Modelling stony debris flows involving culverted streams: the Abbadia San Salvatore case (Mt. Amiata, Italy)

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Short note

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ABSTRACT

In urbanised areas, debris flows may encounter, along their path, closed sections due to culverted or buried streams. The solid phase can clog these sections, almost instantaneously transforming an effective work into a source of hazard. This condition requires particular attention in the design and model-based verification stage of these hydraulic works and needs advanced modelling approaches to describe the deposition process leading to clogging. In this work, we present a case study in the Abbadia San Salvatore town (Mt. Amiata, Italy), where a new culvert was realised after a debris flow event, which may potentially undergo clogging. Starting from the results of a previous study aimed at the back-analysis of a clogging event that occurred in 2019, this paper focuses on evaluating the susceptibility to clogging of the new culvert. Using the TRENT2D debris flow model, two scenarios were analysed: the former consisting of the sole new culvert and the latter considering an additional open check dam to be located upstream of the culvert. Results show that the first solution is effective, even though not providing a reasonable safety factor against clogging, while the second scenario provides a more robust configuration. Additionally, this study offers outcomes and considerations that can be used in a more general design context.

KEY-WORDS: debris flow, Mt. Amiata, numerical modelling, culverted streams, TRENT2D-WEEZARD.

INTRODUCTION

Stream burial, the rerouting of streams into underground culverts (Hintz et al., 2022), is a typical urban management practice allowing, in situations of limited space availability, to gain areas for different human activities (Napieralski & Carvalhaes, 2016). This practice is also applied, at least in Italy, in sites located in urban, mountainous areas. The drawback with this solution is that in the case of either debris flows or intense bed load transport, a buried channel may be clogged by the transported debris (without considering wood debris, as in this paper), so switching almost instantly from an effective work into a source of hazard and damage (e.g., Chen et al., 2019). This peculiarity requires particular attention in the design and verification stage and needs an advanced modelling approach to catch the basic phenomenon leading to clogging, namely the deposition process (over fixed or mobile bed) that can occur near the entrance section of a buried channel. Similar considerations can be made regarding culverts built along streams susceptible to debris flows.

Moreover, in-depth knowledge of the spatial distribution of the geo-engineering properties of both the bedrock and the loose deposits where the debris flow occurs is a fundamental requirement for advanced numerical modelling. This constraint is particularly relevant for those models that allow to consider, within a catchment, both erodible and non-erodible areas (i.e., fixed or mobile bed areas).

In the last decades, climate change has contributed to increased high-discharge flow events (IPCC, 2014), possibly making debris flows even larger and more frequent than in the past (Stoffel et al., 2014). Moreover, the variations in the rainfall regimes (Blöschl et al., 2019; Tramblay et al., 2020) have led to new regions being affected by intense rainfall events (Martel et al., 2021; Wasko et al., 2021) and possibly to both heavy bed load transport and debris flows. This condition makes the study of underground channels and culverts susceptible to debris flows more and more relevant. Despite this fact, the topic is scarcely faced in the literature (see, e.g., Molinas et al., 2001; Paik & Park, 2011; Zhong et al., 2021). Moreover, the modelling approach implemented in these works is based on a 1D mono-phase description unsuitable for reproducing deposition processes in cases of stony-type debris flows.

A significant case of culverted stream clogging occurred in Abbadia San Salvatore (Mt. Amiata, Italy) on 27-28 July 2019: a very intense rainfall caused a rapid increase in the water discharge in the Risola creek, which, in turn, produced intense erosions along the stretch just upstream the urban area, where the creek enters an underground concrete culvert. From a mechanical point of view, given the loose debris involved in the flow, the slope of the stretch (~7.5°), and the estimated water discharge (Amaddii et al., 2022), the transport phenomenon that occurred in 2019 can be classified as an immature stony debris flow (Takahashi, 2007). During this event, the transported debris clogged the culvert entrance, diverting the debris flow into the village and causing damage to buildings and infrastructures. Following Amaddii et al. (2022), the size of the solid phase ranged from a few millimetres (sand and gravel) up to boulders with an average diameter of 20 cm and, in some cases, of the order of one meter. The same Authors presented a back-analysis of this event: by integrating advanced models with an innovative approach to evaluating the clogging time, they were able to accurately reproduce the event in terms of debris volume, erosion rates, deposition area, and timing of the obstruction (see the original paper for further details).

