Research paper

The Holocene
22(1) 91–105

DOI: 10.1177/0959683611409778
hol.sagepub.com
SAGE

Simulating fluvial fluxes in the Danube watershed: The 'Little Ice Age' versus modern day

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Abstract

Climate change and human activities in Europe have altered erosion and riverine sediment transport for thousands of years. The Danube River basin, the second largest watershed in Europe, provides a unique study area to examine these impacts on fluvial discharge through available reconstructed climate data during the 'Little Ice Age' cold interval, as well as documented timing of deforestation and large dam emplacement. Suspended sediment flux of the Danube watershed and its variability in response to both climatic adjustments and human influences is analyzed at the sub-basin scale using a numerical modeling approach (*HydroTrend 3.0*). The system is examined over three time periods under conditions corresponding to: (1) modern day, (2) pre-dam and (3) the 'Little Ice Age'. Modeled results indicate that modern-day suspended sediment flux is approximately 60% and 80% lower than that simulated under pre-dam and 'Little Ice Age' conditions, respectively. Disregarding the effects of modern-day dams, sediment flux has decreased 46% since the 'Little Ice Age', largely due to declining rates of deforestation since the mid to late twentieth century. High-resolution (decadal) analyses based solely on climate change, i.e. assuming no human impact, suggest that suspended sediment flux should be approximately 5% higher today than during the 'Little Ice Age', despite a 10% decrease in water discharge.This supports the view that human influence is the dominant forcing agent in modifying, and even reversing, natural processes on the Earth's surface. Results also suggest that a 4°C increase in average European annual temperatures, as predicted by the Intergovernmental Panel on Climate Change for the end of this century, could result in increased sediment flux by 16–63% in individual basins.

Keywords

climate change, Danube, fluvial discharge, HydroTrend, 'Little Ice Age', suspended sediment

Introduction

The Danube River basin in central Europe is home to 83 million people (~103 persons/km^2) and extends through 19 countries, making it the most international river basin in the world (International Commission for the Protection of the Danube River (ICPDR), 2009; Sommerwerk et al., 2009). The watershed is the second largest in Europe after the Volga River and ranks as the 25th largest watershed worldwide, covering approximately 8% of the European land mass (Hofius, 1991; Natchkov, 1997). For thousands of years, the Danube River basin has been modified by short-term climatic variations and human pressures, both of which have altered erosion of the land surface and sediment transfer in the river. The quantity and quality of suspended sediment in the modern Danube River is strongly linked to anthropogenic activities within the watershed. Channel dredging and dam emplacement have reduced the suspended sediment load to the Black Sea, which has led to delta degradation (Giosan et al., 1999) and coastal erosion (Panin and Jipa, 2002), however, intensive land use practice and localized urbanization have had the opposite effect. These influences, in combination with naturally occurring climate-driven fluctuations, make fluvial sediment transfer extremely variable across both spatial and temporal scales (Syvitski et al., 2005a).

The history of human influence in the Danube region is very long, thus, it is difficult to distinguish direct human impacts from climatic variations (Hooke, 2006; Levashova et al., 2004; Rumsby and Macklin, 1996; Starkel, 2005; Thorndyncraft and Benito, 2006) and for this reason, the Danube basin is a region uniquely suitable to examine how fluvial fluxes respond to these impacts.

Data availability is limited in many Danubian countries, thus basin-wide examination of fluvial sediment is a challenging task (Schwarz et al., 2008). Jaoshvili (2002) states that that even though the Danube is one of the most-studied rivers in Europe, published sediment load estimates at the mouth vary significantly. Additionally, proxy data are not easily obtainable to resolve the spatial and/or temporal scale of the study; therefore validated numerical simulations are used to provide an alternative method to examine river discharge and sediment flux.

We examine two time periods, (i) 1500 to 1850 and (ii) 1975 to 2000, representing conditions during the 'Little Ice Age' and modern-day, respectively. The latter period includes the effects of a number of large dams. In order to isolate the dam retention effect, we also simulate sediment flux for the same period (i.e. under modern-day environmental conditions) without the presence of these structures (hereafter referred to as the pre-dam period). The period of record used for 'Little Ice Age' simulations

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Received 24 October 2010; revised manuscript accepted 22 February 2011

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Figure 1. Geographic location of the Danube Watershed (shaded) and its extent within the European continent (see inset) with national borders, the Danube River (thick line), tributaries (thin lines) and dams (triangles) with most significant dams labeled

is 350 years, while modern-day simulations are constrained by emplacement of large reservoirs (i.e. 25 year period). Therefore, in order to facilitate a comparison of different time-frames, eight additional high- resolution analyses (decadal) were carried out for each time period. These results enable a direct comparison of 10-year periods from each time frame without producing biases due to differences in averaging period lengths. Finally, we simulate water and sediment flux from individual sub-basins under a 4°C temperature increase by applying future climate projections estimated by the Intergovernmental Panel on Climate Change (IPCC, 2007) to provide a preliminary assessment on potential changes in sediment flux.

Numerical techniques are implemented through the use of the hydrologic model *HydroTrend 3.0*, which simulates river discharge and sediment load transported to the river mouth based on basin morphology, climate, reservoir impact, human-induced soil erosion and hydrologic parameters (see Kettner and Syvitski, 2008a; Syvitski et al., 1998). *HydroTrend* has been successfully applied to watersheds including the Eel River, CA (Syvitski and Morehead, 1999), the Waipoa River, New Zealand (Kettner and Syvitski, 2007), the Po River, Italy (Kettner and Syvitski, 2008b), the Lanyang River, Taiwan (Syvitski et al., 2005b), the Pee Dee, Santee and Savannah Rivers, USA (McCarney-Castle et al., 2010) and the Magdalena River, Columbia (Kettner et al., 2010), among others. This study represents the first detailed application of *HydroTrend* in central Europe and is the first comprehensive analysis regarding the impact of the 'Little Ice Age' and recent climatic changes on suspended sediment flux in catchments of the Danube River basin.

Regional setting

The Danube River is the second longest river in Europe (2857 km), originating in the Black Forest of Germany at an elevation of 1078 m and discharging into the Black Sea via the Danube delta in Romania and Ukraine (Levashova et al., 2004; Sommerwerk et al., 2009). The Danube River has approximately 120 tributaries, an average runoff of 246 mm/yr and a mean flow of 6550 m^3/s at its mouth (Hofius, 1991; Panin and Jipa, 2002). The geographic location of the Danube basin, the location of the river within the basin, and major reservoirs are shown on Figure 1. The difference in terrain between the headwaters (northernmost and northeastern Alps) and the mouth is over 3000 m (Figure 2); however the average elevation within the basin is approximately 400 m. More than one-third of the basin is covered in loess, while flysch, deep marine siliciclastic rocks, comprises another third. Secondary limestone and hard magmatic rocks are found largely in the uppermost reaches of the basin (Breu and Tomasi, 1989; Garnier et al., 2002).

The physical and hydrological characteristics of the watershed are examined through individual sub-basin analysis. Seven naturally defined subcatchments (Figure 2) are assessed, which include the: (1) Upper Basin, extending from the headwaters to

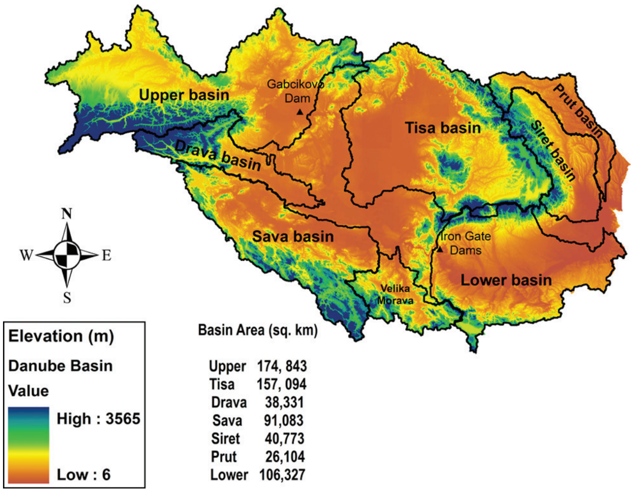

Figure 2. Digital elevation model of the Danube basin and its delineated sub-basin boundaries (black lines) with respective basin sizes (km^2)

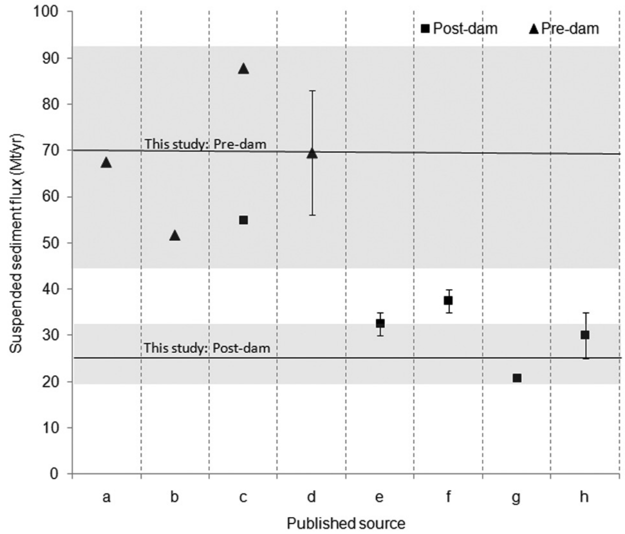

Figure 3. Previously published values and ranges of sediment flux at the mouth of the Danube River with average post-dam and pre-dam values (solid horizontal lines) from this study and yearly standard deviation (shaded). Sources: (a) Stancik et al. (1988); (b) Bondar et al. (1991); (c) Mikhailova and Levashova (2001); (d) data cited in Jaoshivili (2000); (e) Panin (1996); (f) Panin (1999); (g) Bondar (2008); (h) Panin and Jipa (2002)

25 km downstream of the Gabçikovo Dam; (2) Tisa Basin; (3) Drava Basin; (4) Sava Basin; (5) Siret Basin; (6) Prut Basin; and (7) Lower main Basin (excluding the Prut and Siret watersheds).

