Landslide-Related Sediment Yield Rate in a Large Apenninic Catchment

Alessandro Simoni, Alessio Ponza, Vincenzo Picotti, and Matteo Berti

Abstract

Diverse sources of information, which describes landslide movement, hillslope-channel connectivity and sedimentation rates, are analyzed to detect trends that took place during the last 12,000 years. We estimate the landslide-related sediment production rates by combining measured landslide velocities and geometries and historical landslide frequency. Coarse sediment deposition rates are measured throughout the Holocene by means of dating and stratigraphy of the alluvial fan and terraced deposits. The comparison between present-day hillslope sediment production and Holocene averaged sediment deposition rates confirms that landsliding is the main agent conveying sediments to higher order trunk streams. The connectivity between hillslopes and the stream network is well developed and no significant sediment sinks influence the sediment transport process. However fluctuations of sediment delivery rates at the outlet of the catchment took place during Holocene and are likely associated to periods of increased hillslope sediment production and channel discharge caused by climatic forcing.

Keywords

Earthflow • Sediment flux • Holocene record

Introduction

The sediment budget of large mountainous catchments is the result of the interaction of many different processes acting along the channels and over the hillslopes and interacting between themselves. The quantification of the contribution of each process to the sediment budget is, indeed, very complicated and involves the measurement or estimate of several variables.

The importance of landsliding as relief-shaping agent has long been recognized (Korup et al. 2010). The amount of total sediment produced by landslides within a given catchment is a function of their magnitude and frequency (Reid and Page 2002). Inventories of landslides show that the frequency of landslide is a function of landslide magnitude both in space and time (Brardinoni and Church 2002; Guzzetti et al. 2002). Such properties can be used to extrapolate predictions, though substantial uncertainty is still not resolved for extreme ends. In general, it can be said that the rate of sediment production from landslides vary greatly depending on the observation period and impact of extreme events (Korup et al. 2010).

Slow-moving, periodic landslides like earthflows (Hungr et al. 2001) have been seldom treated as source of sediment to regional sediment budget. Only very recently, Mackey and Roering (2011) made an effort to quantify earthflow movement over significant spatial and temporal scales. By taking a 60 years observation period, they measured earthflow movements exceeding 5 m (> 80 mm/year) and estimated the sediment production from earthflows in a weak-rock basin. Results demonstrate that earthflows are capable to generate a sediment yield that is more than half the estimated total sediment yield.

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In this work, we analyse earthflow activity over a large portion of the Reno river catchment, where clay shales outcrop. The estimate of hillslope sediment delivery rate to the channel network is based on mapped connectivity, mean earthflow velocity (inclinometer readings), and geometric similarities describing the depth of sliding. We take advantage of peculiar lithological characteristics of the rocks involved in earthflow, to isolate the volumetric fraction of the Holocene deposits (fan and terraces) that can be ascribed to the Ligurian units. We then compare present day hillslope sediment yield rates and Holocene deposits to assess the contribution of earthflow movement to regional erosion rates and their control of landscape evolution.

Regional Study Area: Reno River

The Reno river catchment is located in the Northern Apennines of Italy (Fig. 1). Its mountainous portion extends over an area of 668 km^2, rising from an elevation of 56 m to the highest point at 1,922 m. A large alluvial fan dominated by gravel deposits is present at the basin outlet.

About 42 % of the catchment is made of geological units pertaining to the Ligurian domain. In the remaining portion, the bedrock mainly consists of stratified sedimentary rocks, dominated by arenaceous flysch.

Ligurian units consist mainly of chaotic clay shales and include limestone clasts (gravel to boulder size) embedded into the clayey matrix as a reminiscence of original calcareous beds (Pini 1999). The clay-shale bedrock shows a structure made of small iso-oriented particle aggregates (scales) with dimension ranging from millimeters to centimeters. Getting close to the surface, the clay-shale is subject to stress relief, swelling and weathering which progressively cancel the scaly structure and induce a color change from dark grey to brown.

The style of landsliding, on Ligurian Units, is dominated by complex earth slides-earthflows (Cruden and Varnes 1996). Hereafter, we use the term earthflow (Hungr et al. 2001) to describe slow-moving landslides with flow-like morphology. Earthflows typically have a bowl-shaped source area, an elongate transport zone and a lobate toe that reaches the trunk stream at the bottom of the slope or, alternatively, merges to other earthflows generating coalescent multiple phenomena.