This paper aims to verify, using a 2D debris flow model and some of the results of the above-cited study, the effectiveness and the susceptibility to clogging of the new culvert entrance built after the 2019 event. Two scenarios are analysed: the former consists of the sole culvert and the latter considers an additional protection structure consisting of an open check dam placed before the entrance of the culverted stream. Finally, based on the outcomes of this case study, we draw some general observations that can be useful in a more general design context.

STUDY AREA

The study area is located close to the Abbadia San Salvatore town, within the mountainous Risola catchment (Mt. Amiata, Central Italy; Fig. 1a). The urban area of the town and its hydrographic network were influenced during the 20th century by cinnabar extraction activities to produce mercury. Indeed, both mining activities and urban development led to the realisation of several culverted streams, including the one we are interested in.

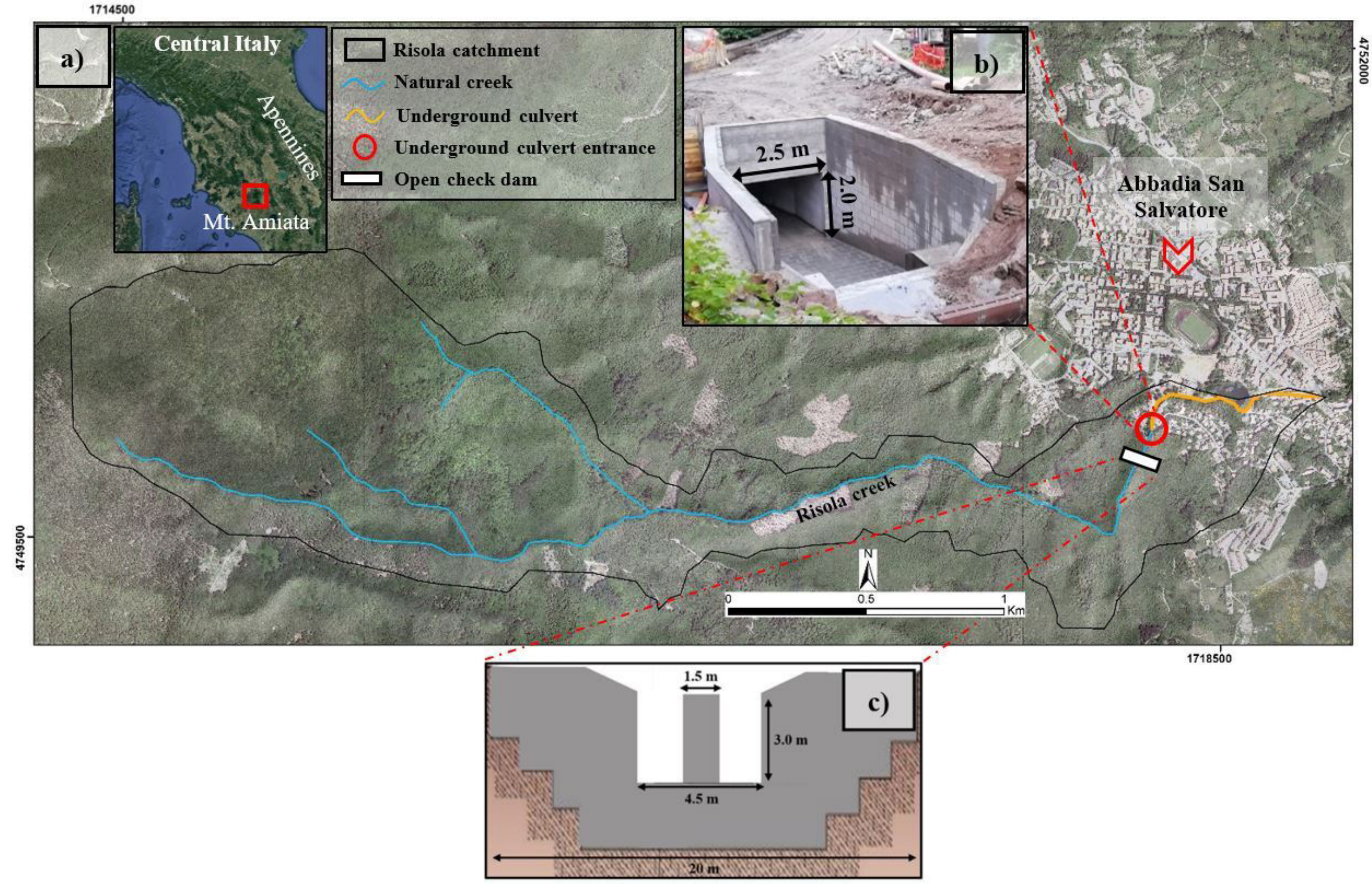

Fig. 1 - a) The Risola catchment on the eastern slope of the Mt. Amiata area (central Italy), and the entrance (red circle) and the path of the underground culvert (orange line); b) the new culvert realised after the 2019 debris flow event preceded by the sediment retention basin; c) the designed open check dam.

A new entrance to the underground culvert under-considered in this study (red circle in Fig. 1a) was realised after the 27-28 July 2019 event. This concrete structure (Fig. 1b) has a rectangular cross-section measuring 2.5 m width × 2.0 m height and a constant slope of ~0.06 m/m along the initial stretch. A sediment retention basin (Fig. 1b) of a few tens of cubic meters in size was also realised before the culvert entrance.

