Strong increase in the flood frequency of the River Meuse in response to Holocene and future climate and land use change: a new perspective for long-term modelling

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Introduction

In recent years floods have caused substantial damage throughout Europe, and increased flood frequencies are expected in the coming century.

This holds true for the Meuse River, which overflowed its banks in 1993 and 1995, causing extensive damage. To date, modelling studies have compared flood frequencies for the 21st century with observed records of the last ca. 100 years. On this timescale it is difficult to assess future changes in the context of natural or anthropogenic long-term trends.

To address this issue we have simulated the discharge and flood frequency of the Meuse over the late Holocene and the 21st Century.

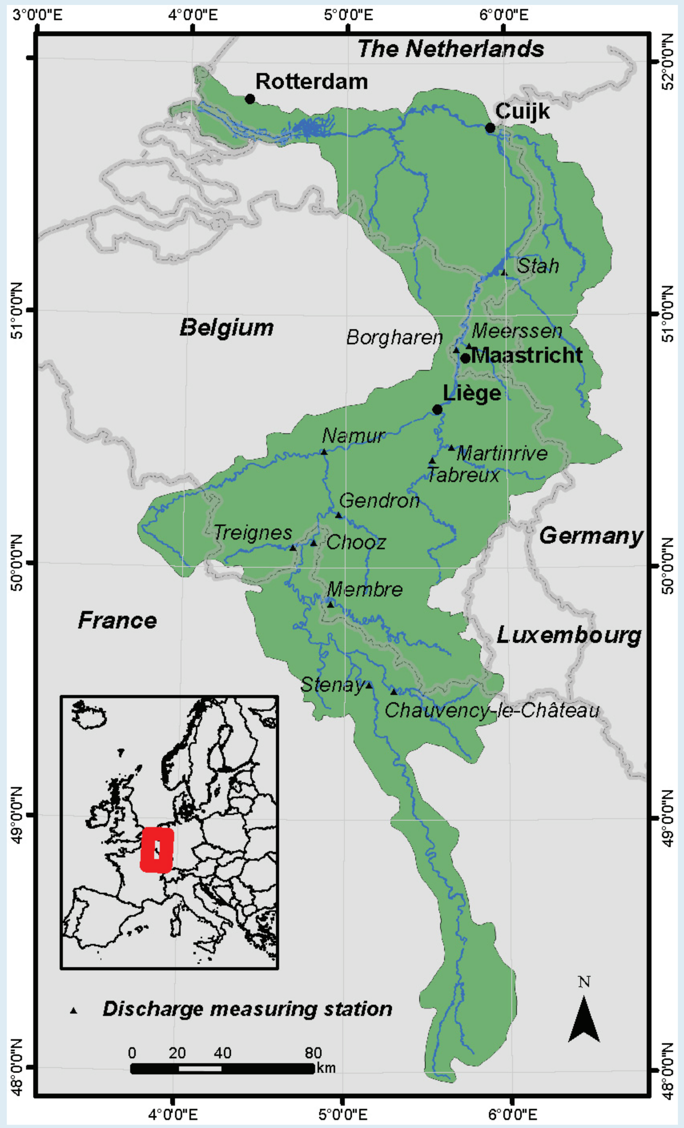

Fig. 1: The Meuse Basin.

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 three time-slices: (a) 4000-3000 BP (natural situation); (b) 1000-2000 AD (includes anthropogenic land use and climate change); and (c) 21st Century AD under SRES emissions scenarios A2 and B1[5].

Land use for the 20th Century is based on CORINE data; past land use is based on historical maps and documents; and future land use is based on the results of the EURURALIS project (www.eururalis.eu)[6].

