# The impact of road construction on suspended sediment and solute yields of headwater streams in northern Apennine, Italy

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**Abstract** We investigated suspended and dissolved loads of two streams which drain into the Bilancino reservoir, the principal water supply of Florence in Italy. In northern Apennine, headwater catchments have been affected by mass movements. In the Bilancino watershed, more than 50% of the landslides are directly connected with the streams, which otherwise tend to transport little sediment due to the presence of 89 check dams, one for each square kilometre. Suspended sediment was monitored for two years using time-integrated sediment traps. One stream, which was impacted by road construction, had a suspended sediment yield of 116 t km$^{-2}$ year$^{-1}$, while a nearby non-impacted stream had a yield of 14 t km$^{-2}$ year$^{-1}$. The stream water chemistry was also affected by the highway construction, which has produced spoils containing albite and Na-bearing olistostrome. The calculated cation flux was 416 t km$^{-2}$ year$^{-1}$ for the impacted watershed and 210 t km$^{-2}$ year$^{-1}$ for the non-impacted one.

**Key words** suspended sediment yields; sedimentation; suspension flows; solute yields; headwater catchments

## INTRODUCTION

The long history of human impacts on the landscape of the Mugello basin, Italy, and their effects on fluvial systems, is only documented downstream of the Bilancino Reservoir. To our knowledge, there have not been major investigations on sediment loads in the study area, especially in the upper reaches, because of the difficulty of access. Historically, in northern Apennine, headwater catchments have been affected by mass movements triggered by tectonic activity. More than 50% of landslides are directly connected with streams. This area has been protected from land management activities using 89 check dams, one for each square kilometre. In humid landscapes, numerous field studies have estimated that at the watershed scale only 20–30% of the suspended sediment and bed load derives from the headwater streams (Benda *et al*., 2005). In the study area, in spite of the friable, olistostrome lithology, which is rapidly disintegrated to fine materials, there is little accumulation of sediment in the headwater channels. However, there are large amounts of fine-grained sediment retention in headwater streams because of human activities associated with highway construction. High surface roughness, associated with wood supplied by riparian forests and the stepped longitudinal profiles, favour the deposition of clay-sized sediments. Nevertheless, most of the sediments remain suspended and are transported into the reservoir. This supports the view of Walling & Collins (2008), who state that catchment management strategies need to consider the sediment system, not only in the downstream areas, but also for the entire catchment. The sediment budget concept has been used as a tool for understanding sedimentary processes and sediment fluxes. A sediment budget accounts for the sources, transfers and storage of sediment within a landscape unit (Dietrich & Dunne, 1978; Slaymaker, 2003).

A sediment budget is an application of the continuity equation and indeed it can be considered as a form of geomorphic accountancy, where in the case of short periods of time the uplift rate can be ignored, hence the conservation of mass is given by:

$$\frac{\partial Z}{\partial t} = E - \nabla . q_s \tag{1}$$

where $Z$ is the ground surface elevation, $t$ is time, $E$ is erosion rate and $q_s$ is the volume flux of sediments and solutes. The continuity equation states that mass is conserved in any system, and so this equation is equally applicable to the conservation of sediment and chemical elements (Slaymaker, 2003). Numerous authors have made the case that chemical weathering, e.g. silicate hydrolysis and salt dissolution, is important to solute budgets of closed lake basins. Rapp (1960) in the arctic Karkevagge watershed, Norway, reported that the dissolved constituents comprised up to 50% of the total mass transport. The dissolved yield at the global scale is of the order of 10–20% of the total mass flux and it can be very high in some cases, such as limestone catchments (Roy *et al.*, 1999). The dissolved yield can be calculated using the chemical weathering rates of silicate per unit area. The main problem associated with the study of silicate weathering, using river dissolved load, is the influence of limestone rocks. Lithology is an essential factor in determining river chemistry especially at the small scale, such as Strahler stream orders 1–3 (Miller, 1961; Meybeck, 1987; Summerfield & Hulton, 1994).

