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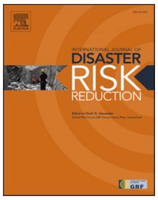

Debris-flow hazard assessment at the archaeological UNESCO world heritage site of Villa Romana del Casale (Sicily, Italy)

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ABSTRACT

Archaeological sites are extremely vulnerable to the impacts of weather-related events, which may lead to irreparable damages to cultural heritage. Here an assessment of the debris-flow hazard for the UNESCO site of Roman Villa del Casale (Italy) is carried out, through a combination of historical analyses, field surveys, geomorphological and hydrological investigations and two-dimensional hydraulic numerical modelling, all performed at river catchment scale. Historical analyses reveal that the site has been hit by several landslides in the far and recent past. This is presently confirmed by the high level of exposure to the impact of rain-triggered debris-flow events, due to the position of the Villa at a closure section of the related river basin and to the hydro-geomorphological characteristics of the basin itself. By applying the proposed approach, a scenario analysis is carried out. Results allow one to highlight the dynamics of the impact of debris flows, thanks to space and time-dependent maps about deposition areas, water depth and speed values, and to identify the most vulnerable archaeological elements within the study site. The numerical simulations are also used to test the efficiency of the existing hydraulic defense systems and to support the implementation of an early warning system for the site protection. Here, we also synthetize the design of the architecture of the wireless monitoring network, the sensor technology adopted to develop an effective real time environmental monitoring system and management platform, to construct a Wireless Sensor Network (WSN) - early warning and reporting system, which can be applied as a prevention measure.

1. Introduction

Harmful events to archaeological sites could derive both from human and natural causes, often interconnected [1]. UNESCO has included 53 properties of World Heritage List in the *List of the World Heritage in Danger*, which comprises sites threatened by both natural and human stress factors, such as earthquakes, flooding, landslides, armed conflicts, urban development, tourism pressure.

Among natural risks, meteorological risk (heat wave; tornadoes; wind, snow and lightning storms; etc.), hydraulic risk (floods; debris flows; avalanches; tide surges; erosion; etc.), and other water-related risks (humidity related decay; corrosion; cracking caused by roots growth; etc.) should be listed as responsible for poor conservation or even permanent loss of cultural heritage [2–4]. Consequences of these natural events are often worsened by interaction with human activities and the location of pre-historical and historical settlements in hazardous areas, that may increase exposition to damages. Such damages can be distinguished between those produced by slow, progressive actions like weathering and erosion, and those produced by catastrophic events with suddenly destructive consequences, such as extreme precipitations,

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floods or water-triggered landslides, also known as debris or mud flows [5–8]. Furthermore, human activities and climate change can cause the worsening of negative impacts of natural events on archaeological sites or cultural assets [1].

According to the United Nation Sendai Framework for Disaster Risk Reduction 2015–2030, awareness raising and improvement of the understanding of water-related risks are key-element to reduce their impacts on cultural heritage. At European scale, the EU Flood Directive support the management of flooding risks in order to protect, among others, cultural heritage sites, which are deemed extremely sensible to such a type of risks.

Floods and landslides are widely studied processes in the context of risk assessment, but they are often considered as a secondary problem for cultural heritage protection. This despite cultural heritage goods may suffer severe consequences due to extreme flooding events. Recently several works have tried to assess hydraulic risks in historical cities, in some cases considering the impacts of climate change [9–12]. As discussed in the following Section, hydraulic risk is also relevant for archaeological sites where excavation activities are carried out to bring to light remains of ancient cultures. To the authors knowledge, the investigation of hazards generated by extreme water-related events, and, in particular, by debris-flow events, impacting such sites has received much less attention [13,14].

The aim of the present work is to highlight the advantages of applying a methodology for the assessment of debris-flow hazards in archaeological sites through a simulated-scenarios approach based on historical researches, field surveys, geomorphological and hydrological analyses and hydraulic numerical modelling, which can help to plan prevention and mitigation measures at the overall catchment area of the site. While a similar approach is often used in flood risk analyses, risk management plans of archaeological sites are most of the time focused just on the protection of the local area where the site is located, disaster response mainly focusing on post-disaster measures. This is often related to lack of risk perception, non-specific legislation, and poor coordination among different actors [10,15]. For example, discussions with several stakeholders of Sicilian archaeological sites, carried out by the authors in the framework of the project "An early Warning System for cultural-heritage. eWAS -" (PNR 2015–2020, cod. ARS01_00926 - PON 2014–2020 of the Italian Ministry for Education, University and Research), revealed that site managers have no direct control on the privately-owned real estates of the catchment basin, where only limits to archaeological activities are presently imposed.

In the present work, we apply the proposed approach to the well-known UNESCO site of "Villa Romana del Casale", a mid IV century A. D. Roman Imperial Villa, located in Sicily, very famous for its beautiful mosaics, which was completely buried by a series of landslides in the Middle Age. This case study represents an ideal test to assess the capabilities of the two-dimensional numerical simulations of the propagation of debris flows to investigate potential impacts on the archaeological excavated site. The analysis of different debris-flow scenarios is also useful to gain an understanding of the flow dynamics at catchment-scale, to detect critical control sections upstream, and thus to design an effective monitoring system. As explained later, both the results of the numerical model and the data coming from the monitoring system will support the development of an Early Warning System (EWS) for the protection of the Villa del Casale. Indeed, in the last decades, monitoring networks and EWSs have been proposed to mitigate the impact of hazardous events on cultural heritage (e.g. Refs. [1,16]. In the present case, the long-term goal of the EWS will be not only to protect tourists visiting the site, but also to increase the awareness of potential hazards due to debris-flow development in the upstream catchment, and to allow site managers to take action for damage mitigation and safeguarding of heritage assets, by putting in place temporary and reversible protection measures, such as local barriers at critical section and openings, covering of mosaics to prevent damages, etc., as reversibility is a key issue for archaeological site conservation and landscape preservation.

The work is organized as follows. Section 2 summarizes the causes of water-related threats to archaeological excavations. Section 3 presents a description of the characteristics of the study area, along with an analysis of its past and present relationship with surface water, considered both as resource and hazard. Section 4 illustrates the conceptual structure of the method applied here, which includes the coupling of in-situ monitoring and numerical modelling, both carried out at catchment scale. Section 5 analyzes the geomorphological and hydrological characteristics of the river catchment within which the Villa is located, in order to highlight the occurrence of dangerous hazardous processes that may threat the site. Section 6 discusses some potential debris-flow scenarios for the Villa Romana and it analyses the results of the numerical simulations. Finally, Section 7 illustrates the main conclusions of the work.

2. Hydraulic hazards for archaeological sites

In most cases archaeological sites are excavated areas with their bottom at a level lower than the surrounding areas or floodplain, usually from 1 to 10 m below current natural ground level. Thus, the site can be easily flooded and water removal is difficult afterwards. Furthermore, excavation, which often implies morphological changes, in addition to climate changes occurring through centuries, can alter local surface and groundwater fluxes. Masonry materials, such as mortars, plasters and some stone types, and decorative features are particularly susceptible to humidity damage [17]. Flood events can strike the site during excavation and suddenly damage also those movable objects already discovered but not yet removed, before they could be located in safe storage buildings. Additionally, the location of archaeological areas, often far away from city centers or in remote countryside locations, may imply lack of supervision and knowledge even by in charge local authorities. This fact, coupled to ineffective involvement of local institutions, associations and individual citizens, could imply inadequate prevention and monitoring measures [18].

Among human activities, the archaeological excavation itself could represent a threat to archaeological remains, since, no longer preserved under an earthen layer, they are suddenly exposed to weathering and a new thermo-hygrometric regime [19–21]. Indeed, the excavation could cause a transformation in soil water content or in water table elevation [17,22]. Excavation under the water table level could trigger or alter groundwater flow regimes, generating hydraulic gradients and making the excavation site prone to flooding or bulkheads collapse. An increasing water table level negatively affects the effective stress in soils, decreasing their resistance. On the other hand, a lowering of the water table level could cause an excessive soil desiccation, with shrinkage phenomena degenerating in structural cracking in the masonry. Moreover, wet soils offer the best conditions to organic materials conservation, such as wood [23]. A non-protected excavation site edge allows the rainfall surface runoff to invade the site and the obvious presence, in an excavation area, of incoherent earth, sometimes added to earthwork waste materials stored too close to the excavation site edge, may increase debris transportation and deposition [22]. Furthermore, rain moistened soil and earthwork waste materials deposited near to excavation site edge increases earth push on bulkheads. Presence of water makes plants growth easy and fast: sometimes plant roots can act as a reinforcement for structures with deteriorated mortar, however vegetation must be taken under control. After excavation under the foundation level of structures, weathering phenomenon and erosion effects on the exposed escarpment could cause structural failures in masonry remains [17,22]. Finally, it is important to say that the bottom of an archaeological excavation site is most of the time on a lower level than the surrounding areas, so that it is easily exposed to water damages caused by rainfall, floods, pipelines spilling etc. The impacts of such events are even worsened by high residence time of water and wet debris in the excavated area [17,22]. This proves the importance of properly facing hydraulic issues during the entire cycle of archaeological site management, from excavation, to protection and public fruition.

Risk mitigation activities should be preferred instead of post-damage tentatives of restorations [24–27], by taking into account not only safety and sustainable fruition of the site [28], but also climate change impacts.

Italy is a country known worldwide for its magnificent cultural heritage, however many archaeological sites are affected by various problems related to the presence of water. The most important, dangerous and harmful ones are floods and debris flows [29]. Fig. 1 (a) summarizes some disasters occurred over the last decades, while Fig. 1 (b)–(d) highlights some of the hydraulic threats related to archaeological excavation.

Finally, geographical position of archaeological sites plays a main role in determining the risk causes, since the choice of a settlement location was often conditioned by water proximity. Many ancient settlements were founded at coastal locations to gain sea access. Today this condition makes these archaeological sites vulnerable to storm surges and coastal erosion damages. To ensure water supply and to gain a waterway for trade settlements many sites were located near a river, sometimes at the outlet of a valley which allowed the building of a dam: unfortunately, the presence of steep hillsides and riverbeds increases the hazard connected to landslides, debris flows or floods during rainfall events.

Among the above-mentioned hydraulic hazards, in the present work, we focus on debris flows, since this type of events have caused major damages to the Villa Romana del Casale, as discussed in the next section.

3. Relevance, location and history of the study site

The Roman *Villa del Casale* is located 4.5 km South-West of the city of Piazza Armerina in Sicily (37°21′53.4’’N 14°20′05.0’’E), 530–550 m above m.s.l. It is one of the most important archaeological sites in the Mediterranean area, enrolled in the UNESCO World Heritage List since 1997. Fig. 2 reports an aerial view of the site taken during one UAV survey.

The extremely high artistic and historical value of the site derives from the 4′000 square metres of almost intact polychrome mosaic paving, a very fragile surface that needs particular care and must be safeguarded especially from water damages.

Originally the location of the Villa was chosen due to its strategic position, close to a major Roman way between two important ancient cities, Catania and Akragas (which was the Greek name for the modern *Agrigento*), and to the Gela river waterway, which is named Nocciara creek in its upper course. The river catchment area in which the Villa is located is a sub-basin of the Gela River, on the left riverbank of the Nocciara creek, at the outlet of a small valley. We will hereinafter refer to it as “Villa del Casale” basin. In particular, the Villa was built on three levels following the topography of the local floodplain. Such a location, in conjunction with the proximity to water springs on the hillside upstream the Villa, allowed rainwater harvesting and spring water supply, through a masonry reservoir. The three terraces-structured building allowed gravity water distribution.

The Roman Villa del Casale is a multi-pavilion, luxury mansion that was probably built in mid IV century A.D., during the first Tetrarchy period, as a rebuilding of a more ancient, I century A.D. *villa rustica*, a farmhouse. It was the mansion of a very rich and powerful Roman citizen, likely a rich senatorial aristocracy member, but the researchers have not reached a shared opinion about this issue. It was the administrative centre of a huge estate,

