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SPATIOTEMPORAL DATA MANAGEMENT OF RECURRENT DEBRIS FLOW EVENTS USING OBJECT-ORIENTED DATA MODELLING

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EXTENDED ABSTRACT

Il presente lavoro è focalizzato sulla gestione “object-oriented” dei dati spaziotemporali relativi ad eventi ricorrenti di colate detritiche che si sviluppano lungo tutti i canaloni che incidono il fronte settentrionale del monte Bulgheria (Geoparco del Cilento, Italia meridionale). In particolare, l’area di studio è costituita da due canaloni principali: il vallone del Moio e Valle della Noce che, in tempi recenti (2015-2018), sono stati interessati da fenomeni di flusso detritico a diversa concentrazione, analoghi a quelli di maggiore magnitudo registrati dalle cronache storiche.

Tali fenomeni costituiscono un fattore di rischio sia per i centri abitati del comune di Celle di Bulgheria, nonché per le principali vie di comunicazione locali. L’assetto strutturale principale del fronte montagnoso è caratterizzato dalla sovrapposizione tettonica tipo piega-faglia delle unità carbonatiche meso-cenozoiche, ridenominate “sub-unità tettonica Bulgheria in Graziano *et alii* (2016) sia sulle formazioni silico-clastiche mioceniche della medesima sub-unità che su quelle bacinali oligo-mioceniche delle Unità Interne (Cammarosano *et alii*, 2004). L’attuale assetto morfologico del versante montuoso è fortemente controllato dall’assetto strutturale sopra descritto, con pareti di interfluvio sub-verticali e profondi canaloni ad alta pendenza. La zona sommitale è caratterizzata da una singolare conformazione a crinali longitudinali sdoppiati, tra i quali sono presenti vallecole colmate da spessori anche decametrici di depositi eluvio-colluviali con matrice piroclastica cineritica alterata, alla cui terminazione inferiore si innestano le testate dei canaloni sopra citati, a forte tendenza retrogressiva (Guida *et alii*, 1989). È proprio da queste vallecole che derivano le frazioni fini dei flussi detritici che, amplificandosi di materiale grossolano lungo i canaloni, raggiungono il piedimonte in forma di ricorrenti colate detritiche e flussi iperconcentrati.

La successione degli eventi è stata ricostruita tramite la consultazione di cronache storiche ed inventari preesistenti, l’analisi di immagini ottiche, sia aeree che satellitari, ed attività di rilevamento diretto a seguito dell’occorrenza dei principali eventi. L’evento di flusso più antico registrato risale al 1878. Esso è stato caratterizzato dall’intensità maggiore ad oggi registrata con danni agli insediamenti ed alle persone. Ulteriori eventi si sono succeduti nell’ultimo secolo, in particolare crolli permanenti dalle pareti più alte e dai fianchi vallivi che hanno progressivamente contribuito al riempimento dei canaloni, successivamente svuotati, in un ciclo filling-discharging-refilling (Guida, 2003). Due episodi di flusso ricostruiti da rapporti di evento si sono verificati tra gli anni ‘80 e ’90, fino ad arrivare all’ultimo decennio, durante il quale si è riscontrata la frequenza più elevata di colate detritiche, a magnitudo crescente.

L’inventario è stato riformulato seguendo lo schema logico e procedurale orientato agli oggetti, denominato LOOM (Landslide Object-Oriented Model, Valiante *et alii*, 2021), in modo da consentire una strutturazione informatica spaziotemporale dei dati e di gestione “ad eventi” delle informazioni utili alle valutazioni di pericolosità e rischio da questi fenomeni ad alta intensità. Nel caso considerato, a partire dalle colate detritiche inventariate, un unico complesso di colate di terra granulare è stato generato; ciò dimostra come il concetto di “complesso di frane” racchiuda sia una connotazione spaziale, di sovrapposizione/sostituzione di una stessa tipologia di fenomeno, sia una connotazione temporale di ricorrenza e ripetitività dello stesso nel medesimo ambito morfologico. Come per i flussi detritici, lo stesso vale per i crolli avvenuti lungo le pareti dei canaloni. L’ordinamento temporale dei diversi tipi di fenomeno, unitamente alla loro sovrapposizione spaziale, conferisce, invece, al concetto di “sistema di frane” il ruolo di scenario dominante dell’evoluzione gravitativa di un versante/fronte montuoso.

Nel caso di studio esaminato emerge la ciclicità nell’attività gravitativa lungo i canali. Il sistema di gestione dei dati illustrato consente di superare sia il tradizionale concetto di “inventario”, che quello di “attività”, suggerendo la introduzione di un nuovo concetto di gestione del dato e delle informazioni inerenti all’intera storia gravitativa ricostruita in termini contemporaneamente diatopici e diacronici e proponendo il neologismo “eventario”, quale base di discussione nell’ambito delle discipline di settore.