There are three main climatic zones that control temperature and precipitation within the basin (Hofius, 1991; Sommerwerk et al., 2009). The western-most watershed (Upper basin) is controlled by Atlantic climate conditions, which contribute to high annual precipitation (average annual >1000 mm/yr), while the southwestern portion of the basin (Sava and Drava) is partly influenced by warmer, more variable Mediterranean climatic conditions with low rainfall during the summer months (average annual ~950 mm/yr). The majority of the watershed (Tisa, Prut, Siret and Lower basins and delta) is controlled by a continental climatic regime with low precipitation (~560 mm/yr) and dry and cold winters (Sommerwerk et al., 2009). Evaporation rates in the Upper basin range from 400 to 650 mm/yr to 100 mm/yr in the Alps, 500 mm/yr in the Tisa basin and ~600 mm/yr in the remainder of the basin (Stancik et al., 1988).

The Danube delta, home to Europe's largest wetland ecosystem, is the sixth largest delta in Europe at 4152 km^2 (Sommerwerk et al., 2009). Sediment and water fluxes to the delta are the most important factors determining delta morphology but human influence has also been significant (Giosan et al., 1999; Syvitski et al., 2005a). Water quality problems associated with particle-attached contaminants have resulted in eutrophication and loss of biodiversity at the coast (Garnier et al., 2002; Lancelot et al., 2002). Delta progradation into the Black Sea, which was active during the last 6000 years (Giosan et al., 2006, 2009), has recently entered a degradational phase, largely in response to a decrease in suspended sediment contribution from the Danube River due to reservoir retention (Giosan et al., 2005; Panin and Jipa, 2002). Overall, the delta is retreating at an average rate of 20 m/yr (McManus, 2002; Panin and Jipa, 2002) while sea level is rising at a rate of 2.5 mm/yr (Tsimplis et al., 2004), which implies continuation of the current trend in coastal land loss.

Anthropogenic impact

Permanent settlements were established in the Danube region by 10.5 ka, though Degens et al. (1991) have suggested that significant increases in sediment did not occur in watersheds of this region until approximately 2.5 ka. Since the time of the Romans (400 BC), patterns of human settlement, agriculture, and war have shaped the Danubian landscape (e.g. Dotterweich, 2008).

Widespread efforts to train and dam the Danube River began as early as the 1870s. Beginning in the mid 1900s, hydropower projects were undertaken in rapid succession and more than 60 dams and weirs were emplaced in the uppermost section of the river, disrupting flow every ~16 km (Stancik et al., 1988). Three major hydroelectric structures exist along the main river course: the Gabçikovo Reservoir, which is located approximately 40 km downstream of Bratislava and 1842 km upstream from the delta, and the two Iron Gate Reservoirs (I and II, respectively), which are situated within a 117 km long gorge (Djerdap) along the border between Romania and Serbia (former Yugoslavia). Iron Gates I and II are located 943 and 864 km upstream from the river mouth, respectively and, together, supply 14 500 Gwh (ICPDR, 2010). The combined volume of the two reservoirs is 3.2 to 5 billion m^3 (ICPDR, 2009; Levashova et al., 2004) and they trap up to 80% of the suspended sediment load (Schwarz et al., 2008).

Although there are hundreds of reservoirs in upper-basin tributaries, prior to the emplacement of the Iron Gates the river was able to recover its full sediment load (i.e. pre-dam load) through downstream scour and tributary inflow before reaching the coast (Panin and Jipa, 2002). After the construction of Iron Gate Dam I in 1972, the river was still able to recover nearly 90% of its load by the Delta apex but after emplacement of Iron Gate II (1986), recovery was limited to approximately half of its pre-dammed load (Panin and Jipa, 2002). Pre-dam suspended sediment flux was 67.5 Mt/yr and currently, sediment discharge is 25–35 Mt/yr (Panin and Jipa, 2002), though others have given higher estimates (Levashova et al., 2004) (see Figure 3). Published estimates (Figure 3) range from 20 to 55 Mt/yr for post-dam conditions (Bondar, 2008; Levashova et al., 2004; Mikhailova and Levashova, 2001; Panin and Jipa, 2002). The annual water discharge is not affected by the reservoirs and the overall residence time has increased by only six days (Garnier et al., 2002).

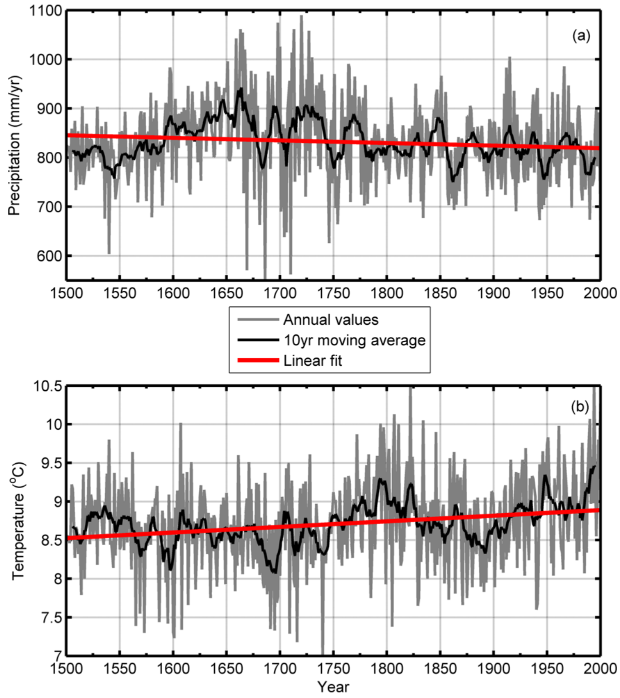

Figure 4. Spatially averaged (a) precipitation and (b) temperature across the Danube Watershed from 1500 to 2000: LIA 1500–1850

Climate impact

Short-term climatic variations have occurred throughout Europe since AD 1200 (Rumsby and Macklin, 1996). This study compares sediment flux in the Danube basin under a warm and dry climate (i.e. modern day) versus a cool and wet climate (i.e. 'Little Ice Age'). Although a detailed discussion of climatic variability is beyond the scope of this study, the differences between modern day and 'Little Ice Age' climatic conditions in this region can be seen in a time series of spatially averaged annual precipitation and temperature for the last 500 years as well as the 10-year average (see Figure 4). These differences are shown as positive and negative slopes of the trend lines in response to temperature and precipitation with time.

Recent research indicates that Northern Hemisphere temperatures of the late twentieth/early twenty-first centuries have been the warmest of the past 1000 years, which has likely been the result of increased atmospheric greenhouse gasses (Moberg et al., 2005; Tett et al., 2007), however, Goosse et al. (2006) note that European summertime temperatures roughly a millennium ago ('Medieval Warm Period') were similar to temperatures of the twentieth century. A period of distinct cooling separated the 'Medieval Warm Period' from today, commonly known as the 'Little Ice Age' (LIA) (Lamb, 1965) which lasted from *c*. 1500 to 1850. This cooler period is defined as a time within the Holocene when glaciers extended farthest down their valleys since the last glacial maximum approximately 20 ka. Overall, annual temperatures were cooler, snow lines were up to 100 m below modern limits, and winters were significantly colder with increased snow precipitation when compared with modern day winters (Grove, 2001; Rumsby and Macklin, 1996). Although deforestation had begun hundreds of years prior to this time, the European land surface changed drastically during the 'Little Ice Age' as people cleared pristine areas to plant crops, creating conditions of accelerated erosion (Fagan, 2000; Kaplan et al., 2009).