Earthflow bodies slowly move downslope. The movement generally exhibits a seasonal pattern and mostly develops along discrete sliding surfaces with internal deformation of the sliding mass. Most often, failures are observed in the source area where they determine the progressive retrogression of the main headscarp and feed the earthflow body. Paroxistic reactivations of the whole deposit are much less frequent and probably related to the downslope transfer of undrained loading (van Asch 2005).

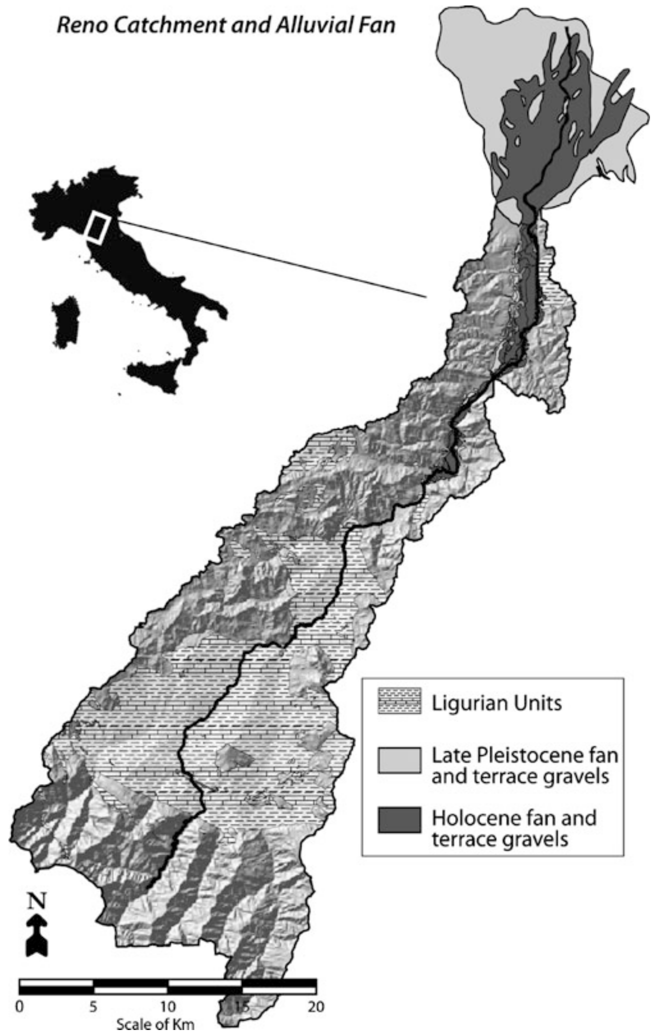

Fig. 1 Sketch map of the Reno river intramontane catchment and alluvial fan

The regional landslide inventory (Regione Emilia-Romagna 2011) reports 2,454 earthflows that cover 40 % of the Ligurian units areal extent. The mean area is 45,414 m^2 and the largest earthflow is 1.8 km^2. The analysis of the non-cumulative frequency area distribution of earthflows (log bin size = 1/16) shows that higher frequencies are associated to areas of about 20,000 m^2 (Fig. 2). The frequency of landslides of a particular size often follows a power-law relationship and the area below which the data set deviates or breaks in scaling between landslide area and frequency is called the roll-over (Guzzetti et al. 2002). In our case, the onset of the power-law dependence is located at 40,000 m^2 (R^2 value of 0.97) and the power law exponent is -1.16. Compared to other literature data (Goswami et al. 2011; Guzzetti et al. 2002, 2009), our data set is described by a large roll-over and a small exponent that we attribute to the peculiar features of earthflows. In fact, small size (100–10,000 m^2) phenomena