ABSTRACT

This work is focused on the study of recurrent debris flow events on the north-facing mountain slope of the Bulgheria massif (Cilento Unesco Geopark, southern Italy). These phenomena pose a threat for at least two villages and infrastructures on the lower slope. The main morpho-structure of the mountain slope is strongly controlled by the tectonic overlapping in form of multiple thrust-folding of the Meso-Cenozoic limestone related to the inner margin of the Apennine Carbonate Platform over lower-middle Miocene marly-clay flysch and previously overthrusted basinal units ranging from upper Oligocene to lower Miocene. Therefore, the mountain slope is sculpted by erosional deep incided ravines and sub-structural interfluve cliffed slopes passing downslope to depositional piedmont by evident and abrupt knick-point. Channels along the slope are periodically filled both through rock fall deposits occurring on channel's flanks and by soil creep and sheet wash phenomena at channel's heads, which supply new material for future flows. Such relationship between infilling rock fall phenomena and debris flows represents an interesting case study of interaction among different and concurrent landslide types providing an optimal example of space-time evolving landslide system. Landslide classes have been stored and mapped using a previously proposed object-oriented and event-based model and producing in this way a multi-temporal database. Landslide objects have been grouped into landslide subclasses using the latest landslide classification available. In the next step, a hierarchical classification has been applied, introducing two levels of aggregation and one level of decomposition. Landslide complexes group landslide objects of the same class sharing spatial connection, defining rock fall complex objects and granular soil wet flow complex objects. Landslide systems group all the interacting landslides, regardless of their type. Landslide components describe the various portions of a single landslide object. Every stored object has its temporal attributes distinguishing between time points (events) and time intervals (time frames). The integration of complex spatial relations through topological analysis and temporal characterization of data allows to build a flexible database structure adaptable to several specific needs and different outputs, such as basic landslide maps or event maps, multi-temporal and frequency analyses, or the study of the interactions among different types of landslide hazards. In this framework, a neologism could be introduced in landslide studies, as landslide eventory mapping, as a challenge for future applications.

Keywords: *landslide object-oriented model, landslide complex, landslide system, Bulgheria mountain, Cilento Geopark, Southern Italy*

INTRODUCTION

In the field of geohazards, debris flow phenomena are one of the most dangerous landslide types, posing major threats to human lives and their related settlements, infrastructures, and activities (Bovis & Jacob, 1999; Perov *et alii, 2017;* Naidu *et alii, 2018;* Cascini *et alii, 2019;* Kean *et alii*, 2019). Producing a data structure and mapping capable of storing temporal occurrence and recurrence of debris flows and their spatial relations with other landslide types could be a useful tool to better improve landslide hazard assessment and mitigation at different scales.

Recently, a landslide object-oriented method (LOOM) has been proposed by the authors (Valiante *et alii*, 2021) in order to tentatively overcome a few limitations in the traditional landslide data model procedures. Please refer to this work for a more in-depth examination of the comparative analysis of existing methodologies.

In fact, the aim of this paper is to describe how we can manage dataset from recorded or surveyed recurrent landsliding events occurred along two steep ravines on the northern slope and piedmont of the Bulgheria Massif, uphill of the Celle di Bulgheria village (Campania region, Italy): the Moio and Valle Noce channels (Fig. 1). Along these channels several landsliding phenomena occurred in the last centuries, such as concurrent and delayed rock falls, debris flows, and shallow soil slips at channel heads, as reported in an un-published report by one of the authors (Guida, 2019), who was in charge to propose a design for risk mitigation. Historically recorded and observed phenomena have been inventoried using a hierarchical object-oriented approach, taking into account geological, geomorphic and climatic constraints, as illustrated in the following sections.

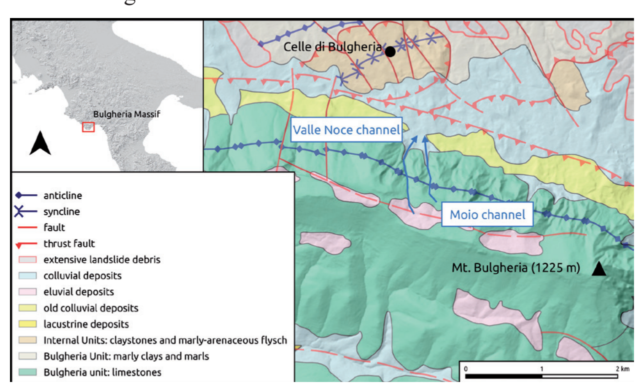

Fig. 1 - Location and geological settings of the study area (modified from ISPRA, 2014)

GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

The Bulgheria carbonatic massif is built up by a platform margin stratigraphic succession ranging from upper Trias to Miocene called Mt. Bulgheria tectonic sub-unit (D'Argenio *et alii*, 1973; Graziano *et alii,* 2016). Along the northern front of the Bulgheria Massif the younger formations of the tectonic unit crop out, and they are mainly composed of stratified calcarenites and calclutites, oolitic calcarenites and bioclastic calcrudites. The youngest formation of Mt. Bulgheria tectonic sub-unit cropping out in the study area is a marly-calcareous and clayey flysch. Previous formations tectonically overlap terrigenous formations belonging to the so-called Internal Units (Bonardi *et alii*, 1988; Cammarosano *et alii,* 2004). From a structural perspective, the Bulgheria Massif is made up by an asymmetrical overturned fold and a complex overlapping structure which includes reverse faults and fault propagation folds, overlapping the carbonatic succession over the terrigenous flysch deposits (Guida *et alii,* 1989). At the foot of the entire mountain front, extensive coarse deposits can be found as partially cemented calcareous breccias or loose debris (Fig. 1).

