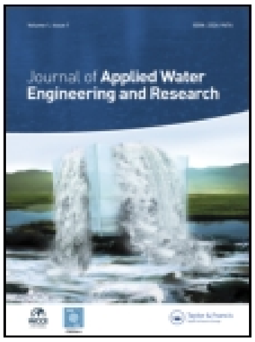

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Riverbed dynamic evolution following landslide dam: a case study

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The landslide phenomenon interfering with river processes is a complex topic and its interpretation through models is still being studied and tested. In this work, the authors describe the investigations carried out on a single-thread gravel-bed reach of the Noce River in Basilicata (Italy), which underwent a progressive morphodynamic change caused by a landslide, mobilized from the right-side slope of the basin, in July 2007. Riverbed dynamics and morphological alterations were analysed by field observations, topographic surveys, and numerical modelling. These methodologies allowed us to provide information on the future morphological variations in the river reach, useful also to the choice of protection interventions of vulnerable works, and civil infrastructures subject to erosion phenomena.

Keywords: landslide dam; sediment transport; river morphologies; monitoring; topographic survey

Introduction

The interference between landslide and river is a topic of great relevance because, to date, many catastrophic events have interested the world (Costa & Schuster 1988). According to the technical–scientific literature on the subject, the disequilibrium elements caused by hillslope-scale natural phenomena, such as landslides or debris flows, may have repercussions on the river system. They can, in fact, determine the upstream backwater, the inundation of the upstream areas, the possible collapse of the dam, and the rapid release of the impounded waters downstream (Casagli & Ermini 1999).

Moreover, a high interference between landslide and river, modifying the cross-section geometry and channel slope, may cause alterations in river channel morphology, sediment transport capacity, and stream habitat (Pizzuto 2002). The associated fluvial processes consist of an incision through the fan with the formation of coarse-grained terraces, erosion of the banks, and lateral channel migration. They also consist of aggradation phenomena, variations in mean bed-material size, and changes in river patterns and geometry in reaches upstream and downstream (Swanson et al. 1985; Miller & Benda 2000; Sutherland et al. 2002; Korup 2004, 2005; Hoffman & Gabet 2007). The evolution of the river system and the reinstatement of an equilibrium configuration vary with time and depend greatly on the mass and grain size of the sediment stored behind the dam, as well as on the characteristics of landslide deposit, on the entity of the floods, and on the morphological behaviour of the river reach. The situation is even more serious when the interactions involve anthropic works in the riverbed, or riverbanks defence. The interpretation of the landslide phenomenon, which interferes with the river, is particularly complex because, at the same time, the process involves both hillslopes and river systems. The phenomenon, though well studied, is still not consolidated into an accredited theory, and is thus particularly suited to be object of scientific research, especially in the modelling field. That is why models of partial or complete occlusion of the riverbed are still in the testing phase.

In this paper, an integrated approach that takes into consideration numerical modelling and field measurements was used to analyse the planimetric and altimetric evolutions of the bed in a gravel-bed reach of the Noce River in the Basilicata region, invaded by a landslide. In particular, the monitoring activities, discussed below in more detail, served to calibrate the model.

Investigated area and observation methods

Case study

The case study is the interaction between a landslide and a narrow gravel-bed reach in the middle valley of the Noce River (total catchment area 413 km^2), located in the Trecchina territory in the south-western Basilicata region, in Italy (Figures 1 and 2). An earth-flow reactivation (Di Maio & Sole 2009; Di Maio et al. 2009), which involved mainly blackish siliceous marls and argillites with fractured carbonate-rock masses, occurred in two different periods, in 2007, along the right-side slope of the basin

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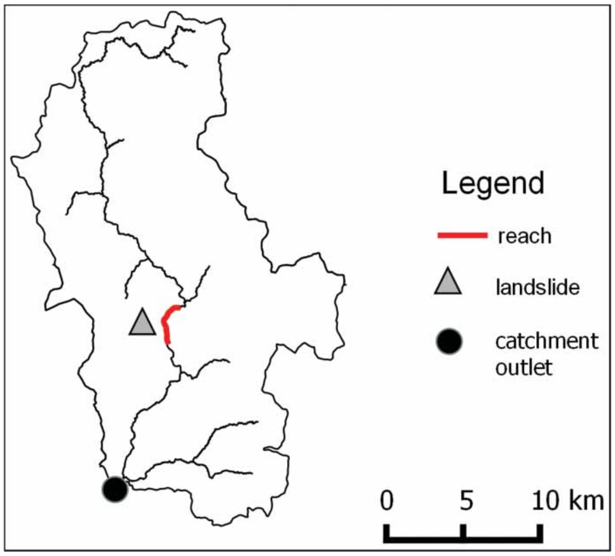

Figure 1. Investigated catchment with indication of the river reach studied.

(Figures 3(a)). This reactivation produced the partial blockage of the watercourse in July and then the total blockage in November, for 120 m of its length, with the formation of a little backwater lake upstream (Figures 3(b)).

The floods that occurred in the following years led the flow away from the landslide bottom, creating a new branch on the left floodplain, thus favouring the dam-emptying process. The migration of the flow towards the left bank generated, in time, a river bend under the S.S. 585 road, producing a partial terrain removal off the floodplain, interrupting an adjacent cart way, and increasing the hydraulic risk for the same road (Dal Sasso et al. 2014).

The combined effects produced by the new river morphological configuration and the induced contraction scour triggered a progressive lowering of the floodplain (Figures 3(c) and 3(d)). The latter highlighted the cyclopean boulders next to the outside bank of the bend, probably belonging to an ancient mass movement on the left side of the hillslope (Figures 4). The landslide induced morphodynamic changes also in the upstream reaches because of the flow slowdown and the deposition of sediments, forming bar sequences and changing the river patterns. At the same time, a selective erosion due to the cut-off of bed load supply occurred downstream causing coarsening and armouring bed structures.

Field survey

The river reach object of the monitoring extends approximately for 2.7 km and is located between two artificial embankments, at the same distance (1.3 km) both upstream and downstream of the stretch intercepted by the landslide. The morpho-evolutive study was carried out on the medium and short term in order to understand the river dynamics before and after the landslide. In the pre-landslide phase, the morphological investigation was carried out using historical maps (1956 I.G.M. maps, 1989, 1994, 2000, and 2006 ortophoto, Regional Technical Cartography 2001 at the scale 1:5000) and field surveys, supplied by the Interregional River Basin Authority of Basilicata in 2003. The analysis of the maps and surveys showed that the reach morphology, in the undisturbed condition (pre-landslide), was that of a single-thread gravel-bed river (Figures 5), prevalently straight with limited possibilities of lateral dynamics, because of the valley confinement (value of confinement level $> 90\%$ according