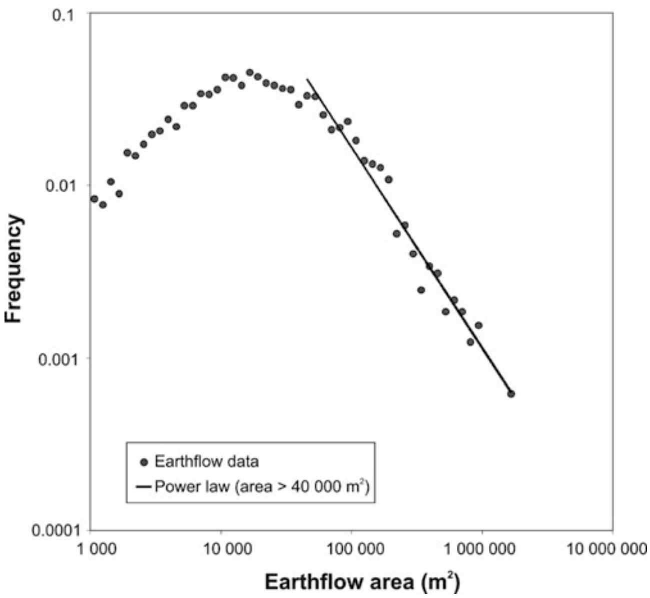

Fig. 2 Area-frequency statistics of earthflows

typically occur in the source area of larger phenomena or coalesce to generate a larger earthflow. Similar results were found by Mackey and Roering (2011) on a smaller data set of earthflows mapped over a time frame of 60 years.

Motivation

As outlined above, landsliding is the main agent shaping the landscape in the Reno catchment. A striking feature is that nearly all hillslopes in the Ligurian units appear to have been affected by mass movement. The drainage network is dense but poorly developed. Beside the main river and few tributaries, ephemeral gullies develop over extensive low-gradient slopes (10–15°) where erosion is dominated by earthflows.

Several approaches have been used to constrain background levels of rock uplift and erosion in Northern Apennines. Thermochronometric data (Zattin et al. 2002) show rapid exhumation (1.2 ± 0.24 mm/year) over the past 5 My which contrast with lower uplift rates (1 ± 0.2 mm/year) measured by geodetic methods (D'Anastasio et al. 2006), and erosion rates of 0.12–0.53 mm/year derived from basin sedimentation data (de Vente et al. 2006). Cyr and Granger (2008), based on cosmogenic nuclide, constrained the recent erosion rate between 0.28 and 0.58 mm/year. They suggested that dynamic equilibrium between uplift rates and both the hillslope and fluvial systems was achieved within a few million years from emergence of the Apennines and still persists today. The morphological features of the Reno catchment also strongly support the hypothesis of steady state landscape evolution. The widespread landslide activity demonstrates that hillslope are close to their limiting angle. The main trunk streams are bedrock-incised with exceptions mainly located in the lowest portion of the catchment. We therefore assume that landscape evolution proceeds with substantial equilibrium between local uplift, mean erosion and river incision rates. Such condition implies that relief doesn't change and that hillslope processes largely outpace channelized bedrock erosion in terms of contribution to the overall sediment yield.

The reconstruction of the sediment budget at catchment scale is far beyond the scope of this paper. We focus on landslide-dominated hillslope sediment fluxes and compare them to the alluvial sediment record. The comparison is possible because (1) Ligurian units contain the only calcareous rocks of the catchment; (2) the geometry of coarse Holocene deposits can be reconstructed; and (3) the relative abundance of limestone clasts measured.

The original calcareous beds of the Ligurian units were disrupted by tectonic deformation and can now be found as large angular fragments embedded into the clay shale matrix. Earthflows transport limestone clasts to the stream network where they are efficiently evacuated by fluvial processes. Sparse gravel deposits are present only in the lower part of the intramontane basin (Picotti and Pazzaglia 2008) while the vast majority of coarse deposition takes place on the fan.

Data

We use the extensive archive of information collected by the relevant territorial authority (Regione Emilia-Romagna). In order to characterize earthflow activity, we used the following: (1) 1:10,000 landslide inventory map; (2) historical landslide archive (Rossi et al. 2010); (3) inclinometer readings (collection of data and analysis performed by the authors). The Holocene fan geometry was reconstructed based on the data set of borehole logs (inclusive of ^{14}C datings) made available from Regione Emilia-Romagna. Terraced deposit mapping from Picotti and Pazzaglia (2008).

Methods and Results

Contribution of Earthflows to Regional Sediment Flux

We aim to quantify the transfer of sediment from slope failures to active channels. As previously stated, we focus on Ligurian units where earthflows largely dominate hillslope evolution.

Individual earthflows continue moving and actively supplying sediment to a channel for thousands of years (Bertolini et al. 2005). Paroxistic reactivations can periodically interrupt the persistent seasonal background movement (Iverson and Major 1987). The distinction between active and dormant phenomena (Cruden and Varnes 1996) only supplies qualitative information about the distance in time from the last reactivation and is not related to the present deformation rates nor to the possibility of future reactivation.