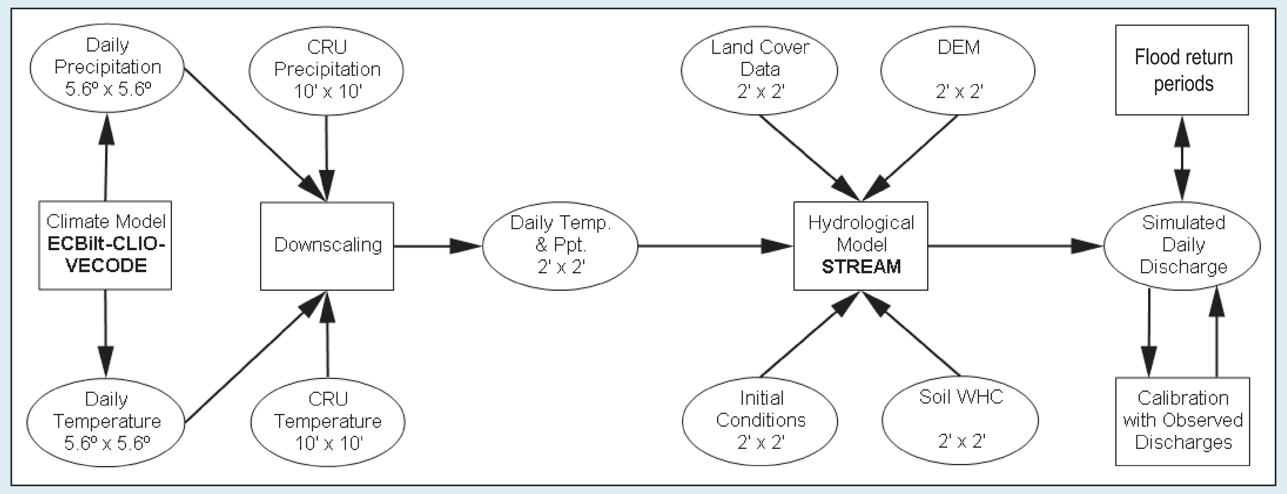

Fig. 2: Overview of the general research approach.

(1) Opsteegh et al., 1998. Tellus, 50A, 348-367.
(2) Goosse & Fichefet, 1999. JGR, 104, 23337-23355.
(3) Brovkin et al., 2002. GBC, 16, 1139.
(4) Aerts et al., 1999. Phys. Chem. Earth, B24, 591-595.
(5) IPCC, 2000. Special Report on Emission Scenarios. Cambridge University Press, Cambridge, U.K.
(6) Verburg et al., 2008. The Annals of Regional Science, in press.