The realisation of a concrete open check dam (approximately 20 m width × 3 m height) about 100 m upstream the underground culvert was also hypothesized (white box in Fig. 1a) in a preliminary study performed by the local administration. The structure includes a central pile with a diameter of 1.5 m and two side openings of 1.5 m each (Fig. 1c). In the planned location, a wider section and gentle slope characterise the stream compared to the surrounding stretches.

Geological and Geomorphological Framework

The Risola catchment occupies a narrow NW-SE trending elongated area of 2.5 km² on the eastern slope of the Mt. Amiata extinct volcano. The geological framework (Fig. 2a) results from the Apennines mountain range Tertiary evolution and later post-collisional events, which led to the development of the Pleistocene Mt. Amiata volcanic complex (Marroni et al., 2015). The Risola creek (hereafter Risola), with an average slope of 0.1 m/m, mostly flows within the Quaranta Formation, except for the upstream portion, where the Bellaria Formation crops out, describing a radial pattern typical of volcanic environments. However, two main tectonic lineaments, oriented SW-NE and NW-SE (Fig. 2a), modify the general hydrographic network geometry (Brogi, 2008; Amaddii et al., 2022), causing an abrupt change of the course direction along the lower stretch of the Risola (Fig. 1a) at about 900 m a.s.l. Upstream to this area, along a gentle slope stretch of approximately

