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Analysis of river bed dynamic evolution following a landslide dam

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ABSTRACT. – Landslides and debris flows can strongly interact with the river network and its mass transport processes, determining modifications of the river pattern with consequent effects on the hydrodynamic phenomena, alterations of the existing morphologies and possible interferences with anthropic works. Modifications of the cross section geometry and channel slope may produce changes in the sediment budget, with consequent repercussions on the stream evolutionary dynamics and its equilibrium configuration, leading to a new river branch arrangement. In this paper, investigations were carried out on a gravel-bed reach in the middle valley of the Noce River in Basilicata (Italy), which in 2007 suffered a progressive morpho-hydrodynamic change caused by a landslide. Because of the phenomenon complexity, mainly due to the mutual interaction between the landslide and the river transport dynamics, an integrated approach that combines field observations and numerical modelling in a spatial scale and natural environment, rarely available in literature, is suggested. The results highlight a satisfying correspondence between the altimetric profiles obtained through the numerical models and those deriving from the field surveys.

Key-words: Sediment Transport, River Morphologies, Landslide, Field Observation, Hydrodynamic Modelling

Analyse de l'évolution dynamique du lit de la rivière suite à la construction d'un barrage due à des glissements de terrain

RÉSUMÉ. – Les glissements de terrain et les laves torrentielles peuvent fortement interagir avec le réseau fluvial et ses processus de transport de sédiments; avec, en conséquence, des effets inévitables sur la configuration en plan de la rivière et sur les phénomènes hydrodynamiques, ainsi que des changements de la morphologie existante et de possibles interférences avec les aménagements anthropiques. Les modifications de la géométrie de la section transversale et de la pente du chenal peuvent provoquer une altération de la quantité de sédiments et avoir un impact sur l'évolution dynamique du cours d'eau et sur son état d'équilibre, donc mener à un nouvel agencement du tronçon fluvial. Dans cet article, sont présentés les résultats d'analyses effectuées en Basilicata (Italie) et portant sur un tronçon de lit fluvial riche en gravier et situé dans la partie centrale de la Vallée du fleuve Noce, lequel a subi en 2007 un changement morpho-hydrodynamique progressif causé par un glissement de terrain. À cause de la complexité du phénomène ,suite surtout à l'interaction entre le glissement de terrain et la dynamique du transport fluvial, on a privilégié une approche de recherche intégrée qui a pris en considération à la fois les observations sur place et la modélisation numérique, à une échelle spatiale et un environnement naturel peu présents dans les essais de la littérature scientifique. Les résultats ont mis en évidence une correspondance raisonnable entre les profils altimétriques obtenus des modèles numériques et ceux tirés des relevés.

Mots-clés : Transport de sediments, morphologies fluviales, glissement de terrain, observation de terrain, modélisation hydrodynamique

I. INTRODUCTION

The interaction between landslides and river network is a frequent phenomenon [Costa, Schuster, 1988]. River damming may cause 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, landslide dams are responsible for changes in the sediment budget with consequent repercussions on the evolution of the channel morphology [Montgomery, Buffington, 1997], the sediment transport capacity, and the stream habitats. Over time, the river responds by changing the cross section geometry and longitudinal slope and reaching a new branch equilibrium configuration. The associated fluvial processes consist in incision through the fan, erosion of the banks and lateral channel migration, aggradation phenomena, variation of mean bed-material size, changes of river patterns and geometry in the upstream and downstream reaches [Miller, Benda, 2000; Pizzuto, 2002; Sutherland, *et al.*, 2002; Korup, 2004, 2005; Hoffman, Gabet, 2007]. Modelling landslide phenomena, which interfere with the river, is particularly complex because at the same time

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the process involves both landslide and river dynamics. Interpretative models of partial or total river bed obstruction and solid material coming from the hillslope are still in the experimentation and testing phase [Costa, Schuster, 1988; Casagli, Ermini, 1999].

In this study, sediment transport processes and river bed dynamics have been described and analyzed in a gravel bed reach invaded by a landslide, on the Noce river in Basilicata region. The study introduces some modalities and tools of investigation which involve cartographic analysis, *in situ* observation and morpho-hydrodynamic modelling.

II. 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-west of Basilicata region (Italy) (Fig. 1). In particular, the landslide is at 40° 01' 0.25"N and 15° 47' 44.64"E according to the UTM coordinate system (Datum WGS84). In July 2007, this reach suffered a significant morphological change caused by an earth-flow reactivation [Di Maio, *et al.*, 2009] from the right-side slope of the basin, which altered its natural morphological characteristics. The landslide and river interaction occurred in a progressive multi-stage way and caused a first partial (July 2007) and then total (November 2007) blockage of the water course, forming a little backwater lake upstream. The following floods led the flow away from the landslide bottom, creating a new branch on the left floodplain, thus favoring 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 (Fig. 2). The combined effects produced by the new river morphological configuration and the induced contraction scour triggered a progressive lowering of the floodplain, highlighting cyclopean boulders next to the outside bank of the bend, probably belonging to an ancient mass movement on the left side of the hillslope [Dal Sasso *et al.* 2014].