Table 1. Significant input parameters to run *HydroTrend*: Danube sub-basin example

Input parameter	Tisa watershed
Yearly Temp. start (°C), change per year and stdev.	9.0 0.0 0.84
Yearly Psum start (m/yr), change per year and stdev.	0.7 0.0 0.53
Rain mass balance coeff., distrib. exponent and range	1 1.3 5
Constant base flow (m^3/s)	350
Monthly climate variables	Dec: Jan: Feb −1.4 3.6 124.8 20
Precipitation average (mm), stdev., Temp. (°C) average, stdev	Mar: Apr: May 9.8 5.8 177.6 30
Precipitation average (mm), stdev., Temp. (°C) average, stdev	Jun: Jul: Aug 19.0 1.3 248.4 10
Precipitation average (mm), stdev., Temp. (°C) average, stdev	Sept: Oct: Nov 10.1 5.4 158.8 15
Lapse rate (°C/km)	6.0
Glacier equilibrium line altitude (m), change/yr	2900 0.0
Dry precipitation evaporation fraction	0.3
Canopy interception αg(−0.1(mm/d)), βg(0.85(−)) (Syvitski et al., 1998)	−0.1 .85
Evapotranspiration α_gwe (10 (mm/day)), β_gwe (common 1 (−))	9 1
Delta plain gradient (m/m)	0.00001
River basin length (km)	600
Reservoir vol. (km^3) and drainage area (km^2)	0.7 (d)75113
Mouth velocity coeff. & exp. (Leopold and Maddock, 1953[AQ])	0.46 0.1
Mouth width coeff. & exp. (Leopold and Maddock, 1953)	8.7 0.5
Average river velocity (m/s)	0.9
Max. and min. groundwater storage (m^3)	4.6e9 3.08e8
Initial groundwater storage (m^3)	4.6e9
Subsurface storm flow (m^3/s)	200
Hydraulic conductivity (mm/day)	400
Long/Lat of river mouth	22.579157 44.300815
Lithologic factor	1
Anthropogenic factor	1

Methods

Model description

Spatial and temporal flux of water and sediment was simulated using *HydroTrend 3.0*, a climate-driven hydrological transport model (Kettner and Syvitski, 2008a). The model converts user-input climate statistics into daily precipitation to simulate a time series of water discharge and sediment flux at a basin outlet using integrated empirical equations (Kettner and Syvitski, 2008a; Syvitski et al., 1998). The most important equations and boundary conditions are described briefly in this section, while Table 1 lists the input parameters for model simulations (excluding hypsometric data).

Water discharge. *HydroTrend* implements a classic water balance model incorporating the effects of rain (r), snow (n), ice melt (ice), groundwater discharge (gr), and evapotranspiration (eva) within the watershed to calculate the daily water discharge rate (Q in m^3/s):

$$Q = Q_r + Q_n + Q_{ice} \pm Q_{gr} - Q_{eva} \tag{1}$$

Sediment transport. Suspended sediment flux is determined by a derivation of the standard empirical sediment rating equation ($Qs = aQ^C$) called the *Psi* model (Morehead et al., 2003). The *Psi* equation generates daily suspended sediment discharge from long-term average sediment transport [$\overline{Q_{S_T}}$] (kg/s):

$$\left(\frac{QS_{[i]}}{\overline{QS_T}}\right) = \psi_{[i]} f \left(\frac{Q_{[i]}}{\overline{Q}}\right)^{c_{(a)}} \tag{2}$$

where $\overline{Q}$ is the long-term averaged water discharge (m^3/s), $Q_{[i]}$ is the daily discharge (m^3/s), $Qs_{[i]}$ is the daily sediment discharge (kg/s) and $\psi_{[i]}$ is a random, log normal variable with a mean of 1 and a standard deviation that is a function of water discharge, such that the model is capable of representing variability (intra- and interannual) typical of most rivers (Kettner and Syvitski, 2008a; Morehead et al., 2003). The term f is a constant of proportionality defined as:

$$f = \left(\frac{\sum_{i=1}^{n} Qs_{[i]}}{\overline{Qs_T}}\right) / n \tag{3}$$

where n is the number of days over the model run. The parameter $C_{(a)}$ in Eq. (2) is the rating exponent and varies annually following a normal distribution; it depends on temperature, relief, water discharge and long-term sediment transport. Descriptions of relationships defining the variability of the *Psi* model, integrated equations and model structure are included in Kettner and Syvitski (2008a), Morehead et al. (2003) and Syvitski et al. (1998) while the variability of standard sediment rating equations in response to unstable climatic periods is discussed in Coulthard et al. (2005, 2007).

The BQART equation. Human pressures on the land (E_h), glacial erosion (I), lithologic composition (L) and reservoir impoundment (T_E) are parameterized in the model through a series of 'B' factors within the *BQART* equation for determining long term sediment load ($\overline{Q_{S_T}}$):

$$\overline{Q_{S_T}} = \varpi B \overline{Q}^{0.31} A^{0.5} RT \tag{4}$$

and

$$B = I\, L\, (1\text{-}T_E)\, E_h \tag{5}$$

where ω is a coefficient of proportionality (0.02 kg/s per km/°C), A is area, R is relief and T is temperature (Syvitski and Milliman, 2007). The long-term suspended sediment load varies with changing basin temperature as determined by empirical relationships derived from 360 global rivers over five pre-defined climatic zones (Syvitski et al., 2003).

Model set up

Individual simulations were carried out for major subcatchments (see Figure 2), thereby increasing spatial accuracy and geographic resolution, while maintaining model efficiency. The Siret and Prut basins are included (geographically) in the Lower Basin; however, we separate them from the lower river reach in order to isolate this portion of the river, which extends from the Iron Gates to the mouth, to better estimate individual sediment contribution. We do not analyze the Mediterranean sub-basin Velika Morava because of its relatively insignificant water discharge (~200 m^3/s) and insufficient sediment data.

Rock durability determines, in part, the availability of source material for transport (Jansen and Painter, 1974). Based on resistance of a rock to erosion, the influence of lithologic type (L) on sediment flux is determined by a numerical index ranging from less resistant (L = 3; e.g. loess) to very resistant (L = 0.5; e.g. metamorphic) as defined by Syvitski and Milliman (2007). L values were calculated using a simple weighted mean of the respective area covered by resistant versus softer rock type based on regional geologic maps of the Danube watershed (Breu and Tomasi, 1989; Garnier et al., 2002). The Upper, Tisa, Drava and Sava basins are composed of a mixture of soft and hard lithologies and thus were assigned a value of L = 1 (Syvitski and Milliman, 2007). The Prut, Siret and Lower basins were assigned a value of L = 2 (alluvium dominated) as each of these have headwaters in the more durable flysch; however, the majority of their watersheds is covered by loosely consolidated sedimentary/alluvial deposits. Lithologic values were not changed between time periods and sensitivity to this parameter is quantified in the Results section. We would like to point out that the basin as a whole was set at L = 2.0 in a global study by Syvitski and Milliman (2007), however, the present study applies higher resolution geologic maps, therefore, we assign L = 1 for 'whole-basin' simulations to indicate a mixture of hard and soft lithology.

A simple equation used to assess human impact on the natural environment and soil erosion is (Goudie, 2000):

$$I = P \cdot A \cdot T_{ECH} \tag{6}$$

where I is human impact, P is population, A is the demand on resources per person and T_{ECH} is the technological factor, or how significantly humans may modify the landscape (i.e. damming, land clearance). *HydroTrend* incorporates these demographic and socio-economic conditions by parameterizing population density