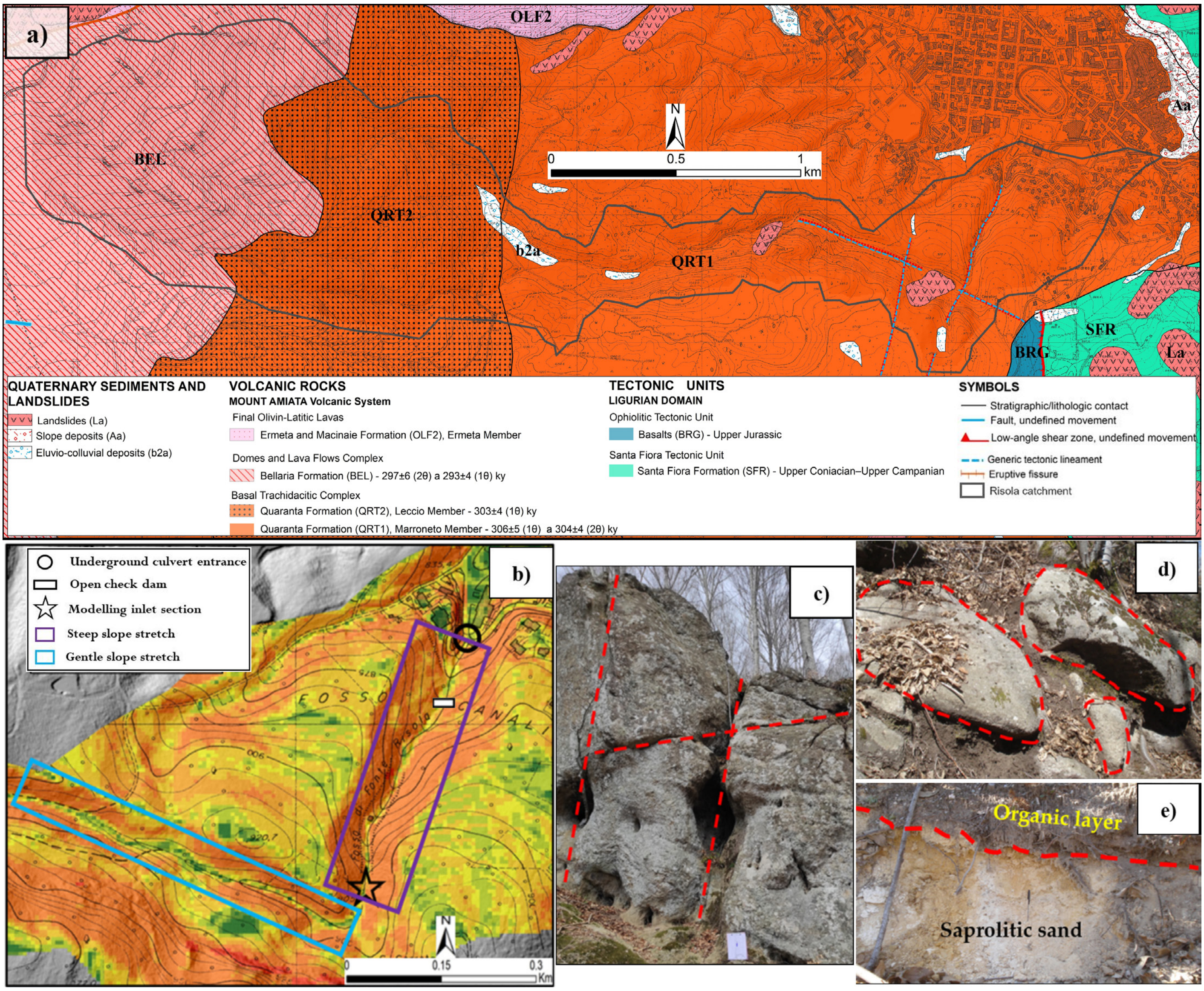

Fig. 2 - a) Geological map of the Risola catchment area (from Amaddii et al., 2022); b) Slope map of the lower portion of the Risola catchment showing the gentle (light blue area) and steep (purple area) stretches. The purple rectangle corresponds to the stretch where the debris flow generates and coincides with the computational domain of the simulation performed with the TRENT2D model. c), d) and e) different weathering degrees of the volcanic bedrock in the Risola catchment: fractured bedrock, corestones, and saprolitic sand, respectively.

500 m length, deposition of coarse loose material occurs (light blue polygon in Fig. 2b). Here, the average slope of the Risola is about 0.04 m/m, which reduces to 0.01 m/m in the area near the change of direction. Instead, the lower portion of the creek until the entrance of the culvert is steeper, with an average slope of 0.13 m/m (purple polygon in Fig. 2b). The above-described tectonic lineaments and the weathering degree of the volcanic rocks influence these slope variations. Indeed, the rocks outcropping in the study area are affected by widespread saprolite weathering processes (Certini et al., 2006; Principe et al., 2017; Principe et al., 2021; D'Addario et al., 2023) of spatially variable intensity, particularly marked in the case of the Quaranta Formation: fractured bedrock, residual rock blocks (corestones), and saprolite sand (Fig. 2c-e). The dominance of the last two weathering types along the Risola (Amaddii et al., 2022) allows us to classify the catchment at unlimited solid supply (Bovis & Jakob, 1999). The high weathering degree of volcanic rocks results in a quite gentle morphology of the Risola catchment, with an average slope of 16°. Moreover, the widespread occurrence of loose debris within the riverbed and the high steepness of the last stretch before the culvert entrance trigger intense erosion phenomena during heavy rainfalls.