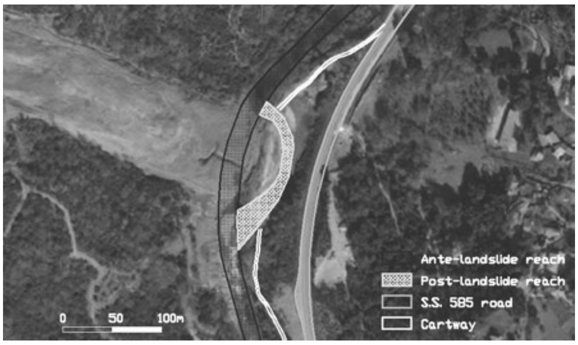

Figure 2: *Orthophoto extract, highlighting the river reach interested by the landslide, and description of its position before and after the event.*

The landslide interference induced morpho-hydrodynamic changes also in the upstream reach, because of the flow slowdown and deposition of sediments coming from upstream, forming bar sequences. Conversely, in the downstream reach, the clayey material coming from the slope, erodible in a very long time as well as transportable mainly in suspension, did not produce significant, observable morphological variations. An overview of the different river morphological phases, previously described, is shown in Fig. 3.

III. FIELD OBSERVATION OF THE RIVER MORPHO-EVOLUTIVE DYNAMICS

The morpho-evolutive study was carried out at 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 ortophoto, 2001 photogrammetry) and field surveys supplied by the Interregional River Basin Authority of Basilicata in 2003. The analysis of those data have highlighted how the reach morphology was that of a single-thread gravel-bed river (Fig. 4), prevalently straight with limited possibilities of lateral wandering, because of

