Predicting sediment flux to the Adriatic Sea; the significance of the LGM Alpine glaciers

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Discharge and sediment flux of the Po River, Italy, are simulated to determine the impact of climate change and sea-level fluctuations on the stratigraphy of the Northern Adriatic Sea. The drainage area of the Po River, one of the major alluvial systems of Europe, was 2.6 times larger during the Last Glacial Maximum (LGM), 21 kyr B.P. due to a 120 m lower Adriatic sea level (fig 1). The late-Würmian ice-sheet covered the Alps almost completely at that time. The Alpine glaciers did not add significant area to the Po basin as the glacier drainage divide at 21 kyr B.P. was roughly similar to the present-day basin divide (Baroni, 1996). Fifteen percent (≈ 2.9 * 10⁴ km²) of the total Po drainage basin was covered by glaciers.

Figure 1. Changes in the drainage basin of the Po river over time. Red and yellow combined indicates the basin during LGM; yellow indicates the present drainage basin.

Hydrotrend, a numerical climate-driven hydrological model, is used to simulate yearly discharge and sediment flux of the Po River outlet since the LGM. We used the global sea-level curve (Fairbanks, 1989) together with present day digital topography (Hydro1k) and bathymetry to determine changing drainage basin properties (river networks, hypsometry, relief and reservoirs) over time. Monthly climate statistics since the LGM are estimated based on the Community Climate Model1 (CCM1) modeled climate
statistics for LGM combined with the present climate statistics and interpolated over time with a normalized $\delta^{18}O$ GRIP curve. Using the CCM1 climate statistics is justified by the fact that Peyron et al. (1998) find cool steppe vegetations to be coherent with conditions predicted by CCM1. According to the CCM1 model the basin mean temperature is much lower (8.8°C vs. 2.4°C) and precipitation increases by 18% compared to present day values. The normalized $\delta^{18}O$ curve also forces glacier equilibrium line altitude (ELA) changes. ELA values are based on global latitude-specific averages both for the LGM and present day. HydroTrend uses the ELA to determine the glacier volume, and ELA changes results in a glacier area change. Bahr et al. (1997) propose an exponential relationship for glacier area vs. volume. Based on this relation HydroTrend simulates glacier ablation or growth which influences the total discharge and sediment flux at the river outlet.

To simulate the sediment fluxes at the river outlet, a stochastic model (Morehead et al., 2003) is used:

$$\left(\frac{Q_{s}}{Q_{l}}\right) = \psi \left(\frac{Q}{\bar{Q}}\right)^{c}$$

Wherein $Q_{si}$ is the daily suspended sediment discharge (kg/s), $Q_{l}$ the daily discharge (m$^{3}$/s), $\bar{Q}_{s}$ the long-term average of $Q_{s}$, $\bar{Q}$ the long-term average of $Q_{l}$, $\psi$ a log-normal random variable and $c$ a normal random variable.

The long-term average of $Q_{s}$ is defined as:

$$\bar{Q}_{s} = \alpha_{3}\bar{Q}^{\alpha_{4}}R^{\alpha_{5}}e^{kT}$$

Wherein $\bar{Q}$ is the long-term average of $Q_{l}$ (m$^{3}$/s), $R$ the maximum basin relief (m), $T$ the basin-average temperature (°C), $\alpha_{3}$, $\alpha_{4}$, $\alpha_{5}$ and $k$ are dimensionless coefficients which depend on climatic zone (Syvitski et al., 2003). Bedload transport is simulated based on river slope and discharge relationship (Bagnold, 1966).

Climate studies in the Alpine region indicate that glaciers reached their maximum extend during the LGM and were approximately at their present position at the start of the Holocene. HydroTrend simulations reflect this trend (figure 2, grey line). Climate changed rapidly during the Bølling and the end of the Younger Dryas. The model shows two melting phases which have a significant impact on the total discharge for the Po (respectively up to 40% and 60% of the total discharge). Bedload is closely related to discharge and consequently shows the same trend. Suspended sediment changes due to climate affect small river basins more dramatically than large river basins like the Po River, due to the modulating ability of large rivers (Syvitski, 2003). Figure 3 indicates that high discharge values have more impact on the bedload than on suspended sediment load. We predict that these periods should be identified by layers with coarser grain sizes in the stratigraphic record. To analyze the significance of the glacier melt contribution we
reran the model without glacier influence (ablation or growth). Suspended sediment flux at the river mouth tends to be less (on average 1.9MT/yr ≈ 5% over the period 21 – 10kyr B.P.). This is most evident for the 2 melting phases when suspended sedimentation rates increases with 13MT/yr due to glacier melt. Apart from changing the grainsize composition as discussed above, it is concluded that the glacial melting increases the sedimentation rates significantly as well.

![Figure 2](image-url)  
Figure 2. Simulated glaciated area (grey line) and changing discharge ratio (Glacier discharge / total discharge) (blue line).

![Figure 3](image-url)  
Figure 3. Black line is the yearly ratio of bedload over suspended sediment over time. The red line indicates the 50 years running average of this ratio over time. Bedload shows a more direct response to glacier melt than suspended load.