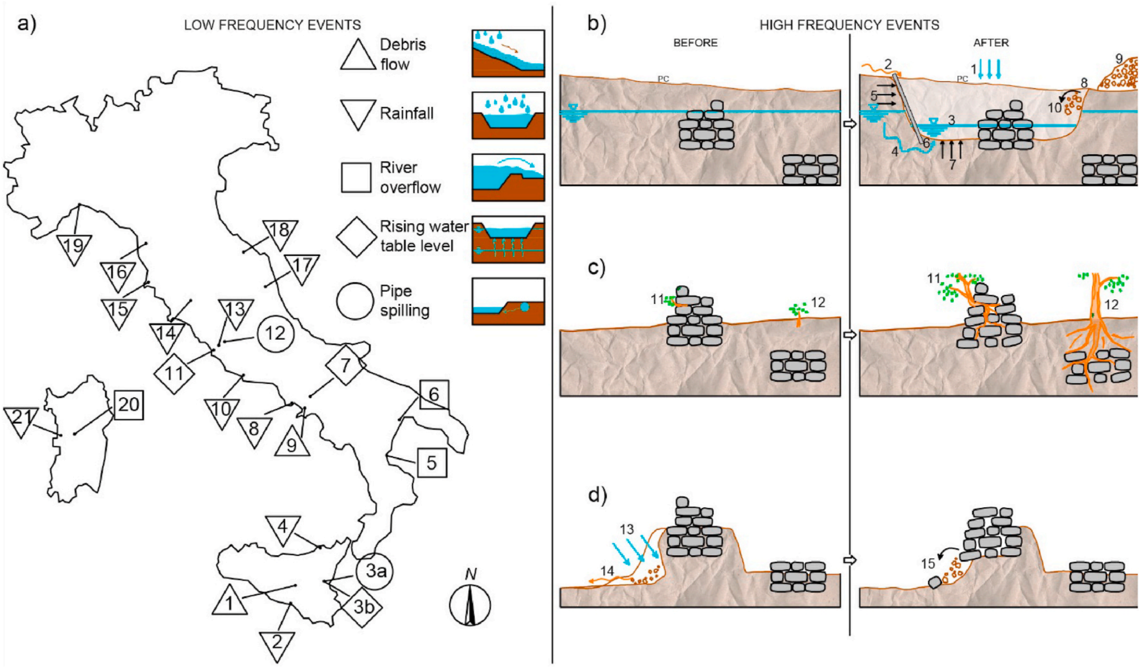

Fig. 1. (a) Digest of archaeological sites damaged by water or extreme hydraulic events during the last years: 1 - *Villa Romana del Casale*, 1991; 2 - *Area Archeologica Demaniale Bosco Littorio*, 2015; 3 - Greek-Roman Theatre and Roman Amphiteatre of Catania, recurrent phenomenon; 4 - Roman villa in Patti Marina, 2009; 5 - Sibari Archaeological Park, 2013; 6 - Metaponto Archaeological Park, 2009, 2011, 2013; 7 - Prehistoric village and *Anfiteatro Laterizio* in Nola, recurrent phenomenon; 8 - *Macellum* of Pozzuoli (wrongly known as Serapi’s Temple), recurrent phenomenon; 9 - Pompeii Archaeological Park, 2009, 2010; 10 - *Fonte di Lucullo* in Sabaudia, 2015; 11 - Ancient Ostia Archaeological Park, 2015; 12 - Mausoleum of Augusto in Rome, 2014; 13 - *Villa Rustica* in Dragona, 2017; 14 - Città del Tufo Archaeological Park: Nercopolis of Sovana, 2012; 15 - Baratti and Populonia Archaeological Park, 2015; 16 - Mound of the Etruscan Prince in Pisa, 2015; 17 - Late-republican Sanctuary of La Cuma Archaeological Park, 2016; 18 - Roman City of Suasa Archaeological Park, 2011; 19 - San Domenico Excavation site: *Fortezza del Priamàr* in Savona, 2016; 20 - Roman Theatre in Fordongianus, 2016; 21 - Mont’e Prama Archaeological Site, 2015. All the information have been gathered from online newspapers and websites. (b) hydraulic problems connected with archaeological excavation: 1 – direct rainfall; 2 – flood caused by surface runoff, often with debris transportation; 3 – excavation site bottom flood; 4 – filtration regimes due to different water table levels; 5 – earth push on bulkheads; 6 – bulkhead failure due to filtration problems; 7 – excavation site bottom uplift 8 – non-protected excavation site edge; 9 – incoherent earthworks waste materials too close to the excavation site edge; 10 – incoherent materials fall. (c) 11 - ruderal vegetation on unearthed structures; 12 – deep growth of plants roots. (d) 13-Weathering phenomena; 14 – eroded materials natural removal; 15 – structural failures in archaeological remains.

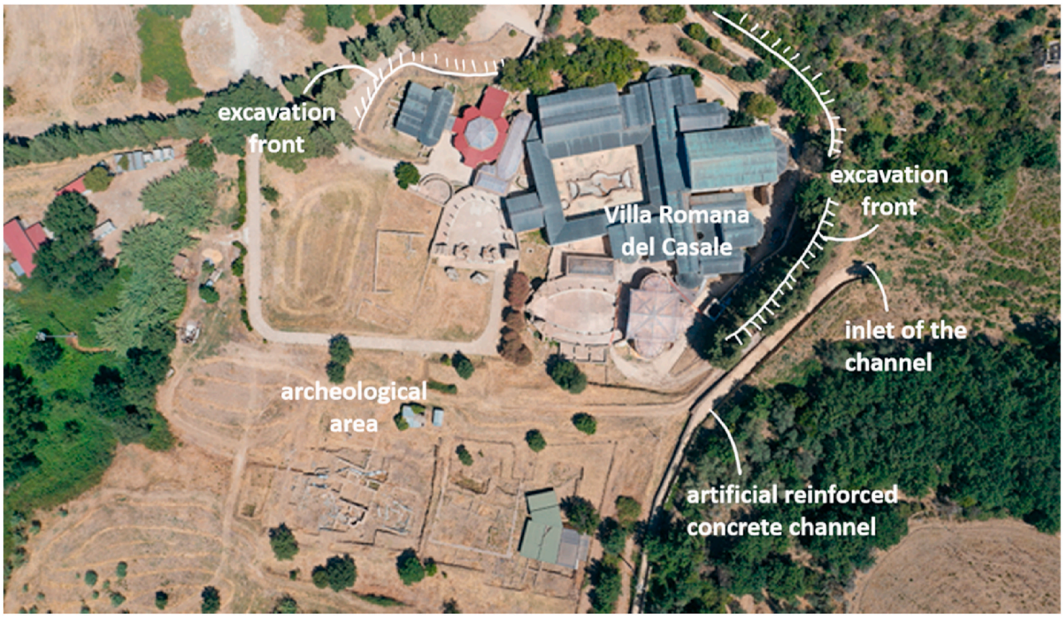

Fig. 2. Aerial image of the archaeological site of the Villa Romana del Casale taken during one UAV survey.

extended probably for 15′000 ha (150 km^2).

Archaeological evidences of ancient restorations, carried out since the Villa building period itself, suggest that a close connection between use and hazard has always been a particular feature of the site, exposed to both natural and anthropic risks during all the centuries of its life. There are restoration traces dating back to IV century A.D., maybe to repair damages due to the earthquakes that hit this part of Sicily between A.D. 362 and A.D. 365 [30]. During the period in which the Villa was inhabited, between IV and VII century A.D., for ordinary maintenance purposes several other repairs have been carried out, especially on mosaics but also on the apse walls of the *Basilica*, which were reinforced with buttresses to counteract dome's thrust [30,31]). Prior to the fall of the Western Roman Empire, during IV century A.D., the Villa started to be fortified for defensive purposes, in the attempt to face hazard due to human activity, like war, in addition to natural event hazard. After barbarian invasions and Byzantine conquer, the fortifications of the Villa were improved by Byzantines, in VI century A.D., and later by the new Arab conquerors during X century A.D. Starting from VII century A.D. until XII century A.D., during the late Byzantine, Arabic and Norman phases, the Villa was transformed through rebuilding or building works for structures realized on the remains of the previous ones, giving birth to an extended settlement [30,31]. Since X-XI century A.D. the Roman structures of the Villa are almost no longer recognizable [31–33]. In fact, after two debris-flow episodes which covered byzantine masonry structures with alluvial debris prior to the Arabic and Norman phase [32,33], a combination of a great flood in A.D. 1000 circa [30,34], the fighting between the soldiers of the Sicily's Norman king William I "the Bad" and rebel Barons' ones in A.D. 1160–1161 and the great earthquake of A.D. 1169 [30,31] forced the inhabitants of the medieval settlement to start abandoning the area. The foundation in A.D. 1163 of the new nearby Piazza Armoring city contributed to reduce the population of the settlement [31]. A landslide detached from Monte Mangone may have struck the site in the second half of XII century [35]. A sequence of several floods and debris-flow events, demonstrated through the stratigraphic analysis carried out during archaeological excavation, caused the definitive decline of the site in XII-XIII century A.D., with the only persistence of a few rural houses which constituted a small settlement known as "Casale" [33,36]. The Villa was buried throughout the centuries under almost 3–8 m of alluvial sediments [37,38], confirming that mud flow represents a major risk for the site. After the ancient Roman water harvesting and supply systems upstream had been abandoned, the exposure to the risk of floods and debris flow increased, being the Villa built on the top of an alluvial fan. Probably during the XV century, another debris flow completely destroyed the medieval buildings and finally persuaded the inhabitants to abandon the settlement definitively [30,33,39]. During the XVII and XVIII century other debris flows buried the remains of a small surviving group of rural structures called "Casale", relegating to oblivion the site [30,33].

After definitive abandonment, ruin and disappearance under alluvial sediments, the existence of the Villa has been known since XVII century, with several citations in historic documents [40–44], and some archaeological surveys during the XIX century [30,34,45–47], but only in 1950 the Italian archeologist Gino Vinicio Gentili started a real, extended and systematic excavation campaign, completed only in 1963.

After excavation, it was urgent to cover the mosaics to shelter them against the weathering, especially rainfall. Finally, after some failed attempts and temporary solutions, in 1967, a definitive but non-invasive roofing made up by glass and steel, designed by Franco Minissi, was built. After almost 50 years, between 2007 and 2012, the roofing was deemed to be extremely deteriorated and it was judged to be no longer adequate, because of the indoor thermo-hygrometric conditions uncomfortable for visitors and unsuitable for decorative feature conservation. The new roofing system was designed by Guido Meli and built with new materials and shape, to ensure optimal thermo-hygrometric regimes for both mosaics and visitors and to improve the conservation conditions of the fragile decorative layers [31,39,45,47,48].

Since it has been built, the Roman Villa del Casale has been damaged over the centuries by extreme natural events as a consequence of its location at the outlet of the basin. Fig. 3 highlights that debris flows, floods and landslides have always been a recurrent problem in this area. Indeed, the "Villa del Casale" is settled in an area prone to landslides, debris flows, floods and related hydraulic problems [31,39,45,48,49]. More in detail, during the last 50 years the Piazza Armerina region has been affected by several destructive hydraulic events, with fatalities and damages to buildings, streets and facilities, so that the hydraulic risk represents a main problem both for property and population. In the recent years, all the phenomena observed have been debris flows, classified as "runoff-generated" in which the generation of debris flow is caused by heavy rainfall that saturates the terrain and the consequent runoff triggers the erosive phenomena [50,51]. Fig. 4 shows an overview of the watershed along with the location of the Villa, at the outlet of the drainage basin, and evidences of active erosive processes on the slopes.

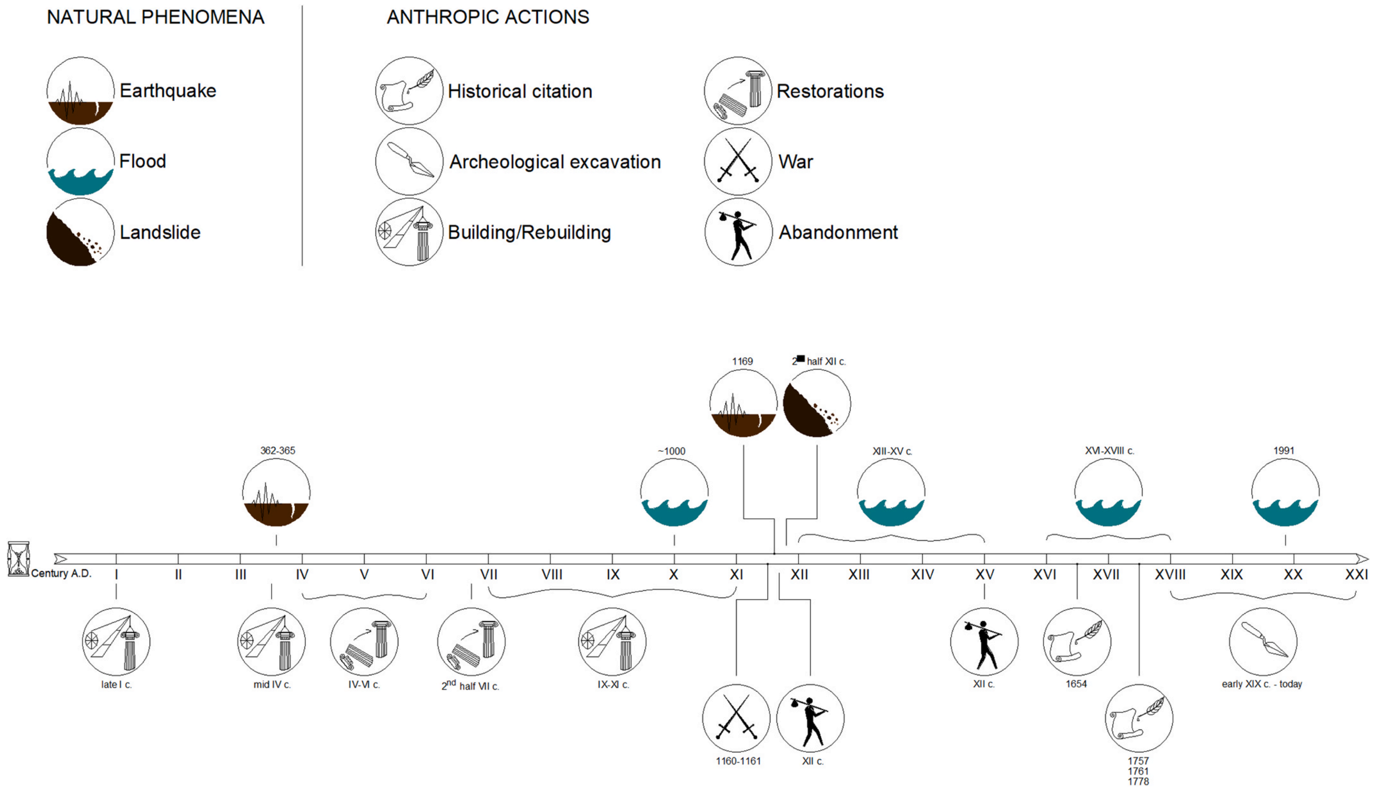

Fig. 3. Main natural phenomena and historical consequences occurred to the Roman Villa del Casale, cited in historical sources by ancient authors and confirmed by archaeological evidence. Debris flows, floods and landslides have always been a recurrent problem in this area.

Fig. 5 reports a timeline of the events occurred over the last 70 years. Data about extreme events come from newspaper's articles, in which the word "landslide" sometimes refers improperly both to landslides and debris flows. Thus, in Fig. 5 each event that was not clearly addressed as "debris flow", or that was impossible to recognize as "debris flow", has been classified as "landslide". The figure shows that almost each landslide event was connected with intense and prolonged precipitation. These events hit not only property, with damages to buildings and infrastructures, like the 1951 flood, but also people, with casualties and injuries, like the 1973 and 1991 landslides and debris flows.