METHODS

The study of the effectiveness of the new culvert entrance and its susceptibility to clogging is performed through numerical simulations. The chosen model is the TRENT2D (Armanini et al., 2009; Rosatti & Begnudelli, 2013; Rosatti & Zugliani, 2015), a two-dimensional two-phase depth-averaged debris flow model which can deal with a mixture flowing over both a mobile bed (under this condition both erosions and depositions may occur) and a fixed bed (in this case, depositions may occur while possible erosions are allowed only up to the elevation of the fixed bed surface). The simulations are managed with the WEEZARD system (Rosatti et al., 2018). This Web-GIS integrated system makes handling all the data and processes required to create, run, and analyse a simulation with TRENT2D easy. We refer the reader to the cited papers for more details.

Computational Domain, Initial Conditions and Model Parameters

The computational domain is defined within the purple rectangle in Fig. 2b and is composed of square cells of size 0.5 m. As initial conditions, the elevation of each cell was obtained, through the WEEZARD system, by using an available DTM based on a LiDAR acquisition (https://www502.regione.toscana.it/geoscopio/cartoteca.html) with a square cell of size 1 m. To properly represent the culvert width (Fig. 1b), this DTM was resampled (using the Resample tool in ArcGIS 10.7TM) to a square cell size of 0.5 m. Thereby, the width of the underground culvert is represented by using five cells, namely with a width of 2.5 m. In addition, as in Amaddii et al. (2022), since the base of the culvert is 2.5 m below the road level, the resampled DTM was lowered by 2.5 m along the path of the culvert. Through this procedure, the closed channel is transformed into a representative open one that can be managed with the WEEZARD system. Following a similar procedure, the sediment retention basin (~10 m × 4 m) located before the culvert entrance (Fig. 1b) was integrated into the DTM too.

As for the bed type, all the computational domain was considered to be mobile, except for those areas where non-erodible structures occur (such as the culverted channel, the retention basin, and the open check dam) or unweathered bedrock crops out (see Amaddii et al. 2022 for the detailed location of these features). In order to include the open check dam in the simulation, we also integrated into the DTM the non-erodible structure depicted in Fig. 1c.

Finally, TRENT2D requires the definition of some parameters that appear in the closure relations used in the model, namely the bed shear stress and concentration formulae (see Armanini et al., 2009 for details). Their values, calibrated in Amaddii et al. (2022), are reported in Tab.1.

Boundary Conditions

The model requires a liquid and solid hydrograph as an upstream boundary condition. The relevant flow rates are applied to the inlet section of the calculation domain (starred section in Fig. 2b). The liquid contribution is derived from a rainfall-runoff model (Amaddii et al., 2022). In contrast, the solid contribution is calculated by assuming a uniform flow condition representative of the flow condition upstream of the inlet section.

Commonly, the protection works are designed considering a forcing rainfall event with a return period of 200 years. For the Risola catchment, the rainfall intensity with a return period of 200 years was obtained by averaging the values provided by the rainfall Intensity Duration Frequency of the three closest rain gauges (TOS11000114, TOS11000115, and TOS0700000, source http://www.sir.toscana.it), and the resulting value is 68 mm/h. Instead, the most intense hourly rainfall phase that occurred during the 27-28 July 2019 rainfall event was characterised by an intensity of 134.5 mm/h, which is about twice the value of the 200-year return period (and also greater than the 500-year value, equal to 75 mm/h). Therefore, given the objectives of this work, we considered it more appropriate to use the hydrograph associated with the most intense phase of the 2019 event (which occurred around 23:30, as reconstructed by Amaddii et al., 2022) instead of that associated with a 200-year return period. The solid discharge at each instant

Table 1 - TRENT2D input parameters for the debris flow (values from Amaddii et al., 2022).