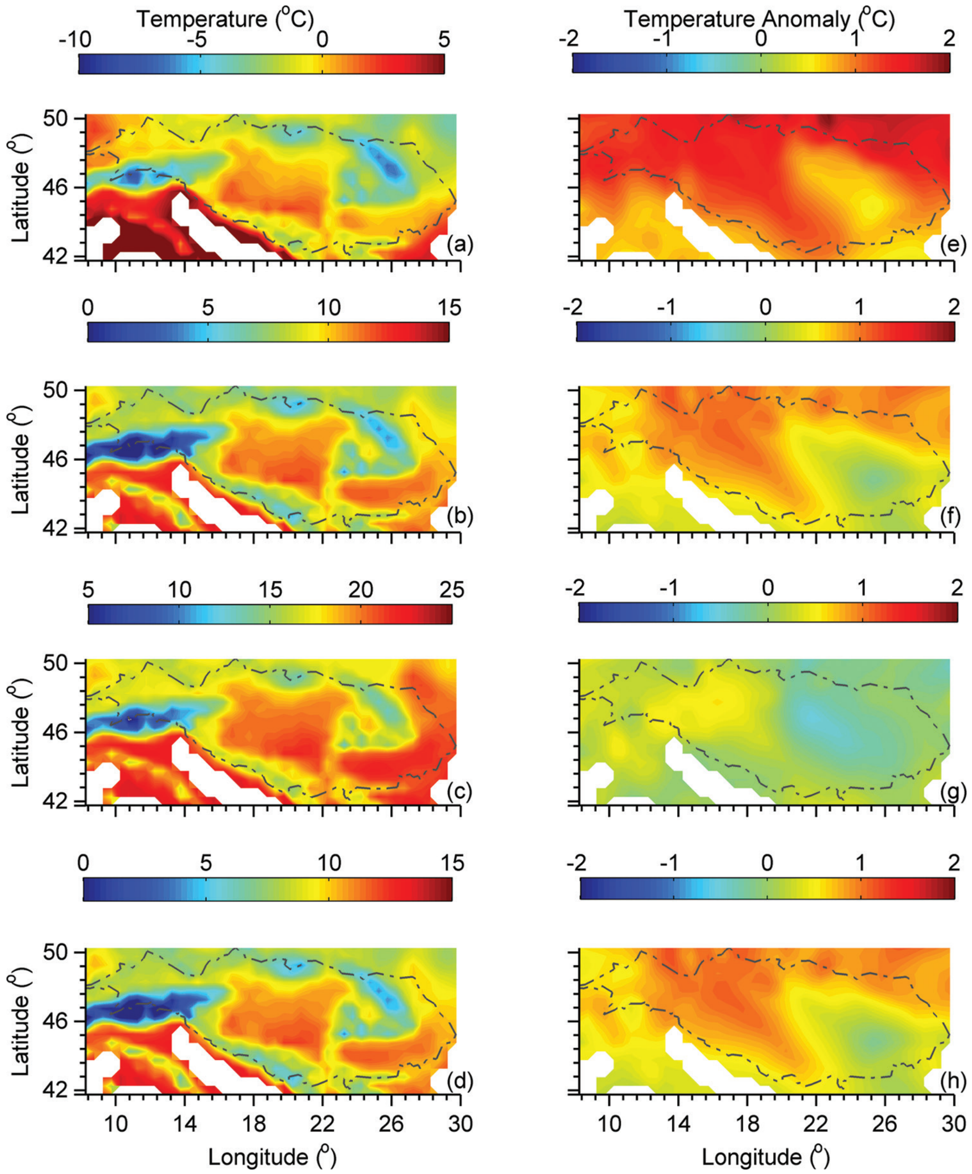

Figure 5. Seasonal average temperatures (°C) within the Danube Basin expressed as absolute values for modern-day conditions (left column) and anomalies between modern-day and LIA conditions (right column): (a & e) winter; (b & f) spring; (c & g) summer; (d & h) autumn (data source: Luterbacher, 2006) (note variable color bar values for each plot)

and gross national product per capita (GNP) in an anthropogenic factor (E_h), which varies from $E_h = 0.3$ to 2, representing low to high soil erosion rates, respectively (Syvitski and Milliman, 2007). To assign a reasonable anthropogenic factor (E_h) during the LIA, we use the global land cover data set of Ramankutty and Foley (1999), the human-influenced erosion factor scale of Syvitski and Milliman (2007), and various other sources of data and literature concerning land use change over recent history (Goldewijk, 2001; Kaplan et al., 2009; Pongratz et al., 2008; Tett et al., 2007). Throughout most of the LIA, deforestation was intense and conversion to agriculture was predominant , therefore we assigned a value of $E_h = 2.0$ to all basins during the LIA, indicating that watersheds underwent deforestation rates near historical peak and/or poor farming practices, as defined by Syvitski and Milliman (2007). Currently, much of central Europe is experiencing a moderate amount of reforestation and abandonment of agricultural area because of economic decline (Ramankutty and Foley, 1999; United Nations Economic Commission for Europe and the Food and Agriculture Organization (UNECE/FAO), 2000). Modern-day anthropogenic conditions were assigned a value of $E_h = 1$ in most sub-basins, representing a mixed degree of erosion and soil conservation. The Upper basin was assigned a value of $E_h = 0.3$ to represent extreme protection measures, high GNP and high population density (>200 persons/km^2) (e.g. Germany, Austria) after Syvitski and Milliman (2007). This methodology serves as an *a priori* approach to establish the relationship between erosion and human activity, which is continually changing. Because of its complexity and lack of a single suitable model to quantify this relationship, a semi-linear approach is adopted (Houghton, 2003; Pongratz et al, 2008; Ramankutty and Foley, 1999). Sensitivity to this parameter is quantified and results are included in the Results section.

Hydrologic and biophysical parameters (e.g. evapotranspiration, canopy interception) that were modified between the two time periods were calculated and averaged throughout the sub-basins to represent present-day conditions based on published data and were extrapolated backwards to represent LIA conditions according to descriptions of climate and land cover (Fagan, 2000; Kaplan et al., 2009; Luterbacher, 2006; Pauling et al., 2006; Ramankutty and Foley, 1999). The uncertainty of this approach,

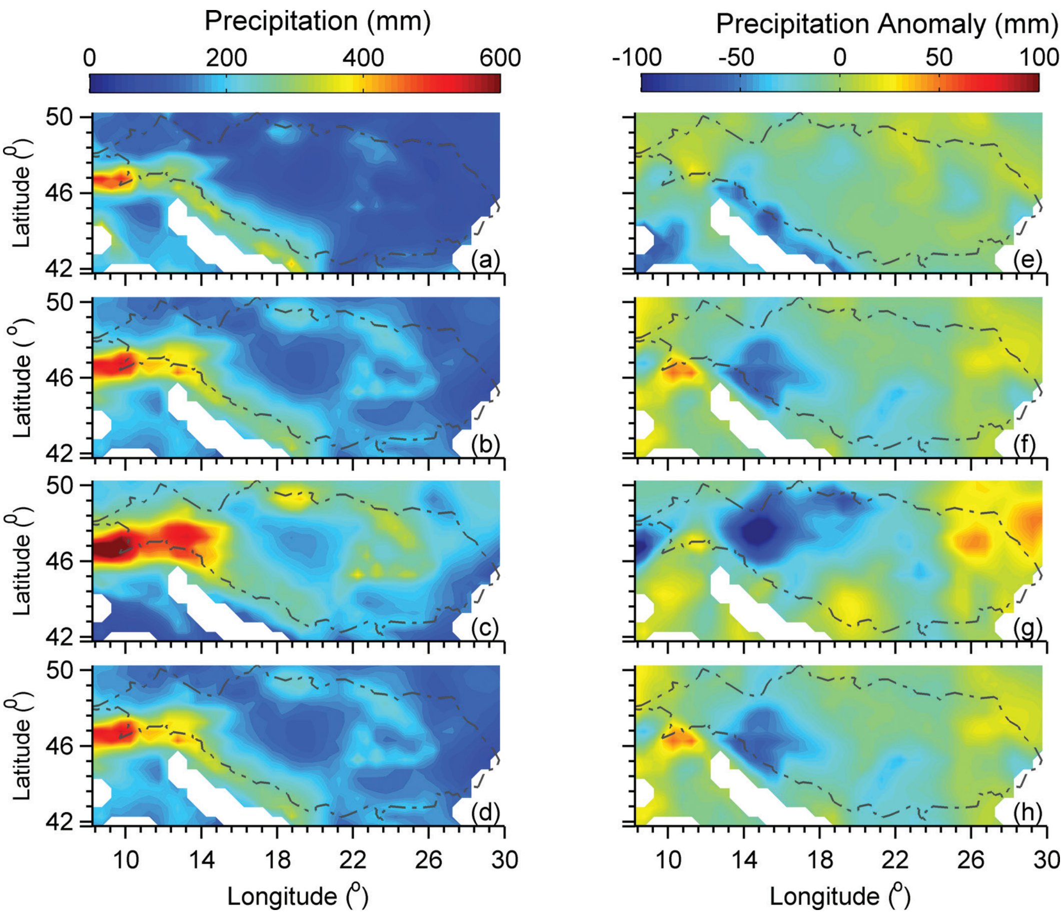

Figure 6. Seasonal average precipitation (mm) within the Danube Basin expressed as absolute values for modern-day conditions (left column) and anomalies between modern-day and LIA conditions (right column): (a & e) winter; (b & f) spring; (c & g) summer; (d & h) autumn (data source: Pauling et al., 2006)

especially during the LIA, must be considered. Sensitivity analyses, which were performed through manipulation of individual variables, were conducted for each sub-basin in order to quantify uncertainty generated by user-defined boundary conditions and stresses.

Trapping efficiency (T_E in %) is used to determine the impact of retention of a dam on fluvial sediment (Brown, 1943). In this study, sediment trapped behind a dam is considered to be held in permanent storage, unlike floodplain-type temporary storage. T_E is calculated via the Brown (1943) and modified Vörösmarty et al. (1997) and Brune (1953) equations for small reservoirs (<0.5 km^3) and large reservoirs (>0.5 km^3), respectively. Finally, glacier erosion processes (I) were found to have no impact on annual sediment flux under examined time periods.

Climate data

The high-resolution seasonal precipitation reconstructions of Pauling et al. (2006), which apply a 0.5°×0.5° grid covering all European land areas (30°W–40°E/30°N–71°N), were used as model input for both modern-day and LIA conditions. Seasonal reconstructed temperature data were obtained from Xoplaki et al. (2005) and Luterbacher et al. (2004). Spatial coverage of each basin was extracted from these large European data sets and basin-wide temperature and precipitation anomalies between time periods and absolute values under modern conditions are shown on Figures 5 and 6, respectively.

