# Modeling Discharge and Sediment Flux of the Rhine River, Central Europe during the Holocene


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## Objective

Simulating the Holocene discharge and sediment flux of the Rhine catchment with the hydrological model HYDROTREND v.3.0 in order to understand fluvial response to changing external forcing factors (climate, human impact, sea level and tectonics) and thus past, present and future changes of sediment flux.

## Study Area

The 1325km long Rhine River is situated in central western Europe and drains in total 158,000 km$^2$ hinterland, including large parts of the Alps with reliefs over 4,0 km, the French and German Low Mountain Ranges and the northern German and Dutch Lowlands (Figure 1).

The Rhine River is chosen as study area because 1) of its wealth of geoscientific case studies and thus extensive data availability ; 2) it's a morphologically diverse basin encompassing glacial, nival and pluvial discharge regimes; and 3) its long story of intense human-riverine interactions resulting in largely man-induced sediment fluxes from the Mid-Holocene onwards.

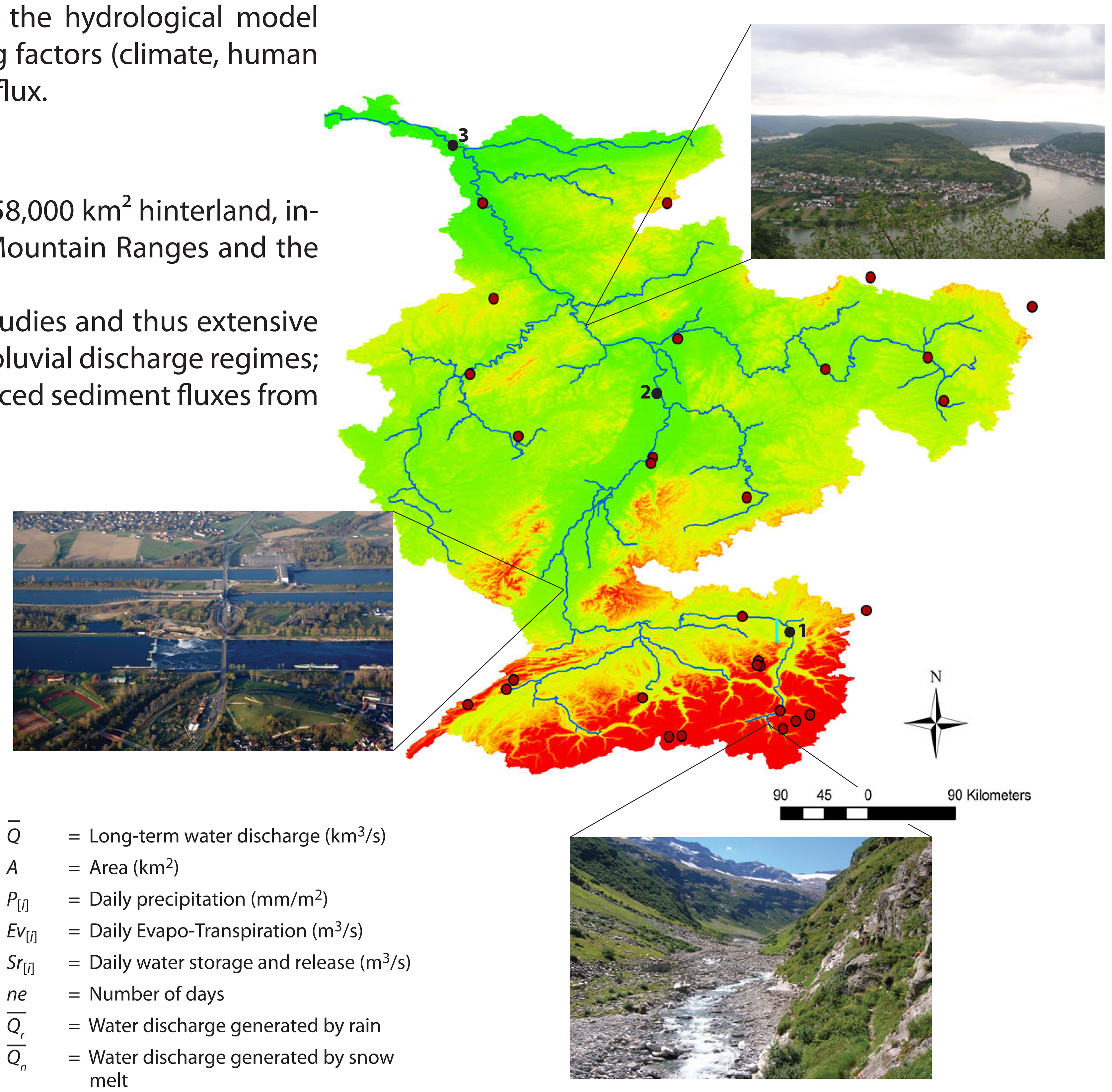


Figure 1: *Center:* Digital Elevation Model of the Rhine catchment with the Rhine River and its tributaries, weather stations (red dots) and gauging stations (black dots). *Bottom:* Rhine close to its source in the south-eastern Swiss Alps. *Middle:* Regulated Rhine River with dam in the floodplain of the Upper Rhine Valley. *Top:* Rhine River in the German Low Mountain Ranges.

## Model Description

HYDROTREND v.3.0 simulates (i) discharge and (ii) sediment load at a river outlet.

(i) Daily water discharge values are calculated based on the classic water balance model (Eq. 1a) considering five runoff processes (Eq.1b). The subcomponents' boundaries are determined with each time step by using the time varying freeze line and glacier equilibrium line altitude in combination with the basin hypsometry, precipitation and temperature (Kettner & Syvitski 2006).