Description	Symbol (unit measure)	Value
DTM square cell size	Δx (m)	0.5
Dynamic friction angle	φ_d (°)	38
Sediment bed concentration	c_b (-)	0.65
Reduced relative sediment density	Δ (-)	1.65
Submergence	Y (-)	5
Slope upstream the inflow section	i_f (m/m)	0.03
Transport parameter	β (-)	$9.78 \cdot 10^{-3}$

was evaluated from the liquid hydrograph and considering the transport capacity in uniform flow conditions relevant to the stretch upstream of the computational domain. Because of the low steepness (0.01 m/m at the sudden change of stream direction), the resulting concentrations are low and related to a bedload transport mechanism. Fig. 3 shows the resulting solid, liquid, and mixture hydrographs.

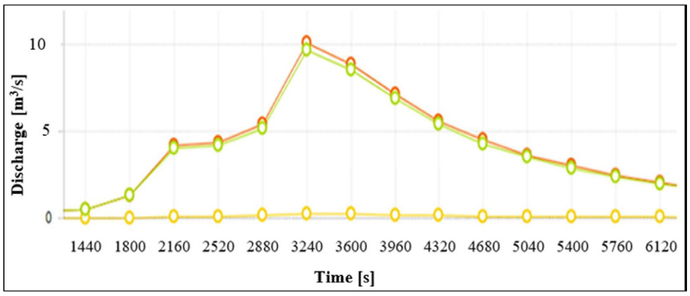

Fig. 3 - The upstream boundary condition for the numerical simulations: mixture (orange), liquid (green), and solid (yellow) hydrographs (Amaddii et al., 2022).

RESULTS

The results of the simulations show that the debris flow that can be generated in the Risola with the assumed liquid forcing can erode and mobilise a debris volume of about 3,000 m³. The differences between the two scenarios are analysed hereafter considering the final bed variation maps (difference between the final and initial bed elevations) and the free-surface maximum elevation change along the longitudinal section (20 m) of the Risola straddling the entrance of the culvert.

As for the first scenario (Fig. 4a), along the simulated stretch, initially, deposition prevails in the centre of the section, with thickness ranging from 0.5 m to 1.0 m, while erosion affects the banks. Further downstream, erosion dominates throughout the section, and this is the area where the debris flow develops. Deposition prevails in the terminal section at the beginning of the culvert. Fig. 4c presents the section relevant to this scenario when the free surface elevation reaches the maximum value. The deposition height at the channel entrance is more than 1 m, while the flow depth is around 0.8 m. Considering the free-surface elevation of the mixture (blue line), it can be noticed that the flow apparently can pass through the culvert section but with a minimal free span, resulting in a high probability of clogging.

The second scenario (Fig. 4b) provides a more interesting result. The open check dam produces a significant final deposit, up to 2 m high, immediately upstream of it, and the relevant retained volume is about 20% of that mobilised during the event. The effect of the lamination of the debris flow peak (and in particular of the solid phase) can be noticed at the entrance of the culvert (Fig. 4d) where, at the instant of maximum free-surface elevation, the deposit height is about 0.5 m, while the flow depth is 0.6 m. Overall, this scenario provides a more significant safety factor than the previous one, resulting in a free span larger than the order of magnitude of the diameter of the largest transported debris material.

DISCUSSION

Checking that the maximum elevation of the free surface is lower than the culvert ceiling elevation (i.e., there is no pressurised flow) is not sufficient to verify the effectiveness of a culverted stream affected by debris flow. Indeed, numerical simulations provide estimates of averaged values of the variables while, in reality, these values fluctuate, for example, due to the passage of a single boulder. We can infer that the transported debris can clog the section before the simulated flow elevation touches the ceiling. A systematic study, both from an experimental and theoretical point of view, of the transition from a working condition to a clogged state of a culvert and the relevant condition of occurrence, as well as their numerical modelling using 2D mobile bed models, to the best of our knowledge, is still missing in the literature. In the meantime, one reasonable criterion for ensuring the operation of a culverted channel may be checking that a significant free span, with an order of magnitude equal to the diameter of the largest transported debris material, is available in case of a very intense event. Considering both this criterion and the results shown in the previous section, clogging is highly probable in the first scenario, while it is less likely to occur in the second one, for two reasons: (a) the maximum free surface elevation is significantly as the check dam allows reducing the deposition at the entrance of the culvert; (b) the size of the transported debris near the entrance of the culvert, is smaller than in the first case, as the check dam allows for grain-size selection. We are still unable to quantify the safety factor (here defined as the free span compared to the diameter of the largest transported debris material) of each scenario but for this case study their difference is quite clear.