Model simulations

Following model validation of seasonal water and sediment discharges, seven sets of model simulations were carried out driven by both climatic and anthropogenic forcings. The first four sets are for: (1) LIA conditions; (2) Modern conditions; (3) Modern conditions without dams; and (4) LIA conditions combined with modern-day erosion conditions through alteration of the E_h parameter (to isolate anthropogenic forcing). Modern conditions assume that all large reservoirs are in place and apply climate conditions averaged over the years 1975–2000. The fifth set of simulations included a basin-wide decadal-resolution study focused on assessing the impact of short-term fluctuations and trends in climate between the LIA and modern-day eras. Four decades from each time period with similar climate conditions (e.g. cold/wet; cold/dry; warm/wet; warm/dry) were selected for this set of simulations. Dam effects were removed and the human erosion index (E_h) was held constant at $E_h = 1$ (no significant net anthropogenic effect), thus isolating climate as the sole driver of the results. Modern climate conditions were extended back to 1940 to increase the subset of climate data. Additionally, these results were used to ensure consistency in our approach of dividing the area into seven sub-basins. The final two sets of simulations focus on identifying the effects of temperature variations on sediment discharge. Each river sub-basin was simulated with a 1°C and 4°C increase in temperature, respectively, corresponding to temperature increases projected for the end of the twenty-first century by the IPCC (2007). These results allow us to tentatively assess how changes in average

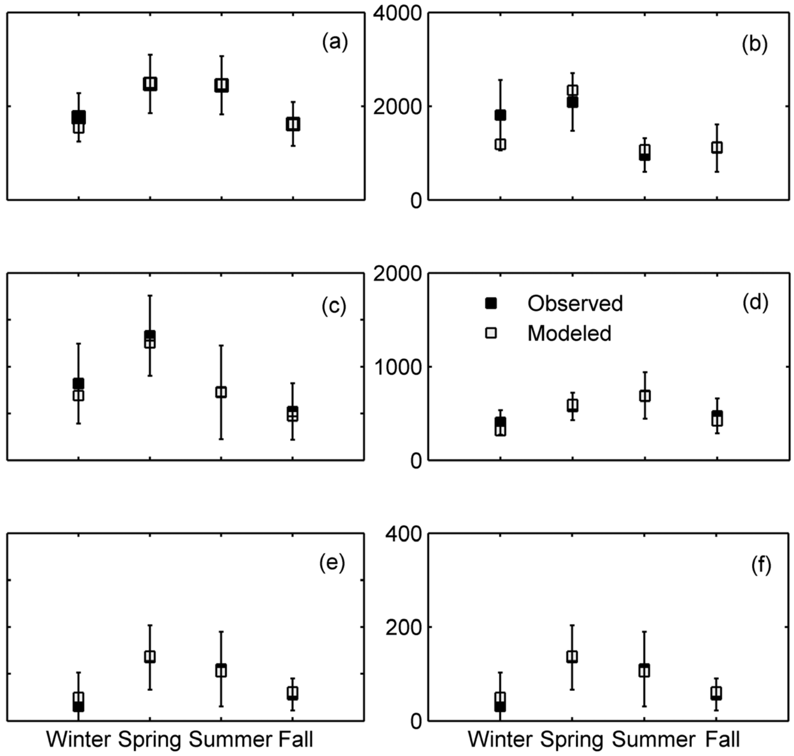

Figure 7. Validation analysis results comparing observed and modeled seasonal water discharge (in m^3/s) shown as black and gray squares, respectively, for each basin (excluding the lower basin). Lines indicate ±1 standard deviation of observed data; (a) Upper basin, (b) Sava Basin, (c) Tisa Basin, (d) Drava Basin, (e) Siret Basin, (f) Prut Basin

temperatures would affect a large basin and how future trends in sediment flux may change in the Danube watershed.

Results

Validation

Simulated water discharge was validated on a seasonal time-step using present-day (1975–2000) river discharge data (Global Runoff Data Centre (GRDC), 2010) from the furthest downstream gage of each tributary and results are shown on Figure 7. Standard deviations of observed discharge values are averaged over each season (i.e. three month periods). Individual correlation coefficients (r^2) between 25 years of observed seasonal discharge versus simulated discharge for the Upper, Tisa, Drava, Sava, Siret and Prut watersheds are 0.97, 0.91, 0.90, 0.61, 0.99 and 0.92, respectively. Validation of sediment was more challenging because of limited data availability; nevertheless a 55 year record of suspended sediment flux from the apex of the Danube delta was used (see Figure 8a, b). Observed average annual sediment flux prior to the construction of the Iron Gate Dams (1945–1972) was 49.1 (±19.1) Mt/yr and has since been reduced to 19.8 (±13.3) Mt/yr, a reduction of 63%, based on data from 1986 to 2000.

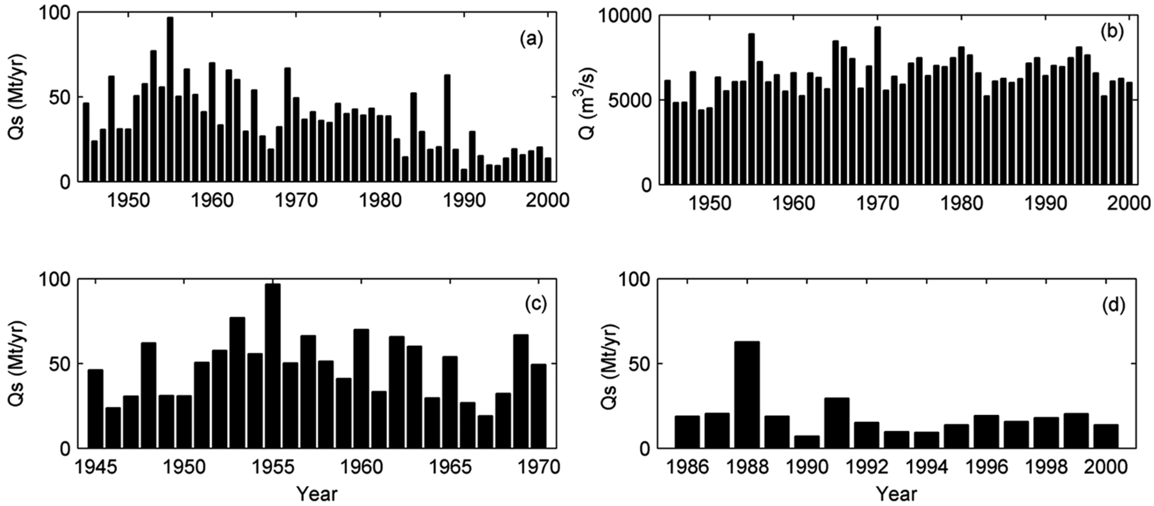

Figure 8. Time series of observed suspended sediment discharge (a) and water discharge (b) at the mouth of the Danube River from 1945 to 2000. Suspended sediment load at the mouth of the Danube River from the years 1945–1970 (c) (i.e. pre-Iron Gate dams) and the years 1986–2000 (d) (i.e. post-dam)

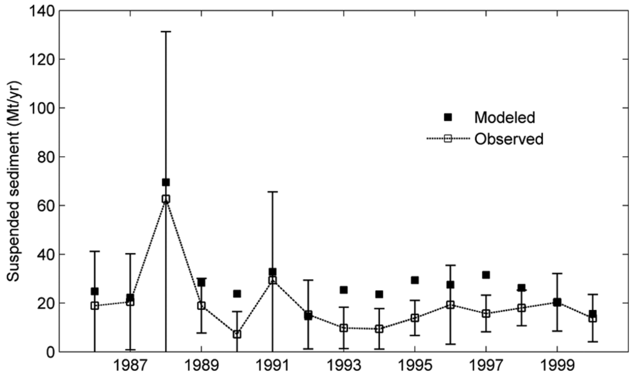

Figure 9. Observed versus simulated suspended sediment flux at the river mouth for the years 1986–2000 (post-dam) with observed (monthly) standard deviations

Suspended sediment flux (Mt/yr) prior to the emplacement of the Iron Gate dams (1945–1970) is shown on Figure 8(c) while sediment flux after dam emplacement (1986–2000) is shown on Figure 8(d). A comparison of modeled post-dam annual fluxes versus observed is presented on Figure 9 with error bars indicating ±1 standard deviation calculated from monthly averages through each year. Validation of sediment flux in the remainder of the basin was complicated by limited and inconsistent published data, however, we used values of point data published in the Food and Agricultural Organization data base (Food and Agriculture Organization of the United Nations (FAO), 2010) and a recent World Wildlife Federation (WWF) report (Schwarz et al., 2008). These data are included with simulated results in Table 2.

Water and suspended sediment discharge

Results of individual watershed analyses, including simulated water discharge, suspended sediment flux ±1 STD, and climate means, are listed in Table 2. On average, the Danube tributaries discharge 80% less suspended sediment, respectively, under modern conditions than during the LIA and are currently transporting 60% less suspended sediment than under pre-dam conditions. When factoring out the impact of dams, suspended sediment load has been reduced by 46% since the LIA. The largest decreases are noted in the Upper and Lower basins, as a result of trapping by the Gabçikovo dam and the Iron Gate dams, respectively, and the simulated values are consistent with published trapping efficiencies associated with these major dams (Schwarz et al., 2008).