In the last decade, the most harmful event for the Villa was the debris-flow event that occurred in 1991. The archaeological site was

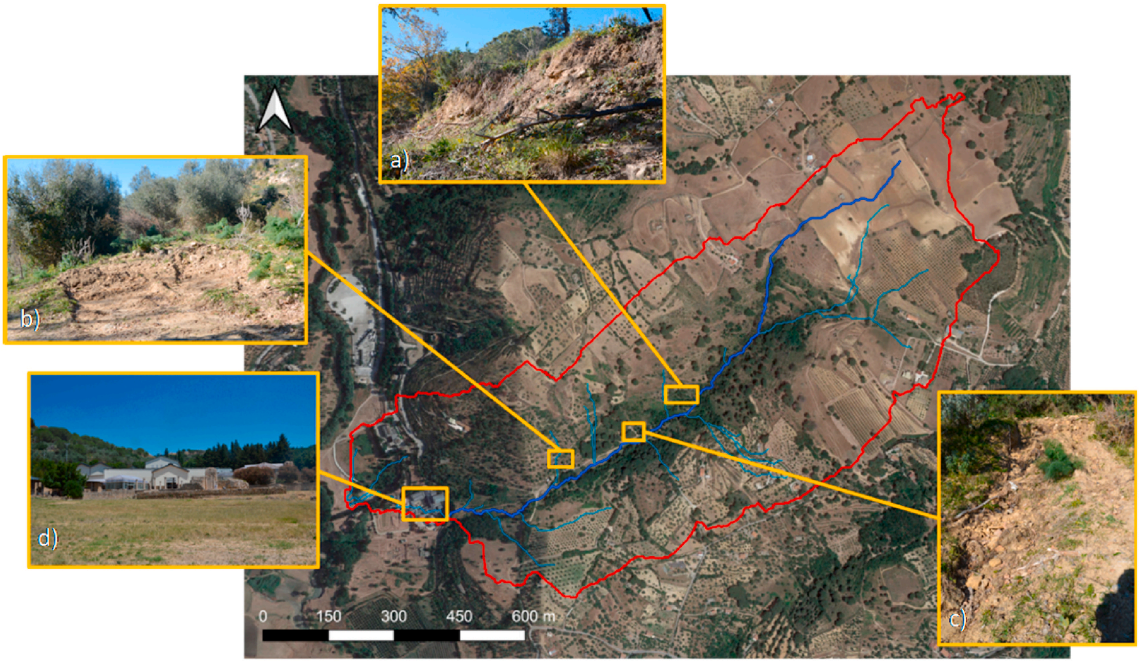

Fig. 4. Overview of the watershed of Villa Romana del Casale. a) to c) evidences of active erosive processes on the slopes; d) archaeological site located at the outlet of the drainage basin.

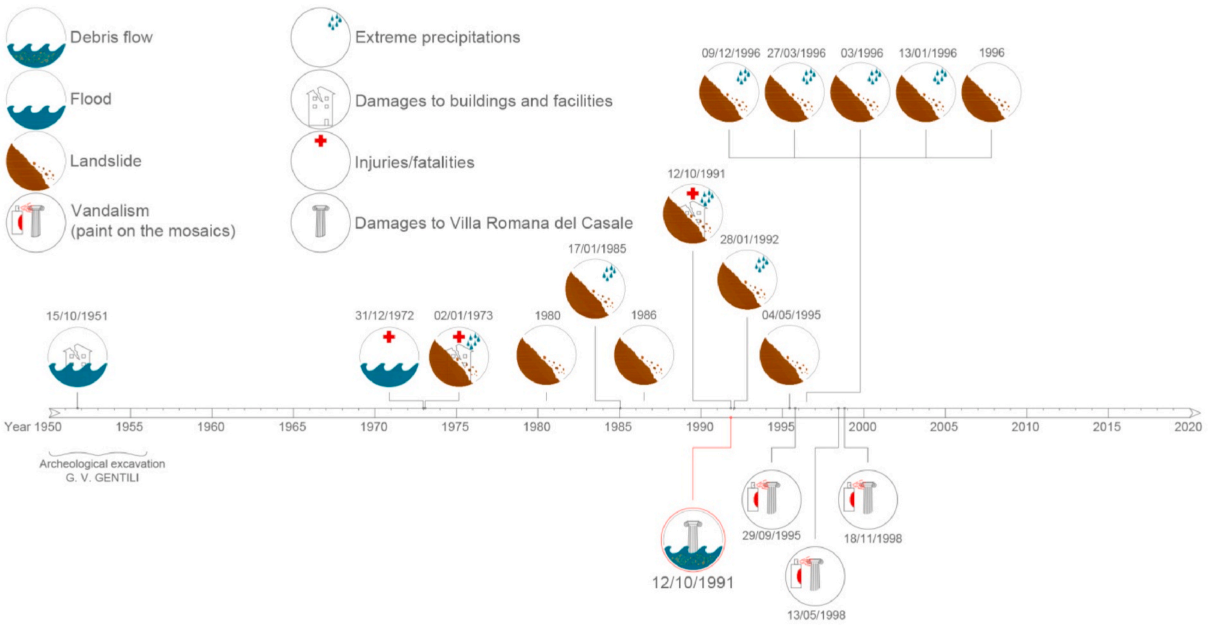

Fig. 5. Main flood and landslide events occurred in the Piazza Armerina region and the archaeological site since 1950. The region is highly prone to landslides, debris flows, floods and related hydraulic problems. Sometimes in addition to damages to structures there are casualties. Hydraulic risk represents a main problem both for property and population.

affected for half of its extension, mosaics covered by debris. Major damages were: the detachment of mosaic tiles and fracture of decorations. Pictures in Fig. 6 show how areas at lower levels are easily flooded and are affected by high residence time, which increases damages to fragile decorative features, like mosaics and frescos, due to the prolonged exposure period to water or wet materials contact. Examining the photographs taken in 1991 after the debris flow event, it has been possible to deduce the areas that were hit and flooded by the flow, as shown in Fig. 7.

The presence and the use of water was a central element in the foundation and development of the Villa. This is demonstrated by the presence of two aqueducts, several reservoirs and the complex underground Roman system for water supply, made up by lead pipelines used to fed fountains, baths and latrines, or by several channels for conveying wastewater. Fig. 8 shows the relationship between the archaeological site and modern and ancient hydraulic systems both for artificial water supply and natural runoff. The artificial reinforced concrete channel upstream of the archaeological site was built in the mid XX century to protect the Roman Villa from rainfall runoff. The presence of a high difference in ground level upstream of the site today makes the location of the Villa disadvantageous from a hydraulic point of view. It can be also seen that the Roman channels follow the natural runoff path.

There are some low areas on the floor in the correspondence of underground channels. The geophysical surveys by [53] showed that in the main hall (the “Basilica”), whose dimensions are 25 × 14 m, the diffuse floor deformations are probably due to heterogeneous filling materials, while the collapse source of the extended important floor failure, of about 1 m at the deepest point, at the next great corridor (the

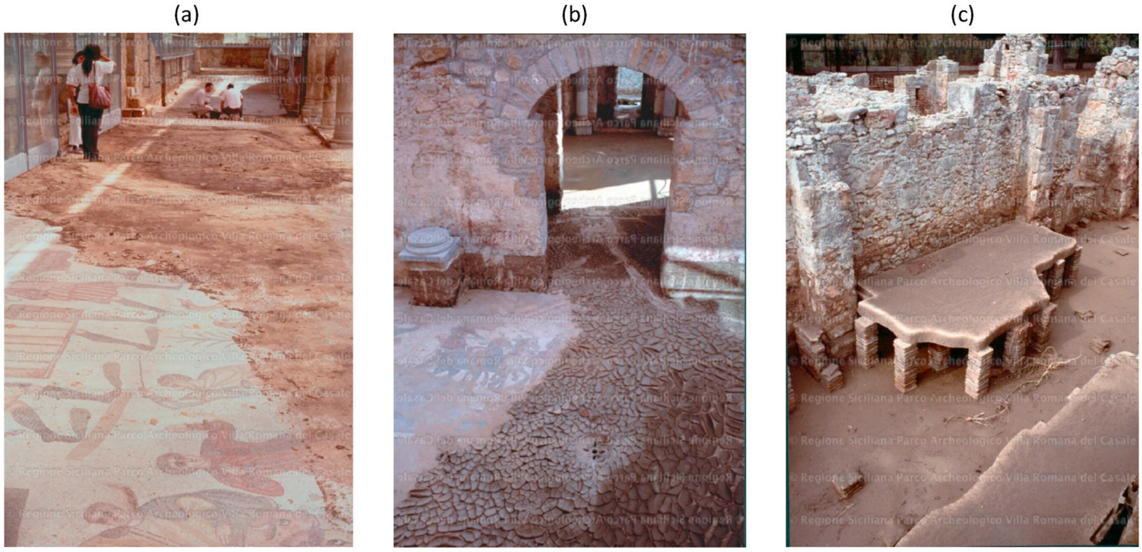

Fig. 6. Debris on the mosaics after 1991 debris flow (a): *Corridoio della Grande Caccia* (“Ambulatory of the Big Hunting Scene”); (b): *Palestra* (“Fitness room”); (c): *Calidarium* (“Warm room”). The absence of the floor and the bottom of the hollow space at a lower level makes the room easy to be flooded (source: www.villaromanadelcasale.it).

Fig. 7. Map of areas flooded in 1991. In dark brown areas with debris on the mosaics recorded through photos; in mid brown adjacent areas, which very likely have been invaded by debris, even if there are no photographs; in light brown areas likely invaded by debris, because of their geomorphological features.

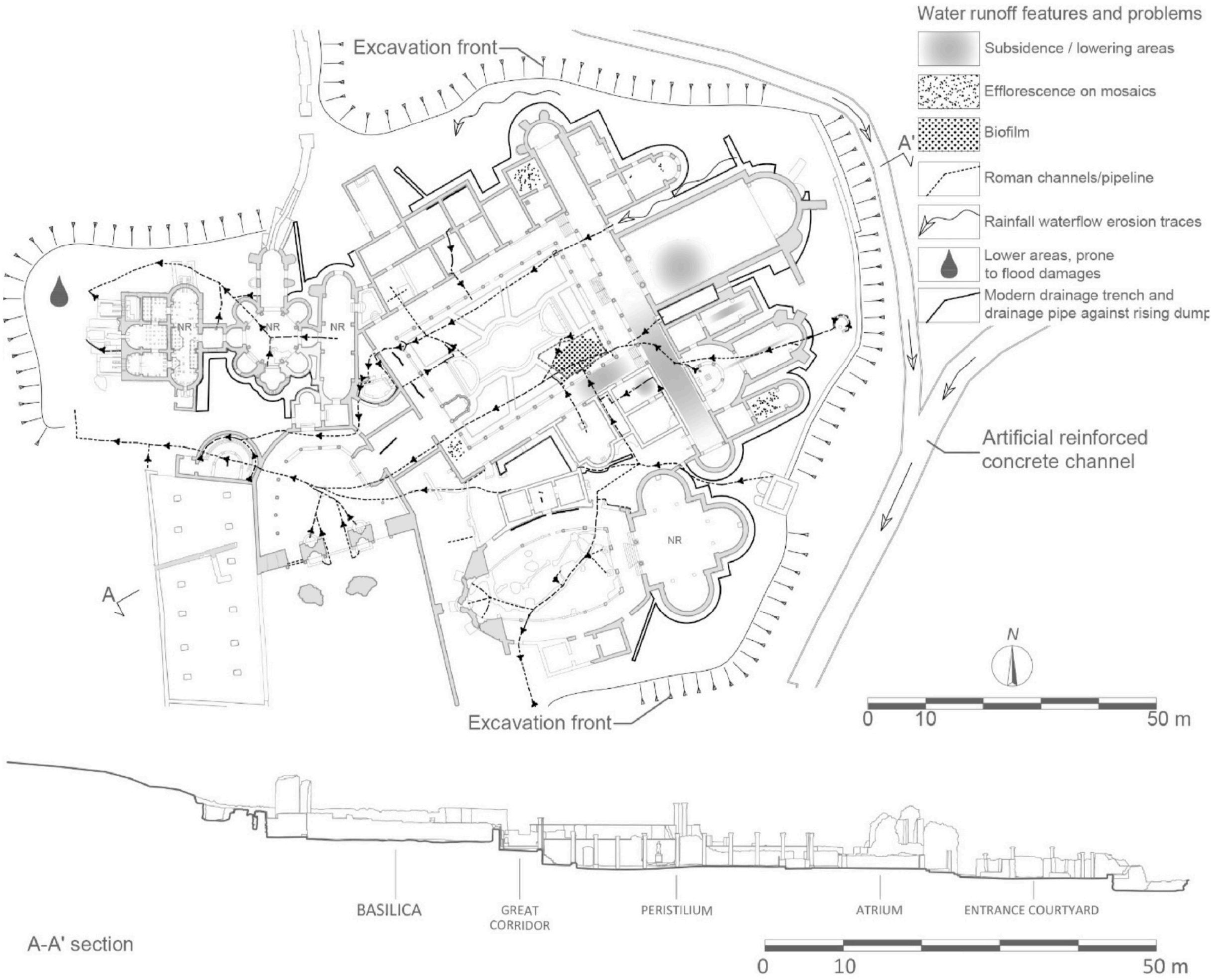

Fig. 8. Water Map of the archaeological site and cross section of the Villa del Casale. The thick lines highlight critical low areas. Background information sources: [31,52].

“Ambulacro della Grande Caccia”), 59 (67 with the apses) x 4.6 m, is probably deeper than 3 m, because the shallow structures are continuous and follow the floor surface down to 3 m. These problems are highlighted in Fig. 8, while Fig. 9 shows the reinforced concrete artificial channel upstream of the Villa, built to deviate the surface runoff of the river catchment upstream of the Villa.

Hydraulic problems affecting archaeological sites during and after excavation are still underestimated and are faced with a site-scale approach, despite the reference geomorphological, hydrological and hydraulic unit should be the entire drainage basin. The management plan of the Roman Villa del Casale confirms that the effectiveness of implemented mitigation measures is not enough. In fact, only three local measures are considered. The first one consists in shaping the runoff surface around the building, in order to convey rainwater runoff downstream towards the Nocciara creek. The second one consists in creating a drainage trench upstream of the Villa, with a drainage pipe at the bottom, in order to convey the rainwater coming from northern areas and from that areas downstream of the artificial concrete channel, towards the Nocciara creek. The third one consists in the delimitation of a buffer zone upstream of the Villa, on the alluvial conoid, where intense rainfall landslides have been generated many times in the past (Sicilian Region, 2012). It follows that no measures at a catchment area scale are planned to ensure archaeological site protection.