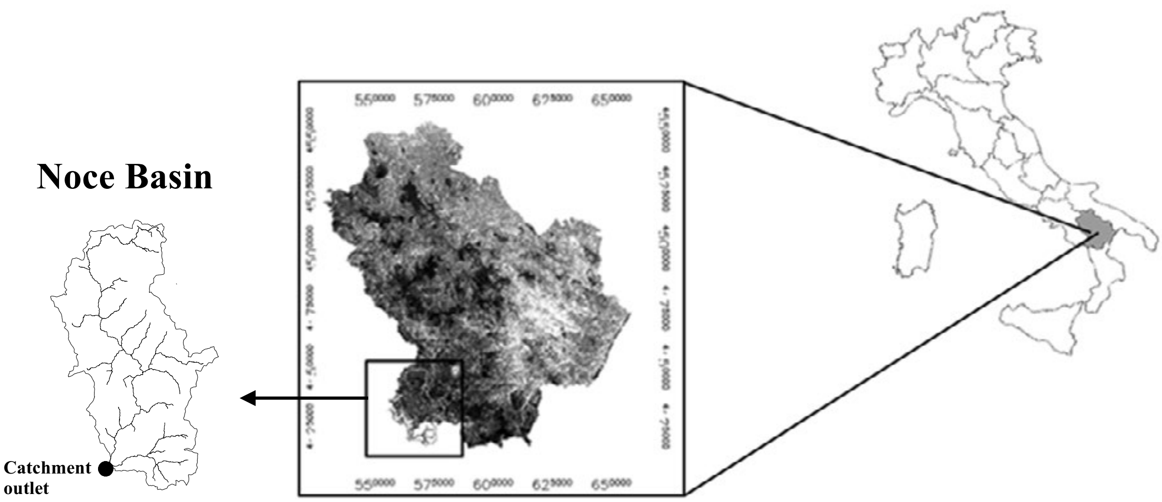

Figure 1: *Location of the study area.*

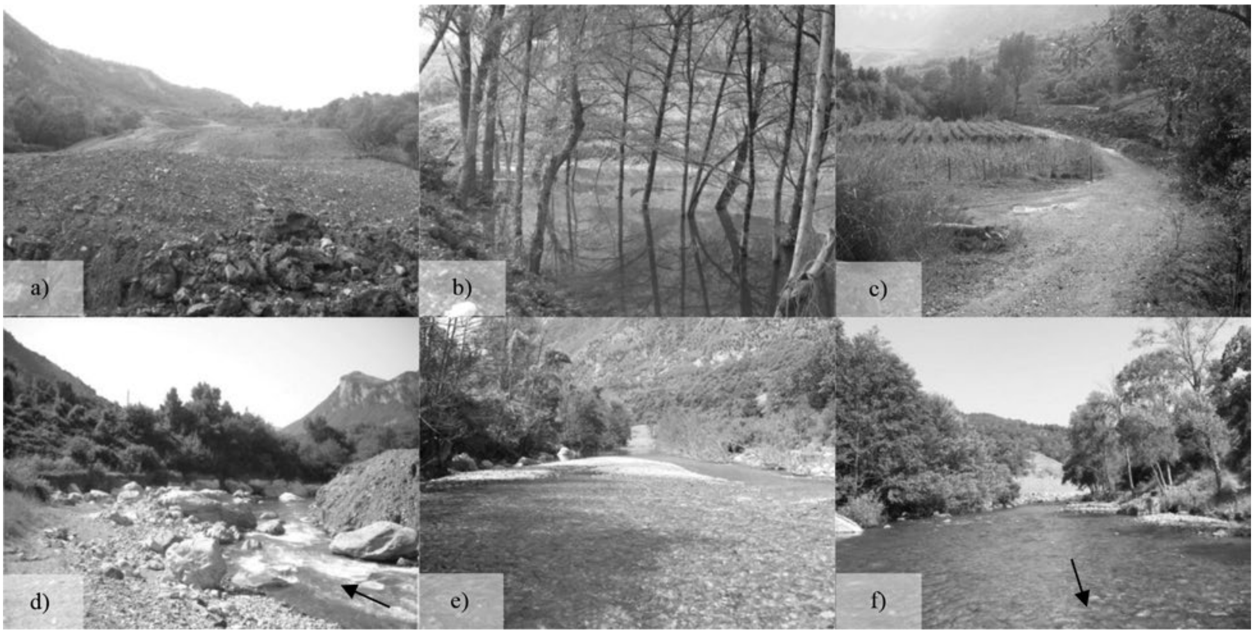

Figure 3: *a) Landslide triggering; b) formation of backwater lake and migration of flow to the left; c) undisturbed floodplain on the left, with vineyard and side cart way ; d) turning of the landslide bottom and surfacing of cyclopean boulders; e) formation of deposit bars in the upstream reach; f) partial degradation and undisturbed conditions downstream.*

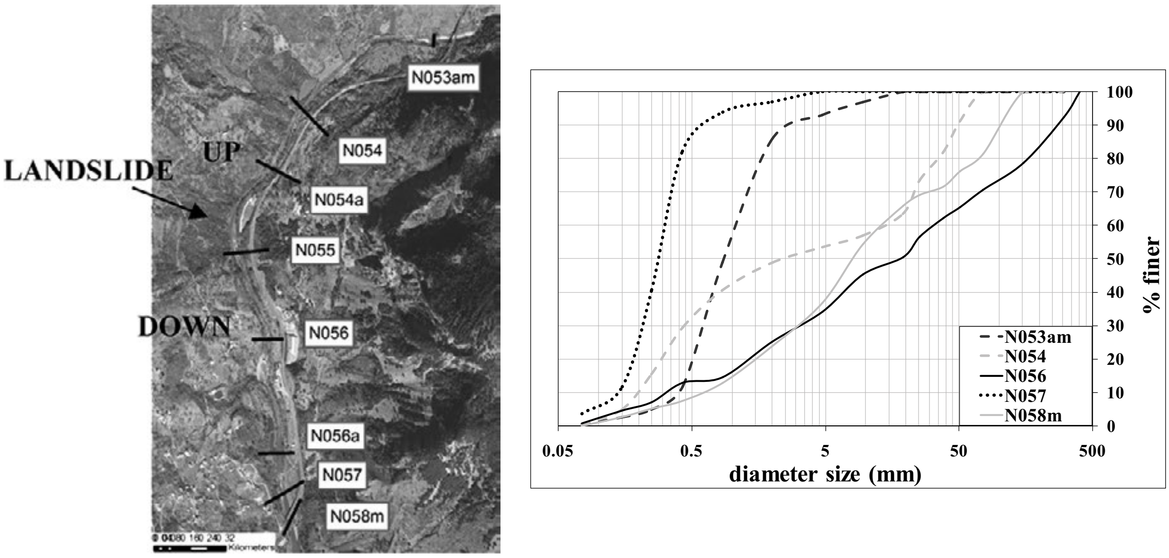

Figure 4: *Granulometric distribution in the 2003 pre-landslide condition.*

the valley wall confinement. The channel average width was about 25 m and its planimetric profile was curvilinear with a radius of about 350 m, probably because of an old debris fan pattern inside the reach and an average slope stabilized at about 1%.

