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

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Objectives
- Determine the long-term and short-term climate changes, and the perturbations from humans, impacting the hydrological routing of water and sediment (e.g., floods, droughts) of the Po River.
- Support the effort to understand the dynamic response of a continental margin to large-amplitude sea-level changes, since the Last Glacial Maximum (LGM).

Geological setting
The northernmost part of the Mediterranean is a relatively shallow rectangular basin bordered to the west by the Apenines, to the North by the Alps and to the east by the Dinaric mountain chain. The sea is for more than 800 km long in a NW-SE direction and has an average width of about 200 km. The Adriatic sea level was about 120 meter below present during the Last Glacial Maximum (LGM) (Fairbanks, 1989). Evolution of the Po basin area since LGM was made based on present-day DEM and bathymetric data. The total area of the drainage basin increased by a factor of 2.6 compared to its present area (Fig. 1). During LGM, the shoreline was about ~250 km SE of the present-day Po outlet. The Alps were almost completely covered by the late-Würmian ice-sheet (Hinderer, 2007) (Fig. 1), but the ice cap did not add significant area to the Po drainage basin as the glacier drainage divide roughly followed the basin divide.

Model description
A river-discharge model, HydroTrend can simulate the natural variability (daily, monthly and annually) in the flow of water and sediment delivered to the coastal ocean. The numerical model is designed to make discharge predictions based on climate, even when field measurements of river flow are not available. Provided that appropriate assumptions are made regarding past climate, the model predicts how a river has behaved in the geological past.

To simulate discharge and sediment discharge, HydroTrend incorporates drainage basin properties (river networks, hypsometry, relief, reservoirs) based on high-resolution digital elevation models (DEM), along with other biophysical parameters (basin-wide temperature, precipitation, glacier equilibrium line altitude (ELA), evapo-transpiration, canopy, soil depth, hydraulic conductivity).

The model uses ELA in combination with the hypsometry to determine glacier area, ELA changes over time result in a glacier area change. Subsequently, HydroTrend uses an exponential relationship to translate glacier area to glacial volume. To simulate glacier ablation or growth which influences the total discharge and sediment flux at the river outlet (equation 2). A stochastic model (Morehead et al., 2003) is used to calculate the daily suspended sediment load flux (equation 3).

Model justification
HydroTrend proved to be an appropriate simulation model for the Ponte-Bocca gauge station, which is located closest to the river mouth before the main channel splits into distributary channels. At this delta apex a high correlation is found between modeled discharges and time series of 12-year daily discharge data (1990-2001) and monthly discharge (1918-2002). Modeled data correlates significantly with the observed data (r2 0.72), as calculated from 100 ms-1 intervals. At the delta apex, HydroTrend predicts an average discharge of 1,542 m3 s-1 and peak discharges comparable to the measured floods of 1951 and October 2000. Based on the formulas 1, 2 and 3, average suspended sediment load of 16 x 10^6 t yr-1 with peak year of ~39 x 10^7 t yr-1 are predicted. Bedload contributes only ~2.5% of the total sediment output of the Po river system (table 1).

Monthly variation in simulated Po River discharge and sediment discharge are similar to measurements (fig. 2). The one difference between simulated and observations is in the area of scatter. The simulations show less variation in the sediment discharge because it does not include hysteresis effects that provide much of the scatter in the rating plot of the observed data.

Results
Climate studies in the Alpine region indicate that glaciers reached their maximum extent during the LGM and were approximately at their present position at the start of the Holocene. HydroTrend simulations reflect this trend (fig. 4 & 6). Based on the World Atlas of snow and ice resources, we reconstructed the glacier extent and analyzed that fifteen per cent (~2.9 x 10^6 km2) of the total Po drainage basin during the LGM was covered by glaciers. A HydroTrend simulation for the LGM, based on the ELA, predicts a similar glacier volume as our GIS reconstruction (fig. 4). Climate changed rapidly during the Bölling and the end of the Younger Dryas. The model simulates several melting phases which have a significant impact on the total discharge for the Po (some even up to 40% and 60% of the total annual discharge). The two highest simulated glacier meltwater pulses are in the similar period as the measured two global major pulses of meltwater entering the world ocean.

Drainage basin area change due to sea level change has a significant impact on discharge and sediment load of the Po River. (r2 0.80). For our simulations we raise the Adriatic sea level in 13 steps. Each step cause a drainage area decrease. The exception for this relationship is occurring during the Younger Dryas. Glacier ablation dominates the hydrological balance.

Figure 5 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. For the entire Po River, we estimate an average Pleistocene (21-10 Cal. yr BP) suspended sediment flux of 32.5 Mt yr^-1 with a bedload of 0.91 Mt yr^-1. This is 1.7 times more then during the Holocene (10-0 Cal. yr BP), when we simulated on average a suspended sediment flux of 18.8 Mt yr^-1 with a bedload of 0.53 Mt yr^-1.

References
- Hinderer, M., 2001 Late Quaternary denudation of the Alps, valley and lake filling and modern river incision Geodinamica Acta 14, 231-263.