4. Methods

Currently, flood risk assessment in river catchments which includes archaeological sites is usually carried out following the traditional approach used for civil protection purposes, without specific indications for cultural heritage (e.g. EU Flood Directive 2007/60). However, some recent works have highlighted the importance for developing reliable methods for assessing flood risk in the case of cultural assets, both at national and at regional scale [54,55], and at local scale, e.g. at art cities [12].

To evaluate hydraulic risk at an archaeological site the first step should be the analysis of the hydrology and geomorphology of the drainage basin within which the site itself is located. Current geomorphology is the result of several natural and artificial interconnected factors. In archaeological areas, this has been influenced and shaped through centuries by building activities since Antiquity, by natural or human processes which may have led to the abandonment or destruction of the area, and finally by archaeological excavation sites during the last three centuries, which may have further altered the pre-existing equilibrium conditions. From the viewpoint of the hydraulic regime, both ancient hydraulic defense works, to protect the original building when it was realized, and modern ones, to protect the excavation sites may co-exist and interact at a specific site.

To define the drainage basin, it is useful to choose the outlet section downstream of the site: this allows one to gather data about the effects of water runoff and debris transportation on the excavation site. An accurate knowledge of the events that occurred is essential, as well as information about geomorphology, hydrogeological and geostructural setting, hydrology, soil composition, land use, etc. [56]. The analysis of geology, including not only surface morphology but also groundwater dynamics and terrain geotechnical characteristics, of past extreme weather-related events, and of current hydrological regime, i.e. of the environmental system, coupled to the knowledge of the past and present history of the site, including excavation and present protection structures, allows one a more reliable hazard assessment, which may be useful to develop effective strategies for risk mitigation. The entire process is summarized in Fig. 10.

Here a method for assessing and monitoring the debris-flow hazard in archaeological sites is proposed, for conservation, protection and enhanced fruition. The approach considers a set of event scenarios, in order to build an effective and reliable Early Warning System (EWS) for cultural heritage.

The main components of the proposed EWS, which must be interacting with each other, are (Fig. 11):

- an hydraulic modelling system, which simulates different debris-flow events, as a function of different triggering conditions, in order to predict the impacts on cultural heritage.
- a monitoring network for the continuous measurement of the evolution of significant hydrological, hydraulic and geotechnical variables.

In this context, the numerical modelling on the one hand supports the design of the monitoring system, by determining (i) the most critical sensor locations; (ii) threshold values for triggering mechanisms and alarms; and (iii) the assessment of different hazard scenarios. On the other hand, data collected by the monitoring system will be used: (i) to calibrate and refine model results; (ii) to better define new site-dependent rainfall thresholds; and (iii) to evaluate consequences of harmful events at the site. In operational mode, the monitoring system coupled with the numerical modelling will identify alert conditions

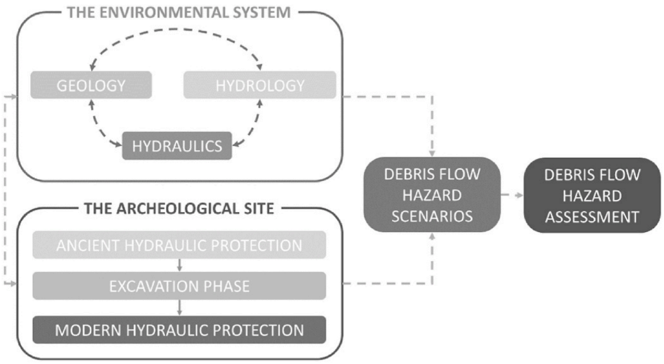

Fig. 10. Sketch of the suggested methodology for debris-flow hazard assessment at archaeological sites.

Fig. 9. The artificial reinforced concrete channel built upstream of the Villa in the XX Century. (a): upstream section at the downstream end of the natural riverbed and inlet of the artificial channel. (b): bottom and banks of the concrete riverbed. The channel is 3 m large and 1.5 m deep.

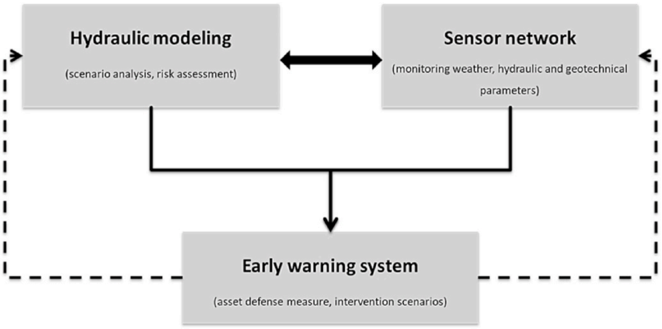

Fig. 11. Interaction between the different components of the early warning system.

which could lead to potentially dangerous events for the Villa del Casale, to allow site managers the possible activation of actions to protect the archaeological site.

The continuous interaction between the constituent elements of the EWS will allow the maximization of the effectiveness of its operation, making the identification of critical situations flexible to any changes in the parameters involved and the dynamics of the events. The system, in its final configuration, will have to be able to manage real-time different scenarios, the trend of which will be studied by coupling advanced numerical modelling of the hydraulic phenomena of interest and artificial intelligence algorithms [57].

4.1. Numerical model

The FLO-2D model, developed by [58]; is used in the present work for the simulation of the event scenarios in the hydrographic basin of the Villa del Casale. This model is based on a monophasic Bingham scheme. The basic equations implemented in the model are the continuity equation (1) and the equation of motion (2). The differential form of the continuity and motion equations in the FLO-2D model is solved with a finite difference numerical scheme.

$$\frac{\partial h}{\partial t}+\frac{\partial (h\cdot v_x)}{\partial x}=i \qquad (1)$$

$$S_{f_x}=\ S_{0_x}-\frac{\partial h}{\partial x}-\frac{v_x}{g}\frac{\partial v_x}{\partial x}-\frac{1}{g}\frac{\partial v_x}{\partial t} \qquad (2)$$

where h is flow depth, v_x is depth-averaged velocity along the flow direction, i is excess rainfall intensity (assumed equal to zero in the present application), x is the generic direction of motion, S_{fx} is the total friction slope, S_{ox} is the bed slope, and g is gravitational acceleration. The above governing equations are numerically solved on a square grid.

The calculation procedure for land flow involves calculating the flow rate through the perimeter of each cell of the grid, considering one possible direction at a time. There are eight potential directions of flow, the four cardinal directions (North, East, South and West) and the four diagonal directions (North-East, South-East, South-West and North-West). Each calculation is one-dimensional and is solved independently of the other seven directions.

FLO-2D can also simulate the debris-flow rheologies using a quadratic rheological model [59]. Based on this quadratic rheology, the frictional slope S_{fx} is estimated as:

$$S_{f_x}=\frac{\tau_b}{\rho\cdot g\cdot h}+\frac{K\cdot\mu_b\cdot v_x}{8\cdot\rho\cdot g\cdot h^2}+\frac{n_{td}^2\cdot v_x^2}{h^{\frac{4}{3}}} \qquad (3)$$

where τ_b is Bingham yield stress, ρ is mixture density, K is the laminar flow resistance coefficient, μ_b is Bingham viscosity, and n_{td} is the pseudo-Manning resistance coefficient which accounts for both turbulent boundary friction and internal collisional stresses.

In particular, the yield stress τ_b, the dynamic viscosity μ_b, and the drag coefficient n_{td} depend on the characteristics of the sediment and can be described by the following equations (O'Brian, Flo-2D User Manual, 2007)

$$\tau_b=\alpha_1\cdot e^{\beta_1\cdot C_v} \qquad (4)$$

$$\eta=\alpha_2\cdot e^{\beta_2\cdot C_v} \qquad (5)$$

$$n_{td}=\ n_t\cdot 0.538\cdot e^{6.0896\cdot C_v} \qquad (6)$$

α_1, β_1, α_2,β_2 are empirical coefficients defined by laboratory tests [59] c_v is the volumetric concentration of the fluid, and n_t is the turbulent value of n_{td} [59].

FLO-2D was developed to simulate flood events on unconfined surfaces. The main limitation of the FLO-2D model is the discretization of the floodplain topography in a system of square grid elements, which forces each element of the grid to be represented by a single elevation and roughness. (O'Brien, Flo-2D User Manual, 2007).

4.2. Monitoring system

A monitoring system to support the numerical modelling, to characterize and to control slope instability and the geomorphological evolution of the basin upstream of the archaeological site of the Villa Romana del Casale, as a part of a more complex Early Warning System (EWS), is under development. Indeed, it has been demonstrated that the reliability of the debris-flow alarm systems may be quite high, and so is its efficiency, depending on the redundancy of the data transmitting devices [60]. Recently [61] have proven the efficiency of a new approach which uses rain-gauges and corrected radar data rainfall estimates for a model-based prediction of debris-flow occurrence.

The proposed monitoring system can be useful to evaluate not only the current but also the future stability conditions, to extend the understanding of sliding mechanisms and the associated risk, and to support planning of mitigation actions [7].

It is well established that three main factors are responsible for the hydro-geomorphological instabilities, especially for the generation of floods and landslides: the rainfall regime, the geological and morphological characteristic of the basin, and the land usage. The combination of hydrological monitoring instruments, which measure data on precipitation and pore pressures, together with various geophysical, geodetic and geotechnical sensors, allows one to reconstruct the relationships between rainfall, groundwater level and consequent slope instability, since an important step to develop an EWS is linking sensor measurements to the possible failure mechanisms which could trigger floods and sliding [62].

Nowadays, several approaches and various kinds of sensors are used to monitor slope instability. Using several sensors for the same purpose and at the same place can be very helpful in maintaining the redundancy of measurements if one instrument fails, avoiding data loss but also false alarms in the case of malfunction of one sensor. Recent advances in monitoring capabilities and the commercial availability of low-power and low-cost sensors, such as micro-electro-mechanical systems (MEMS) and the development of more efficient wireless data transmission systems, have led to extensive research on and deployment of remote Wireless Sensor Networks (WSN [63], for environmental monitoring (e.g. [64,65]. A WSN can be equipped with multiple sensors.

For the experimental WSN of Villa del Casale (named CAS_NET), a prototype of device based on a module Pycom FiPy connecting different low-cost, small size, high-sensitive, low power and reliable accuracy kind of sensors has been realized. Currently, the device module includes two MEMS sensors, for vibration and inclination measurements, mounted on the same board. It can externally connect to other sensors such as a moisture and a temperature probe to measure soil water content and temperature. In more detail, the node under test presents (Fig. 12): (1) a 3-axis MEMS digital high-sensitive and very low noise

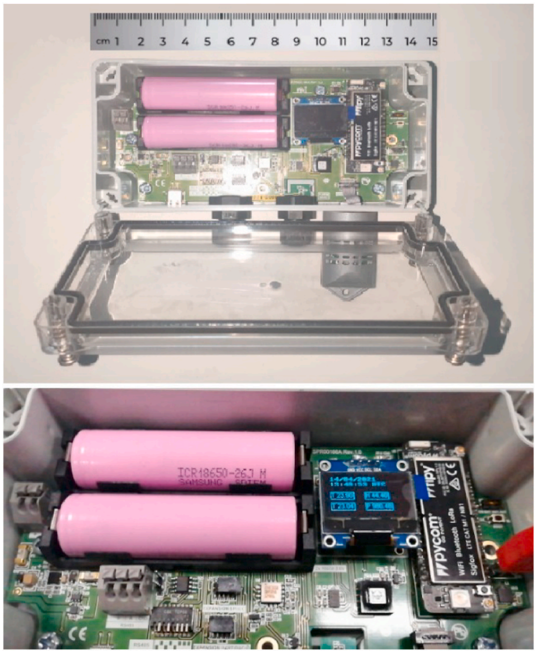

Fig. 12. Photo of the multi-parametric device with integrated tri-axes MEMS accelerometer and inclinometer allowing the connection of the other sensors (moisture and temperature probe) and several mode of data transmission (WiFi, Bluetooth, LoRa, Sigfox and dual LTE-M (CAT-M1 and NB-IoT)).

accelerometer (ADXL355, Analog Devices); (2) a dual-axes MEMS digital inclinometer (ADIS16209, Analog Devices), specifically designed and adapted for tilting applications with an accuracy <1°; (3) a Watermark Soil Moisture Sensor and (4) a temperature probe, designed to measure soil temperature in order to provide temperature compensation for the Watermark. All these sensors, thanks to their low power consumption, are suitable for wireless systems.

The node-device sends data via wireless and/or with a 3G/4G modem, and can be accessed remotely by means of a web application which provides users with real time data. Moreover, the prototype has the capacity of getting information about geolocation as well as platform status (e.g. CPU load, temperature and energy consumption).

In summary, the configuration of the proposed experimental WSN monitoring and surveillance network (Fig. 13), will be the following:

- 11 multiparametric nodes;
- 3 electric piezometers to monitor variations of the ground-water table level, that will be located in the three 10-m-deep boreholes realized along the riverbed of the creek upstream of the Villa del Casale (Fig. 13);
- 1 metereological stations (Davis Vantage Pro 2 wireless, DW-6152EU), that will be located near the Villa del Casale, to gather the localized rainfall regime and quantify the pluviometric thresholds that can trigger instability phenomena;
- 1 high-resolution webcam, that will be located near the Villa del Casale, looking to the channel upstream of the Villa.

Moreover, the installation of load cells to evaluate the soil total stresses and pressure transducers, to measure neutral pressures and to monitor water table levels, is under evaluation.

The data acquisition and transmission system, based on wireless networks, will be integrated into a web platform in order to allow the data access to the archaeological site managers.