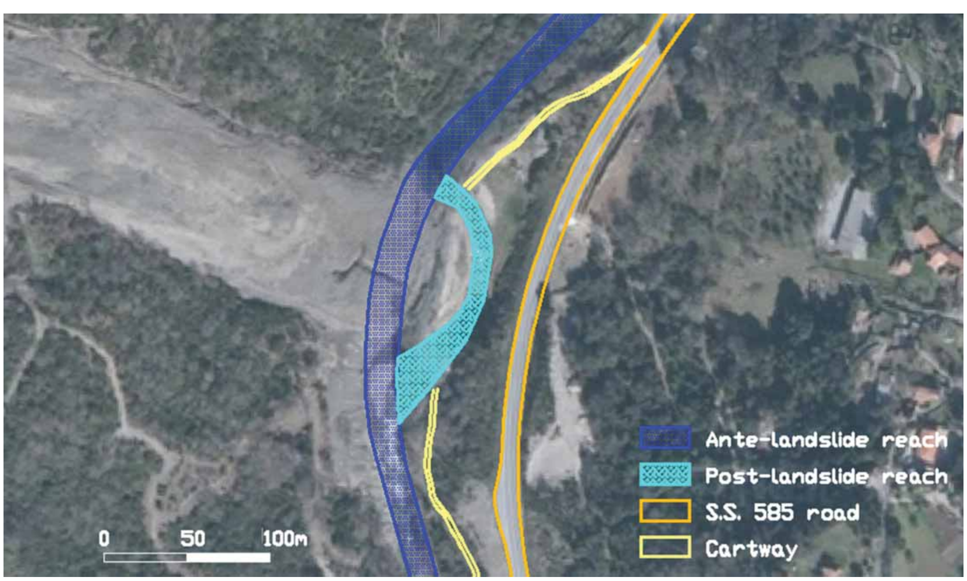

Figure 2. Orthophoto extract, highlighting the river reach interested by the landslide, and description of its position before and after the event.
Source: Google Earth map 2010 (https://www.google.com/earth/).

Figure 3. Landslide body (a), landslide dam (b), floodplain in the 2007 pre-landslide (c), and post-landslide (d) phase.

to Brierley & Fryirs 2005). The channel average width $W = 25$ m was similar to the equilibrium width estimated by Julien and Wargadalam's hydraulic geometry equations (Julien & Wargadalam 1995). Its planimetric profile was sinuous (Sinuosity Index, SI = 1.2, Thorne et al. 1997), especially in the reach affected by the landslide, because of an old debris fan pattern to the left of the floodplain.

In the post-landslide phase, more detailed analyses, both spatial and temporal, were performed, comparing different data: the topographic surveys, carried out by the Basilicata Region with Differential Global Positioning System technology in 2008, and the airborne laser-scanning data, surveyed by Geocart s.r.l. in 2010. In particular, three transversal profiles of the landslide foot for a length of 120 m within the river valley were extrapolated from Digital Terrain Models (DTMs), in order to evaluate morphological planimetric and altimetric changes. Moreover, monitoring campaigns (2007–2010) concerned the obstructed river reach, as well as those upstream and downstream, in order to understand both the in-progress and the potential morphodynamic processes. In order to document grain size changes in the bed sediments, volume sediment samplings were carried out according to the Church et al. (1987) methodology.

Furthermore, during the monitoring period, surveys were conducted in order to estimate the water discharges responsible for the channel evolution after landslide event. Figures 6 reports the hourly discharges from November 2007 to May 2012, deriving from rating curves, estimated at the hydrometric station 'Le Fornaci', located 2.5 km upstream of the landslide. The rating curves were constructed comparing the measures of the water discharge Q, through field campaigns, and the use of the one-dimensional numerical model Hydrologic Engineering Centers River Analysis System (Hydrologic Engineering Center):

$$Q = 27.26H^{7.73} \quad (H < 0.90\,\text{m}) \tag{1}$$

$$Q = 12.54H^{2.54} \quad (H \geq 0.90\,\text{m}) \tag{2}$$

in which H is the hydrometric level.

The choice of two rating curves was due to the change in the cross-section shape for $H = 0.90$ m.

Analysis of the river morpho-evolutive dynamics

The historical analysis of the longitudinal river profiles in the years 1956, 1989, and 2003, in a 2.7 km reach, centred

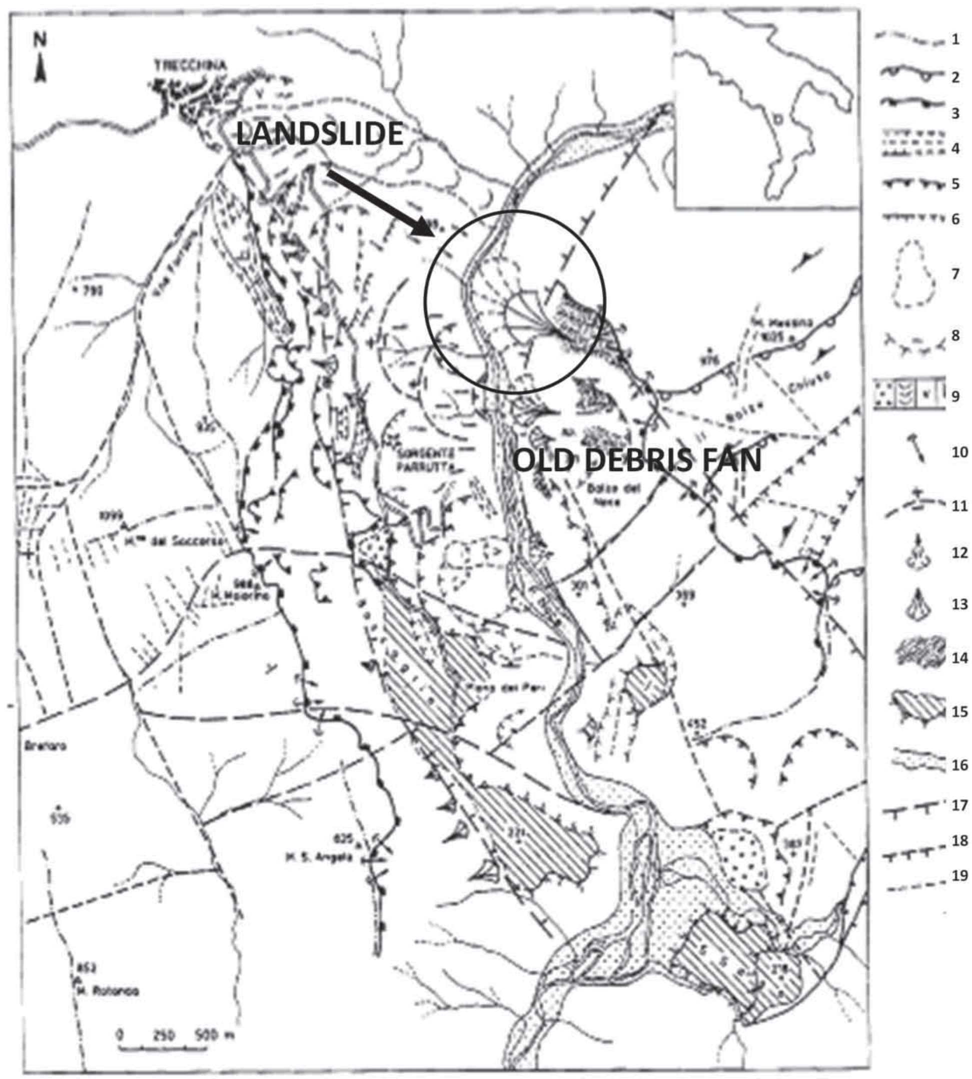

Figure 4. The old debris fan in the left side of hillslope (geomorphological map, Cotecchia et al. 1993).

on the landslide, provided information on the evolution of the bed elevation.