The northern hillslope of the Bulgheria Massif has experienced an initial evolution following a slope replacement model, exploiting structural features such as bedding and fault planes (Guida *et alii,* 1989). Such evolution produced the actual morphology characterized by steep rocky cliffs on the upper section of the relief, and a less sloping lower section produced by the accumulation of detritical materials. Along the main ridge, longitudinal valleys can be found as hollows, often filled with pyroclastic and residual soils. All of the mountain front is nowadays carved by straight channels having different incision rate, producing a series of debris fans at the footslope, such as the Moio and Valle Noce channels, on which this study is focused.

EVENTS HISTORY

The events history has been reconstructed through the analysis of pre-existing available inventories (ex-Left Sele River Basin Authority, now Southern Apennines Hydrographic District, 2012 - PSAI), satellite and aerial photointerpretation and original data collected during field surveys.

The oldest reported event dates back to September 25, 1878 as it is stated in the PSAI inventory. This is the event with the highest volume of displaced material, and it was originally inventoried using archive material from the involved municipality. This event is well known in the local history and related documents as "Acqua della Montagna" (Lit. "Mountain's water"), luckily no casualties were registered.

Another smaller event is reported on the October 7 of the previous year, but unfortunately, the available information is not enough to properly insert a record in the inventory. Other flow events have been registered in the second half of 1900, and the most recent events occurred in 2001, 2015, 2017 and 2018. Flows occurred on September 5, 2001 can be related to an extreme rainfall event following the dry season, which triggered several flows along the entire mountain front including also the channels object of this study (Fig. 2a). On September 24, 2015 several debris flows were triggered again by a heavy rainfall, damaging public and private properties. During this event, most of the debris flows evolved in debris flood -like phenomena exploiting existing roads as preferential flow paths (Fig. 2b, c). The next event involving the Moio channel occurred on November 11, 2017 causing also damages to agricultural activities (Fig. 2d). The latest recorded event occurred on August 20, 2018. In this case, floods originated from the debris fan reached the Celle di Bulgheria village flowing along local roads (Fig. 2e, f).

Survey activities performed after the latest events (2001, 2015, 2017, 2018) highlighted heterometric limestone boulders deposits along the channels produced by the recurrent accumulation of rock fall debris occurring on channel's flanks (Fig. 2d, f). Such rock falls have been inventoried by field surveys and through the analysis of optical images, both aerial and satellite.

Within channel heads, shallow soil creep phenomena were observed, which, combined with diffusive erosion, concurred to the accumulation of loose material at the hollow's bottoms.

BUILDING OF THE LANDSLIDE DATABASE

The inventory database has been built using the LOOM data structure (Valiante *et alii,* 2021). Such data structure is composed of hierarchical levels organized following an object-oriented paradigm (Hegenhofer & Frank, 1992) and the focal level of this hierarchy contains landslide objects. Focal objects result from the aggregation of landslide components such as detachment areas, channels, debris, etc., so that every landslide object is represented by a single aerial geometric feature (polygons). At the focal level, the landslide class is specialized into 21 sub-classes based on the main type of movement (Hungr *et alii,* 2014). Referring to the landslide types analysed in this work, movements classified primarily as debris flow are instances of the *granular soil wet flow* class, while rock falls are instances of the *rock fall* class.

Starting from the focal level of the hierarchy, two levels of aggregation store landslide complex objects and landslide system objects. The landslide complex class derives from the generalization of 21 landslide complex sub-classes which are built from the aggregation of the 21 landslide sub-classes. The aggregation procedure to build a landslide complex object is triggered only if two or more landslide objects of the same type satisfy the relation of Functional Interaction defined in the LOOM data structure, so that a landslide complex can be defined as a set of landslides of the same type spatially overlapping. A further level of aggregation takes as input both landslide complex objects and landslide objects previously excluded from the aggregation, performing again the Functional Interaction check. In this level landslide system objects are generated, and they can be defined as a set of landslides spatially connected, regardless of their type.