Such a system will keep track of the movement of the hill slopes and detect a possible overcoming of the threshold value before failure movements, thus that alert can be triggered to give an early warning. In this wireless system, the radio frequency has been applied to communicate between the sensor node and the remote system.

The inset of Fig. 13 displays the architecture of the multiparametric

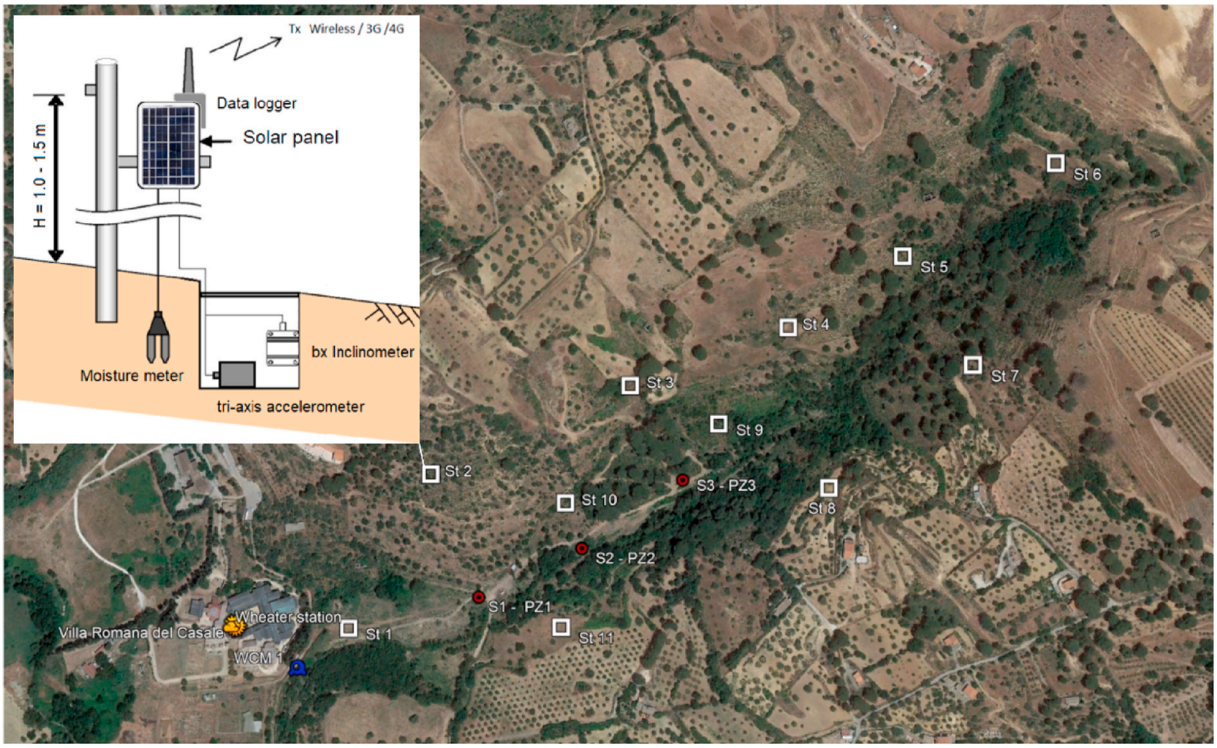

Fig. 13. Map reporting the experimental setup of the monitoring network in the area just upstream of the Villa del Casale. In the inset a scheme of the multiparametric node configuration is shown. In the map, the white squares indicate the multiparametric node, the red circles the location of holes. Furthermore, the locations of the weather station and the webcam are also reported.

node, with sensors of temperature, humidity, inclination and acceleration that can capture variation of a single parameter or a combination of parameters, to detect any noticeable slope movement.

A first field evaluation of the initial prototype multiparametric node has been already conducted by the TME Srl, partner of the project "An early Warning System for cultural-heritage. eWAS -" (PNR 2015–2020, cod. ARS01_00926 - PON 2014–2020).

One of the objectives in CAS_NET is the development of a Decision Support Information System (DSS) from which data can be structured, aggregated and managed in a single homogeneous environment and related to one another. The system will communicate with the sensor network through the SOS (Sensor Observation Service) protocol, through which the sensor information will be displayed on the device itself in real time. In addition, considering a reasonable time period of operation, by a careful analysis of the data it would be possible to identify the warning thresholds about the potential triggering of mudslides and debris phenomena. This will improve the ability to respond to extreme weather-climatic events that expose to risk the safety of people and the Villa del Casale itself.

Overall, the technical and functional specifications of the system are:

- The system uses a WSN communication network that can cover a large and open territorial area (outdoor less than 1 km^2);
- The data are transferred within the WSN network, via radio frequency, through an appropriate protocol certified, according to an international standard (e.g. ZigBee, M-bus) or in alternative via modem 3G/4G;
- The system will allow the detection of any transmission errors;

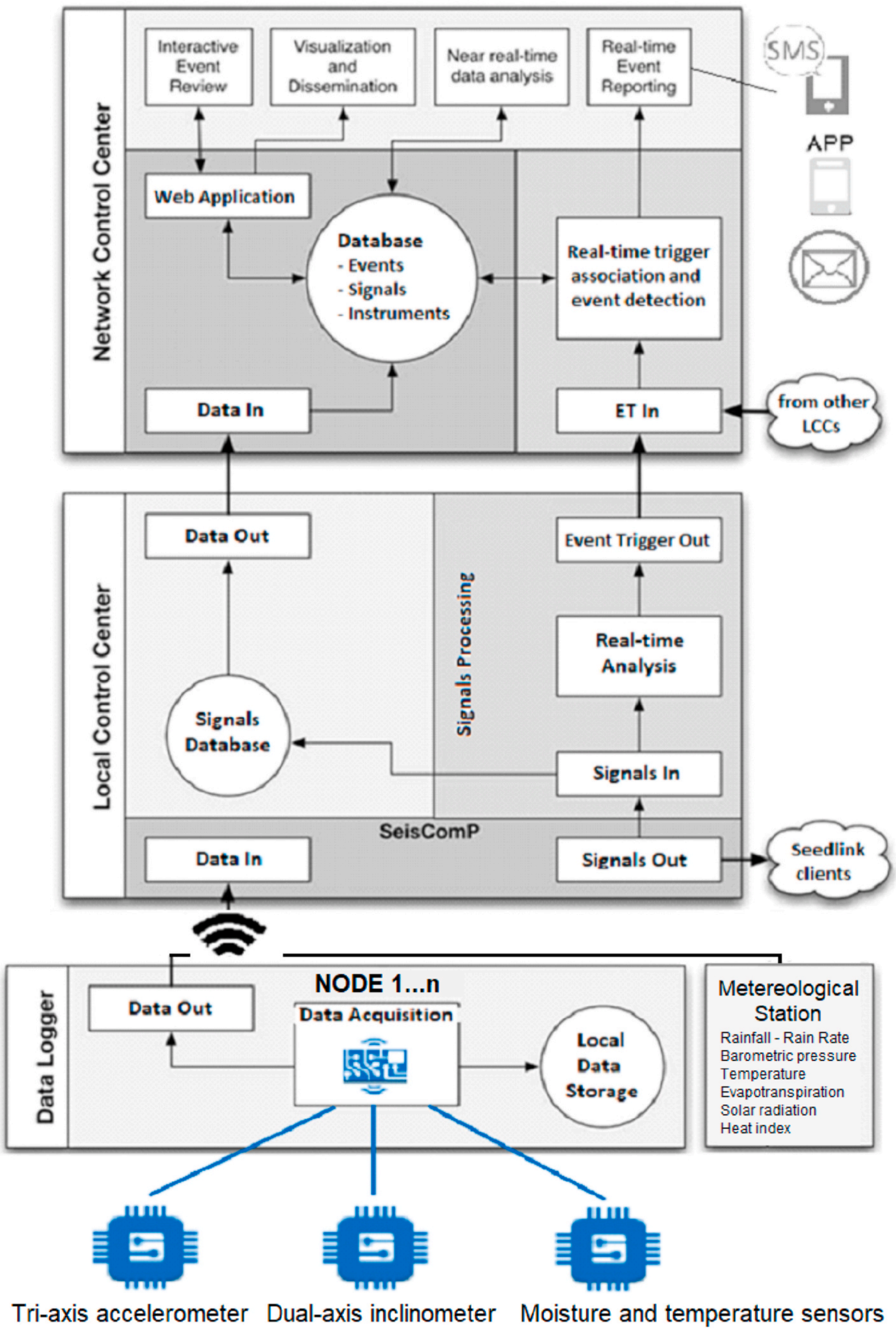

Fig. 14. Scheme of the data flow through the CAS_NET network (redrawn from [66]. The acquisition and analysis are divided into three levels (Data Logger, Local Control Center, Network Control Center) that characterize the physical structure of the network.

- The system will be implemented in modular form with the possibility of activate/deactivate its functions, via remote configuration;
- The data of all the devices that make up the network will be collected by a Coordinator Node/Local Control Center, located at the Villa del Casale;
- The system will also transfer the data measured by the sensors to a central server via an Internet connection.

Concerning the software architecture of the CAS_NET monitoring network, it will be entirely based on open protocols and open source software packages mainly developed by the international seismological community (SeisComP, Swarm, Earthworm, Swarm) or designed ad hoc for the intended purposes.

The transmission protocol used is the SeedLink protocol and the data format is the Mini-SEED. The SeedLink protocol is a robust data transmission system, developed for use on the Internet or private circuits that support TCP/IP, originally created as layer of transport for the SeisComP software package (SeisComP, software, http://www.seiscomp.de/).

The real-time data management of the CAS_NET network will be organized in three main logical levels, which follow the physical structure of the network (Fig. 14).

The basic level is the data-logger (sensor node), where the signals of vibration, inclination, water content and soil temperature are digitized, time stamped and sent through a network connection. Other specific node such as the meteorological station, hydrometers and webcams are as well part of this logical level.

The intermediate level is the Local Control Center (LCC), where data flows from remote local stations/node are analyzed in real-time. The LCC also manages the Early Warning System and a database, where the waveforms for the seismic data and the time series of the other geophysical and environmental signals (inclinometric, soil humidity, temperature, etc.) are stored. The Villa del Casale local network server (LCC) will be a computer suitable for managing the entire workload of data acquisition and to the first processing in real-time.

The last level is the Network Control Center (NCC), where the association of phases and the detection of events are performed, and where the central database of the system resides.

At the same time, the NCC is the access point for further applications (e.g. near real-time analysis, modelling, etc.) and for the end-users.

5. Geomorphological and hydrological characteristics of the drainage basin

The analysis of the drainage basin of the Villa Romana del Casale and the modelling of the flooding and debris-flow events that may impact on the site has been carried out considering several datasets. Data acquisition was performed through the analysis of literature and archive documentation, cartography and historical photographic reports, and through on-site inspection. In particular, the following in-situ survey were performed:

- a UAV (Unmanned Aerial Vehicle) survey. Three flights performed with the Phantom 4 Pro drone made it possible to acquire almost 450 images processed with the SfM (Structure from Motion) technique. The survey was conducted by carrying out a first flight inspection in order to determine the level of arboreal cover and the possibility of inserting GCP (Ground Control Point). However, it was evaluated that the best solution was to couple the survey to a series of GCPs common to the official ATA CTR 1: 10,.000 ed. 2012–2013 (fast update) with 0.25 m resolution for the orthophoto and 2 m for DEM (Digital Elevation Model). The processing of the acquired images has been carried out with the Agisoft Photoscan software which allowed to obtain the following products: the dense cloud of points, the mesh, the DEM, the orthophoto of the area overflown. In conclusion, it was possible to obtain the 3D model, the DEM (Digital Elevation Model with a spatial resolution of 24.4 cm/px) and the ortho-image (spatial resolution 6.1 cm/px) of the river catchment.

- Continuous core drilling geognostic surveys over a depth of 10 m, at three different measuring points of the basin of the Villa del Casale. Open pipe piezometers for future monitoring of the water table level have been realized. Undisturbed samples have been analyzed through geotechnical laboratory tests.

The information of the DEM has been used in the area close to the Villa, where no vegetation is present, in order to have detailed data about the upstream channel and excavated area. These have been integrated within a DTM 2 × 2m provided by the Sicilian Region (2007). The SAGA-GIS software has been used to have information on the catchment area and on the drainage network, extracted from the DTM according to the classical method proposed by [67]. The Villa del Casale basin, reported in Fig. 15, whose closing section is located near of the Villa, has an extension of approximately 0.75 km^2, with a total height difference of approximately 244 m between the maximum altitude of 778.3 m and the minimum of about 534.3 m. The basin is characterized by several small tributaries that come down from the slopes. There are high slope values on the top, with local values often higher than 90 %, and averaged values over the entire surface of the basin which are around 26 %. This causes the development of a branched hydrographic network, though for the most part of low hierarchical order. The high slope allows the surface runoff waters to have a high erosive potential. The main reach originates in the upper part of the basin on the slopes of Mount Mangone. It has an overall development of about 1.6 km and an average gradient of 12 %. The concentration time is about 15 min.

An analysis of the historical evolution of elevation contour lines transformation during the last century provides information about active erosion processes. Fig. 16 (a) shows the overlap of the contour lines extracted from the 2012 DEM with those of a 1: 25.000 scale 1933 map. Although comparison of maps gathered using different techniques could lead to potential errors [69], it is worth pointing out that the data presented in Fig. 16 are used here only for highlighting qualitative trends of the site evolution over a relatively long period. By analyzing Fig. 16 (a), it emerges that erosion has transformed the basin geomorphology in the last 90 years with the northern hillside more affected by erosion. As Fig. 16 (b) shows, the lower slope of the northern hillside is a circumstantial evidence of a more advanced erosive stage, due to scarce soil cover and thermic stress due to southern exposure. Fig. 16 (c) shows that the soil depth is higher on the southern hillside, confirming that erosion on the northern hillside is at a more advanced stage.

Due to their intense use of water, we can argue that the Romans built a dam-like structure upstream of the Villa, to feed the reservoirs and to ensure water supply. This altered the natural runoff in the area and after the Villa was abandoned, during centuries with no enough maintenance, the settling generated an increase in ground level [52].