After an initial phase of incision, which occurred from 1956 to 1989, some dikes were constructed to stabilize the channel. Since 1980, the values of the riverbed slope, which in 1956 showed a marked variability ranging from 7‰ to 4%, have tended to stabilize at about 1% and even more in the reach affected by the landslide. This indicates a possible condition of a vertical dynamic stability (Figures 7), which adds to the lateral side, due to the high hillslope confinement (Figures 8).

The analysis of the post-landslide phase was performed comparing the DTMs of the area before the event, which was generated from ground points of Regional Technical Cartography 2001, after one year (in 2008) and after three years (in 2010). This analysis allowed us to quantify the solid volumes coming from the landslide and the eroded ones from the floodplain. The DTMs were generated by a kriging interpolation method and have a resolution cell equal to 5×5 m (Figures 9). The comparison showed that the solid volume coming from the landslide in the river reach was about 60,000 m^3, while the floodplain erosion induced by the contraction and local scour was about 3000 m^3 in 2008, reaching about 6500 m^3 in 2010. The analysis of the cross-section profiles (Figures 10), extracted from DTMs, showed that the riverbed suffered

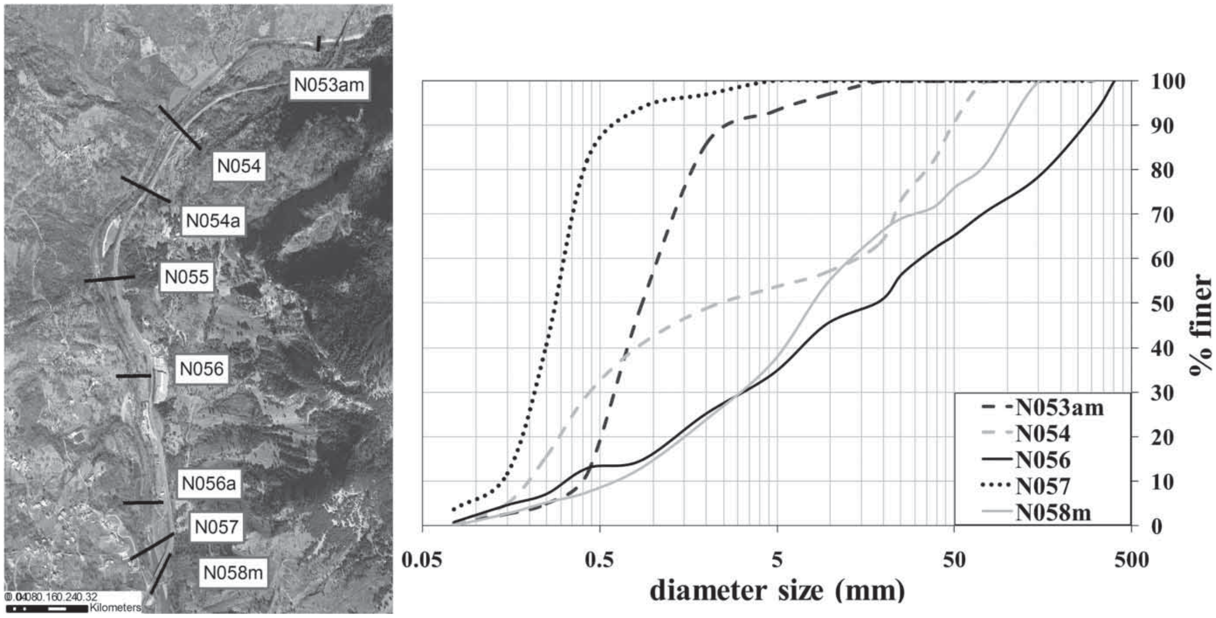

Figure 5. River reach (left) and granulometric distribution (right) in the 2003 pre-landslide condition. Source: Ortophoto 2003 (from Interregional River Basin Authority of Basilicata field survey).

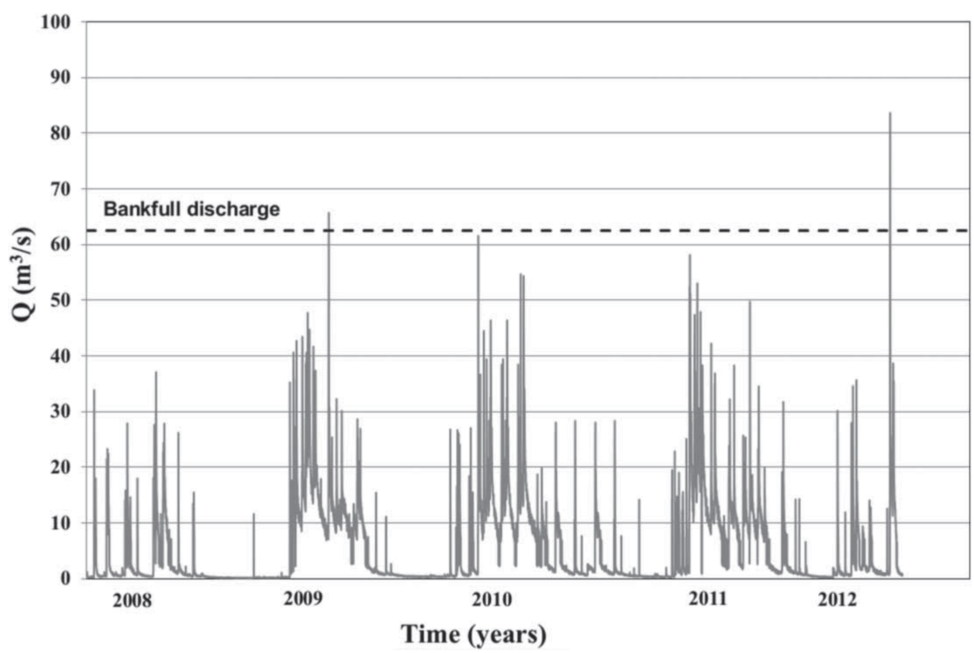

Figure 6. Hourly flow hydrographs after the landslide dam.

a left planimetric translation next to the landslide, forming a bend with a curvature radius of about 70 m, which went towards the S.S. 585 road. In this area, significant vertical bed incision and lateral erosion along the landslide foot and the left bank were observed and calculated (Table 1). The main changes observed and measured between 2008 and 2010 in the reach affected by the landslide, in terms of floodplain and landslide foot soil erosion, are linked to the flood discharges with peak flow corresponding to bankfull discharge (about 1.5–2 year flood).