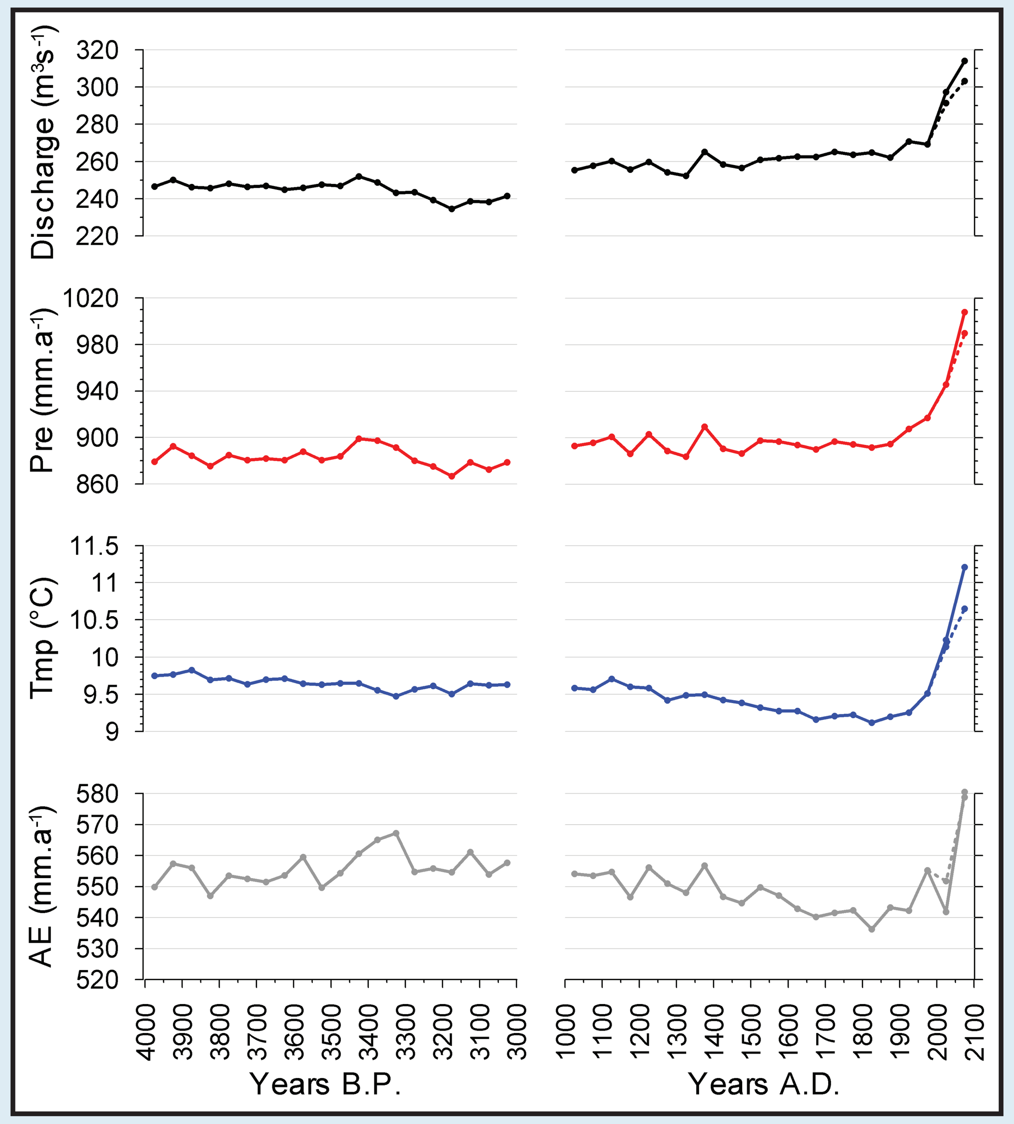

Fig. 3 (left): Long term changes in mean annual discharge, precipitation (pre), temperature (tmp), and actual evapotranspiration (AE) (50-yr means). For the 21st Century the A2 scenario is shown as an unbroken line, and the B1 scenario as a dotted line.

Long-term trends

Over the natural reference period (4000-3000 BP) mean annual discharge is fairly constant (244.8 m^3s^{-1}); for the period 1000-2000 AD mean annual discharge (261.0 m^3s^{-1}) is significantly higher (t-test, $p < 0.001$) (Fig. 3). Over the course of the last millennium discharge shows an increasing monotonic trend (Mann Kendall test, $p < 0.001$), despite no significant trend in precipitation. This is almost fully caused by the conversion of forested land to agriculture (decreased actual evapotranspiration); climatic change had almost no role in the increased discharge on this timescale.

For the 21st Century, strong increases in discharge are expected under both the A2 and B1 scenarios. On this timescale the effects of projected land use change alone are minimal (Table 1); the large increase in discharge is the result of a strong increase in precipitation, particularly in the winter half-year.

Probability of flooding

The probability of high-flows increased significantly over the late Holocene, with further increases expected in the 21st Century. High-flows greater than 3000 m^3s^{-1} (similar in magnitude to the floods in 1993) occurred approximately once per 77 years in the period 4000-3000 BP; by the 20th Century AD they occurred almost twice as frequently (once per 40 years). On this millennial timescale almost all of this increase can be attributed to the effects of land use change (Table 1).

In the 21st Century, high-flows similar in magnitude to those during the floods of 1993 are simulated once per 20 years (A2), and once per 25 years (B1). The increase in relation to the 20th Century is almost entirely due to climatic change, and namely increased winter precipitation.