Climate analysis

While average yearly climate values do not indicate a significant change, basin-wide seasonal analyses show that winter, spring, summer and autumn temperatures during the LIA were 1.13, 0.65, 0.0, and 0.25°C cooler than today. Intra-annual temperatures within sub-basins have increased by 1.15±0.24, 0.71±0.25, 0.20±0.13, and 0.24±0.28°C as shown on Figure 10. To further investigate climatic differences on a seasonal scale, we carried out a high-resolution study by comparing two different years characterized by the coldest (1709) and the warmest (1990) winters on record. On a seasonal scale, the year with the warmest winter (1990) exhibited higher temperatures by 8.25, 2.31, 0.01 and 0.54°C for winter, spring, summer and autumn, respectively, which corresponds to an increase

Table 2. Simulated and observed water discharge (*Q*) and sediment flux (*Qs*) and reconstructed average climate under modern day and LIA conditions. Modeled means and standard deviations are calculated at a seasonal resolution

Basin	Epoch	Climate means		Water discharge (m^3/s)		Suspended sediment (Mt/yr)	
		Temp (°C)	Precip (mm)	Observed	Modeled	Observed	Modeled
Upper	Modern	7.74	956	2075	2060	1.7[b]	1.9±1.0
	Pre-dam	7.74	956	2075	2060	5.2[c]	9.2±5.3
	LIA	6.96	1010	n/a	2468	n/a	21.7±18
Tisa	Modern	9.78	658	848	843	4.1[d]	4.4±4.2
	Pre-dam	9.78	658	848	843	6.8[c]	14±15
	LIA	9.29	710	n/a	966	n/a	23±32
Drava	Modern	10.38	889	467	459	1.5[d]	3.2±1.8
	Pre-dam	10.38	889	467	459	n/a	5.7±3.5
	LIA	9.59	987	n/a	555	n/a	9.3±7.6
Sava	Modern	10.2	971	1491	1457	3.3[d]	6.2±5.5
	Pre-dam	10.2	971	1491	1457	n/a	11±12
	LIA	9.6	1041	n/a	1649	n/a	20±22
Siret	Modern	9.04	529	200	206	8.2[e]	4.3±3.7
	Pre-dam	9.04	529	200	206	14.2 [f]	5.4±4.7
	LIA	8.51	492	n/a	204	n/a	9.5±7.9
Prut	Modern	9.04	529	83	80.3	1.3[f]	2.0±2.2
	Pre-dam	9.04	529	83	80.3	2.7 [f]	3.8±4
	LIA	8.51	492	n/a	80	n/a	5.1±6.7
Lower	Modern	10.25	607	745 [a]	906	n/a	4.0±3.2
	Pre-dam	10.25	607	745 [a]	906	27[f]	21±30
	LIA	10.0	636	n/a	1621	n/a	40±51
River Mouth	Modern	9.4	5139	6245	6011	20.7–55	26± 6.3
	Pre-dam	9.4	5139	6245	6011	51.7–87.8	70.1± 25
	LIA	8.9	5368	n/a	7534	n/a	128.6± 51

n/a, data not available.
Sources: Observed water discharge data from GRDC (2010); Climate data from Pauling et al. (2006); Luterbacher (2006) and Xoplaki et al. (2005). Sediment data from: [a]Bondar (2008); [b]Klaver et al. (2007); [c]FAO (2010); [d]Schwarz et al. (2008); [e]Radoane et al. (2007); [f]Stanescu and Stanculescu (1967).

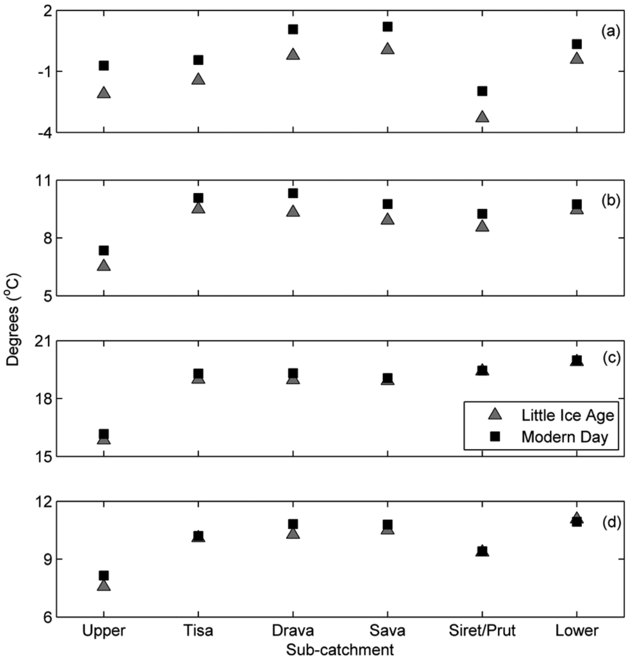

Figure 10. Average intrabasin seasonal temperatures during the 'Little Ice Age' (gray triangles) and under modern conditions (black squares) for (a) winter, (b) spring, (c) summer, and (d) autumn. Note that each seasonal plot has a different vertical scale with a uniform range of 6°C

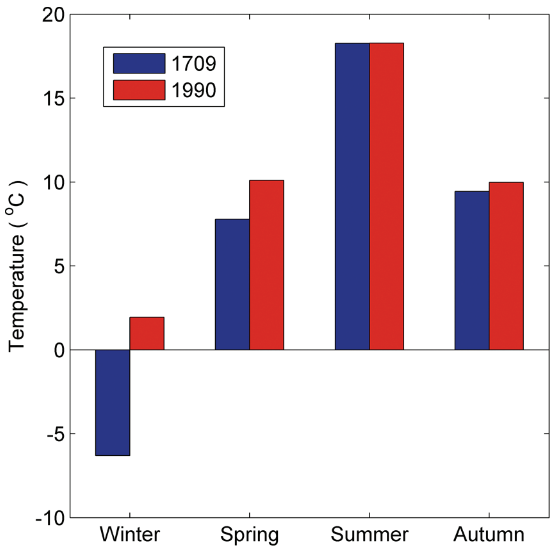

Figure 11. Averaged seasonal temperatures in the Danube basin between the years 1709 and 1990. Note the difference in winter temperature and coincidence of summer temperatures

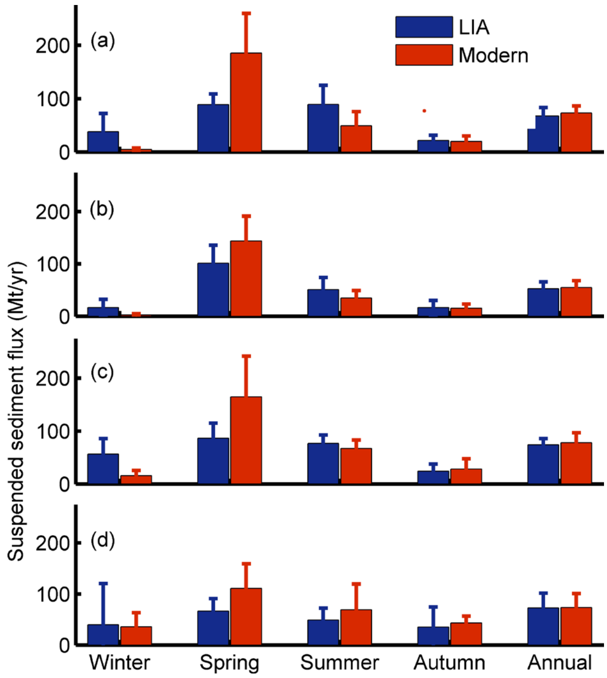

Figure 12. Seasonal flux results for decadal simulations based on varying climate scenarios: (a) cool/wet, (b) cool/dry, (c) warm/wet, (d) warm/dry. Refer to Table 4 for climate details

of 130, 30, 0.05 and 6%, respectively (see Figure 11). The change noted in temperature within the year is approximately 45% greater during 1709 than during 1990 owing to the significantly different winter temperatures. The summer temperatures, however, are nearly identical between the two years.

Average annual temperature and precipitation during the 'Little Ice Age' (1501–1850) within the Danube Watershed are 8.7±3.0°C and 842±383 mm, respectively. Average annual temperature and precipitation for the modern era (1975–2000) are 9.2±2.9°C and 801±387 mm, respectively.