In particular, the changes undergone until 2010 allowed the channel to later reach a configuration similar to the pre-landslide period, in terms of bed elevation and width of the cross-sections. Furthermore, so far, the bed and the bank of the reach formed under the S.S. 585 road have been protected naturally by boulders and stones, belonging to an ancient mass movement on the left side of the hillslope (Figures 11). During the surveyed period (2007–2010), changes in the river patterns were also observed in the reaches upstream and downstream. Upstream, in particular,

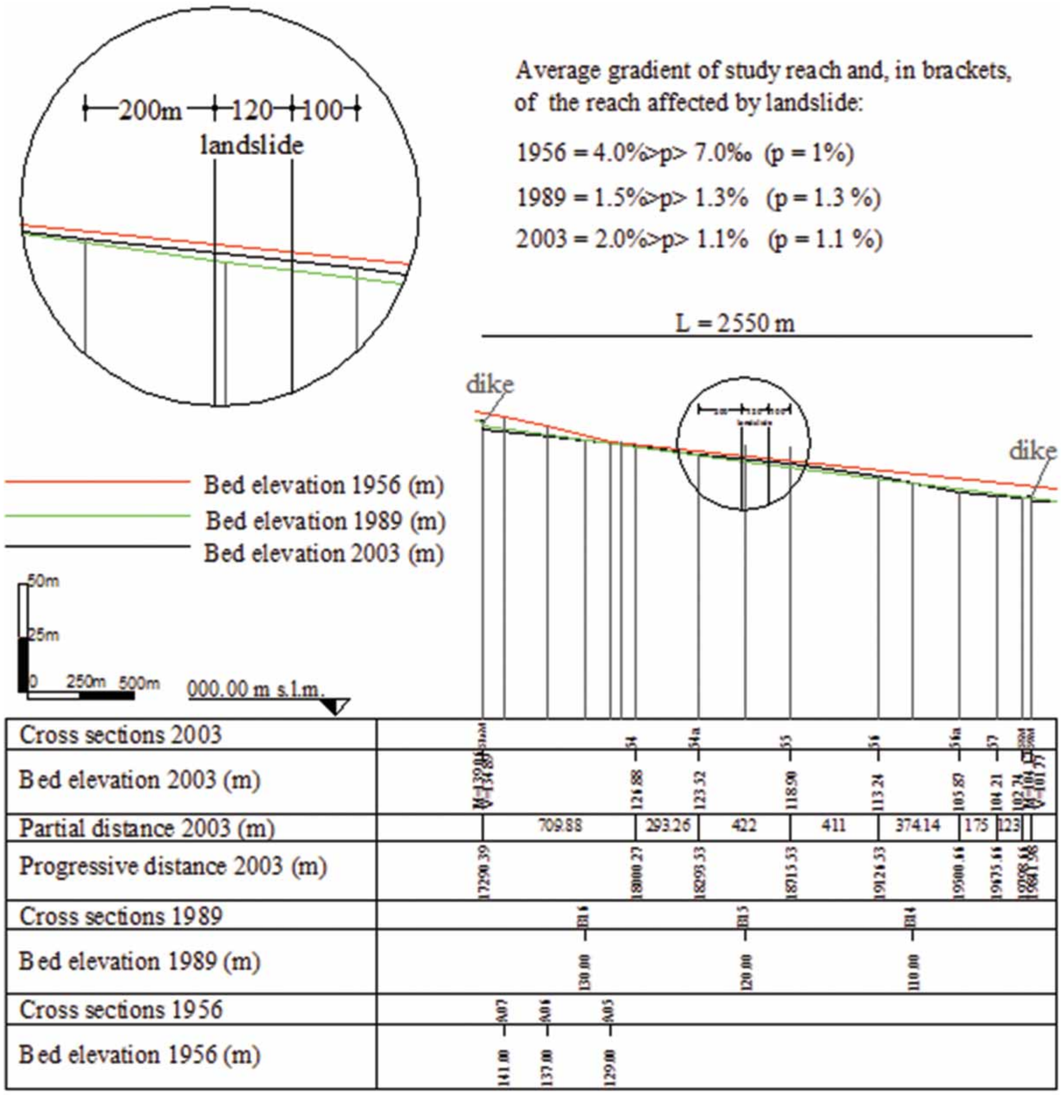

Figure 7. Comparison of river longitudinal profiles in 1956, 1989, and 2003 over the segment of interest (2.7 km) and the one affected by the landslide (120 m).

the hydraulic backwater curve caused the reduction of the sediment-carrying capacity of the flow, leading to a deposition of gravel and coarse material, up to a depth of over 2.5 m, and decreasing the riverbed slope.

These changes also increased the median diameter size of the substrate (from $D_{50} = 2.8$ mm to $D_{50} = 67.9$ mm) (Figures 12(a) and 12(b)). Initially, after the emptying of the backwater, sediment deposition produced the formation of central and lateral bar sequences (braided type). Later, over time, the channel became a single one with alternate bars (wandering type) (Figures 12(c) and 12(d)). Downstream of the avulsion, the reduction in sediment transport induced channel adjustments, with the partial degradation of the bed (1.5–2 m), contributing to the formation of fluvial terraces and armoured bed (Figures 13). Conversely, the fine material eroded from the landslide bottom and floodplain did not produce significant riverbed modifications in the other reaches downstream.

Simulation of river dynamics and evolution

In order to understand the riverbed morphological dynamics and evolutionary tendencies in the reach invaded by the landslide and immediately upstream and downstream, the SRH-1D sediment transport model (Sedimentation and River Hydraulics – One Dimension, Version 2.6) was used. In particular, since the entity of the transport of sediments downstream coming from the hillslope is negligible, the modelling of the phenomenon was simplified. In fact, the landslide body could be regarded as a partial obstacle to the normal outflow and not as an active contribution to the sediment transport.