In the post-landslide phase, the analysis was carried out through the topographic surveys, performed by the Italian local Authority (the Region of Basilicata) with Differential Global Positioning System (DGPS) technology in 2008, and the airborne laser-scanning data, surveyed in 2010 by the Engineering Society (Geocart s.r.l.). Moreover, monitoring campaigns concerned the obstructed river reach as well as those upstream and downstream, in order to understand both the in-progress and the potential morpho-hydrodynamic processes. All the mentioned data, together with the pre-landslide phase ones, permitted the creation of the Digital Terrain Models (DTMs) of the area before the event, after a year (in 2008) and after three years (in 2010). Those DTMs 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 5x5m (Fig. 5). The comparison shows that the solid volume coming from the landslide in the river reach is about 60000 m^3, while the floodplain erosion induced by the contraction and local scour is about 3000 m^3 in 2008, reaching about 6500 m^3 in 2010.

In particular, the extrapolation from those DTMs of the three cross sections (‘C’, ‘B’, ‘A’) by the landslide for a

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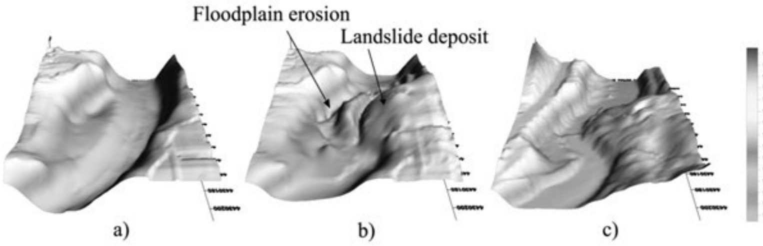

Figure 5: *The digital elevation models of the studied branch (upstream/downstream view) in: a) pre-landslide, 2003; b) post-landslide, 2008; and c) post-landslide, 2010.*

length of 120 m has allowed us to evaluate morphological planimetric and altimetric changes (Fig. 6). The analysis of the cross section profiles shows that the river bed suffered a left planimetric translation next to the landslide, forming a bend with a curvature radius of about 70 m which goes toward the S.S. 585 road. In this area, significant vertical incisions and lateral erosions, caused by the water discharges shown in Figure 10, can be observed. In particular, the river bed incisions, from upstream to downstream, vary from a minimum of 1.7 m measured in the year 2008 to a maximum of 3.7 m measured in the year 2010 in cross section ‘C’, from 2.5 m (2008) to 4.9 m (2010) in cross section ‘B’ and from 2.5 m (2008) to 4.4 m (2010) in cross section ‘A’. The channel width varies from 20 m to 35 m because of the bank erosion on the left (floodplain) and on the right (landslide bottom). The airborne laser-scanning data, surveyed in 2010, indicate that the vertical and lateral adjustments have allowed attaining a new channel configuration with elevation and width similar to the pre-landslide one.

During the surveyed period (2007-2010), changes in the river patterns were also observed in the upstream and downstream reaches. In particular, in the upstream, after the emptying of the backwater, sediment deposition produced the formation of central and lateral bar sequences (braided type); later, over time, it became a single channel with alternate bars (wandering type) (Fig. 7). Moreover, the reduction of the current velocity and sediment carrying capacity of the flow, due to the reduction of the bottom slope, produced deposition of gravel and coarse material up to a depth of over 2.5 m (Fig. 8). Downstream, near the avulsion, the reduction of 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 (Fig. 9). Further downstream, the prevalent fine material