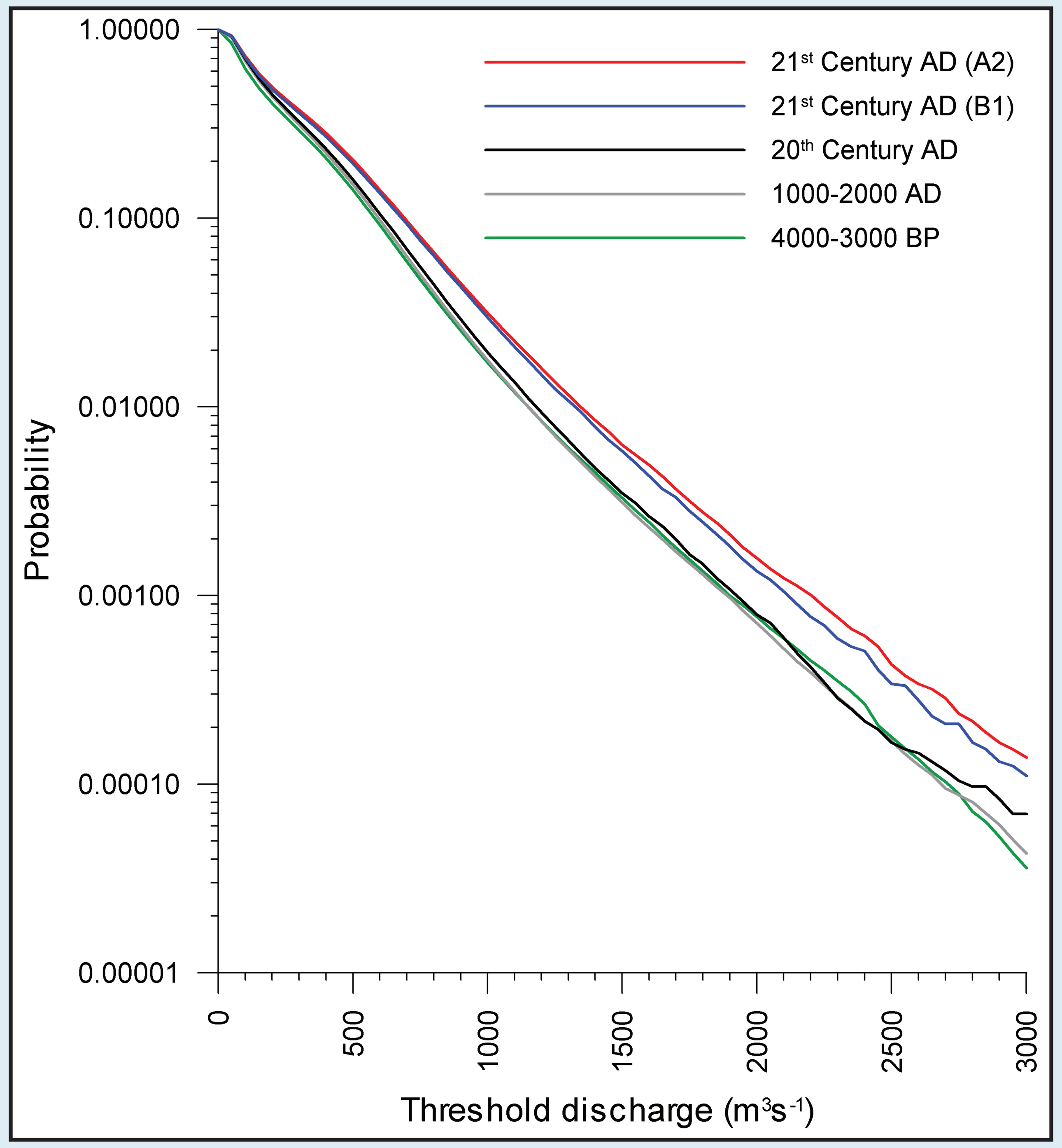

Fig. 4 (right): Probability of daily discharge above a given threshold.

	Q_{ann}	Q_{90}	Q_{95}	Q_{99}	$Q_{99.9}$
Percentage change between 4000-3000 BP and 20th Century AD					
Climate and land use	+12.5	+7.1	+5.6	+4.1	+2.0
Climate only	-	+0.6	+0.1	-0.6	-2.4
Land use only	+12.5	+6.6	+5.5	+4.7	+4.4
Percentage change between 20th Century AD and 21st Century AD (A2 scenario)					
Climate and land use	+13.2	+12.8	+12.9	+13.8	+14.4
Climate only	+13.2	+12.6	+12.7	+13.7	+14.4
Land use only	-	+0.2	+0.2	+0.1	-
Percentage change between 20th Century AD and 21st Century AD (B1 scenario)					
Climate and land use	+10.1	+11.2	+11.3	+12.2	+9.6
Climate only	+10.7	+11.4	+11.5	+12.3	+9.8
Land use only	-0.6	-0.2	-0.2	-0.1	-0.2

Table 1 (left): Percentage change in mean discharge (Q_{ann}) and various high-flow percentiles between the natural reference period (4000-3000 BP) and the 20th Century AD, and between the 20th Century AD and 21st Century AD (SRES scenarios A2 and B1).