Besides the above scenarios, other configurations could be considered as well. For example, as the debris flow generates in the very last stretch before the culvert entrance, this reach could be transformed into a stone-lined ditch. However, this solution has the drawback of compromising the naturalness of the watercourse, nowadays a matter of increasing importance in the scientific and civil community. A possible additional alternative would be to use a check dam to laminate the flood wave upstream of the stretch. In this way, the water would have less erosion capacity, thereby mobilising a smaller volume of debris. However, selecting the most appropriate mitigation measures also entails an economic analysis which is beyond the scope of this paper.

The magnitude of the rainfall to be chosen as liquid forcing in analysing the susceptibility to clogging of a culverted channel is a further relevant issue. This is commonly estimated using the rainfall Intensity Duration Frequency curve for a given return period. Nevertheless, in the present case, it is worth considering the following points: (a) in the context of climate change, these curves may no longer be reliable, possibly providing underestimates that can negatively affect the assessment; (b) advanced hydrological approaches capable of addressing this problem, to the best of our knowledge, are still not available; (c) clogging generates a sudden

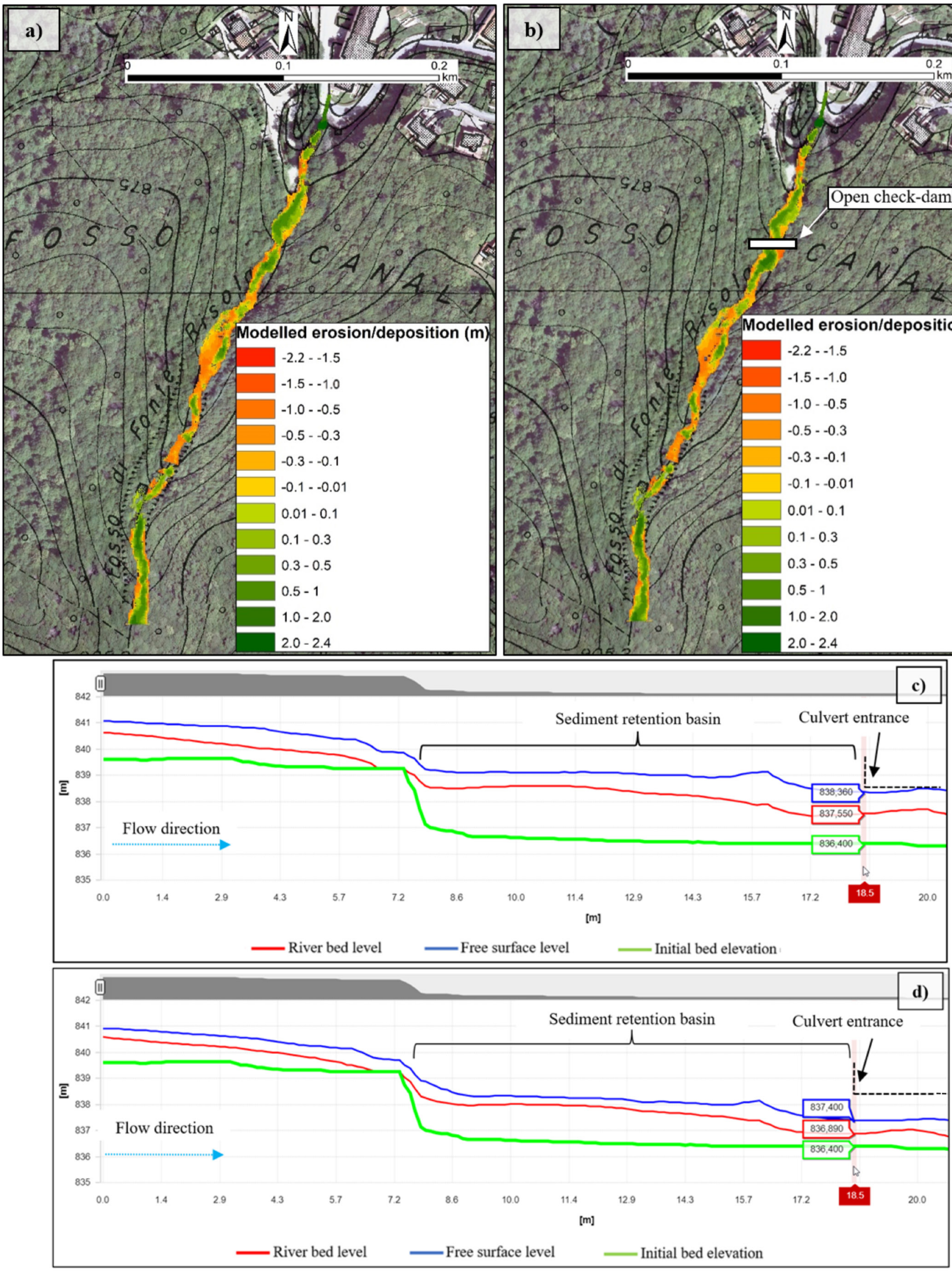

Fig. 4 - Results of the debris flow modelling using the WEEZARD system. Maps of final erosion and deposition areas considering the two scenarios: first scenario (a) with the new culvert, and second scenario (b) with the new culvert plus a possible open check dam (b). Longitudinal sections of the stretch straddling the entrance of the culvert at the instant of free-surface maximum elevation for both scenarios, i.e., (c) and (d), respectively. The y-axis represents an elevation (expressed in m a.s.l.), while the x-axis represents the planimetric distance from a reference section.

and somewhat unpredictable increase in hazard; (d) considerable uncertainties still exist in the description of the whole process. We think that a reasonable and practical way to get rid of these issues is to use a return period much larger than the values commonly used in designing these kinds of hydraulic structures (e.g., 1,000 years) or, as in the present case, to use a forcing associated to a very large registered event. More defined specifications are desirable, but they require further investigation to be expected in the future.