Climate-driven sediment fluxes

The results of water and sediment flux from short-term (decadal) simulations controlled solely by climatic conditions under both the LIA and present day (see Table 3), indicate that currently, water discharge should be lower (~10%) and suspended sediment flux should be higher (~5%) than during the LIA (if not for the effects of humans). Interannual water and sediment discharge standard deviations over each decade are similar between the LIA and modern day, with largest standard deviations occurring in years where climate was warm and dry. When considering the

Table 3. Simulated water and suspended sediment results from climate-driven decadal study (with STD through specific decade)

Epoch	Scenario	Period	Precipitation (mm)	Temperature (°C)	Discharge (m^3/s)	Sediment flux (Mt/yr)
LIA	Cool/wet	1650–1660	885	8.4	7929 ± 787	67.3 ± 16
	Cool/dry	1709–1719	861	8.3	7616 ± 815	52.91 ± 13
	Warm/wet	1770–1780	865	8.9	7728 ± 748	74.1 ± 11.5
	Warm/dry	1530–1540	794	9.0	6207 ± 826	72.9 ± 29
Modern	Cool/wet	1960–1970	850	8.8	7399 ± 784	73.0 ± 24
	Cool/dry	1940–1950	778	8.9	7209 ± 725	55.0 ± 13
	Warm/wet	1975–1985	818	9.0	7186 ± 626	77.8 ± 19
	Warm/dry	1990–2000	790	9.5	5068 ± 792	73.8 ± 27

Table 4. Current and predicted suspended sediment flux (Mt/yr) and standard deviation with 1°C and 4°C annual temperature increase and total percentage change under a 4°C increase relative to current flux

Temperature (°C)	Suspended sediment flux (Mt/yr)						
	Upper	Tisa	Drava	Sava	Siret	Prut	Lower
Current	1.9±1.0	4.4±4.2	3.2±1.8	6.2±5.5	4.0±3.7	2.3±2.2	4.0±3.2
+1°C	3.7±1.6	4.6±3.6	3.7±2.4	7.0±5.0	4.6±3.6	2.5±3.2	4.4±3.6
+4°C	5.2±1.1	5.1±2.2	5.2±2.6	9.3±5.8	6.2±2.7	3.0±2.3	5.8±3.5
% increase	63	16	62	50	55	30	45

Table 5. Example of sensitivity analysis with ±10% modification in select model input parameters. Results are shown as percentage change as well as absolute value change: (Δ*Q*) in m^3/s and suspended sediment flux (Δ*Qs*) in kg/s

Input Parameter	10% increase				10% decrease			
	Δ Q		Δ Qs		Δ Q		Δ Qs	
	m^3/s	%	kg/s	%	m^3/s	%	kg/s	%
Canopy through fall	118.0	12.0	17.8	2.4	−107.8	11.2	−26.6	3.6
Lapse rate	4.3	0.5	−24.0	3.3	−3.4	0.4	24.0	3.3
Dry precipitation evaporation	−16.6	1.7	−4.0	0.5	17.1	1.8	4.0	0.5
Evapotranspiration	−37.9	3.9	−9.1	1.2	44.2	4.6	10.3	1.4
Subsurface storm flow	3.7	0.4	0.8	0.1	−3.3	0.3	−0.8	0.1
Hydraulic conductivity	n/a	n/a	n/a	n/a	20.9	2.2	4.9	0.7
Lithology (L)	0.0	0.0	73.9	10.0	0.0	0.0	−73.9	10.0
Anthropogenic (E_h)	0.0	0.0	73.9	10.0	0.0	0.0	−73.9	10.0

seasonal response to climate variations, the results indicate a significant and consistent increase in present-day spring sediment discharge over any another season (Figure 12). Note that these results predict the response of climate only (temperature and precipitation) whilst changes in other hydrologic parameters that could also reduce discharge (e.g. evapotranspiration) are not incorporated in this set of analyses. Total system flux ranges from 55.0±13 Mt/yr to 77.8±19 Mt/yr, which agrees well for summed individual pre-dam model runs (70.1±25 Mt/yr).

The impact of possible future temperature changes on sediment flux was investigated through a number of hypothetical cases. We ran model simulations to determine what effect a 1°C and a 4°C temperature increase would have on sediment flux (Table 4). The latter value is the projected temperature increase for central Europe by the end of this century (IPCC, 2007). When averaging across the basin, our results show that sediment flux could increase by 0.6 Mt/yr with a 1°C temperature increase and by 1.5 Mt/yr with a 4°C increase. The sub-basins that showed the most change in sediment flux with the 4°C temperature increase (>50%) were the Upper, Drava, Siret and Sava basins, while the Prut, Lower and the Tisa basins showed the least change in flux (<50%). The deviation between basins is caused by individual basin relief and altitude, with basins having the greatest change in relief and the largest portion of their basin at altitudes >500 m showing the most significant increase in sediment flux (Syvitski and Milliman, 1992).

Sensitivity analysis

Results of comprehensive global uncertainty analyses regarding the long-term sediment equation applied in this study have been presented elsewhere (Syvitski and Milliman, 2007; Syvitski et al., 2003) and thus, are beyond the scope of this contribution, however Syvitski and Milliman (2007) found that the model accounted for 96% of the variation from river to river (n = 488) with a bias of only 3% across six orders of magnitude. Additionally, Syvitski et al. (2003) noted that uncertainties in typical modeled (*HydroTrend*) results are of the same order as those from empirically derived equations based on observations (Syvitski et al., 2003). In this work, our sensitivity analysis was focused on determining how much error a feasible amount of variation in input could introduce, thereby evaluating sensitivity of model results to boundary conditions. Each significant hydrologic parameter was altered by 10% in both the positive and negative direction and sediment flux and water discharges were generated (Overeem et al., 2005). Results of one watershed analysis (Tisa Basin) are listed in Table 5. Relative percentage differences hold true for either time periods and alterations in flux (%) are comparable from basin to basin. Results indicate that the maximum percentage that water and sediment discharge would vary with an applied positive or negative uncertainty of 10% is 12% and 10%, respectively. The maximum *cumulative* error or deviation from absolute predicted values that may be introduced by the combination of these parameters set at their highest realistic levels are 20.4% and 29.6% for water and sediment discharge, respectively, which lie well within the annual variation of observed discharge for most rivers (Syvitski et al., 2003).

Discussion

Water and sediment validation and fluxes

Sub-basins were analyzed individually on a seasonal time-step to determine their annual contribution of water and suspended sediment to the Danube River under basin-specific pressures, morphology and climate. The cumulative contribution of these separate watersheds accurately reproduces modern-day basin-wide water discharge and sediment flux observed at the delta and analyses were conducted for the entire system to confirm these results (deviation <2%). Modeled average annual water and sediment fluxes at the river mouth (Table 2) from pre-dam and post-dam periods agree very well with published data. Inclusion of the Velika Morava River would potentially contribute an additional ~2 Mt/yr of sediment (Schwarz et al., 2008) and 230 m^3/s of water (GRDC, 2010) to the total flux, thereby strengthening agreement with published loads. Individual river discharge may vary slightly from observed conditions because of heavily modified sections of river or other alterations (e.g. Tisa basin), which are not accounted for in the model. The largest deviation between simulated and observed discharge is seen in the Sava River ($r^2 = 0.61$), which is affected by both Atlantic and Mediterranean climate regimes, causing short-term variations in river flow. In a separate study (applying a different hydrological model) Garnier et al. (2002), found a similar disagreement between simulated and observed discharge for this basin indicating a likely short-lived event (natural or anthropogenic), which models do not accurately simulate. Remaining basins average an r^2 of 94% across 25 years of observed seasonal discharge data.

Based on recorded data from near the river mouth, a clear overall trend in decreasing sediment is seen for the period of record (see Figure 8a). There was a slight but consistent decrease in sediment flux prior to dam emplacement, which has been typical since peak erosion conditions ended approximately 1000 years ago (Degens et al., 1991), however, after closure of Iron Gate II in 1986, sediment loads significantly declined and became less variable from year to year. Modeled results of this period tend to overpredict measured conditions, possibly because of sediment extraction or storage within the lower reaches, neither of which are parameterized in the model. Results accurately capture large flood events (e.g. 1988), are in good agreement with observed conditions and also agree well with suspended sediment load data published by Walling (2006) and Bondar and Blendea (2000).

Published sediment flux estimates used as validation points within sub-basins do not include range or error associated with the mean values, nor are the period of records identified, therefore these data must be used with caution. Additionally, published values may represent conditions prior to the emplacement of newer reservoirs (e.g. Siret). Conversely, observed ‘pre-dam’ conditions for both the Upper and Tisa basins were recorded in 1974 (FAO, 2010) when there were many dams in place already, so these published numbers do not represent true pre-dam conditions and should be much closer to simulated pre-dam fluxes. Simulated fluxes could also be overestimated in some of basins (e.g. Sava and Drava) because of sand and gravel extraction (Bonacci and Oskorus, 2010). Furthermore, floodplain storage (e.g. Tisa, Sava) is not incorporated into *HydroTrend* so modeled results may slightly overpredict suspended sediment quantities when a large alluvial plain is encountered (Kettner et al., 2010; McCarney-Castle et al., 2010; Phillips et al., 2004). In the absence of formal monitoring programs, published estimates must be used to help validate sediment transport models; however, the lack of available data in such an internationally important watershed is unfortunate.