The measurements of earthflow displacement (72 inclinometers) confirm that deformation takes place preferentially along discrete sliding surfaces (76 % of data). Mean velocities range widely, from virtually zero to tens of mm per month. Based on velocity, there is no statistically significant difference between earthflows mapped as active or dormant. Therefore, we do not adopt any distinction based on the state of activity and jointly analyze the data to characterize the landslide velocity and its variability. The frequency distribution (Fig. 3) can be approximated by a lognormal peaking at 1.68 mm/month and associated to significant variability. We found no relationship whatsoever between velocity and geometry of phenomena (i.e., area, width, depth) and therefore assume the mean velocity (V_{av}) as representative of the displacement taking place in earthflows.

Inclinometer data supply precious information also about the geometry of gravitational movements. They confirm the existence of geometric similarities between earthflows of different sizes. Scaling relationships were observed in different contexts and generally described by area-volume power-law equations (Guzzetti et al. 2009; Larsen et al. 2010; Parker et al. 2011). Figure 4 reports a selection of our data, regarding the median-lower part of earthflow deposits, where we observe a relationship ($R^2 = 0.63$) linking the depth of sliding surface (D) and planar area (A), across 2.5 orders of magnitude:

$$D = 0.07 \cdot A^{0.44} \quad (1)$$

The relationship is in general agreement with similar relationships in the literature. Some of them have been reported in Fig. 4 by simply equating the depth of sliding surface to the average landslide depth (Volume/Area).

In calculating sediment production from earthflows, we distinguished earthflows that discharge sediment directly into a channel or major gully from flows that are disconnected from the channel network and do not represent active sediment sources. In other terms, we map the earthflow-river connectivity based on their relative position. Figure 5 reports a schematic example that illustrates how the regional landslide inventory map is used to measure the width of each connected earthflow (W). A total of 1,314 earthflow-river connectivity segments were mapped and measured, and associated to the planar area of the corresponding earthflow.

The average annual sediment flux from earthflows of the Ligurian units (Q_{EF}) was simply estimated using the following:

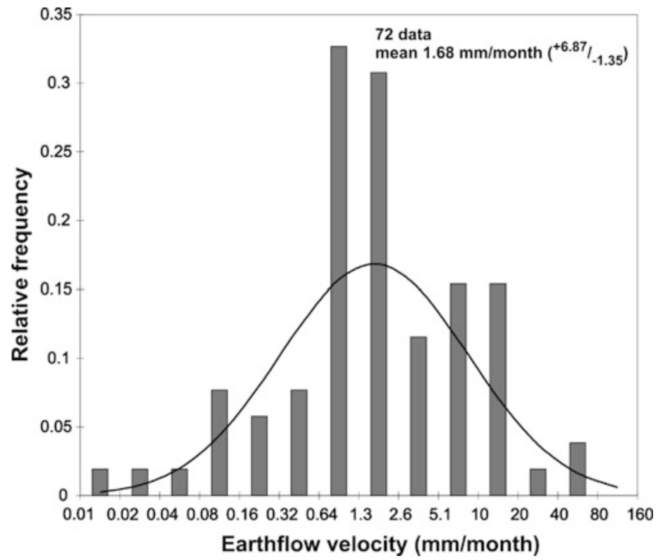

Fig. 3 Frequency distribution of earthflow velocities measured through inclinometers. A lognormal distribution described by mean and st.dev of the data is over imposed

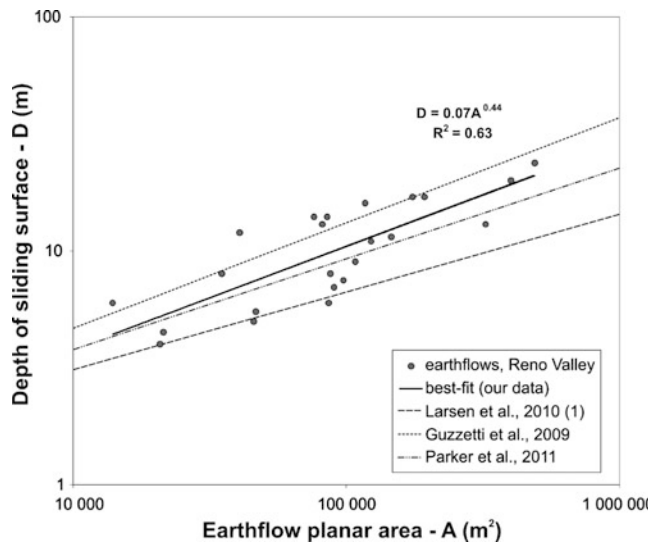

Fig. 4 Earthflow depth versus planar area. Data are from inclinometers positioned in the medium-lower part of the earthflow. When multiple inclinometers are available, the average value of depth is reported. Our data are compared to similar relationships reported in the literature

$$Q_{EF} = \sum_{i=1}^{i=n} (W \cdot D(A)) \cdot V_{av} \quad (2)$$

where n is the number of earthflows and D is estimated for each earthflow based on (1).