Debris-flow phenomena are generally caused by intense rains that induce the rapid saturation of masses of loose granular material, with an increase in interstitial pressures and a rapid decrease in intergranular resistances, undermining the static balance of the potentially unstable solid material. Many studies have tried to propose statistical hydrological models to define rainfall thresholds above which the risk of landslide is very high. These models are mostly experimental and calibrated on the analysis of a large number of basins and observed debris-flow events. Relations like $I = aD^{-b}$, where the intensity of precipitation I is expressed in mm/h and the duration of precipitation D is expressed in hours, are quite used in the literature. By plotting the duration and intensity in a Cartesian graph, it is possible to draw a threshold curve that divides the Cartesian plane into two half-spaces representing the conditions of stability (upper) and instability (lower) respectively. One of the first of such models was proposed by [70]. He used data from 73 casting events and identified the threshold with the following equation $I = 14.82\ D^{-0.39}$. Relations of this type are proposed for Italian basins in relation to various sites and regions [71–74].

Although these relationships cannot have an absolute general validity, because they are validated on basins that cannot be perfectly

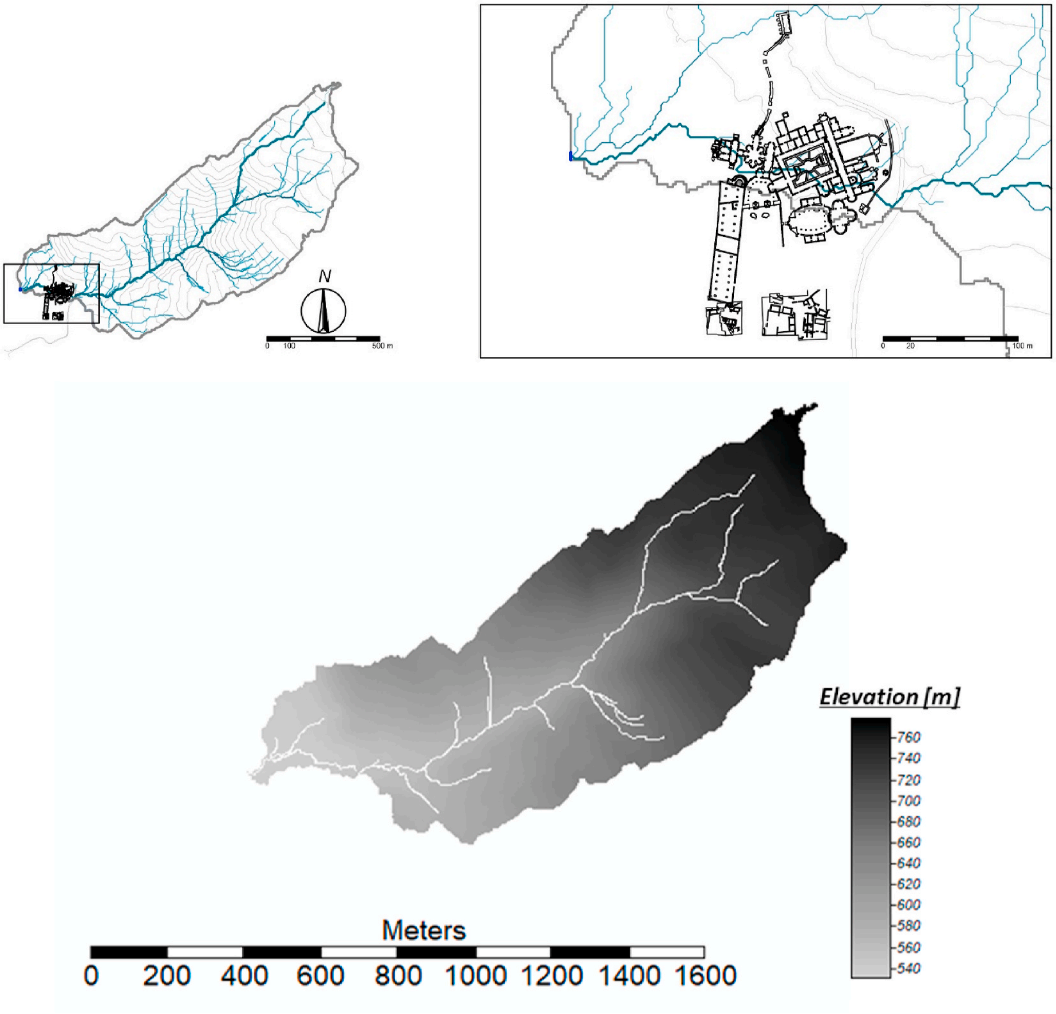

Fig. 15. Upper panels: location of the Villa at the closure section of the catchment area. Bottom panel: DTM of the drainage basin and network used for the numerical computations.

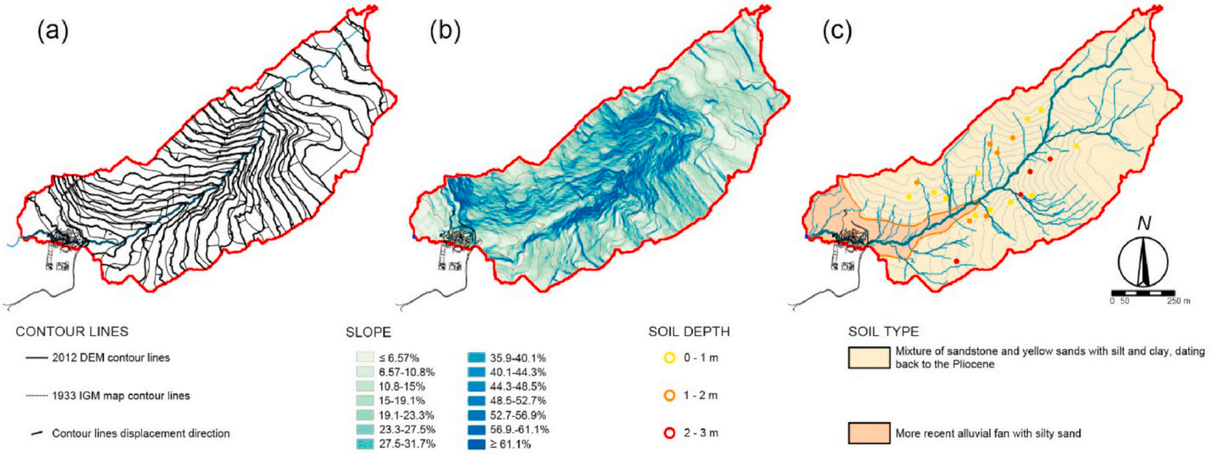

Fig. 16. (a): Overlap of the contour lines extracted from the 2012 Sicilian Regional DEM with and those of a 1:25′000 scale 1933 IGM map, sheet 268, II S.E. The arrows indicate the contour lines displacement direction. (b): Slope map. (c): Geological map. Yellow, orange and red points indicate different soil depth values. Source of background informations: Carta Geologica d'Italia, [49,52,68].

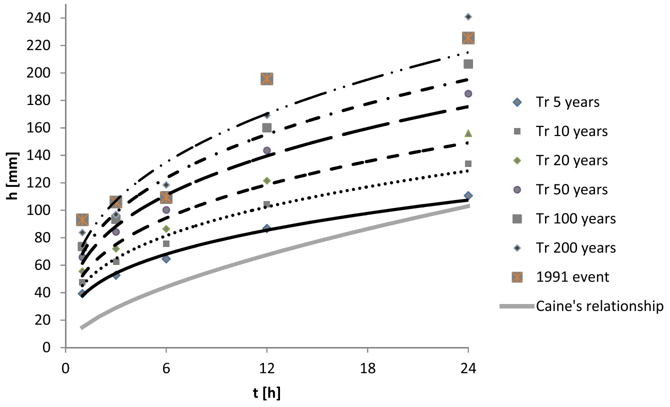

Fig. 17. Pluviometric probability curves reconstructed using pluviometric data recorded by the pluviometric station in Piazza Armerina (data refers to the period 1928–2015). Comparison with the Caine threshold curve and identification of the 1991 flood event.

superimposed on the case study considered, they allow a rough assessment of the actual risk of triggering debris flows. Once the monitoring system will become operational, the development of a rainfall threshold for this specific site will be developped [75]. By analyzing pluviometry data, results in Fig. 17 indicate that even events of intensity corresponding to events to return times of less than 5 years could cause the triggering of casting phenomena inside the basin. The pluviometric curves reveal also that the estimated return period of the 1991 event should be larger than 200 years, but it is important to stress the fact that as an effect of climate change, extreme precipitations could occur more frequently, thus reducing the return period of such an event [76].

More specific approaches on the initiation and propagation of debris flows consider numerous other aspects such as infiltration and the elevation of the groundwater table [77] but are less immediate in their application.

The geomorphological evolution of the Villa del Casale basin was investigated considering: (i) the analysis of the UAV aerial photos; (ii) in situ on ground observation; (iii) land use cover of the Gela River Hydrogeological Plan [78]; (iv) and Google Earth satellite images over the past decades, in order to identify possible areas likely prone to triggering of debris-flow phenomena. One of the critical issues that emerged is the deforestation of various areas of the Villa basin, due both to fires, such as those occurred in 2004 and 2010, and to civil works, such as the construction of a large parking lot in an area immediately upstream of the Villa. All these facts had negative hydraulic effects, favoring the generation of more intense surface runoff and erosional processes. In Fig. 18(a), (b), (c), (d), (e) we summarize the transformations in terms of vegetation cover over time, while Fig. 18(f) identify four possible debris-flow source areas.

Data on the geotechnical characteristics of the soil have been used to define the rheological properties of the water-sediment mixture, needed for the numerical modelling of debris-flow propagation. To this aim, three boreholes were realized on-site (Fig. 19) and the collected samples were analyzed. An undisturbed sample was taken for each of the boreholes on which a granulometric analysis, whose results are reported in Fig. 20, was performed, while the stratigraphic structure was reconstructed along the entire drilling hole (Fig. 21).

6. Analysis of debris-flow event scenarios

6.1. Setup of the numerical model

The numerical modelling of the propagation of debris-flow events, that could impact on the Villa del Casale, has been carried out at catchment-scale. The Villa del Casale basin is modeled using 5 × 5m side square mesh grid, whose elevation data are obtained by interpolating the elevation data of a 2 × 2m DTM. In particular, the grid comprises the part of the basin within which phenomena of debris flows can initiate, propagate and settle. Therefore, it was considered appropriate not to include the very upstream and southern parts of the basin, characterized

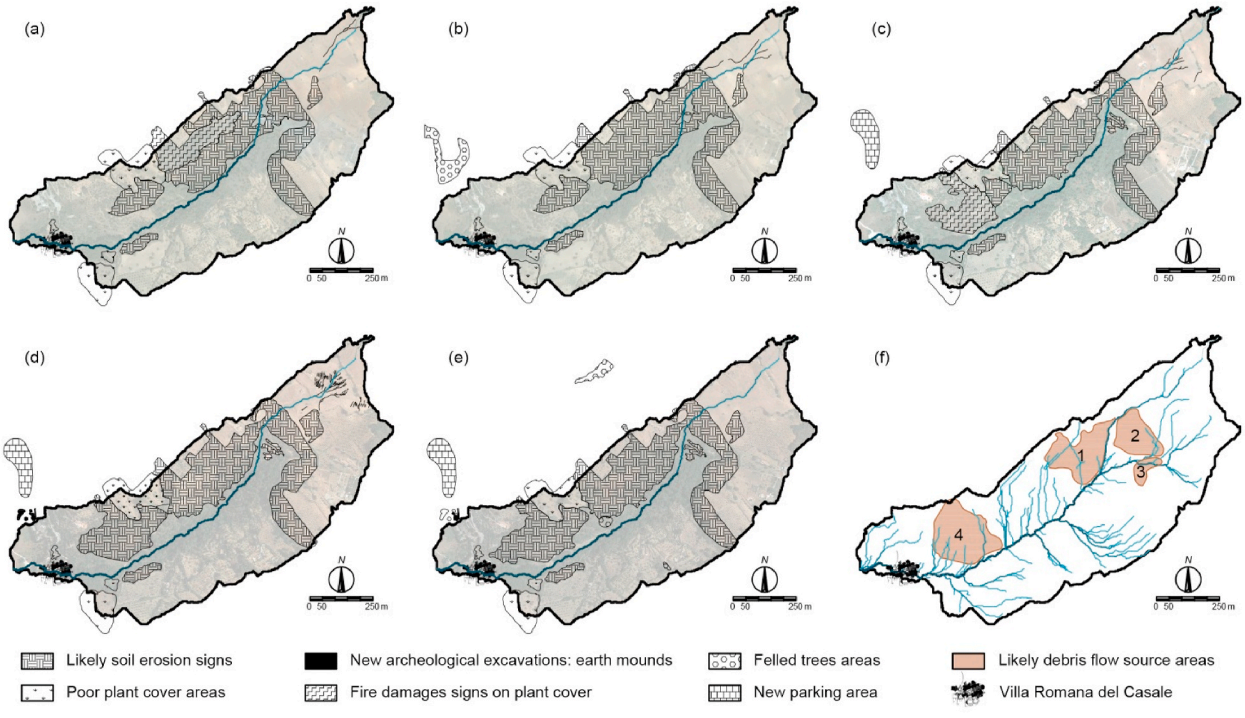

Fig. 18. Comparison between different years satellite images that makes the predisposing causes of debris-flow development more evident. Areas that show erosion signs increase over the years, especially after fire action. (a): October 02, 2004. (b): July 12, 2005; (c): May 09, 2010; (d): July 28, 2013; (e): June 15, 2017; (f): four likely debris-flow source areas identified.

Fig. 19. Location of the three boreholes realized within the basin of the Villa Romana del Casale.