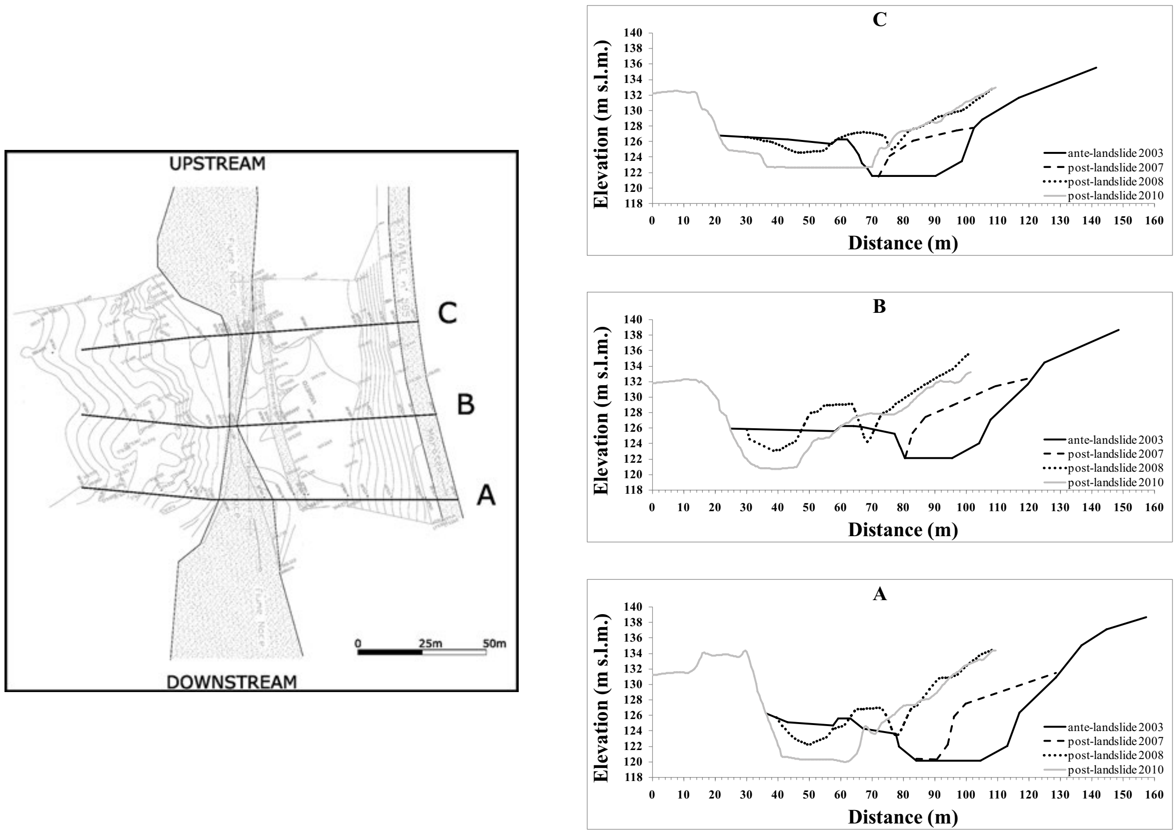

Figure 6: *Multi-temporal comparison of the cross sections ‘C’, ‘B’, and ‘A’ extracted from DTM.*

a) b)

Figure 7: *Upstream aggradation and change of the river morphologies from a) braided (2008) to b) wandering channel (2009-2010).*

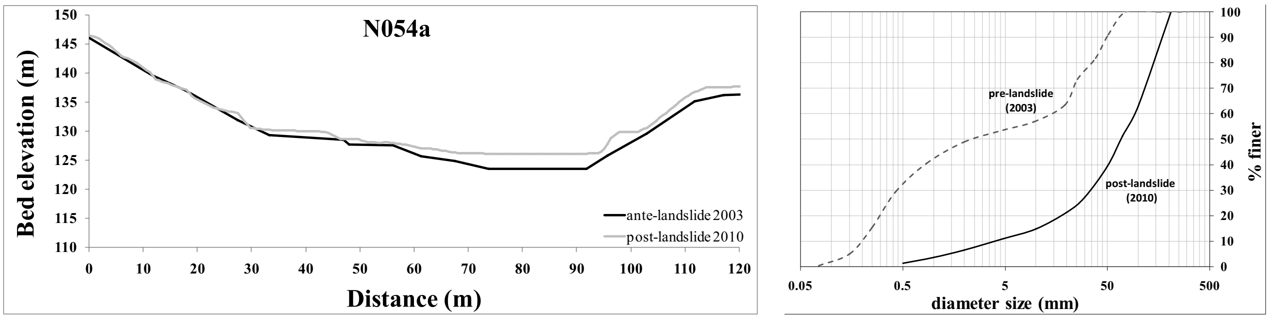

Figure 8: *Aggradation in the upstream reach and changes in grain size distribution.*

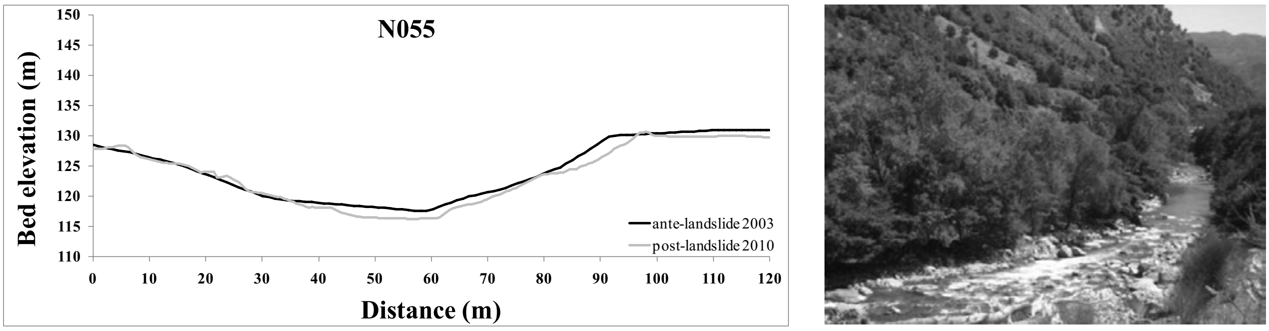

Figure 9: *Partial degradation and bed armouring in the lower reach.*

eroded from the landslide bottom and floodplain did not produce significant observable river bed modifications.