We estimated an average sediment flux of 61,124 m^3/year for 1,314 earthflows that can be considered tightly connected to the fluvial system.

As previously stated, we do not distinguish dormant and active earthflows. We believe that a discrete boundary

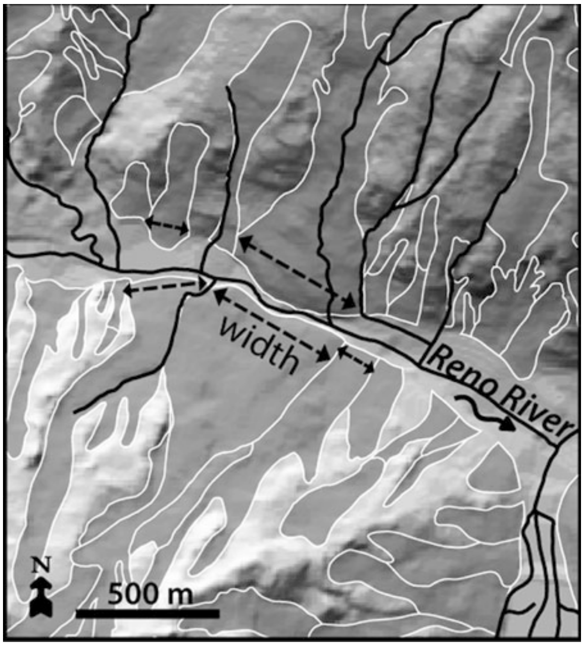

Fig. 5 DEM-derived hillshade map and landslide inventory illustrating the measurement of earthflow width

between the two does not exist and available data (Fig. 3) tend to confirm such view. Nevertheless, we know that earthflows periodically experience paroxistic reactivations causing the sudden increase of velocities up to tens of centimeters to meters per day. In such cases, displacements may reach values of tens of meters. Available historical information was used to make a tentative assessment of the frequency of paroxistic earthflow reactivations. Despite inherent uncertainties associated to the historical descriptions, we identified 111 events occurred between 1900 and today (1 event/year). We used such frequency together with the mean values of our earthflow population (*W*, *D*), and 20 m of total displacement to estimate a sediment flux of ~38,000 m^3/year due to the contribution of paroxistic reactivations.

The total sediment flux sum up to ~ 100,000 m^3/year and includes weathered clay-rich regolith, clay shales, and limestone clasts whose relative abundance was measured (24 % averaged over four sites) to quantify the specific contribution to the channel network. The simple procedure gives an estimated 24,000 m^3/year of limestone sediment flux.

Holocene Fan and Terraced Deposits

The Reno River deposited a large alluvial fan at the outlet of the intramontane valley. The fan deposits are mostly composed of gravels with subordinate sand and silt. Thanks to the availability of a large number of borehole logs (Fig. 6), including scattered ^{14}C datings, we could define the areal extent of Holocene coarse deposits together with the associated thicknesses. Here, we refer to Holocene deposits intending those younger than 12ky. Point-wise data describing the base and top where interpolated and subtracted to estimate the total volume of coarse sediments deposited through Holocene (Table 1). Terraced deposits of the same age (Picotti and Pazzaglia 2008) were also considered based on their extent and field-estimated thickness. As expected, the vast majority of coarse deposit is stored in the fan, and intramontane deposits account for less than 4 %.

In order to compare data with earthflow sediment flux, we converted the total volume of sediments into corresponding volume of limestone clasts. Experimental measurements of porosity, grain-size and limestone abundance (Table 1) were used. Overall, the results lead to an estimate of 170,000,000 m^3 of limestone gravel sediments deposited through Holocene by the Reno River.