Landslide objects are described also by temporal attributes in order to store and retrieve the temporal succession of the events. The temporal information is managed using temporal intervals (temporal frames) for temporally undetermined landslides, and

Fig. 2 - a) 2001 debris flow deposit; b) 2015 debris flow erosional features; c) 2015, filling deposit within the main channel; d) 2017, boulders along the channel; e) 2018, half-buried shelter; f) 2018, boulders along the channel (Photos by D. Guida)

temporal points (events) for landslides having an exact date of occurrence. Time frame's boundaries are derived both from known events and from time references of the exploited materials, such as images and other inventories. For the Moio and Valle Noce channels case study, the following events-time frames have been implemented:

1. Event - September 25, 1878
2. Time frame - Late 1878 - 1943
3. Time frame - 1944 - 1988
4. Time frame - 1989 - 1994
5. Time frame - 1995 - 2000
6. Time frame - January 1, 2001 - September 4, 2001
7. Event - September 5, 2001
8. Time frame - Late 2001 - 2006
9. Time frame - 2007 - 2012
10. Time frame - 2013 - September 23, 2015
11. Event - September 24, 2015
12. Time frame - Late 2015 - November 10, 2017
13. Event - November 11, 2017
14. Time frame - Late 2017 - August 19, 2018
15. Event - August 20, 2018
16. Time frame - after August 21, 2018

After the first described debris flow event occurred in the 1878, a few rock falls have been noticed in the images referred to time frames 2 and 3, and a debris flow has been inventoried within time frame3. During time frames 4 and 5 other falls have been inventoried and another flow has been reported which should have been occurred in 1996 in accordance with technical documentation from the local municipality. Within the successive time frames, other rock falls have been identified, noticeable in 2010 and 2015, before event 11. Minor falls have been also reported in the latest time frames. Soil creep phenomena have been identified after field surveys performed following events 11 and 15 (Fig. 3 to Fig. 11).

DISCUSSIONS

The LOOM data structure allows the management of complex spatial arrangements of landslides. Spatial overlapping between landslide objects has been handled through the evaluation of the topological relations between such features, categorizing those relations satisfying a Functional Interaction threshold and those which does not. This procedure leads to the simplification of the initial complex arrangement of objects through the hierarchical aggregation. From the first cycle of aggregation, landslide complex objects are generated. Regarding granular soil wet flow objects (debris flows), a single granular soil wet flow complex object has been generated (Fig. 12). In this case, the spatiotemporal connotation of a landslide complex object is exemplified: from a spatial point of view, within this landslide complex, phenomena occurring in two different channels are aggregated because of the overlapping