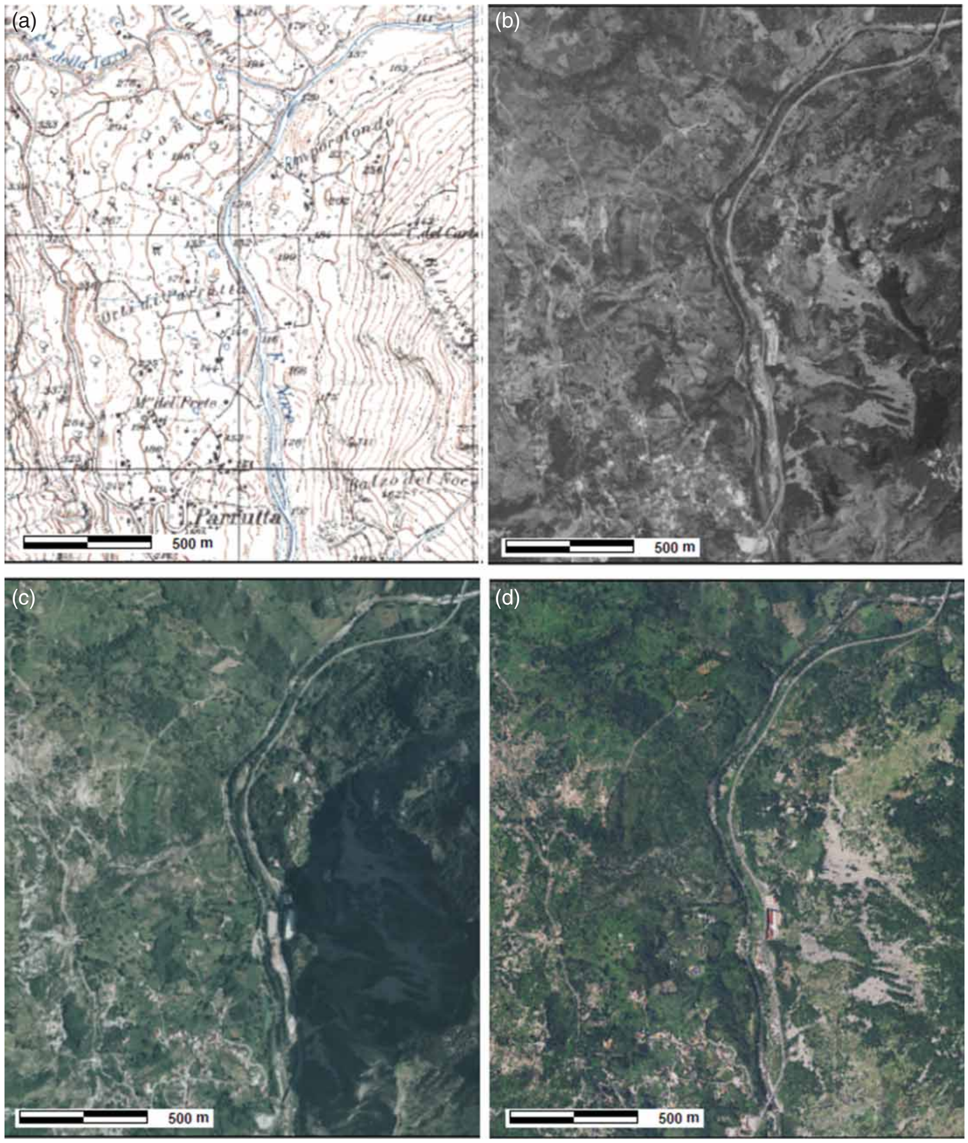

Figure 8. Map comparison of the river reach in the years 1956 (a), 1989 (b), 2000 (c), and 2006 (d).
Source: The National Geoportal (NG) of the Italian Ministry of the Environment (http://www.pcn.minambiente.it).

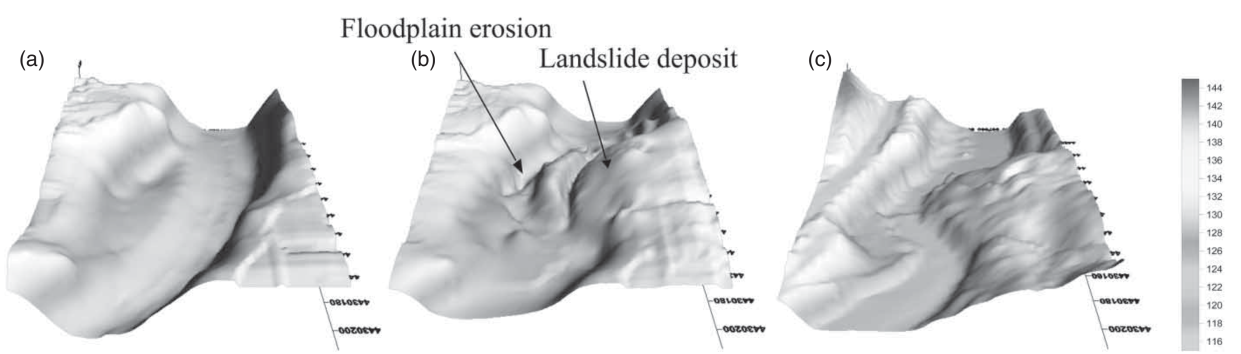

Figure 9. The digital elevation models of the studied branch (upstream/downstream view) in: (a) pre-landslide 2003, (b) post-landslide 2008, and (c) post-landslide 2010.

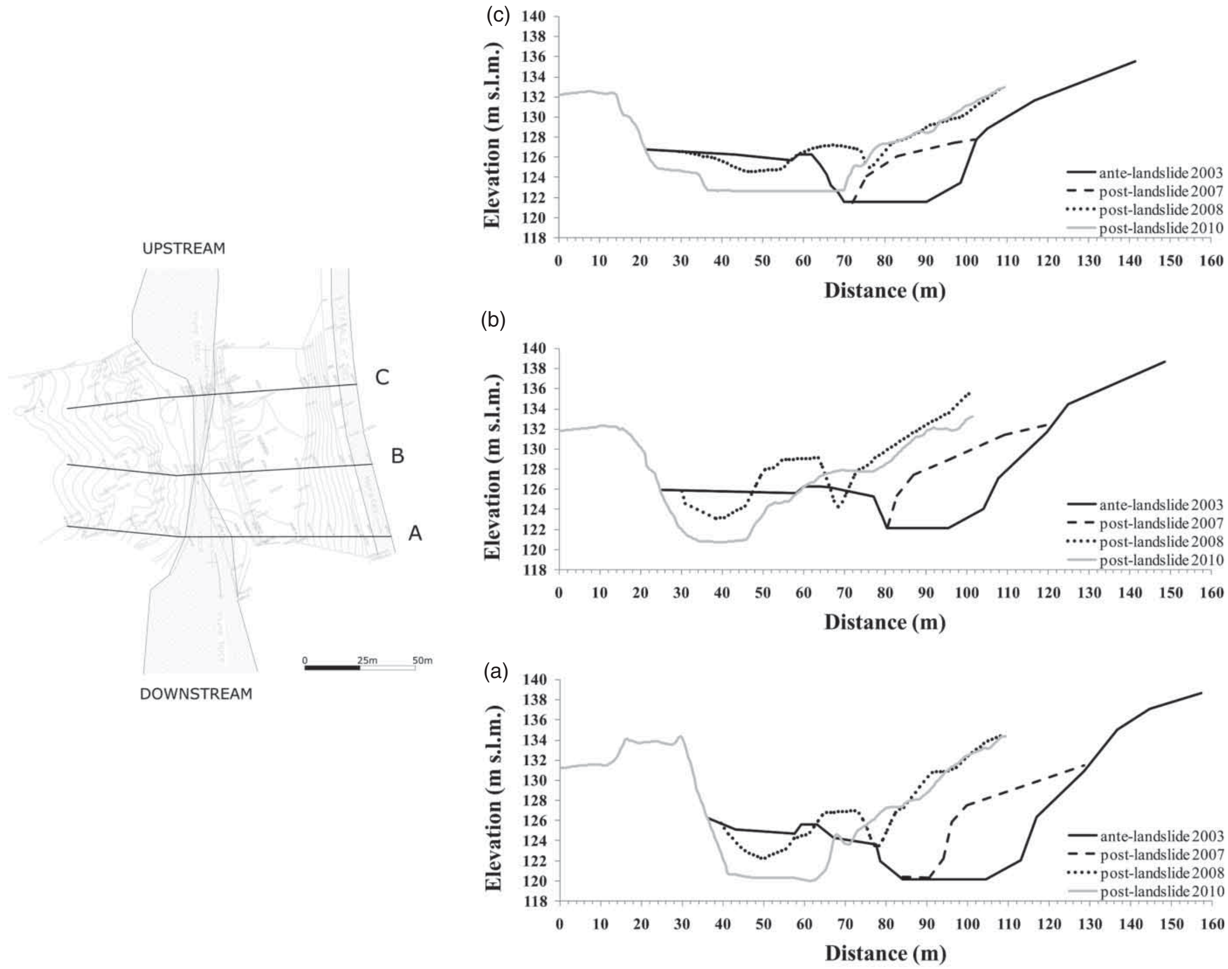

Figure 10. Multi-temporal comparison of the cross-sections 'C', 'B', and 'A' extracted from DTM.