IV. NUMERICAL MODELLING OF THE RIVER MORPHO-EVOLUTIVE DYNAMICS

The mobile boundary hydraulic and sediment transport computer models HEC-RAS 4.1 (Hydrologic Engineering Center, of the United States Army Corps of Engineers, HEC-RAS, River Analysis System, 2010) and SRH-1D (Sedimentation and River Hydraulics – One Dimension, Version 2.6, Huang J.V., Greimann B., 2007) were used to simulate the river bed morphologic dynamics and evolutionary tendencies, in terms of erosion and deposition, in the reach invaded by the landslide and immediately upstream and downstream.

The models adopt similar hydraulic and sediment transport algorithms. The standard step method is used to solve the energy equation for steady gradually varied flows in quasi-unsteady flow condition. The sediment transport algorithm is uncoupled from the hydraulic one and calculated

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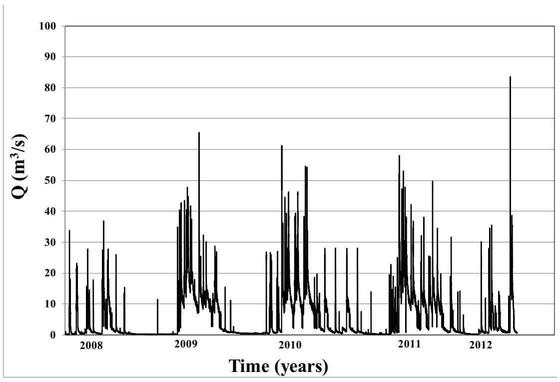

Figure 10: *Hourly hydrograph following the landslide event used for the simulations.*

by solving the sediment continuity equation. Different sediment transport functions are used for this purpose, including total load and bed load equations. Exner 5 is the "three layer" algorithm that divides the active layer into two sub-layers, simulating bed coarsening by removing fine materials from the thin cover layer. The fall velocity of sediment particles is computed in the SRH-1D model using values recommended by the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation in 1957, while in the Hec-Ras model multiple fall velocity methods are developed (Report 12, Ruby, Toffaleti and Van Rijn). Moreover, SRH-1D is a quasi-2D mobile bed model simulating bank erosion, using angle of repose conditions, and including the possibility to perform fully-unsteady sediment transport simulations. The numerical models were implemented after acquiring the geomorphologic, hydrologic and geologic information of the drainage basin upstream the study area. The river reach, object of the hydrodynamic simulations, extends approximately for 2.7 km and is located at 1.3 km upstream and 1.3 km downstream of the stretch intercepted by the landslide between two artificial embankment discontinuities.

The three phases considered in the modelling are: the first channel configuration immediately after the landslide (2007 - 2008), the second one in between 2008-2010, and the last one representing the future evolution after 2010. For each one, the geometry used for the model implementation was deduced from the existing cartography, integrated with the cited topographical surveys of the cross sections following the landslide event. Starting from such surveys, using GIS (Geographic Information System), a TIN (Triangulated Irregular Network) digital model was generated, from which 36 meaningful cross sections were extrapolated for the plane-altimetric characterisation of the river reach. In this implementation, the local erosion due to the presence of boulders in the river bed was neglected, while the landslide body was considered as a partial obstacle to the normal outflow and not as an active contribution to the sediment transport.

The hydrodynamic simulations, in a quasi-unsteady flow condition, were carried out using the hourly discharges deriving from the theoretical rating curve, estimated at the hydrometric station 'Le Fornaci', located 2.5 km upstream of the landslide. The value of the roughness coefficient ($n = 0.035\ s/m^{1/3}$) was calibrated comparing the measured water levels H with the ones calculated from the one-dimensional numerical model HEC-RAS. Then, the model was used to extrapolate the rating curves according to the studies of Sole *et al.* (2010) and Di Baldassarre and Claps, (2011):

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

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

in which H is the hydrometric level.

The choice of two rating curves is due to the change of the cross section shape for H=0.90m.

The value of n calculated in 2010 was used to simulate the post-landslide conditions because there were no significant variations of the section geometry and bed roughness on the hydrometric station. Moreover, the ordinary flood discharges, chosen to describe the dynamic evolution of the studied river branch, are not influenced by geometrical characteristics or bed sediment distribution.

In Figure 10 the hourly hydrograph, showing the water discharges versus time, is reported from November 2007 to May 2012. In detail, the water discharges were obtained through the rating curves (1) and (2) starting from the water levels measured by the hydrometric station. In the models, beside the geometric information, the initial and boundary conditions were also added. For the initial conditions, those of dry bed and the bed sediment granulometric curves of 2003, that is the heterogeneous superficial alluvium with sand and gravel alternation as in Fig. 4, were specified. The boundary conditions are those of the hydrograph upstream and the normal depth downstream and beside that of morphologic equilibrium of the reach, adopting Yang's formula (1973, 1984) and Ackers-White's method (1973) modified by HR Wallingford (1990) for the calculation of stream transport capability for gravel-bed rivers. The results, that provided the best balance between model stability and run time, turned out sufficiently in agreement with the two formulations, as shown in the following figures.