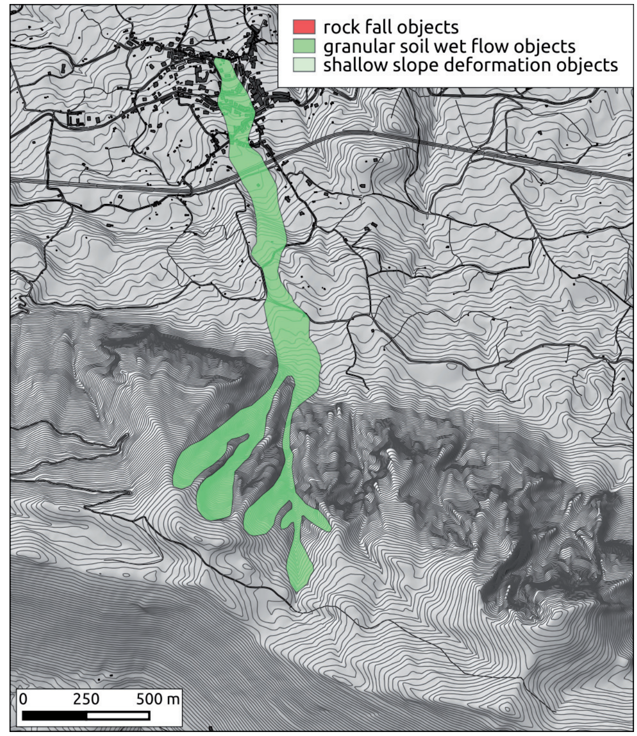

Fig. 3 - Event 1 - September 25, 1878

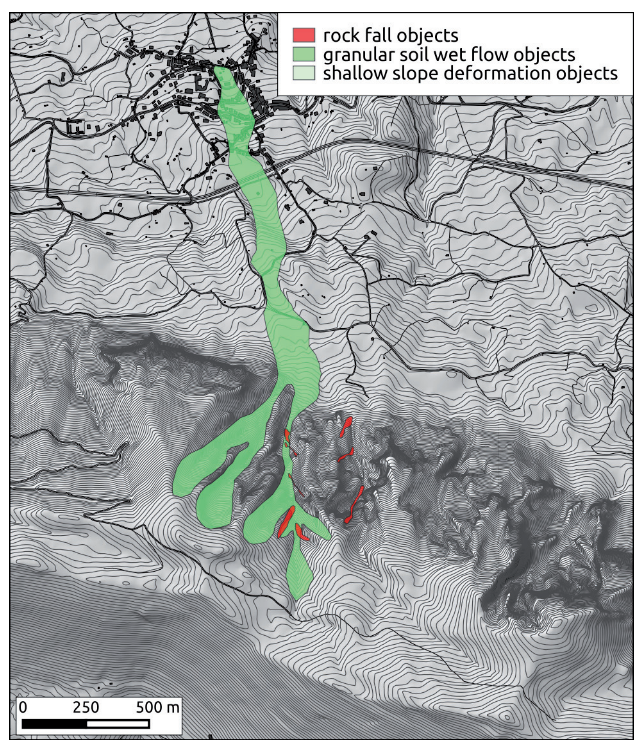

Fig. 4 - Time frames 2,3 - from late 1878 to 1988

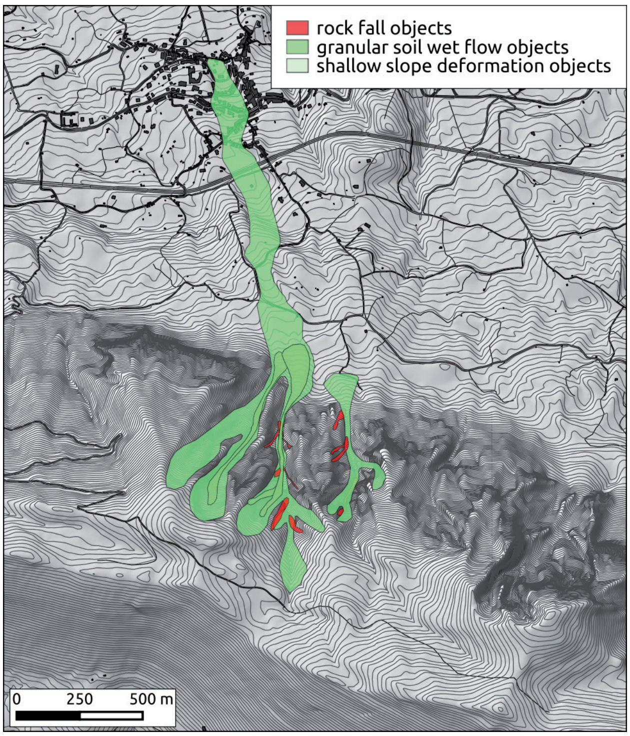

Fig. 5 - Time frame 4 - 1989 - 1994

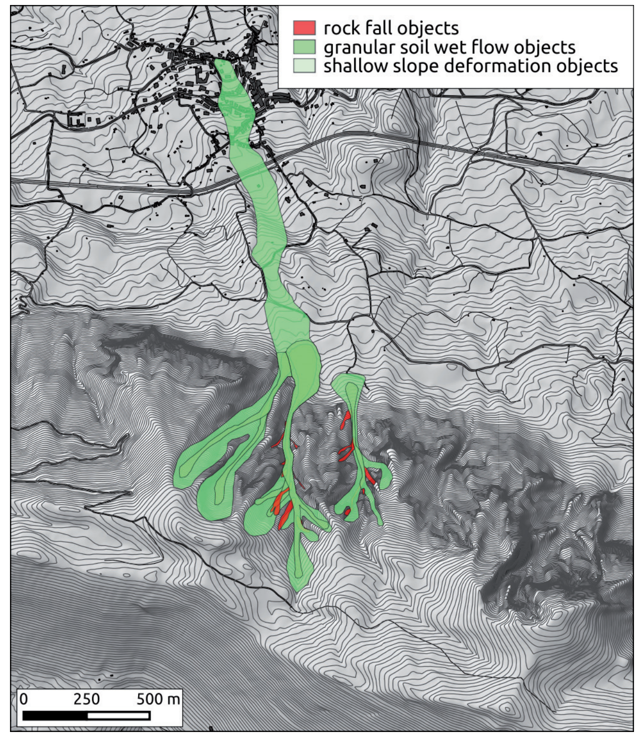

Fig. 7 - Time frame 6 - 2001 and event 7 - September 5, 2001

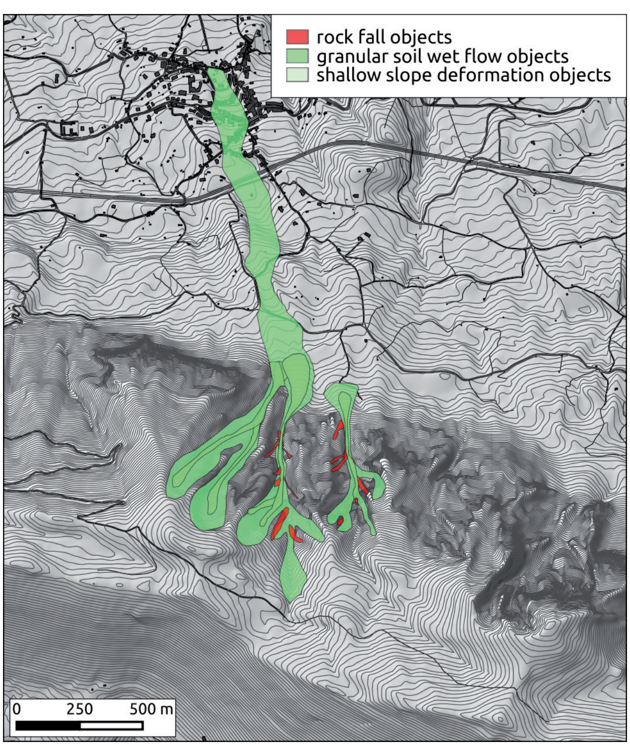

Fig. 6 - Time frame 5 - 1995 - 2000

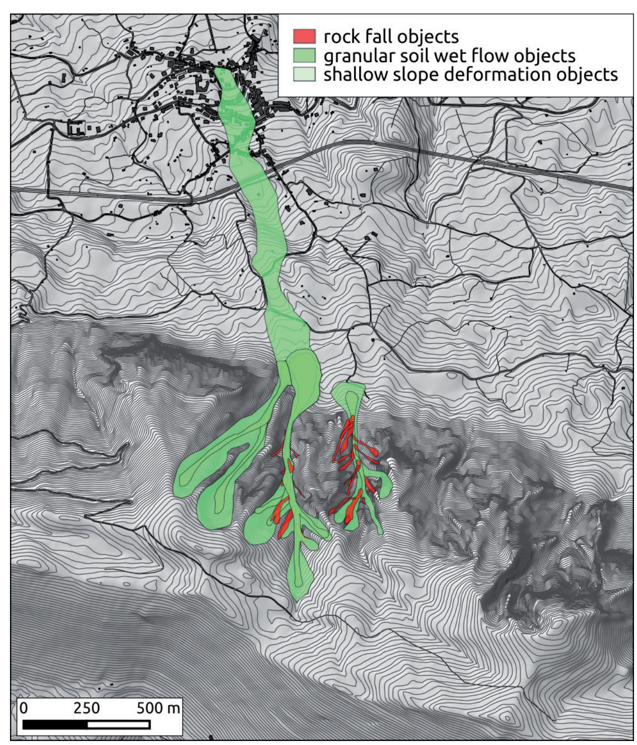

Fig. 8 - time frames 8, 9 and 10 - from late 2001 to 2015

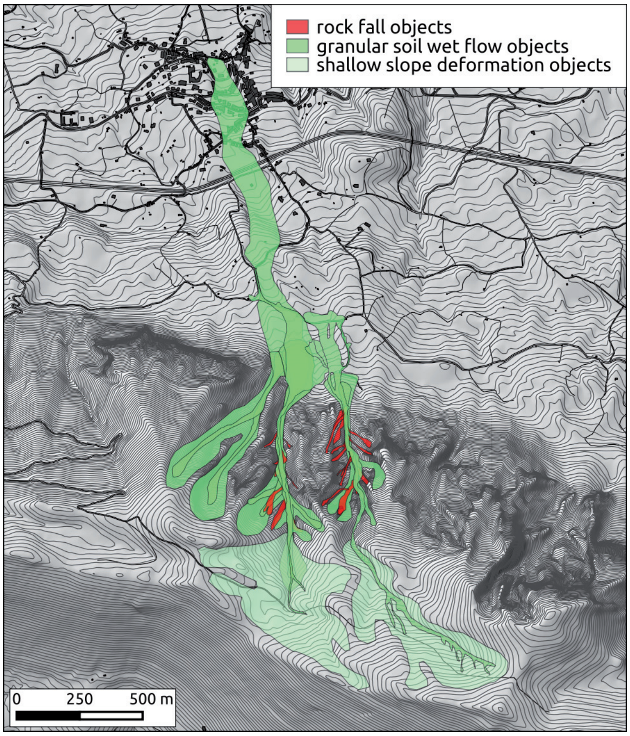

Fig. 9 - Event 11 - September 24, 2015

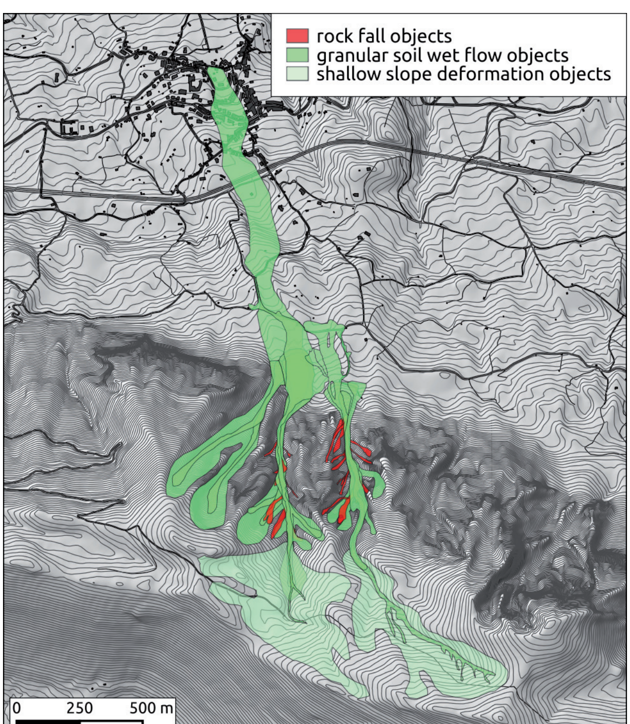

Fig. 10 - Event 13 - November 11, 2017

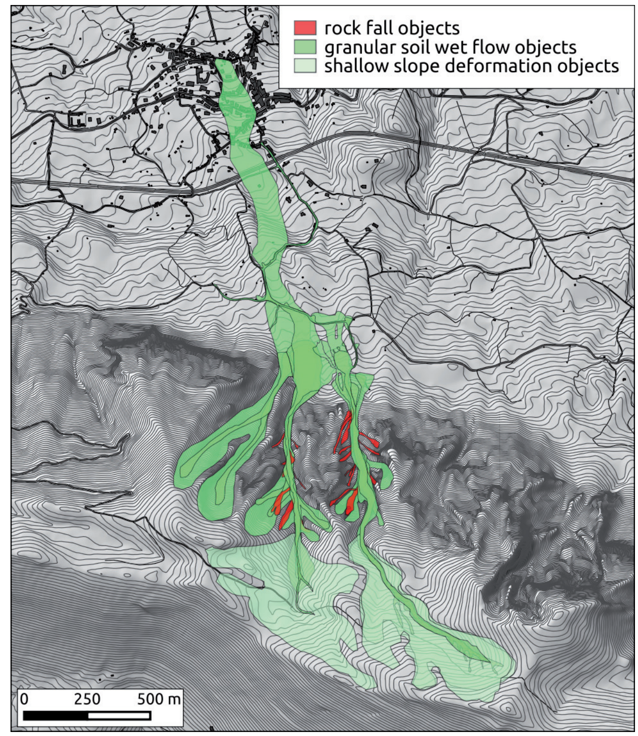

Fig. 11 - Event 15 - August 21, 2018

in the accumulation area, which in turn means that specific accumulation area is the result of those phenomena happening in two different basins intended as morphological units; from a temporal perspective instead, we have the aggregation of several events occurred in the same channel highlighting the repetitiveness of the phenomenon. These considerations hold true also for the various rock fall complex objects aggregated at this step, in fact, the presence of several rock fall complexes shows the periodical discharge of loose debris from channel's flanks to their bottom. At the top of the relief, a shallow slope deformation complex is produced from the enlargement of the soil creep affected area at the Moio channel's head over the years. The second aggregation step produced landslide system objects. In this case study, all of the landslide objects inventoried produced the aggregation of a single landslide system object (Fig. 13). Data-wise, a landslide system has been defined has a spatial overlap between different landslide typologies and that is indeed the basic concept which allows the automatic aggregation procedure. Nonetheless, in the spatiotemporal framework, the concept of landslide system also retains the temporal interaction between different kind of phenomena. In this perspective, the event succession encapsulated in the landslide system definition can be thought as a conceptual model of the gravitational evolution of the investigated geomorphological system. In our case study, we