The main purpose of this study was to quantify the suspended sediment and dissolved loads of two streams that drain into the Bilancino Reservoir. Suspended sediments were collected using integrated sampling traps. The suspended sediment yields obtained were compared with erosion rates derived from the RUSLE equation by Borselli *et al.* (2007, 2008). The dissolved yields were calculated from the summation of major cations (Ca, Mg, Na and K) and the water discharge. The contributions of suspended and dissolved loads were used to determine the total load in t year$^{-1}$.

## MATERIALS AND METHODS

### Study area

The Bilancino watershed (Fig. 1), 30 km northwest of Florence, covers an area of about 150 km$^2$ in the northern Apennine of Italy. The altitude ranges from 225 to 1094 m a.s.l. The Bilancino Reservoir, with a capacity of $84 \times 10^6$ m$^3$ of water, is the principal water supply for the city of Florence. The northeast margin of the watershed is underlain by Palaeocene-Eocene calcareous turbidites and claystones with limestone and serpentinite blocks, tectonically overlying Early–Middle Miocene sandstone and siltstone turbidites. On the southwest margin of the basin, Oligocene–Early Miocene calcareous and terrigenous coarse-grained turbidite deposits are exposed. The infilling of the basin occurred during the Villafranchian period and the recent alluvial phase. For the investigated streams (Fig. 1) baseflow stages typically vary between 150 and 200 mm whereas peak flow stages reach about 1000–1500 mm. Maximum flow velocities of ~1.3 m s$^{-1}$ have been recorded with a flow meter. The mean annual discharge is about 3.2 m$^3$ s$^{-1}$. The Bilancino watershed is 63% forested, 16% is arable land and the remainder is under pasture. In 2003, land use in part of the basin changed due to the construction of a road, which involved major phases of earth moving, and the construction of tunnels, overpasses and the build-up of spoil heaps directly connected to the drainage network.

### Catchment monitoring and assessment

The Stura stream drains an area underlain by claystones and sandstones, with a watershed of 17.9 km$^2$, and has been impacted by the road construction activities, while the adjacent Tavaiano stream mainly drains a limestone and siltstone watershed of about 16 km$^2$, and was not affected. In these streams, suspended sediment samples were collected using time-integrated sediment traps (for design see Phillips *et al.*, 2000). While these traps were developed to collect bulk sediment samples, we used them for quantifying suspended sediment fluxes. During baseflow conditions, with discharges of 0.6–4.4 m$^3$ s$^{-1}$, tests showed that the traps retained 80% of the sediments as estimated by the use of a depth integrating sampler (type USD H-81). The sediments deposited within the sampling trap were recovered after storm events and provided information on the overall contribution of the potential sediment sources. A total of six individual sampling sites were located on the channel bed of the Stura and Tavaiano streams (Fig. 1). The locations of the sites were selected to take into account the influence of lithology, human impact and check dams. In this paper, all suspended sediment concentrations refer to total sediment: mineral and organic.

Flows were determined using the velocity-area method to produce a stage–discharge rating and followed the procedures described by Herschy (1995). Water level measurements were