Discussion and Conclusion

Our results show that earthflows are the primary erosion process in weak rock lithologies dominated by clay shales. Slow-moving gravitational movements contribute to deliver sediments to the channel network at a rate of ~100,000 m^3/year. Coarse calcareous fragments floating in the clay shales make up 24 % of such flux (~24,000 m^3/year) and can be tracked down to the end of the intramontane valley where terraces and alluvial fan store the coarse deposits. Their volume is used to calculate the Holocene-averaged deposition rate (~14,000 m^3/year) that reveals that hillslope sediment production and river deposition are similar to one another to within a factor of two. Considering that some fraction of limestone fragments are dissolved along the course of the river (ongoing assessment), we can state that a substantial equilibrium exists.

The sediment yield from the 278 km^2 of earthflow-prone Ligurian units (350 m^3/km^2/year) corresponds to an averaged erosion rate of 0.36 mm/year that is very similar to millennial-scale cosmogenic nuclide data (0.28÷0.58 mm/year) of nearby Apennine valleys (Cyr and Granger 2008). Our results are much likely under-estimated because they do not include hillslope erosion and creeping of stable slopes. Anyhow, they indicate that that present-day erosion proceeds at a pace similar to that recorded by sedimentation in post-glacial times. This argument suggests that the landscape evolution of the Reno catchment is a state of dynamic equilibrium.

Steady-state conditions were punctuated, through Holocene, by episodes of higher sedimentation that are recorded in the terraced deposits of the lower intramontane valley (Picotti and Pazzaglia 2008). Such pulses may be related to climate-driven variations of hillslope and channel sediment yield that rapidly propagated downslope to the fan.

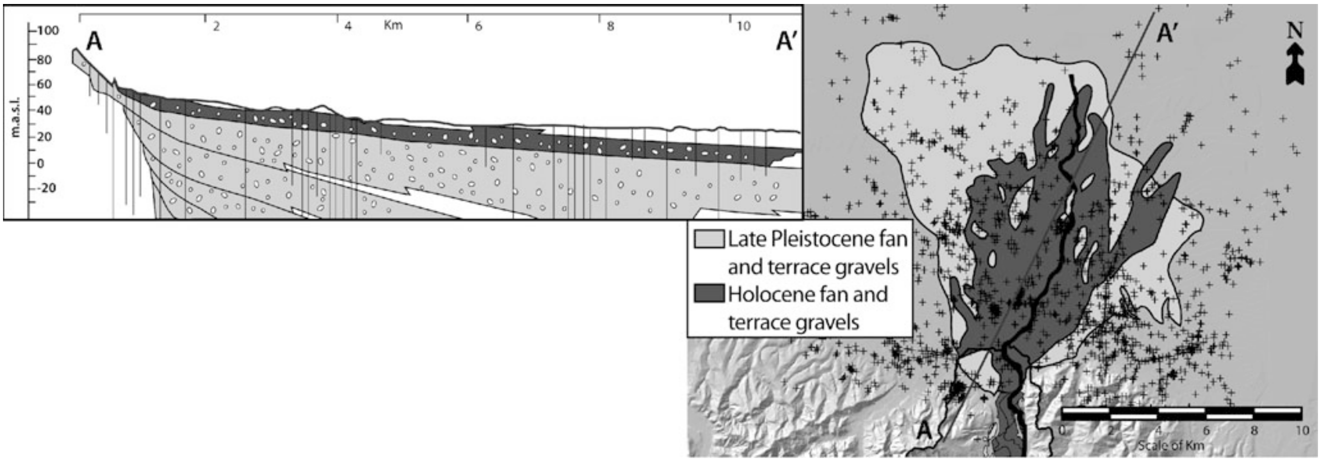

Fig. 6 Map and longitudinal section of Reno alluvial fan. *Cross-symbols* indicate the location of available borehole logs and cone-penetration tests

Table 1 Summary of data regarding Holocene coarse deposits of the Reno river

Variable	Mean value	St. dev.	Samples/ measurements	Methods
Volume of Holocene coarse deposits in the fan (m^3)	670,908,670	–	–	Areal extent and thickness based on borehole logs and ^{14}C datings
Volume of Holocene terraces (m^3)	26,204,080	–	–	Mapping + field estimated thickness
Soil porosity	0.24	0.02	3	In-situ volume measurements
Gravel fraction (% by volume)	83.88	1.86	6	Grain-size analysis (in situ measurements + lab sieving)
Limestone fraction (% by volume)	55.83	3.13	6	Qualitative clasts-counting

Among future developments, we intend to refine temporal correlations within the fan deposits to obtain intra-Holocene sedimentation rates that can be compared to studies of past climate scenarios.