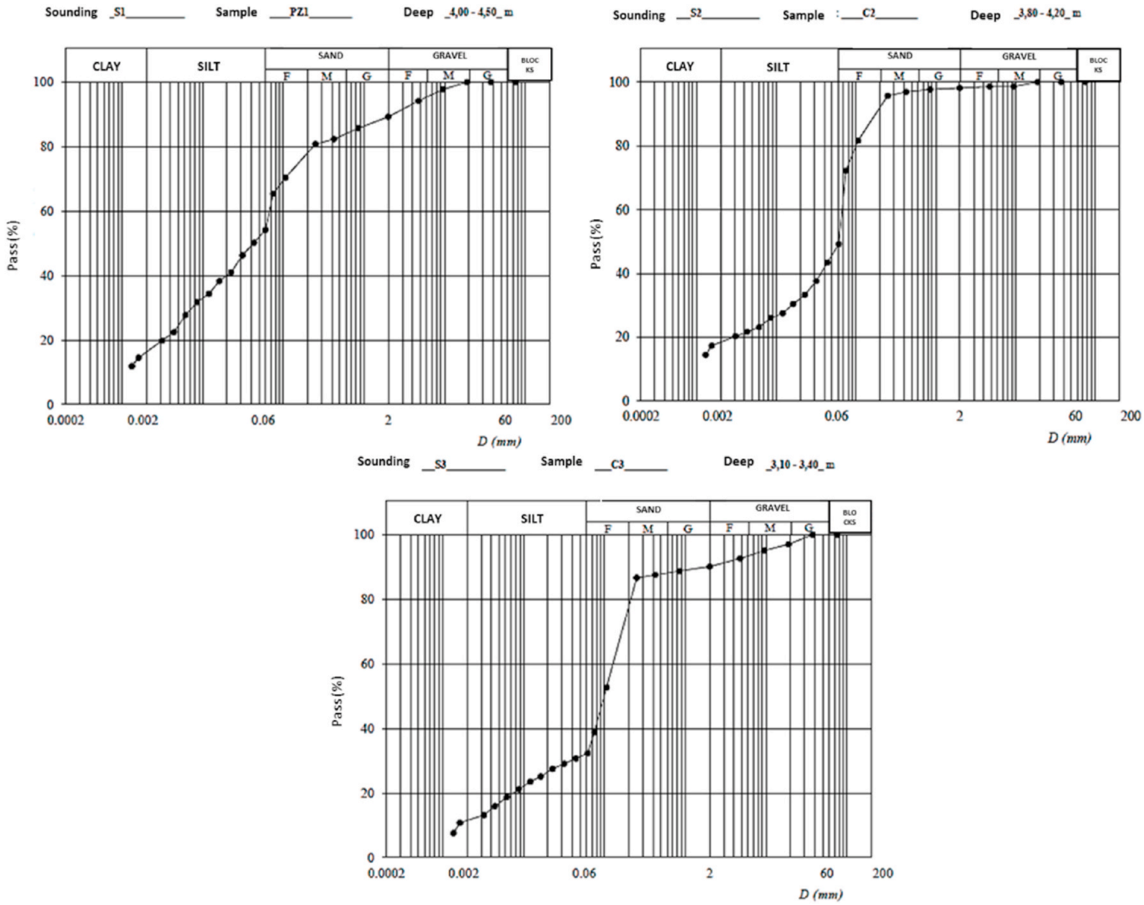

Fig. 20. Granulometric curve of the three examined soil samples.

by more modest value of the slopes. The percentage of the simulated catchment area is 70 % of the total catchment surface. Additionally, in order to properly investigate deposition processes which may be relevant for the proper management of the archaeological site, the alluvial area downstream of the Villa, up to the right bank of the Nocciara creek, has been included in the simulations.

To verify the dynamics of possible debris-flow events, which may impact the archaeological site of Villa del Casale, and the effectiveness of the protection measures present, the structure of the Villa was simulated as a single closed body (Fig. 22). In this way, the elements of the grid corresponding to the Villa cannot be invaded by the incoming flow. Thus, these areas can deflect the flow but cannot hold any

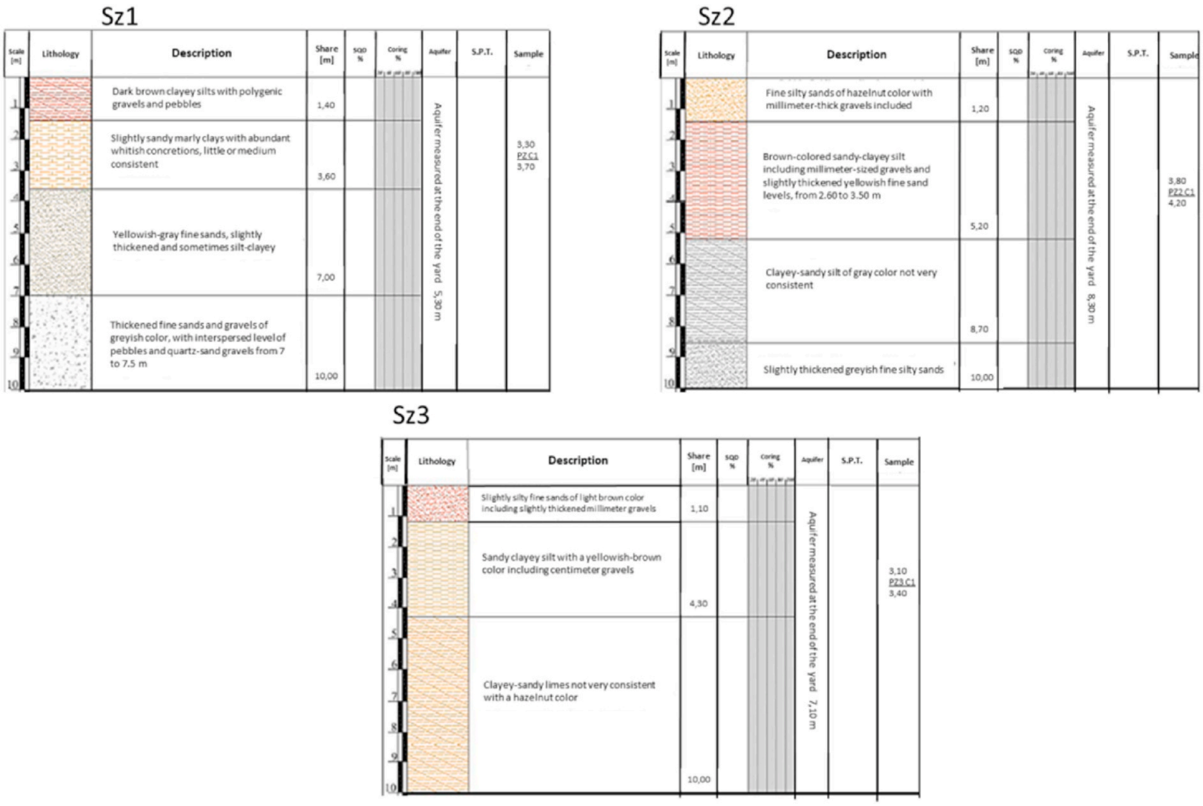

Fig. 21. Soil stratigraphy for the three boreholes carried out on site.

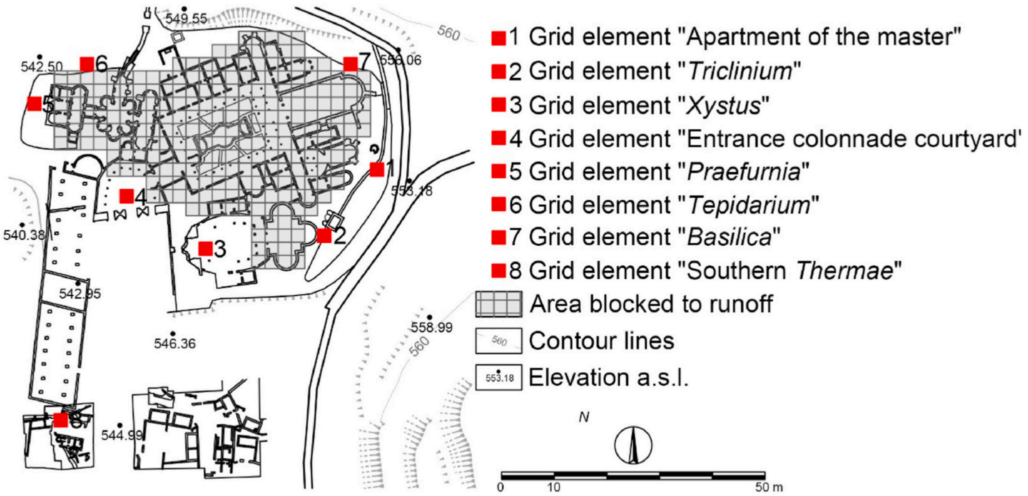

Fig. 22. Position of the numerically blocked area of the Villa (in gray) and of the representative grid elements located along the perimeter of the Villa (in red) and used for the analysis shown in Fig. 24.

sediment volume. The presence of the reinforced concrete channel, built upstream of the Villa to divert the flows coming from the upstream basin, was modeled in order to evaluate its effectiveness in terms of hydraulic protection.

6.2. *Characteristics of different debris-flow event scenario*

In the present work, in order to provide an overview of potential impacts of debris flows on the Villa del Casale, a scenario analysis that investigates a range of volumes of sediments that could be mobilized within the drainage basin has been carried out. Such an approach has been used by several authors [79–82] to overcome the determination of the return period of a debris-flow event, which would require the estimate of return period requires an extensive modelling (e.g. recurring to Montecarlo simulations) making an estimate of different phenomena variability (e.g. rainfall, soil saturation, sediment availability, stratigraphy distribution of the basin, etc.). In particular, here, given the small dimension of the basin, for each scenario, all the unstable areas upstream of the Villa are assumed to contribute to debris-flow formation, each scenario being characterized by a different thickness of the mobile sediment layer, in the range 0.2–0.8 m.

The aim is to analyze different possible scenarios which, together with the monitoring sensor network, will be able to provide a real-time assessment of the hazards for the Villa del Casale in relation to different possible situations. The results of the risk scenario analysis will allows us also to select and design effective protection systems.

The time evolution of the simulated event is represented by the input triangular solid-liquid hydrograph, whose duration is set equal to 6 min. Such a value is deemed representative of a rapid trigger of an event of high specific intensity [77,83]. Table 1 summarizes the volumes and the maximum flow rate for the four areas which could be affected by sediment entrainment processes (Fig. 18(f)), for each of the simulated scenarios. In particular, the terrain void ratio is set equal to 0.6. Since runoff-generated debris flows are considered, the terrain is fully saturated, leading to a minimum of 0.4 volume of water in the mixture, which is further increased by a sligthly larger amount of water that comes from the runoff that triggers the debris flow. This latter is estimated to be an additional 0.2 water volume, which leads to a 0.5 concentration of the entire debris-flow mixture [84]. The peak flow rate relates to the peak of the solid discharge, while the debris-flow mixture flow rate is obtained by considering a 0.5 concentration.

The empirical coefficients α and β, needed for the definition of the rheological characteristics of the soil, have ben set according to [59]. Taking into account the geotechnical characteristics of the in-situ sample, described in Section 5, a corresponding soil with cohesive characteristics comparable to those measured in laboratory for the study site has been assumed. The following values have been used: $\alpha_1 = 0.000201$, $\beta_1 = 33.1$, $\alpha_2 = 0.291$, $\beta_2 = 14.3$.

The overall duration of the numerical simulation of the debris-flow propagation and deposition is set equal to 24 h, in order to evaluate a possible natural emptying of the flooded areas at the end of the event.

6.3. Results

The numerical simulations performed using the FLO-2D model provide a map of the flooded areas. The maximum depth of debris flow recorded at all the cells of the river catchment for the three simulated scenarios is depicted in Fig. 23(a), (c), and (e) respectively, while Fig. 23 (b), (d), and (f) report the thickness of the residual debris deposit at the end of the simulation. Such a final debris depth value is due to the fact that debris flow stops when the shear stress at the bed falls below a threshold that depends on the fluid properties.

Notwithstanding the fact that depth maps are provided at catchment-scale, it is possible to observe some critical areas in the nearby of the Villa. Indeed, it results that the artificial protection channel, located upstream of the Villa, seems not able to convey a significant portion of the flow coming from upstream, with a consequent overflow that reaches the archaeological site, located at a much lower level than the upstream floodplain (about 12 m).

Moreover, the area behind the Basilica (see grid element 7 in Fig. 22, for location) represents the main area for the deposition of debris material. It should be noted that this area, located on the hydraulic right of the channel, is not only the area where the debris flow first hit the building of the Villa, but also the area were deposition of debris material occurs. It should be remembered that the limits of the present numerical simulations, in particular the size of the computational grid and the fact that the structure of the Villa is modeled as a block, may induce an overestimation of the volume of material deposited outside of the Villa. In any case, since in reality such a debris-flow volume will enter the building and will be deposited there, as it occurred during the 1991 event described in Section 3, the present simulation are able to quantify the overall volume of sediments that would be trapped at the site.

In order to evaluate the effects that the different scenarios have on the archaeological area in terms of height of debris material and speed of the debris flow, eight representative gauge-cells have been considered at key locations within the archaeological area (Fig. 22). Fig. 24 reports the evolution of the debris-flow height and velocity at such locations.

It can be observed that the results of the three scenarios are quite similar in terms of debris-flow depth, with a sudden increase when the flow hit the structure, due to the flooding wave, followed by a slower decrease up to the deposition depth at all points. Interestingly, not only the most upstream area, i.e. those behind the Apartment (1) and the Triclinium (2), are interested by the large instantaneous depth values, ranging between 2.5 and 4.5 m, but also some more downstream area, such as the Praefurnia (5), the Tepidarium (6), and the Entrance (4), with values in the range 1.4–3 m. This is likely due to the fact that close to this area, due to the presence of the downstream excavation front, which is about 5–6 m high, and acts like a dam for the coming flow. It should also be noted that due to that also the final deposit height are the largest here, as shown by the values at Praefurnia (5), equal to about 2 m. The lowest depths are registered behind the Basilica, due to the presence of a watershed point.

The largest velocities are recovered close to the Triclinium (2) area, with values that reach 0.2 m/s. In general, velocities are quite low, O (0.01–0.1 m/s), indicating the fact that as soon as the debris flow reaches the archaeological area, it slows down, favoring the accumulation of debris and mud.