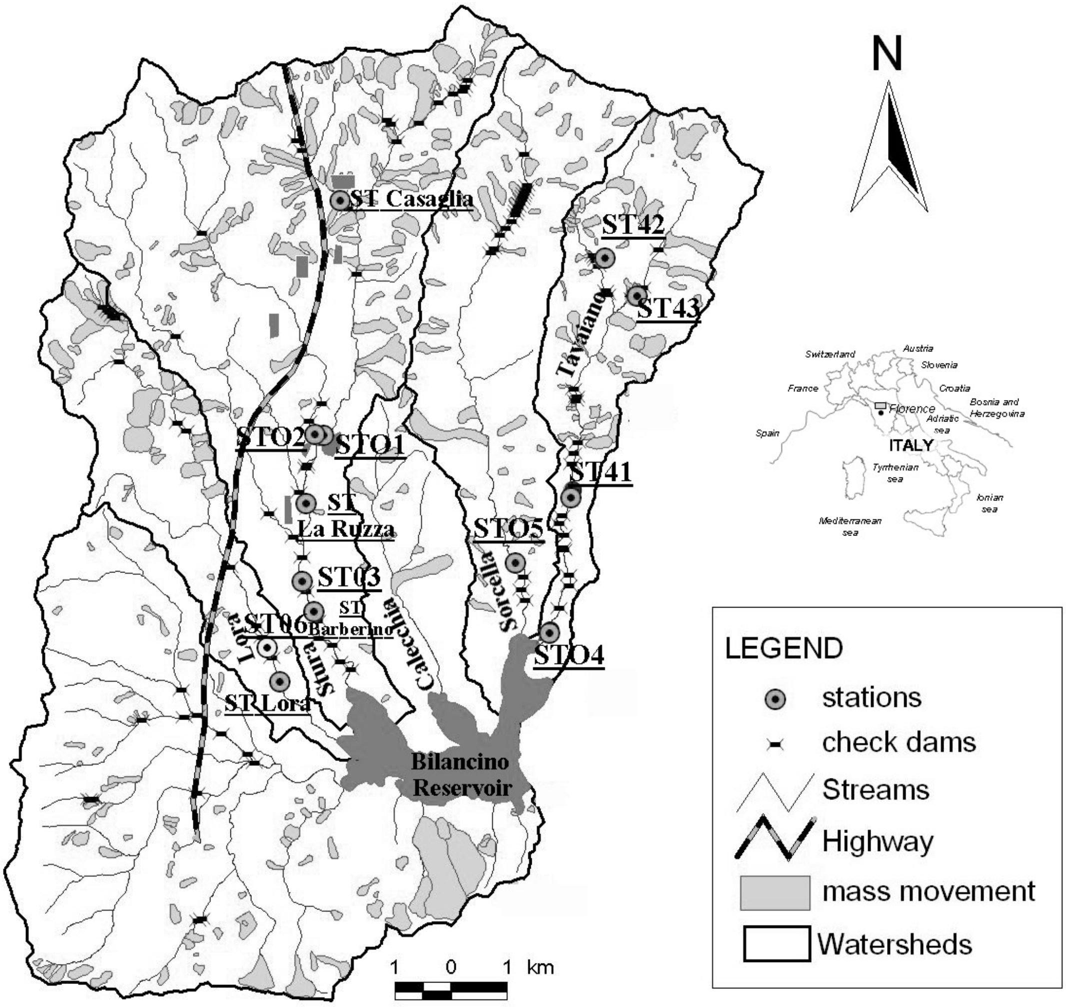

**Fig. 1** The Bilancino watershed (Florence, Italy) showing the locations of sediment sampling traps and surface water samples (ST, number), and the continuous water quality monitoring (ST, name).

collected using pressure transducers with a data logger recording at 10-min intervals: this information was obtained from various agencies and flow meters. The total sediment load, $Q_s$, over a period of time $t$ was determined from equation (2), following Ferguson (1987):

$$Q_s = \int_0^t Q_{si} = \int_0^t C_i Q_{li} \mathrm{d}t \qquad (2)$$

where $C_i$ is the instantaneous suspended sediment concentration, $Q_{si}$ is the instantaneous suspended sediment load, and $Q_{li}$ is the instantaneous discharge of the river. To solve this equation, continuous or regular measurements of both water discharge and suspended sediment concentration are required.

The sites for the surface water samples (Fig. 1) included those six sites where sediment samples were collected, and additional sites so as to represent all major lithologies. The water samples were filtered through cellulose filters (0.45 µm). Samples were acidified with $HNO_3$. Temperature, pH, Eh, TDS and salinity were determined in the field using a multi-parameter tester (EUTECH Instruments). Silica was analysed by spectrophotometry using a Varian photometer, whereas Na, K, Ca, Mg were determined by optical emission spectrometry using an Analytic Jena instrument. Primary and secondary minerals were identified by X-ray diffraction using $Cu_\alpha$ radiations ($\lambda = 0.154$ nm) using non-oriented samples.