Figure 11 shows the altimetric bed profile in the 2007 post-landslide stage (Profile 2007), the calculated profiles using the Ackers-White's method and Yang's formula with both HEC-RAS and SRH-1D models in correspondence to ordinary flood events (2007-2008), and the data measured in 2008. The model application shows that, in the studied river branch, the presence of the obstruction and the formation of a little backwater lake, upstream of the landslide dam, determine a sediment deposition of up to 2.5-3 m of thickness which propagates upstream attenuating itself. On the contrary, in the new fluvial branch generated inside the floodplain, a river bed erosion of about 2.5m occurs and propagates downstream also attenuating itself (Fig. 11). The simulation values with both models are in agreement with those measured in the reach intercepted by the obstruction. Conversely, the profiles simulated with the HEC-RAS model are less stable in the reach upstream of the landslide obstruction and underestimate altimetric erosion in the floodplain.

In the 2008 post-landslide stage, the input discharges used for the model simulations are which occurred during the 2008-2010 period. In this phase, the progressive full incision of the floodplain was predicted behind the landslide foot by both models, but aggradation phenomena upstream and bed changes downstream are not in agreement with the numerical models (Fig. 12).

In the 2010 scenario, numerical results demonstrate that changes in cross section geometry are generally limited and that the river branch is relatively stable for the peak flow discharge which occurred in the years 2010-2012 (Fig. 13).

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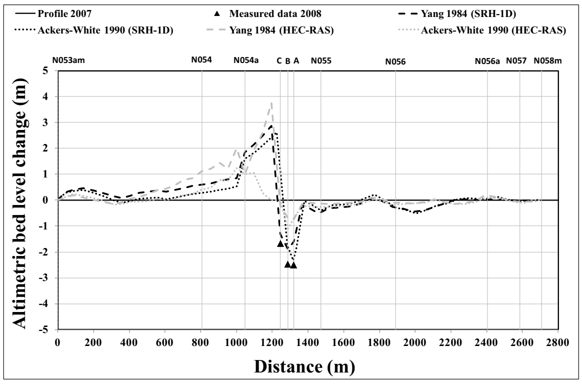

Figure 11: *River bed altimetric evolution in the studied branch in the 2007 post-landslide stage simulated with both HEC-RAS and SRH-1D numerical models.*

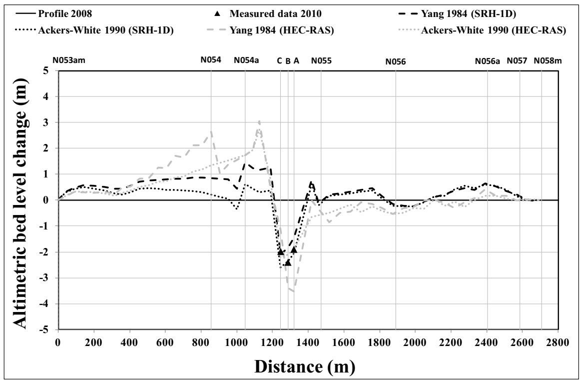

Figure 12: *River bed altimetric evolution in the studied branch in the 2008 post-landslide stage simulated with both HEC-RAS and SRH-1D numerical models.*

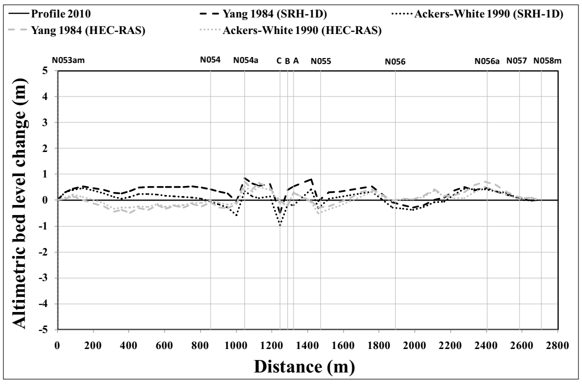

Figure 13: *River bed altimetric evolution in the studied branch in the 2010 post-landslide stage simulated with both HEC-RAS and SRH-1D numerical models.*

Moreover, for the 2010-2012 period the simulation results show that the river branch affected by the landslide is recovering a new equilibrium dynamic condition, with slow erosion and deposition in the upstream and downstream reaches (Fig. 13). However, at present, the lack of measured data showing real altimetric bed evolution does not allow us to confirm the results of the two software simulations.