Table 1. Deepening and widening of the three cross-sections.

Section	Progressive vertical erosion (m)				Cross-section width (m)	
Years	2007–2008		2008–2010			
ID	Measured	Modelled	Measured	Modelled	2007–2008	2008–2010
C	1.67	2.24	3.66	4.86	20	34
B	2.47	2.92	5.21	5.22	17	28
A	2.77	2.20	4.54	4.23	24	31
RMSE	0.53		0.72			

Note: RMSE, root mean square error.

The SRH-1D model generally includes the standard step energy method for steady flows. The sediment transport algorithm is usually uncoupled with the hydraulic one and calculated by solving the Exner equation.

Different sediment transport functions were used for our purpose, including total load and bed load equations. Bed-material mixing was modelled by dividing the bed into an active layer and a series of underlying inactive layers. This model also allowed simulating bank erosion, using a relationship between erosion width and flow rate and an angle of repose condition for bank stability (Huang & Greimann 2010).

The phases considered in the modelling were the channel configurations before and after the landslide, using the quasi-unsteady flow condition: post-landslide 2007 and 2008 in order to interpret past dynamics and calibrate the

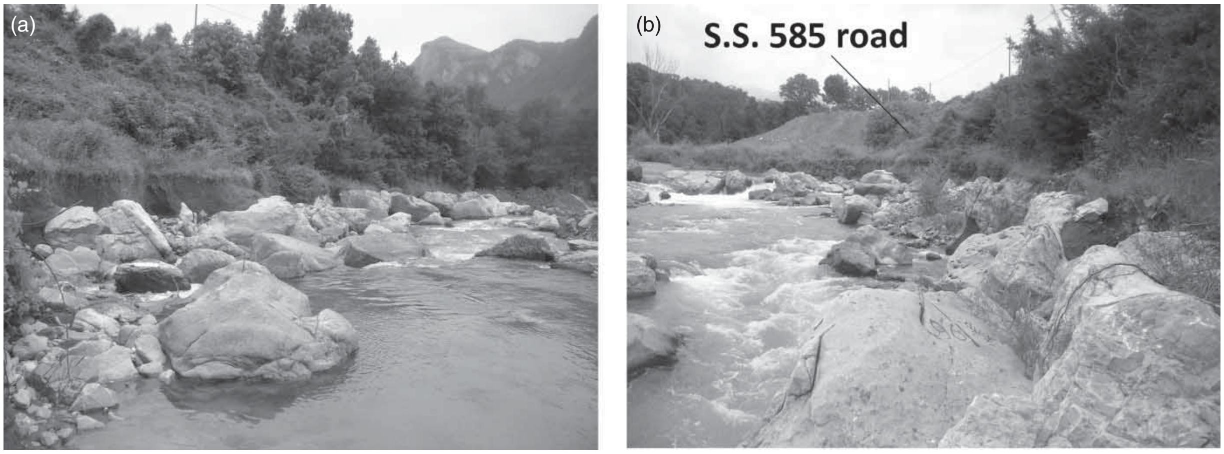

Figure 11. The bank near S.S. 585 naturally protected by boulders and stones (a) upstream and (b) downstream.

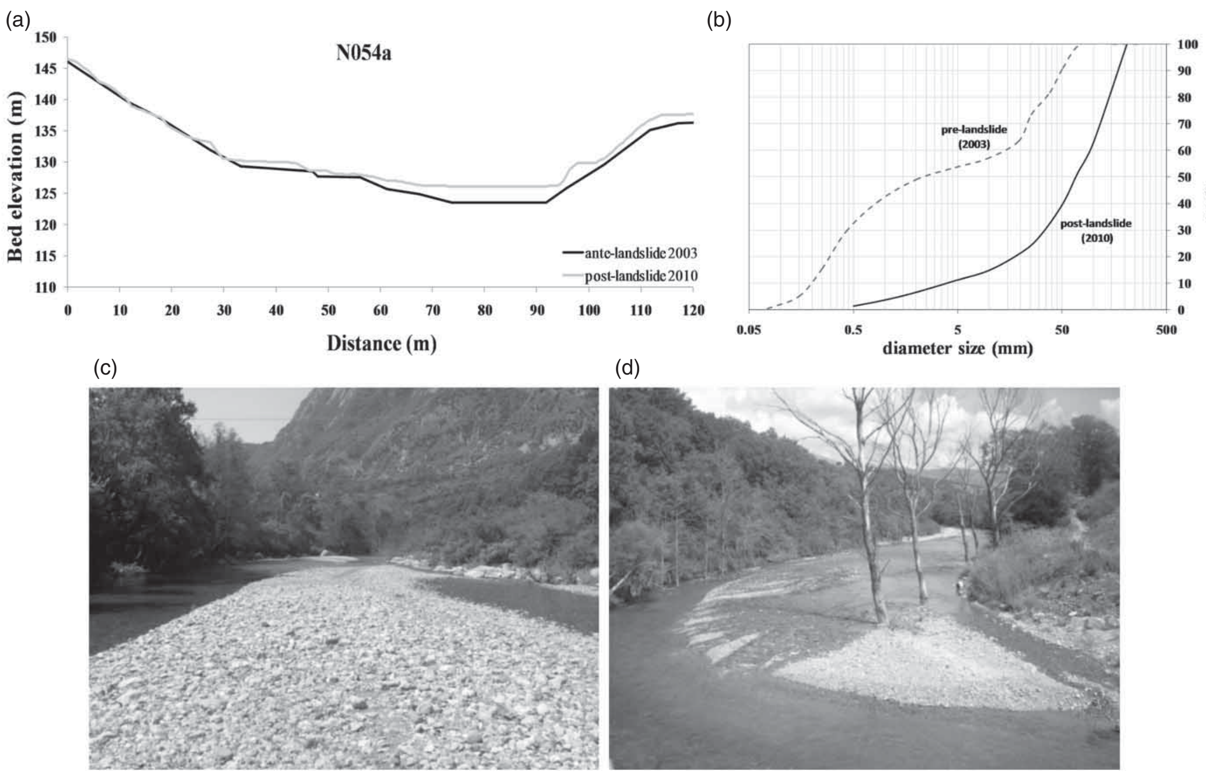

Figure 12. ((a) and (b)) Aggradation in the upstream reach and grain size distribution modification. Change in the river morphologies from (c) braided (2008) to (d) wandering channel (2009–2010).

model and post-landslide 2010 in order to acquire information of future river changes. The geometry used for the model implementation was deduced from the existing cartography, integrated with the cited topographical surveys of the cross-sections. In particular, the geometry was integrated with the topographical surveys following the landslide event. Starting from such surveys, using geographic information system (GIS), a Triangulated Irregular Network (TIN) digital model was generated, from which 36 meaningful cross-sections were extrapolated for the plane-altimetric characterization of the river reach (Figures 14).