A chemical flux method (White & Blum, 1995) was used to calculate the solute discharge flux $Q_{dis}$:

$$Q_{dis} = C_{dis} \frac{V}{At} \tag{3}$$

where $C_{dis}$ is the chemical concentration, $V$ is the fluid mass, $A$ is the area of the watershed, and $t$ is time. The solute fluxes were calculated for the major cations (Ca, Mg, Na, K). The contribution of the solute concentration in precipitation (Mantelli, pers. comm. 2009) was subtracted from the mean concentration of the cations in the river water samples.

## RESULTS

The annual suspended sediment yields in the Bilancino watershed range from 116 t km$^{-2}$ year$^{1}$ for the impacted Stura stream, to 14 t km$^{-2}$ year$^{-1}$ for the non-impacted Tavaiano stream (Fig. 2). According to Dedkov & Mozzherin (1996), human activities have resulted in an increase in suspended sediment load by a factor of eight for small rivers. The results for the study streams were compared with the RUSLE erosion model applied to the same study area by Borselli *et al.* (2007). Results of this simulation predicted that the mean annual net erosion was 243 t km$^{-2}$ year$^{-1}$ for the impacted stream, and 313 t km$^{-2}$ year$^{-1}$ for the non-impacted stream (Fig. 2). As net erosion is the difference between erosion and deposition, this corresponds to sediment delivery ratios (SDR) of 0.48 and 0.05 for the impacted and non-impacted streams, respectively. In contrast, our study considers the suspended load in the streams, which could be derived from bank erosion, landslides or human activities. However, field observations suggest that the main source of sediments is the highway construction activities rather than bank erosion. Hence, the measured suspended sediment yields can be compared to the results of the RUSLE model.

Furthermore, for the impacted stream, suspended sediment transport occurs under average rainfall conditions due to the remobilisation of fine-grained sediments that are stored in the stream bed. These findings are supported by continuous turbidity monitoring. A cumulative distribution function (cdf) analysis of the turbidity data set shows that 90% of the values range from 90 to 400 NTU. The highest value is recorded for the upstream Casaglia station, while the lowest one is recorded at the downstream Barberino station (for locations see Fig, 2). The results indicate a decrease in NTU values measured at the Casaglia station, which represents sediment input to the system, and the values measured at the Barberino station, which represents sediment output. There is an initial phase where there is a tendency for sediment storage on the channel bed, followed by a phase with a tendency of sediment re-suspension and removal. It appears that within the span of 4 years, the balance between input and output of sediments favours net accumulation.

Results from the water chemistry investigation show that the total dissolved solids (TDS) values range from 260 mg L$^{-1}$ to about 540 mg L$^{-1}$. The mean cation concentration values range from 50 to 115 mg L$^{-1}$. The contribution from precipitation ranges between 2.4–3.4%. The specific

**Table 1** Mean solute concentrations, dissolved yields and dissolved loads for the streams draining into the Bilancino reservoir. The + symbols represent the impacted streams.

| Stations | Mean cations concentration (mg L$^{-1}$) | Watershed (km$^{2}$) | Dissolved yield (t km$^{-2}$ year$^{-1}$) | Dissolved load (t year$^{-1}$) |
|---|---|---|---|---|
| + LORA (ST06) | 79 | 7.0 | 422 | 2954 |
| + STURA (STO1) | 114 | 17.9 | 416 | 7452 |
| + NAVALE (ST02) | 96 | 9.2 | 387 | 3556 |
| SORCELLA (ST05) | 75 | 15.3 | 182 | 2783 |
| TAVAIANO (ST04) | 82 | 15.2 | 200 | 3042 |
| TAVAIANO (ST41) | 76 | 13.5 | 210 | 2835 |
| TAVAIANO (ST43) | 71 | 5.9 | 447 | 2636 |
| TAVAIANO (ST42) | 52 | 1.0 | 939 | 939 |