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References

Brardinoni F, Church M (2004) Representing the landslide magnitude-frequency relation: Capilano River basin, British Columbia. Earth Surf Process Land 29:115–124

Bertolini G, Guida M, Pizziolo M (2005) Landslides in Emilia-Romagna region (Italy): strategies for hazard assessment and risk management. Landslides 2:302–312

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides: investigation and mitigation. National Academy Press, Washington, DC, pp 36–71

Cyr AJ, Granger DE (2008) Dynamic equilibrium among erosion, river incision, and coastal uplift in the northern and central Apennines, Italy. Geology 36(2):103–106. doi:10.1130/G24003A.1

D'Anastasio E, De Martini PM, Selvaggi G, Pantosti D, Marchioni A, Maseroli R (2006) Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data. Tectonophysics 418:219–234. doi:10.1016/j.tecto.2006.02.008

de Vente J, Poesen J, Bazzoffi P, van Rompaey A, Verstraeten G (2006) Predicting catchment sediment yield in Mediterranean sediment sources and basins. Earth Surf Process Land 31:1017–1034

Goswami R, Mitchell NC, Brocklehurst SH (2011) Distribution and causes of landslides in the eastern Peloritani of NE Sicily and western Aspromonte of SW Calabria, Italy. Geomorphology 132(3–4):111–122. doi:10.1016/j.geomorph.2011.04.036

Guzzetti F, Malamud BD, Turcotte DL, Reichenbach P (2002) Power-law correlations of landslide areas in central Italy. Earth Planet Sci Lett 195:169–183

Guzzetti F, Ardizzone F, Cardinali M, Rossi M, Valigi D (2009) Landslide volumes and landslide mobilization rates in Umbria, central Italy. Earth Planet Sci Lett 279:222–229

Hungr O, Evans SG, Bovis MJ, Hutchinson JN (2001) A review of the classification of landslides of the flow type. Environ Eng Geosci 7(3):221–238

Iverson RM, Major JJ (1987) Rainfall, groundwater flow, and seasonal movement at Minor Creek landslide, northwestern California: physical interpretation of empirical relations. Geol Soc Am Bull 99:579–594

Korup O, Densmore AL, Schlunegger F (2010) The role of landslides in mountain range evolution. Geomorphology 120:77–90

Larsen IJ, Montgomery DR, Korup O (2010) Landslide erosion controlled by hillslope material. Nat Geosci 3:247–251. doi:10.1038/NGEO776

Mackey BH, Roering JJ (2011) Sediment yield, spatial characteristics, and the long-term evolution of active earthflows determined from airborne LiDAR and historical aerial photographs, Eel River, California. GSA Bulletin 123(7/8):1560–1576. doi:10.1130/B30306.1

Parker RN, Densmore AL, Rosser NJ, de Michele M, Li Y, Huang R, Whadcoat S, Petley DN (2011) Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth. Nat Geosci, advance online publication, 4 pages, doi:10.1038/NGEO1154

Picotti V, Pazzaglia FJ (2008) A new active tectonic model for the construction of the Northern Apennines mountain front near Bologna (Italy). J Geophys Res 113, B08412, 24 pages, doi:10.1029/2007JB005307

Pini GA (1999) Tectonosomes and olistostromes in the Argille Scagliose of Northern Apennines, Italy. Geological Society of America Special Paper 335, 70 p

Regione Emilia-Romagna (2011) Inventario del dissesto. URL: http://www.regione.emilia-romagna.it/wcm/geologia/canali/cartografia/sito_cartografia/web_gis_dissesto.htm. Last accessed 17 June 2011

Reid LM, Page MJ (2002) Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology 49:71–88

Rossi M, Witt A, Guzzetti G, Malamud BD, Peruccacci S (2010) Analysis of historical landslide time series in the Emilia-Romagna region, northern Italy. Earth Surf Process Land 35:1123–1137. doi:10.1002/esp. 1858

Van Asch TWJ (2005) Modelling the hysteresis in the velocity pattern of slow-moving earth flows: the role of excess pore pressure. Earth Surf Process Land 30:403–411

Zattin M, Picotti V, Zuffa GG (2002) Fission-track reconstruction of the front of the northern Apennine thrust wedge and overlying Ligurian Unit. Am J Sci 302:346–379. doi:10.2475/ ajs.302.4.346