In the model, besides the geometric information, the initial and boundary conditions were added too. Initial conditions were represented by the bed sediment granulometric curves of 2003, which showed the existence of heterogeneous superficial alluvium with sand and gravel alternation. The boundary conditions were hydrograph

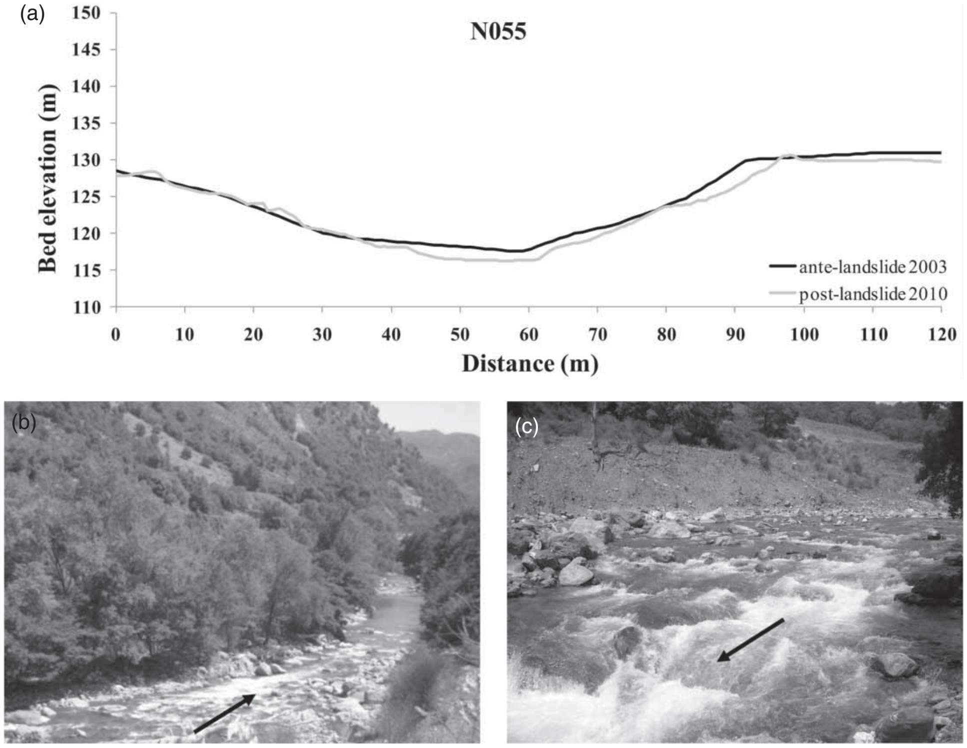

Figure 13. Partial degradation and bed armouring in the lower reach.

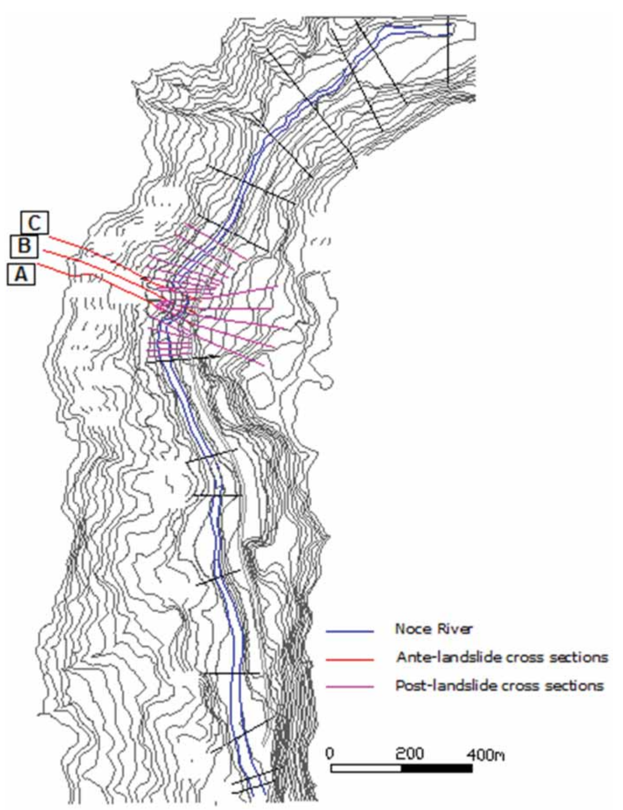

Figure 14. Planimetric map of the river reach with the indication of the cross-sections used by the simulation.

upstream, the normal depth downstream, and the morphological equilibrium of the reach.

The information acquired by the simulation of river dynamics in 2007–2008 stage was used to calibrate the model and simulate the riverbed evolution in the next years (Figures 15). The roughness coefficient $n = 0.035$ s/m$^{1/3}$ and the Ackers–White's method (1973), modified by Wallingford (1990) for the calculation of stream transport capability for gravel-bed rivers, proved to be the best combination to represent sediment transport activity in the investigated reach.

Numerical results show that, in the 2008 post-landslide stage, the progressive full incision of the floodplain was correctly predicted behind the landslide foot. In the 2010 post-landslide stage, cross-section geometry changes were generally limited; the river branch appears to have been relatively stable for the peak flow discharge occurred in the period 2010–2012. Figures 16 illustrates the evolution of the cross-sections for the 2007–2008 and post 2010 stages in which, after a rapid vertical incision and widening of the channel, the phenomena observed after three years started slowing down.

The final results highlight a satisfying correspondence between the altimetric profiles, obtained through the numerical models, and those deriving from the field surveys (Table 1), whereas, for bank erosion, information achieved is only partial and qualitative.

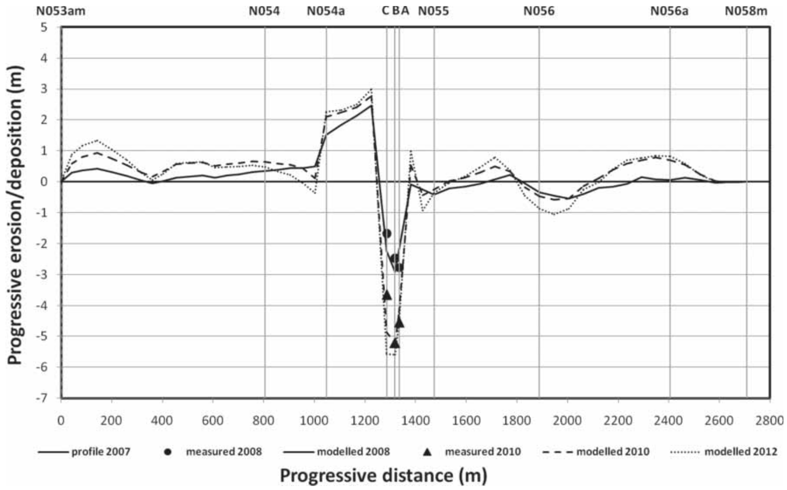

Figure 15. Progressive erosion and deposition in the studied branch simulated in the 2007, 2008, and 2010 post-landslide stage.