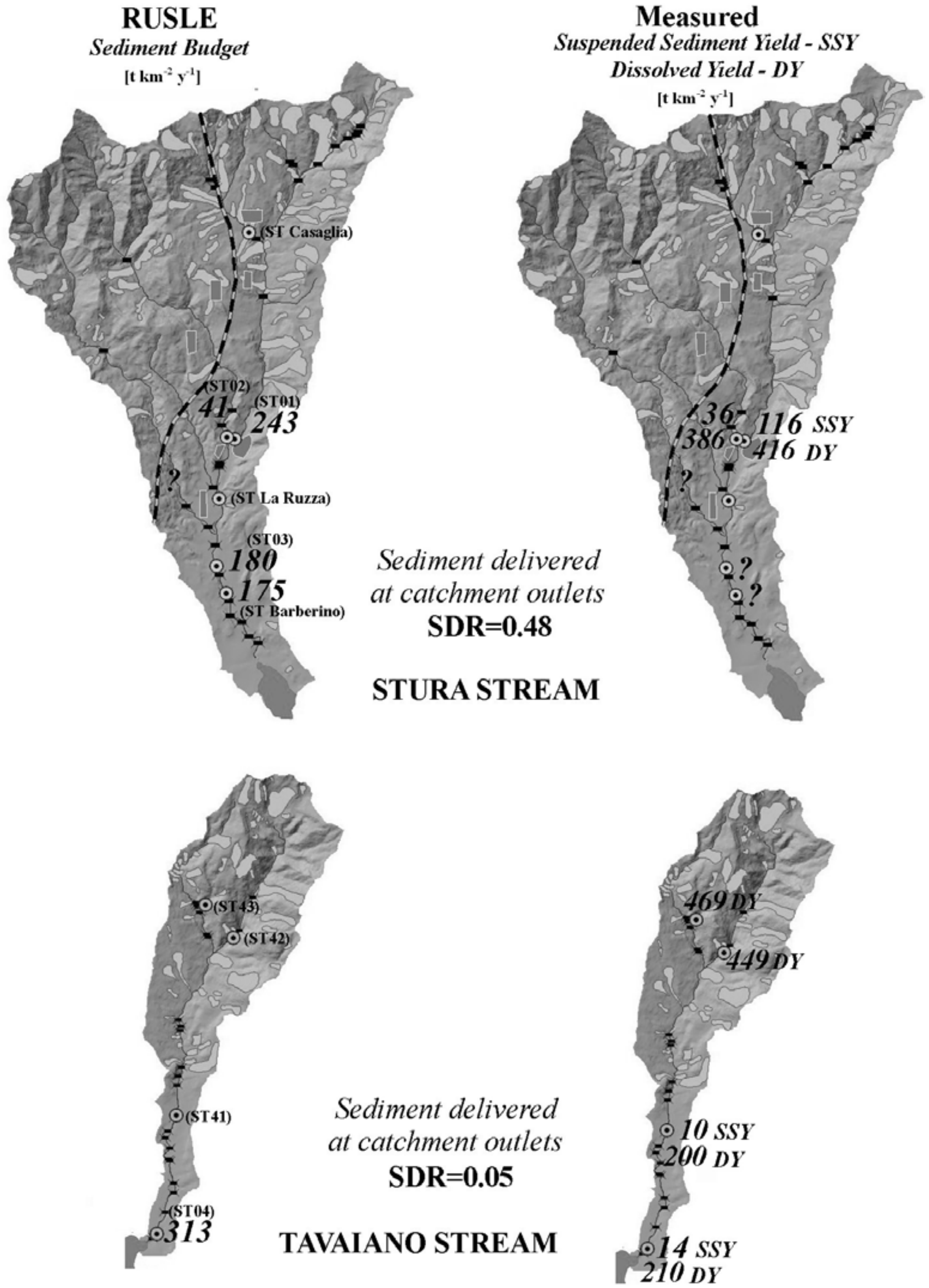

**Fig. 2** Predicted (RUSLE) and measured suspended sediment yields (SSY) for the Stura and Tavaiano streams. Dissolved yields (DY) are also reported.