Daily water discharge:

$$\overline{Q} = A \sum_{i=1}^{ne} P_{[i]} - Ev_{[i]} \pm S_{[i]} \qquad \text{Eq. 1a}$$

$$\overline{Q} = \overline{Q}_r + \overline{Q}_n + \overline{Q}_{ice} - \overline{Q}_{Ev} + \overline{Q}_g \qquad \text{Eq. 1b}$$

(ii) Long-term sediment load is derived from the empirical BQART equation which relates the long-term sediment load to basin area, discharge, relief, temperature, average basin lithology, glacier extention, human activity and sediment trapping efficency of lakes or reservoirs (Eq. 2a, 2b) (Kettner & Syvitski 2006).

The stochastic PSI equation (Morehead et al. 2003) is used to study the inter-annual variability of sediment flux variability.

Long-term sediment load:

$$\overline{Qs} = w\, B\, \overline{Q}^{0.31} A^{0.5} R\, T \qquad \text{Eq. 2a}$$

$$B = I\, L\, (1 - T_E)\, E_h \qquad \text{Eq. 2b}$$

Daily suspended sediment:

$$\left(\frac{Qs_{[i]}}{\overline{Qs}}\right) = y_{[i]} \left(\frac{Q_{[i]}}{\overline{Q}}\right)^{C_{(a)}} \qquad \text{Eq. 3}$$

- $\overline{Q}$ = Long-term water discharge (km$^3$/s)
- $A$ = Area (km$^2$)
- $P_{[i]}$ = Daily precipitation (mm/m$^2$)
- $Ev_{[i]}$ = Daily Evapo-Transpiration (m$^3$/s)
- $Sr_{[i]}$ = Daily water storage and release (m$^3$/s)
- $ne$ = Number of days
- $\overline{Q}_r$ = Water discharge generated by rain
- $\overline{Q}_n$ = Water discharge generated by snow melt
- $\overline{Q}_{ice}$ = Water discharge generated by glacier melt
- $\overline{Q}_{Ev}$ = Water discharge loss evapo-transpiration
- $\overline{Q}_g$ = Water discharge generated by groundwater
- $\overline{Qs}$ = Long-term suspended sediment (kg/s)
- $Qs_{[i]}$ = Daily suspended sediment (kg/s)
- $R$ = Relief (km)
- $T$ = Basin average temperature (°C)
- w = constant; 0.02 (-)
- $I$ = Glacier erosion factor (-), function of glacier extention
- $L$ = Basin average lithology factor (-)
- $T_E$ = Trapping efficiency (-)
- $E_h$ = Anthropogenic factor (-)
- $y_{[i]}$ = Rating parameter (-)
- $C_{(a)}$ = Annual rating coefficient (-)


