deforestation in the basin.

Over the last 100 years a large increase in annual and winter precipitation has caused a further increase in mean discharge and flood frequency; climatic change has overwhelmed land-use change as the dominant mechanism on this timescale.

Further information can be found in:
Aerts et al. 2006. Geophysical Research Letters, L19401, doi:10.1029/2006GL027493
Ward et al. 2007. Global and Planetary Change, doi:10.1016/j.gloplacha.2006.12.002