V. CONCLUSIONS

In this paper, an integrated approach that combines surveys, *in situ* observations and numerical models was used to study the river morphology and the dynamics of a gravel-bed reach, affected by a landslide, located along the Noce river in Basilicata region. The field observations and topographic surveys were conducted both at a general and local scale in a short temporal duration, documenting the changes in river patterns and fluvial processes. Sediment incision, armoring, changes in grain size distributions, avulsions and bank erosion occurred three years after the landslide invasion in the reach immediately affected by the obstruction, but also upstream and downstream. The one-dimensional numerical models like HEC-RAS and SRH-1D, although with some approximations such as neglecting long term bank erosion and transverse sediment transport, have allowed us to acquire information on the river bed vertical evolutions in various morphologic phases, following the landslide obstruction. In particular, the measured data of bed profiles and the predicted results by the SRH-1D model are in agreement while, in the same parametrical condition, the HEC-RAS profiles are more unstable in the phases in which rapid spatial variations of cross sections are produced by the landslide obstruction (post-landslide 2007 and 2008). In this regard, in order to reduce the instability problems and improve the quality of simulation results, an accurate definition of the computation increment as well as the spatial discretization of the domain are necessary.

Moreover, the numerical results, according to the topographic surveys, seem to indicate that, in time, the changes in cross sectional geometry become slower and, therefore, the river branch is recovering a new dynamic equilibrium channel configuration.

Finally, it is important to underline how the integrated approach can represent a useful tool not only to predict evolutionary dynamics of river subject to complex phenomena, like that of landslide obstruction, but also to reduce the time and costs of detailed field observations and surveys.

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VII. REFERENCES AND CITATIONS

Ackers P., White W.R. (1973) — Sediment transport: a new approach and analysis. *J. Hydraulic Eng.* **99(11)** 2041-2060

Casagli N., Ermini L. (1999) — Geomorphic analysis of landslide dam of Northern Appenine. *Transaction of the Japanese Geomorphological Union.* **20(3)** 219-249

Costa J.E., Schuster R.L. (1988) — The formation and failure of natural dam. *Geological Society of America Bulletin.* **100** 1054-1068

DOI 10.1051/lhb/20150073

Dal Sasso S.F., Sole A., Pascale S., Sdao F., Bateman Pinzòn A., & Medina V. (2014) — Assessment methodology for the prediction of landslide dam hazard. *Natural Hazards and Earth System Sciences.* **14** 557-567

Di Baldassarre G., Claps P. (2011) — A hydraulic study on the applicability of flood rating curves. *Hydrology Research.* **42(1)** 10-19

Di Maio C., Sole A. (2009) — Analisi geotecnica e idrologico-idraulica sul problema del versante in frana e degli effetti sul fiume Noce in c.da Zillona di Trecchina (Pz). *Report for Basilicata Region*

Hec-Ras, River Analysis System (2010) — User's Manual, Version. *4.1, CPD-68, January 2010. Hydrologic Engineering Center, Institute for Water Resources, U.S. Corps of Engineers, Davis, CA*

Hoffman D. F., Gabet E.J. (2007) — Effects of sediment pulses on channel morphology in a gravel-bed river. *Geological Society of America Bulletin.* **119(1-2)** 116-125

Hr Wallingford (1990) — Sediment transport, the Ackers and White theory revised. *Report SR237, HR Wallingford Company, England*

Huang J.V., Greimann B. (2007) — 2.0.5. Bureau of Reclamation User's Manual for SRH-1D V

Korup O. (2004) — Landslide-induced river channel avulsions in mountain catchments of southwest New Zealand. *Geomorphology.* **63** 57-80

Korup O. (2005) — Large landslides and their effect on sediment flux in South Westland, New Zealand. *Earth Surface Processes and Landforms.* **30** 305-323

Miller D.J., Benda L.E. (2000) — Effects of punctuated sediment supply on valley-floor landforms and sediment transport. *Geological Society of America Bulletin.* **112** 1814-1824

Montgomery D.R., Buffington J.M. (1997) — Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin.* **109(5)** 596-611

Pizzuto J. (2002) — Effects of dam removal on river form and process. *BioScience.* **52** 683-691

Sutherland D.G., Ball M.H., Hilton S.J., & Lisle T.E. (2002) — Evolution of a landslide induced sediment wave in the Navarro River. California. *Geological Society of America Bulletin.* **114** 1036-1048

Sole A., Copertino V.A., Dal Sasso S.F., Mirauda D., &Volpe Plantamura A. (2010) — The evaluation of rating curve in bed rivers with sediment transport. *L. Pfister, N. Martinez-Carreras, E. Clot & L. Hoffmann ed., EGU Leonardo Topical Conference Series on the hydrological cycle 2010. 10-12 November 2010, Luxembourg.* 64-65

Yang C.T. (1973) — Incipient motion and sediment transport. *J. Hydraulic Div.* **99(10)** 1679-1704

Yang C.T. (1984) — Unit Stream power equation for gravel. *J. Hydrology.* **40** 123-138