## References

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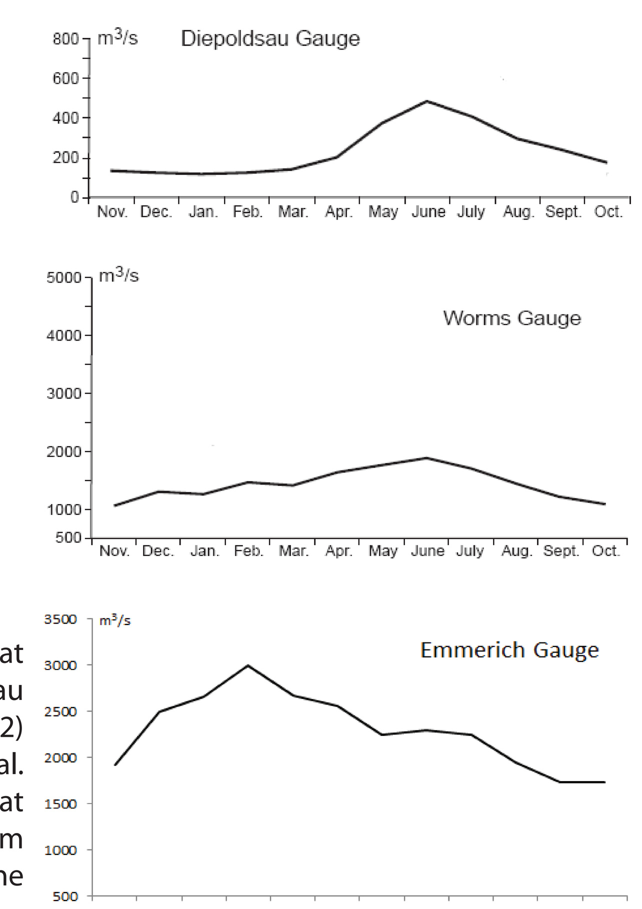


FIgure 6: Mean monthly discharge at the gauging station Diepoldsau (Figure 1, 1) and Worms (Figure 1, 2) during 1960-9991 (Kempe et al. 2005). Mean monthly discharge at the gauging station Emmerich from 1984-2004 after data from the German Department of Hydrology.

## Data

*Climate* Precipitation data from 26 weather stations and over a period of 20 years was analyzed. Monthly, annual totals and standard deviations have been spatially averaged for the present day climate statistics of the Rhine catchment (Figure 2).

To assess Holocene climate conditions, climate values for 10,000 BP have been extracted from the CCSM3 climate model (Otto-Bliesner, yet unpublished). These were combined with the present day data and interpolated over time using the normalized temperature curve of Davis et al. (2003) as forcing factor (Figure 3).