Under conditions prevalent during the LIA, model results suggest that as much as 130 Mt/yr of suspended sediment was discharged from the Danube with water discharge moderately higher than today at 7534 m^3/s. The response of the river to human impact is revealed through results from simulations that disregarded dams and focused on the land-use parameter (E_h). When we ran the scenario using LIA conditions combined with present-day anthropogenic erosion, suspended sediment was reduced by nearly half within each sub-basin. This suggests that nearly half (40%) of the reduction in suspended sediment between the LIA and modern day may be explained by significant human induced erosion (i.e. deforestation) during the LIA. Assuming that approximately 60% of the reduction is explained by dam retention and approximately 40% is explained by declining land use and reforestation, it is possible that these drivers could potentially mask the effects of climate variation, which is consistent with the work of Zolitschka et al. (2003), who noted that the human signal was so significant in sediment archives taken from locations throughout Germany that it completely overprinted any indication of climatic influence. There are, however, locations throughout Europe where climatic influence was more significant than human-induced sediment erosion as evidenced by sedimentary deposits (e.g. Macklin and Lewin, 2003; Thorndyncraft and Benito, 2006) such that influences are extremely spatially variable. We acknowledge the sensitivity of the anthropogenic parameter within the model and the potential of this component to affect predicted flux results if not controlled carefully; sensitivity results are included in Table 5. The uncertainties of any parameterized model that attempts to predict physical processes are many and the need to simplify the environmental record and processes acting on a catchment over time is obvious (Coulthard et al., 2005), however, while the absolute values of the results may change corresponding to parameterized boundary conditions, the relative findings supporting the conclusions should not.

Climate-driven fluxes

During both the LIA and modern periods, water discharge in individual basins is greatest during spring, corresponding to peak floods (see Figure 7). The Upper and Drava basins, with the coldest temperatures and highest elevations, are the exceptions, as increased water discharge typically occurs during the summer months. According to our climate-driven decadal basin-wide results, sediment flux is highest under warm/wet conditions and lowest under cool/dry conditions (Figure 12). Patterns of sediment discharge are similar between seasons of the LIA and modern day; however, modern-day spring fluxes have been greatly increased because of significantly warmer winter temperatures. Autumn fluxes are nearly identical as summer conditions are similar between the two time periods and summertime fluxes between periods are also similar, with slightly higher summer-time fluxes during the LIA under three of the four scenarios (Figure 12a,b,c). Winter sediment fluxes during the LIA are higher than present day because of larger intradecadal variations in temperature but are within range of flux errors for modern-day discharge. As this component of our study does not include human-induced soil erosion, these results represent the response of the fluvial system to climate only. Overall, despite higher water discharge during the LIA (due to increased precipitation), there is less suspended sediment being transferred through the system (per year) when compared with modern conditions. Similar to our findings, results of a study of the Hungarian Danube tributaries by Nador et al. (2003) indicate that suspended sediment flux typically decreased during cooler periods and increased during warmer periods throughout the Pleistocene. Rumsby and Macklin (1996) found that, when considering climate forcings alone, fluvial activity was decreased during the 'Little Ice Age' in 19 locations throughout Europe when compared with today and other warm periods. We display our results as an overall basin average over only one decade under each climatic scenario, thereby discounting the effects of orography and topography in individual basins; nevertheless, our results support published (proxy) results when considering yearly fluxes (Mt/yr). Higher resolution (monthly) analyses would help to further disentangle the fluvial response in relation to climate change.

Our results show a simultaneous increase in sediment flux with decreased precipitation, therefore, we believe that temperature has played a more important role than precipitation; however, we acknowledge that a simple relationship between climate fluctuations and fluvial sediment erosion and transport is difficult to define (Nador et al., 2003) because of interaction with additional internal and external stimuli (Coulthard et al., 2005). This is consistent with Syvitski et al. (2003) who found that while the effects of temperature are less important than land use and lithology, temperature variations have the potential to play a larger role in determining sediment discharge than precipitation changes. We also acknowledge that application of these assumptions in the future would need to consider the role of increased frequency of precipitation events, as predicted by the IPCC Working Group I (2001), which has the potential to increase sediment erosion more than increased quantity of precipitation (Groisman et al., 2001; Pruski and Nearing, 2002).

In general, higher rates of erosion occur in warm humid regions and lower rates occur in cooler continental climates, with most significant erosion rates found in areas of high altitude and relief (Fournier, 1960; Jansen and Painter, 1974; Milliman and Meade, 1983; Syvitski and Milliman, 1992; Syvitski et al., 2003). Harrison (2000) detailed the significance of basin gradient as a prominent driver in erosion and determined that an increase in average temperature by 10°C could increase the rate of erosion by a factor of approximately 4.5. Our results indicate that suspended sediment flux in the Danube Basin could increase by a factor of approximately 1.5 with a 4°C increase in average temperature, which is consistent with Harrisons' (2000) findings, however, within individual sub-basins, erosion and hence, sediment flux, would vary considerably, conditioned by catchment relief, slope, elevation of headwaters and availability of sediment in storage. The smallest changes in fluxes would occur in large, flat basins (i.e. Tisa) because of increased storage capacity and potential to buffer out changes upstream (Phillips et al., 2004; Syvitski and Milliman, 1992; Walling and Fang, 2009), while significant changes would occur in steeper basins with greater relief (i.e. Drava). It is the complex interaction of influences, both natural and anthropogenic, that determine changes in suspended sediment flux within a basin.

Land use

Wilkinson (2005) notes that humans are an order of magnitude more important at moving sediment than the 'sum of all other natural processes' operating on the surface of the planet. Our results reveal an increased suspended sediment load by a factor of 2 when considering land use alone during the LIA, accounting for nearly half the decrease in sediment load between LIA and the present day. As significant as this is, our projection could be underestimated, as intense land use (i.e. deforestation) has been known to increase erodibility of soils by an order of magnitude in both large and small basins (Saunders and Young, 1983). A reconstruction of sediment transport via rivers draining to the Black Sea using sediment core analysis by Degens et al. (1991) showed that sediment flux began to increase *c*. 2500 years ago due to initial land clearance and, during its highest peak approximately 1000 years ago, sediment flux was likely four times greater than under natural conditions. While sediment flux began to decline at this time, another distinct peak (albeit smaller) in the theoretical sediment flux associated with the timing of the 'Little Ice Age' indicated increased flux of approximately 2.5 times today's loads (Degens et al., 1991), which agrees with the results of our study.

Future implications

A look back in time to a period of significantly different climatic trends is useful in assessing how fluvial systems operate under conditions other than present day. Over the next century, central Europe's landscape will continue to be modified and future plans to improve navigation and construct new reservoirs in the Danube basin will further alter hydraulic regime and sediment transfer through the basin. Walling (2006) notes that modern-day sediment flux is likely similar to flux under 'natural' conditions because of reservoir retention, however, sediment loads at the river mouth are still decreasing, years after initial dam emplacement. If this trend continues, sediment loads will fall below natural conditions, which has been documented in the Santee and Savannah Rivers, USA (McCarney-Castle et al., 2010) and other large rivers around the world (Syvitski, 2003; Syvitski et al., 2003). As sea level continues to rise, coastal erosion will most certainly accelerate. Increased population, pressure on the land, demand for water, warmer temperatures and changing precipitation patterns will have a direct impact on sediment erosion and transportation within the Danube watershed and quantification of these impacts will be essential to calculating low-flow criteria and reservoir sedimentation, assessing ecological functioning thresholds, and understanding coastal implications. All of these factors underline the importance of applications of numerical models that can account for changing climatic conditions and anthropogenic pressures.

Conclusions

(1) The cumulative sum of present-day simulated water and sediment flux from each watershed is in good agreement with sediment load and water discharge values observed at the mouth, indicating that *HydroTrend* is an efficient tool to use at the sub-basin scale for calculation of total system mechanics.

(2) Within the Danube basin, seasonal precipitation patterns are similar between the 'Little Ice Age' and modern day; however, total yearly precipitation has declined by approximately 5% since the 'Little Ice Age', resulting in decreased river discharge (10–15%). More significant are the seasonal differences noted between the two time periods, with winter temperatures up to 8.25°C warmer, producing significantly higher sediment flux in the spring. Present-day summer temperatures, however, are nearly identical to summer temperatures during the 'Little Ice Age'. Higher resolution changes (monthly) in sediment flux would be worth exploring further.

(3) Suspended sediment flux during the LIA was up to 5.5 times (80%) higher than under present-day conditions, with reservoirs accounting for more than half of the decline and decreasing land-use pressure from peak deforestation accounting for the other half.
(4) Climate-driven fluvial activity during the 'Little Ice Age' was less prominent than today. Modeled results reveal that without human influence on the land, suspended sediment flux (Mt/yr) would be higher today than what was typical during the LIA, despite decreased precipitation under modern climate regimes. It cannot be disputed that the impact of human activity is not only extremely widespread, but can also alter and even offset natural processes.
(5) The IPCC (2007) has estimated that average annual temperatures may be 4°C higher than present-day by the end of this century. This could result in increased basin-wide sediment flux by 45%; however, a proportional response at the river mouth is not implied or even suggested. Suspended sediment loads at the Danube river mouth have consistently displayed a decreasing annual trend in recent observed and modeled data, even two decades after large dam emplacement, and this trend will most likely continue into the future, exacerbating coastal erosion as sea level rises.

Funding

G. Voulgaris was partially supported by the National Science Foundation (NSF Awards OCE-0451989 and OCE -0535893). L. Giosan acknowledges support from Romanian grant CEEX X2C20/2006 in providing access to Danube discharge and sediment load measurements from Ceatal Izmail for the period of record 1945–2000 and partial support from NSF Award OISE-0637108. A. Kettner was partially supported by NSF Award 0952116.

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