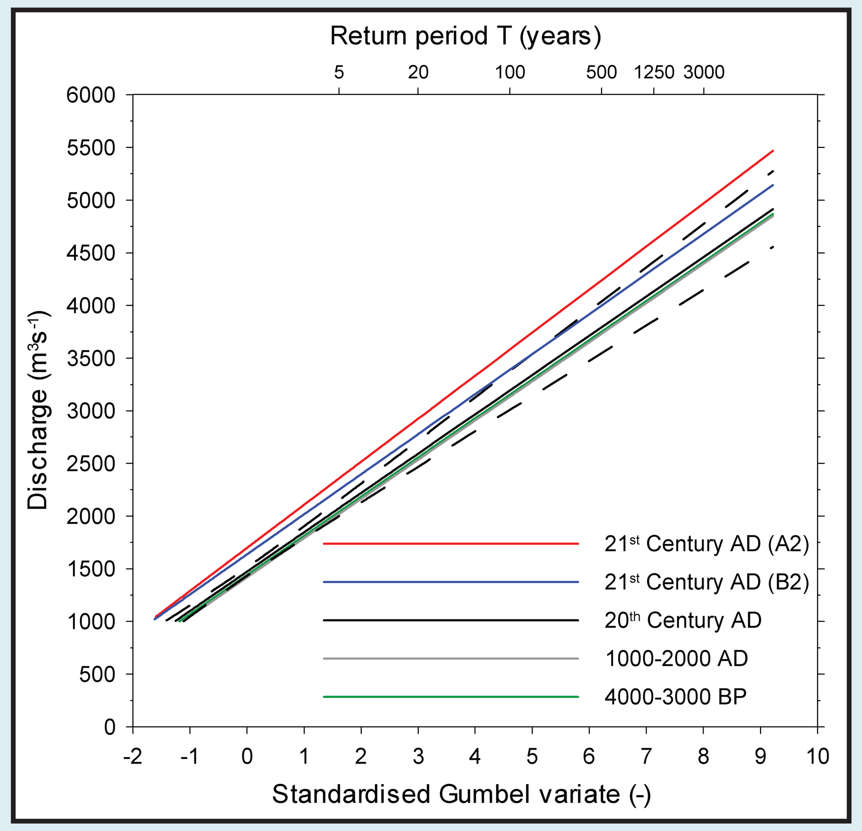

Fig. 5: Return periods of extreme high-flows estimated by fitting the Gumbel distribution to the simulated annual maximum discharges. For the 20th Century AD the 95% confidence limit is indicated by dotted lines. The Gumbel plot for the 21st Century AD (scenario A2) falls outside this confidence limit.

Extreme flood events

In the Netherlands, flood defence measures on the embanked Meuse are designed to withstand a discharge with a return period of 1250 years (design discharge). By fitting a Gumbel distribution to our annual maximum discharge results (Fig. 5) we estimated the magnitude of floods with a return period of 1250 years:

4000-3000 BP:	4093 m^3s^{-1}
20th Century AD:	4137 m^3s^{-1}
21st Century AD (A2 scenario):	4615 m^3s^{-1}
21st Century AD (B1 scenario):	4350 m^3s^{-1}

The estimate for the 21st Century (scenario A2) falls outside the 95% confidence limit of the 20th Century estimate. For scenarios A2 and B1 the expected land use changes had no significant effect.

Conclusions

Between 4000-3000 BP and the 20th Century AD the mean discharge and flood frequency of the Meuse increased significantly. These increases can be almost fully attributed to the large-scale deforestation of the basin.

In the 21st Century AD mean discharge and flood frequency show a further sharp increase; almost all of the increase between the 20th and 21st Centuries can be attributed to the simulated increase in precipitation (especially in the winter half-year) in response to global warming.

Extreme value statistics suggest that the magnitude of floods with a 1250 year return period will increase significantly in the 21st Century. Expected land use change has no significant effect on these flood magnitudes.

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Related publications:
Ward et al., 2008. Hydrology and Earth System Sciences, 12, 159-175.
Ward et al., 2007. Global and Planetary Change, 57, 283-300.
Aerts et al., 2006. Geophysical Research Letters, 33, L19401.