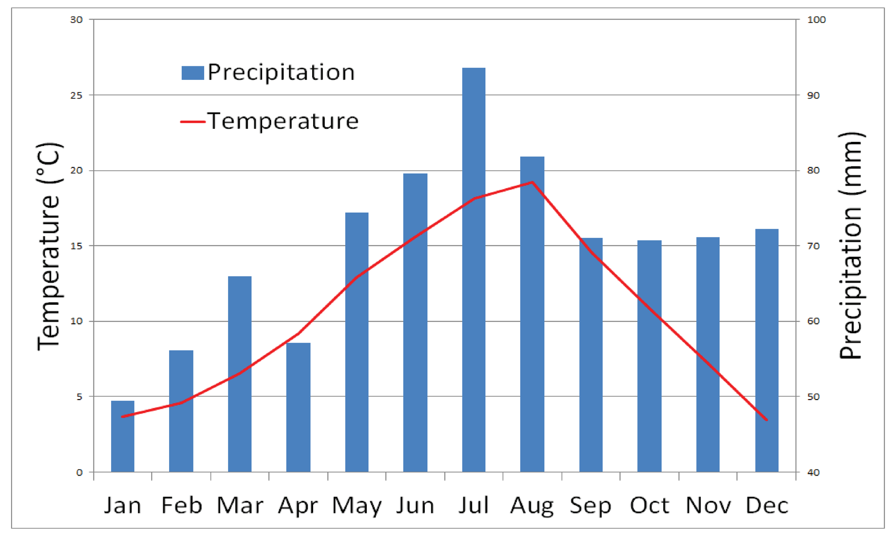


Figure 2: Present-day monthly mean temperature and total precipitation in the catchment. Derived from 26 weather stations of 6 elevation classes over a time period of 20 years .

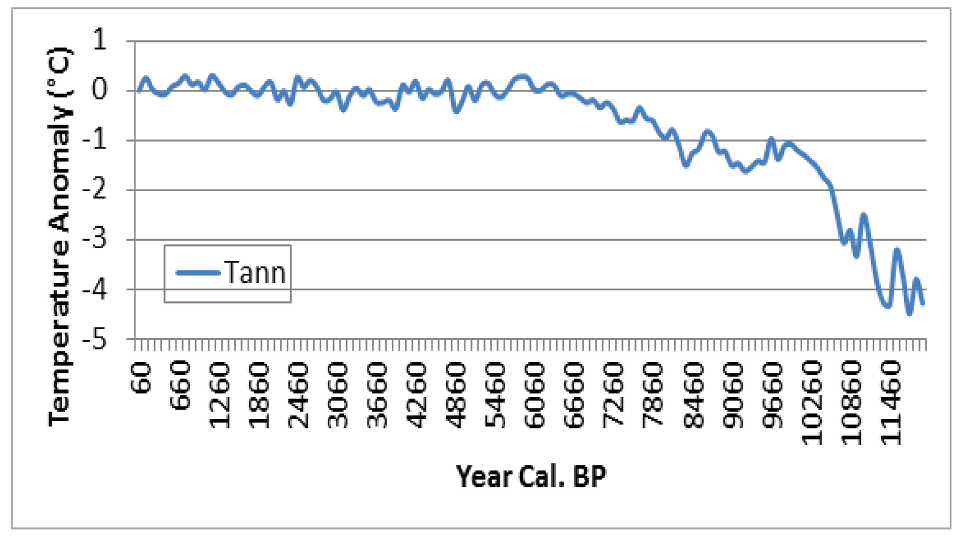


Figure 3: Mean annual Temperature Anomalies from 12,000 BP to present in central western Europe derived from Pollen data by Davis et al. (2003). The warming in the early Holocene to the Mid-Holocene Maximum around 6,000 BP is followed by stable conditions with temperature fluctuations between 1°C for the remainder of the Holocene.

*Lithology and Reservoirs* A representative lithology factor was calculated for the whole Rhine basin from Dürr et al. (2005).

Lakes with an average volume of 16 km$^3$ catch sediment of a total upstream area of 18,855 km$^2$ (Figure 4). Smaller dams in the main stream have not been incorporated in the simulation, as they will not influence the sediment flux at the outlet.