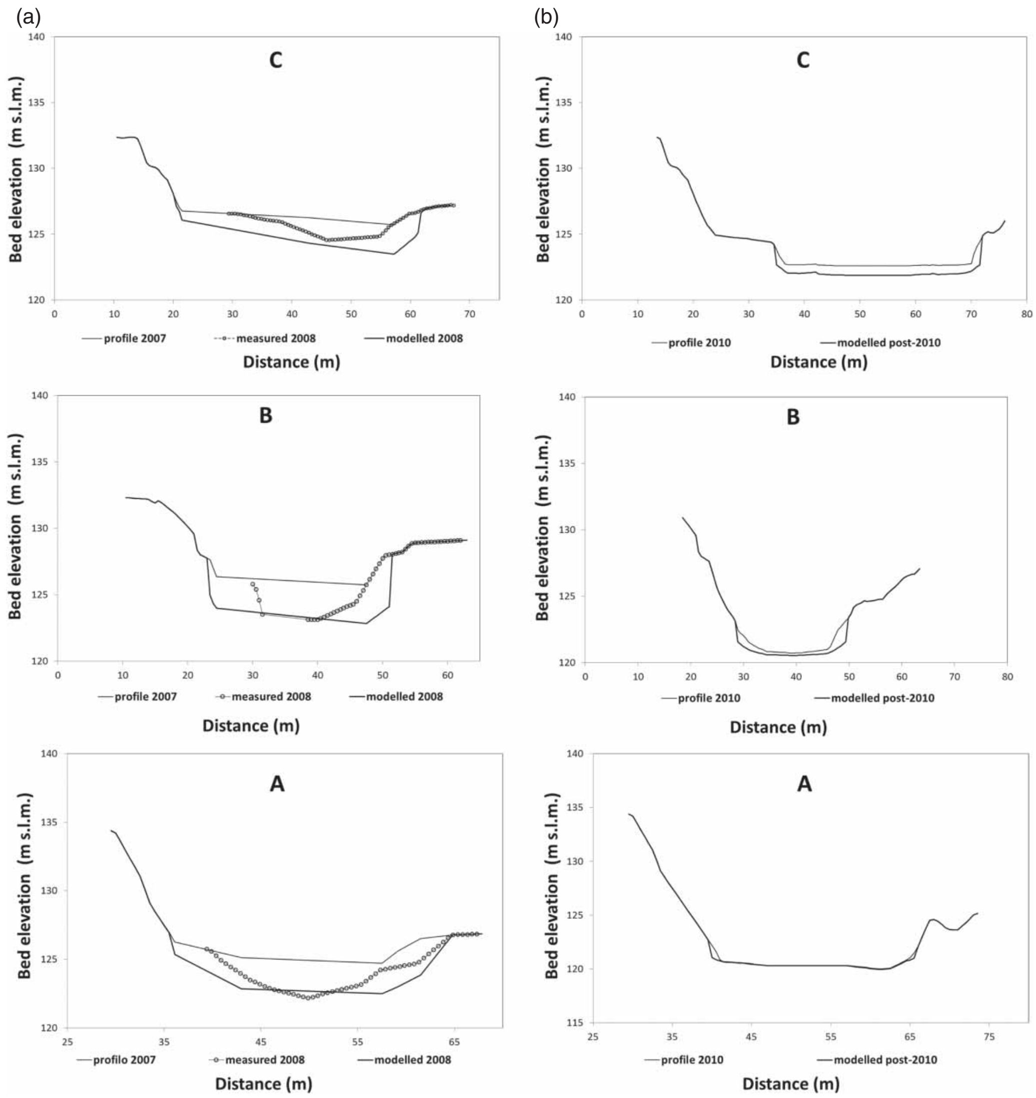

Figure 16. Cross-section changes modelled in the 2007 (a) and 2010 (b) scenarios.

Conclusions

An integrated approach that takes into consideration numerical modelling and field measurements was used to understand the complex phenomena of the interaction between landslide and river in more detail. This information could help the decision-makers to identify specific actions and strategies oriented to the prediction, control, and management of these environmental emergencies.

This study shows the spatial and temporal changes in the river morphology and the dynamics of a gravel-bed reach of the Noce river, in Basilicata region (Italy), a few years after a landslide dam event. A quantitative monitoring was performed, through topographic surveys and *in situ* observations, in order to assess of the geomorphological response of the river to landslide interference. Bed incision, avulsion, and bank erosion occurred in the years after the landslide invasion in the reach immediately affected by the obstruction. Armouring phenomena and changes in grain size distributions, upstream and downstream, with the domination of coarse-grain samples fraction, were also observed. Three years after the landslide dam, sediment incision of the left floodplain allowed us to attain a new channel configuration, with cross-section elevation and geometric shape similar to the pre-landslide ones. The use of the mobile-bed numerical model SRH-1D, although with some approximations such as neglecting transverse sediment transport, changes in width due to bank erosion or deposition, and formation of multi-dimensional features such as alternate bar allowed us to acquire useful information on the riverbed evolution in various morphological phases, following the landslide obstruction, and to estimate subsequent bed changes. Final results underline a satisfying correspondence between the measured and calculated altimetric bed profiles. The simulation of lateral erosion by the 1D model is, instead, only descriptive of the general trends of the phenomenon because the transverse variation in shear stress and bed load are ignored.

The reliability of the numerical results allowed predicting potential shape and bed elevation of the quasi-equilibrium condition of the channel in the years after 2010. This approach could reduce costs and time for the understanding of the phenomenon that, otherwise, with a constant observation, would require higher costs, more time, and specialized technicians. In addition, this analysis might be useful to local authority in defining and guiding the possible structural interventions in order to regularize the fluvial course and to protect public works (S.S. 585 road) from further erosion processes.

Up to the present, the bed and the bank of the new reach formed under the S.S. 585 road have been protected naturally by boulders and stones, belonging to an ancient mass movement on the left side of the hillslope. In the near future, further detailed and updated information on the landslide foot and road bank stability, on the basis of morphodynamic surveys that are in progress, will be achieved.

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Antonio Volpe Plantamura graduated in Mechanical Engineering at Basilicata University in 2007 and got his Ph.D. in Methods and Technologies for Environmental Monitoring in 2011. He has experience of research in the fields of hydraulics and fluid mechanics, with particular attention to the study of dynamic response of structures submerged in steady and unsteady flows.

Vincenzo Masi graduated in Civil Engineering in 1984 at the University of Napoli and has been Assistant Professor of Fluvial Hydraulics at the School of Engineering at Basilicata University since 2004. The main research activity is currently addressed in the field of environmental engineering and fluvial hydraulics.

Disclosure statement

No potential conflict of interest was reported by the authors.

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