As the intensity of the simulated scenario increases, the time intervals between the starting of the phenomenon from the hill slopes and the reaching of the site decreases, going from about 2 h to 6 min in the case of scenario 1, to 1 h and 48 min in the case of scenario 2, up to 1 h and 27 min in the case of scenario 3.

Table 1

Summary of input data for each of the simulated scenarios. For each of the four detachment areas identified on the basin, the following parameters are reported: surface area [m^2]; thickness of the mobilized debris layer characteristic of the simulated scenario [m]; total volume of the mobilized solid mass [m^3]; characteristic void index of the soil deduced from the geotechnical analyses [−]; net volume of mobilized debris [m^3]. Data for the construction of the event solid-liquid hydrographs are also reported: total duration [min] and peak flow rate of the solid flow rate [m^3/s].

	Areas of Detach. no.	Surface [m^2]	Release Depth [m]	Gross Volume [m^3]	Void Ratio	Net Volume [m^3]	Event Duration [min]	Q_{max} [m^3/s]
Scenario 1	1	11,000	0.20	2200	0.60	1375	6:00	7.67
	2	17,000	0.20	3400	0.60	2125	6:00	11.83
	3	5000	0.20	1000	0.60	625	6:00	3.50
	4	2000	0.20	400	0.60	250	6:00	1.39
	total	35,000		7000		4375		
Scenario 2	1	11,000	0.50	5500	0.60	3438	6:00	19.11
	2	17,000	0.50	8500	0.60	5313	6:00	29.56
	3	5000	0.50	2500	0.60	1563	6:00	8.72
	4	2000	0.50	1000	0.60	625	6:00	3.50
	total	35,000		17,500		10,937		
Scenario 3	1	11,000	0.80	8800	0.60	5500	6:00	30.56
	2	17,000	0.80	13,660	0.60	8500	6:00	47.22
	3	5000	0.80	4000	0.60	2500	6:00	13.89
	4	2000	0.80	1600	0.60	1000	6:00	5.56
	total	35,000		28,000		17,500		

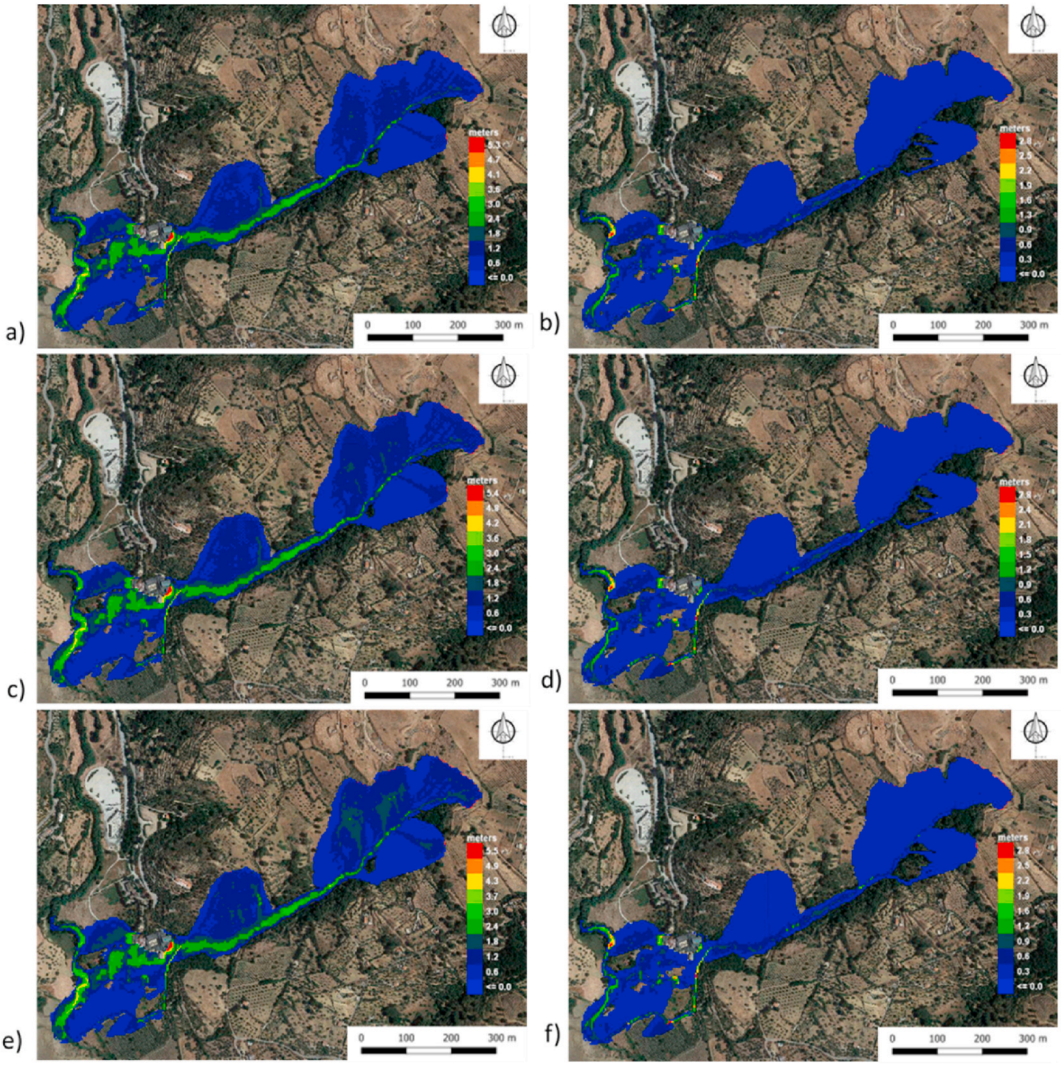

Fig. 23. Maximum level of debris flow recorded during the simulation, for scenario 1 a), scenario 2 c), scenario 3 e). Final debris level at the end of the simulation for scenario 1 b), scenario 2 d), scenario 3 f).

7. Conclusions

In the present work, an approach to assess the debris-flow hazard for archaeological sites is presented, based on a combination of geomorphological and hydrological analyses, field survey and in-situ measurements, monitoring system and hydraulic numerical modelling. The idea is to take into account specific features of the site by overcoming the actual risk management practice, which often for administrative reasons is focused just on the specific archaeological area, and to highlight the fact that it is necessary to extend the analysis, and thus the application of future flood mitigation measures, to the overall river catchment of the archaeological site.

The investigation is carried out with reference to the case study of the Villa Romana del Casale (Italy). The analysis presented here showed that the entire history of this UNESCO site has been strictly linked to its conflictual relationship with water, since its foundation in mid IV century A.D., development, following abandonment and destruction in Middle Age, archaeological discovery in 1950, and present management of the site. Indeed, on the one hand water availability and Roman hydraulic engineering skills allowed the settlers the development of many advanced hydraulic systems within the Villa (e.g. hot and cold thermae), on the other hand, water-related disastrous events, such as a series of flood and debris flow, caused the destruction of the site. Even nowadays the site is significantly threatened by mud flows that periodically damage the unique mosaic decorative apparatus.

The vulnerability of the site to debris-flow events has been assessed through field measurements and a numerical analysis of debris-flow propagation that could be generated on the slopes of the river catchment. Based on literature trigger thresholds, even low-intensity rainfall events could induce movement of solid material from unstable slopes, especially where erosional processes have already started. In this preliminary analysis, three risk scenarios were considered, with three different values of the thickness of the mobilized layer of sediments within four possible trigger areas. The two-dimensional simulation of different debris-flow scenarios allows one to draw space and time-dependent maps about deposition areas, water depth and speed values, and test the efficiency of the existing hydraulic defense systems.

The results of the numerical simulations indicate that the excavation area, located 5–13 m below the surrounding floodplain, is easily flooded by the debris-flow material for all the considered scenarios. Moreover, once flooded, the low sloping bottom and the pool-shape of the excavation favor the accumulation of sedimentary material, especially in the correspondence of walls or obstacles to the flow. The large flow depth values, up to 4.5 m, reached along the perimeter of the Villa when the flow hit the structure, represents an additional hazard for the site, since large amounts of debris could actually enter the Villa from the openings (i.e. windows, doors, low walls) and damage its valuable mosaics. The simulations also showed that the actual hydraulic protection of the site,

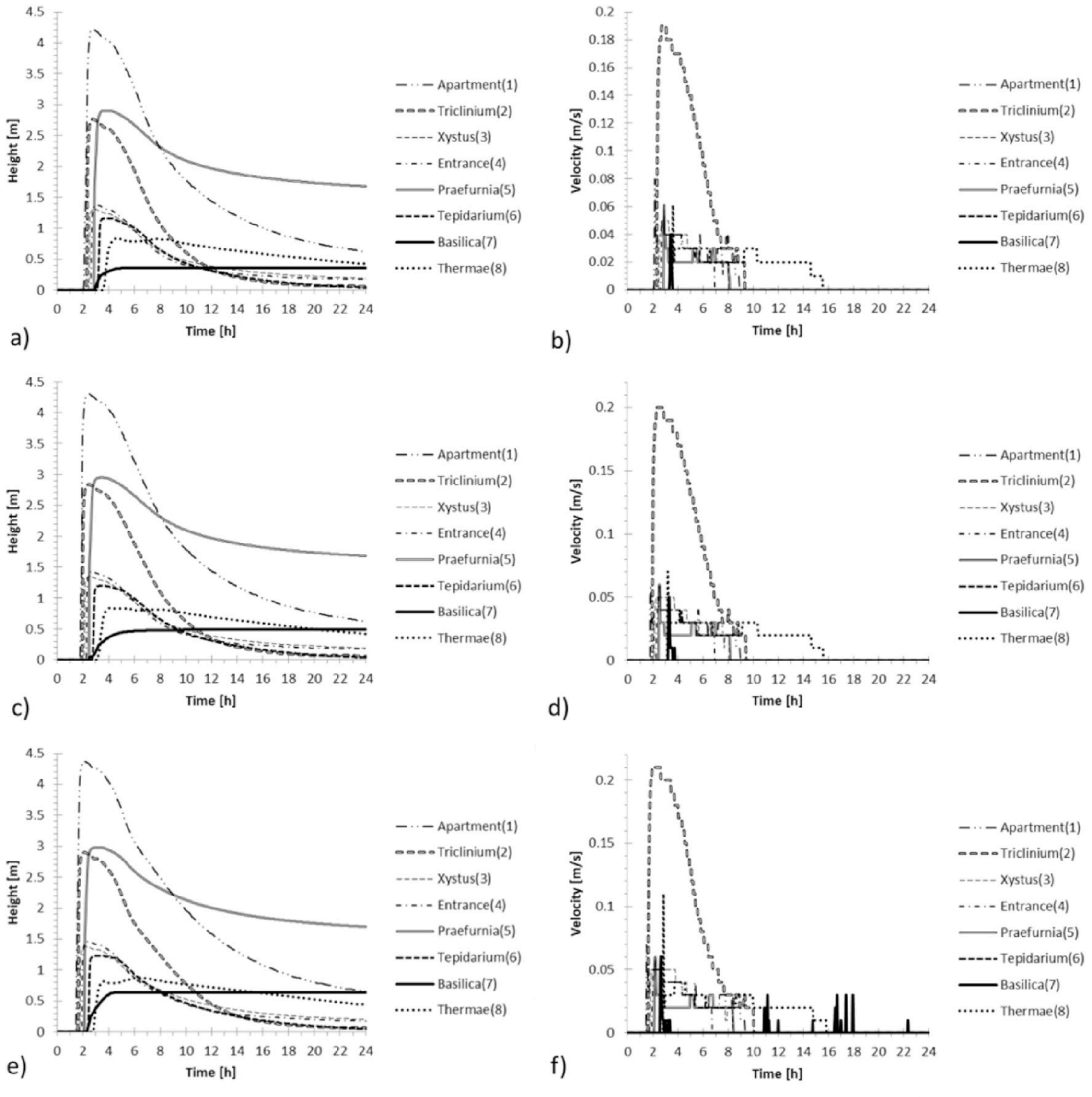

Fig. 24. Time evolution of debris-flow event at key locations around the Villa Romana del Casale (see Fig. 22) for the three simulated scenarios. Debris-flow depth: (a) scenario 1; (c) scenario 2; (e) scenario 3. Debris-flow velocity: (b) scenario 1; (d) scenario 2; (f) scenario 3.

represented by a concrete channel upstream of the Villa aimed at deviating the upstream fluxes, is not efficient, as it works only during the initial phase of the debris-flow event, but later on, due to high viscosity of the fluid, the flow slows down, saturating the hydraulic section of the channel and overflowing toward the Villa.

The analysis presented here is based on literature triggering thresholds for debris-flow events and model parameters. This limits the value of the analysis, as the process dynamics is strongly site-dependent, and results obtained using parameters calibrated on different conditions should be considered with care. Future development of the work will overcome such limitations by taking advantage of the measurements of the sensor monitoring system presently under development, which will be installed over the catchment area. On the other hand, the results will be used coupled to those of the monitoring sensor network, to implement an Early Warning System (EWS). To this aim both a more extensive risk scenario analysis and more detailed simulations at the site-scale are planned. The application of the proposed approach will be also useful to define proper protection and prevention strategies against mud flow risk damages considering a catchment-scale perspective.

Results also showed that the time elapse between the triggering of the landslide and the arrival of the flow inside the excavation area of the Villa del Casale is O (1–2 h). It follows that the time interval available for alerting and adopting protection measures is very short. This observation support the need for the development of an EWS, on the basis of the information coming from on-site monitoring and numerical modelling (multi scenario approach) that must be efficiently integrated with downscaled weather forecast.

The foreseen EWS for cultural heritage will be useful to support the day-by-day management of the archaeological site, by providing data-driven event-based alerts which could trigger the implementation of local temporary mitigation measures, such as covering of decorated surfaces and mosaics, use of sandbags or more complex barriers for realization of temporary levees at key locations, etc., that could be easily removed after the event without affecting a sustainable fruition of cultural heritage site.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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