| Name | Lake outlet | | | Drainage Area (km$^2$) | Volume (km$^3$) |
|---|---|---|---|---|---|
| | Latitude | Longitude | Elevation (m) | | |
| Lac de Neuchatel | 47° 7'8.48"N | 7°15'17.16"E | 433 | 2831,8 | 26,69 |
| + Bieler See | | | | | |
| + Thuner See | | | | | |
| + Brienzer See | | | | | |
| Lake of Constance | 47°39'15.35"N | 8°52'28.50"E | 400 | 11553,2 | 48 |
| Zürichsee | 47°21'58.90"N | 8°32'35.75"E | 407 | 1965,9 | 6,4 |
| + Walensee | | | | | |
| Vierwaldstätter See | 47°22'0.09"N | 8°32'35.53"E | 407 | 2252,64 | 11,9 |
| Zuger See | 47°10'44.92"N | 8°27'44.20"E | 413 | 252,135 | 3,18 |
| | | | | Sum: 18855,675 | Average: 16,0283333333333 |

FIgure 4: Upland drainage Area and Volume of the biggest lakes in the catchment.

*Anthropogenic impact* The Rhine has a long history of human intervention leading to largely man-induced sediment fluxes from the Mid-Holocene onwards (Houben et al. 2007, Hoffmann et al. 2010).

Quantifications of forest/cultivation land ratios during the Holocene in Central Europe are made by Kaplan et al. (2009). This values still need to be assigned to an anthropogenic factor.

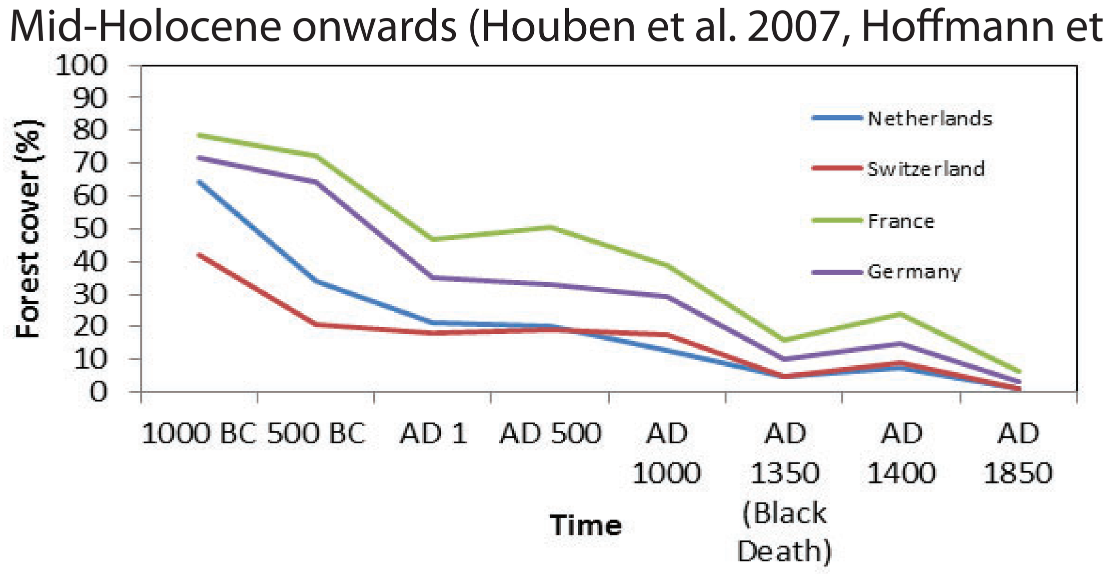


Figure 5: Forest cover percentage on usable land from 1,000 BC to AD 1850 in the Netherlands, Switzerland, France and Germany after Kaplan et al. (2009).

## Future Work

After validating the model against sediment load and discharge observations of the present day Rhine, a simulation run over the entire Holocene period will be done. Changes in sediment flux and discharge are analyzed with regard to the dominant external drivers, climate and human impact, on the Rhine fluvial system.

The second project will be a spatial resolution of the model. This will be done by considering several sections of the Rhine River as outlets. The sediment load and discharge output will be compared in regard to the allocation of sediment sources and sinks. This is relevant because the Rhine discharge regime gets strongly influenced by its tributaries, changing it from a summer peak glacial regime to a winter peak pluvial regime (Figure 6) (Kempe et al. 2005).