cation flux is estimated to be 416 t km$^{-2}$ year$^{-1}$ for the impacted watershed and 210 t km$^{-2}$ year$^{-1}$ for the non-impacted watershed (Fig. 2). In terms of dissolved load the value range from 7452 to 3042 t year$^{-1}$ (Table 1). More specifically, the chemical composition of the streams shows an alkaline pH, with values ranging from 6.9 to 8.8 (the highest was 9.2). The major cation was Ca (50–70 ppm), followed by Mg (8–14 ppm), Na (4–6 ppm) and K (0.5–2.5 ppm). High values of Na (28 ppm) are measured in the Stura stream. The source of Na is likely to be the olistostrome geology which is now exposed in places as a result of the excavation for highway construction (Borselli,

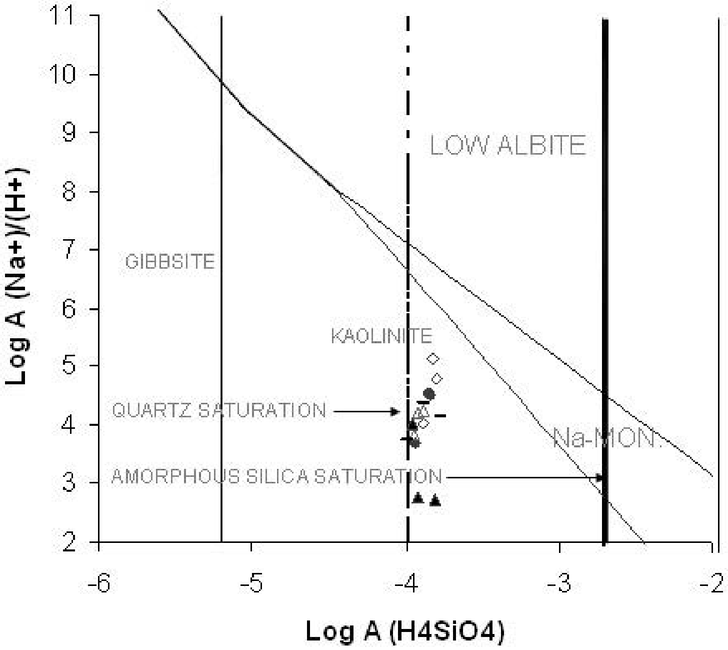

**Fig. 3** Logarithmic activity diagrams for the system HCl-$H_2O$-$Al_2O_3$-$Na_2O$-$SiO_2$ at 25°C. The symbols represent the chemical composition of the stream water.

pers. comm. 2009). Also, the weathering of low albite, identified by X-ray in the collected sediments, may contribute to the Na. Stability diagrams (Garrels & Christ, 1965; Nordstrom & Munoz, 1994) show that low albite is thermodynamically unstable under the present environmental conditions, resulting in a tendency for dissolution, while the silica activity of the stream water plots next to the equilibrium line of quartz (Fig. 3). These findings are supported by the work of Boschetti & Toscani (2008) also in the northern Apennine.

## CONCLUSION

Highway construction has caused an 8-fold increase in suspended sediment load in a watershed in the northern Apennines relative to a watershed only affected by natural landslides and agricultural activities. Furthermore, when the results obtained from field data are compared with results from the RUSLE model, the SDR values indicate that there was sediment storage on the channel bed of the impacted stream, while there was no channel bed storage for the non-impacted stream. This discrepancy may be due to an underestimation of hillslope deposition by the RUSLE model.

Sedimentation in the channel bed of the impacted stream and sediment suspension are affected by the Ca- and Na-rich waters. Both ions are controlled by the lithology and thermodynamic equilibria of the minerals in these waters.

**Acknowledgements** The authors are indebt to Dr Phil Owen for improving the original version. This research was supported by a PhD scholarship granted by the University of Florence.

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