The last issue we want to stress is that the clogging susceptibility (Fig. 4c,d) depends on the grain size and shape of deposits more than the flow depth. Indeed, considering only this last parameter, in mono-phase models, both scenarios would show a sufficient free span. It is, therefore, clear why we have repeatedly emphasised that it is fundamental to use a numerical model, such as TRENT2D, able to simulate accurately the deposition process near the entrance of a culverted stream.

CONCLUSIONS

The modelling of stony debris flows involving culverted streams, as in the Abbadia San Salvatore case analysed in this study, despite its relevance, is a challenging task that has not yet been addressed in depth in the literature. The possible clogging of the entrance section of these hydraulic works requires careful consideration of several issues, the most important of which are: (a) the use of a numerical model able to cope with significant bed aggradation; (b) the definition of a condition that offers reasonable safety margin against clogging; (c) the definition of a suitable forcing hydrograph.

The implementation of two scenarios concerning the Risola provided reasonable answers to the questions arising from the case under study. Moreover, it also allowed us to get some general hints on the topic:

- using a two-phase debris flow model such as the TRENT2D seems to be adequate to face the basic mechanism leading to clogging. Nevertheless, the use of advanced numerical models must be supported by an accurate knowledge of the spatial distribution of the geo-engineering properties of both the bedrock and the overlying loose deposits affected by the debris flow;
- the safety factor we have introduced (i.e., a free span of the order of magnitude of the diameter of the largest transported debris material) is reasonable, but it requires to be confirmed through laboratory research;
- the use of rainfall forcing with return periods much longer than the values usually considered for hydraulic works should be large enough to manage the uncertainty linked to the entire phenomenon, the model simplifications, and the effects of climate change, as well as to manage the safety requirements against a sudden and non-progressive event.

There is still much work to be done on the numerical modelling of stony debris flows involving culverted streams, but we are confident that the contribution made by this work will be a good impulse for future research.

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