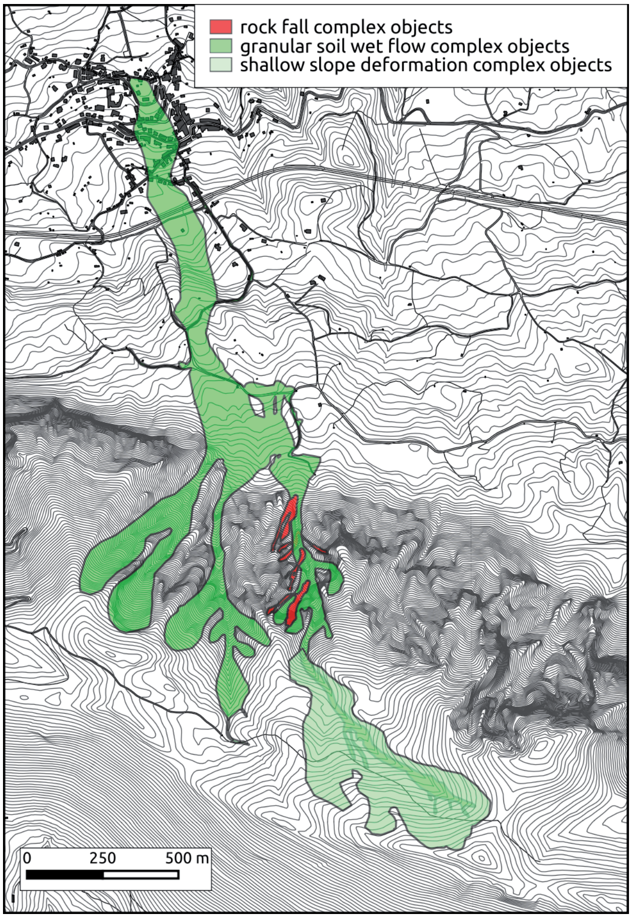

Fig. 12 - Landslide complex objects

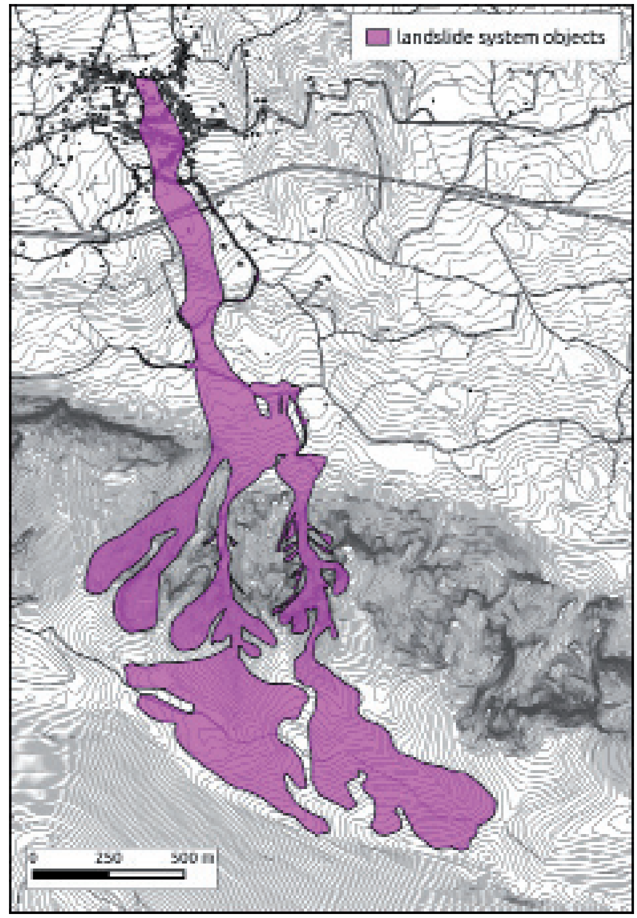

Fig. 13 - Landslide system objects

have slow shallow deformations accumulating loose material at the channel's head and rock falls supplying boulders and debris in the middle section of such channels. In turn, periodically these channels are emptied through impulsive phenomena such as the observed debris flows.

Temporal attributes technically allow the vertical sorting of the overlapping features for the visual representation. Moreover, the temporal sorting of the inventoried objects showed a discontinuous event distribution over the investigated time period. Besides the 1878 event, we have a few events between 1980 and 2001 and a cluster of events in the 2015-2018 time period. Such intermittent activity could be related to the evolution model discussed before for the landslide system, which could be described as a cyclic recurrence of "recharge" phases interrupted by impulsive events (Guida, 2003). Further efforts are needed in the study of this peculiar activity style and its conditioning factors. For instance, in the investigated area the rainfall contribution could be difficult to assess as it is characterized by extreme localized events, due to local orographic seeder-feeder effects (ROE, 2005, Cuomo *et alii,* 2011, Furcolo & Pelosi, 2018), as it was for the 2015 event (Fig. 14, Fig. 15).

CONCLUSIONS

In this study, a hierarchical object-oriented data model for landslides has been applied for the study of recurring debris flow events. Such model aims at preserving spatiotemporal relations between landslide objects for an optimal inventorying and representation of complex superimpositions of landslide events.

The application has been carried out along two channels on the northern front of the Bulgheria Massif (southern Italy). The hierarchical classification allowed to simplify all of the inventoried landslide objects into landslide complex objects and into one landslide system object. Landslide complex objects derive from the spatial overlap of landslides having the same type and its definition also enclose the concept of temporal repetition of a phenomenon within the same geomorphological unit. On

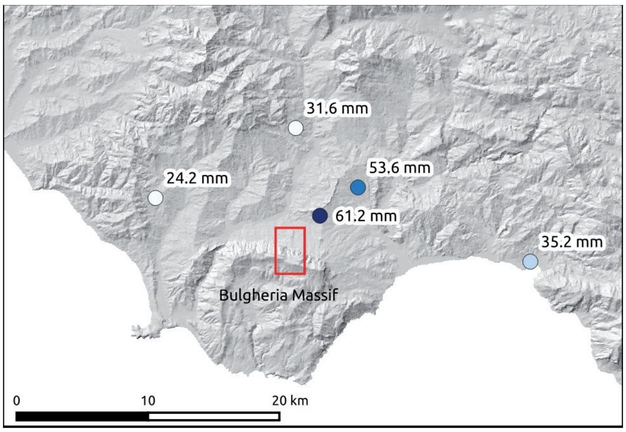

Fig. 14 - Precipitation values for the September 25, 2015 event, the red box highlights the study area (data from Multirisk Functional Centre, Campania Region).

Fig. 15 - Weather conditions along the northern front of the Bulgheria massif early in the morning of September 25, 2015, highlighting feeder-seeder effect (Photo by D. Guida)

the other hand, the definition of a landslide system, defined as the spatiotemporal overlap of landslides of any type, can be considered a synthesis of the gravitational history of a hillslope.

Along the Moio and Valle Noce channels a cyclic type of activity has been highlighted, showing how those channels experience "refilling" periods, thanks to creep-like phenomena in the channel heads and to rock fall episodes in the middle section; those inactive phases are then interrupted by debris flow occurrences, which produce the channel discharge.

In this framework, being the data structure event-based, a landslide database built following the LOOM data structure, could be defined as *landslide eventory* rather than landslide

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