Hydrologic-hydraulic modelling in the Vezza catchment (Alpi Apuane, Italy): an area prone to flash floods and debris flows

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Abstract. The Alpi Apuane (Italy) are located a few kilometres from the coast of the Ligurian Sea, and they are characterized by peak elevations up to two thousand meters above sea level, as well as narrow, deeply incised valleys and steep slopes. Due to these morphoclimatic conditions, heavy rains are frequent, causing floods, landslides, and debris flows, particularly within the Vezza catchment. In this work we applied two different hydrological-hydraulic models to this catchment, focusing on the catastrophic debris flow event of June 19, 1996. Firstly, recent, well-documented rainfall events were used to validate the engineering geological model of the study area, then we began to analyse the rainfall-runoff and debris flow event of 1996 in the Cardoso sub-catchment. As models, we used the FLO-2D and a novel experimental model, developed by some of the authors and based on TRENT2D, in which the dynamic of a debris flow is fully coupled with the rainfall-runoff response of a basin. Preliminary results show how the used approach allowed us to gain some insight into the hydrological behaviour and debris flows formation, erosion, transport, and deposition in the Cardoso sub-catchment.

1 Introduction

In recent decades, climate change has led to an increase in extreme precipitation and runoff events [1], which can make flash floods and debris flows even larger and more frequent than in the past [2]. In urbanized mountainous areas, these types of events pose a major threat to local environments, populations, and infrastructures, leading to loss of life and livelihoods [3].

The study area selected for this work is the Vezza catchment located in the Alpi Apuane (Italy), a region particularly susceptible to intense precipitation events due to peculiar morphoclimatic characteristics. The Vezza catchment experienced severe flooding and debris flows over the centuries, like the catastrophic debris flow event that occurred on June 19, 1996, in the Cardoso sub-catchment. Several authors have studied the geological, geomorphological, hydraulic, and geotechnical factors controlling the slope stability of the study area [e.g., 4-6]. However, specific rainfall-runoff simulations, as well as modelling of erosion, transport, and deposition rates by debris flows are lacking so far.

The objective of this paper is to model the debris flow processes of the 1996 event through two different numerical modelling approaches: the FLO-2D hydrological-hydraulic model [7, 8] and a novel experimental model, developed by the authors belonging to the University of Trento, based on the TRENT2D model [9, 10]. In the latter, the dynamics of debris flows are fully coupled with the rainfall-runoff response of a basin. Both models are based on physical conservation principles.

For the 1996 event, rain gauges were not available within the Cardoso sub-catchment, nor were direct runoff measurements available. Hence, an in-depth hydrological analysis was performed in the Vezza catchment by modelling some well-documented recent rainfall events. For this task was used the FLO-2D model applying the Green-Ampt (G-A) infiltration approach [11] to a well-constrained engineering geological model of the study area. The satisfactory matching between simulated discharges of each event and the discharges recorded by the hydrometric station at the outlet of the Vezza, allowed us to check the robustness of the engineering geological model.

Both hydrological and debris flows modelling of the 1996 event were then carried out, which allowed us to highlight key processes which affected hillslopes and streams, such as widespread erosional processes or temporary deposition and subsequent erosion causing impulsive waves typical of debris flows.

2 Overview of the study area

The Vezza catchment (27 km^2) is located in north-western Tuscany (Alpi Apuane, Italy) in the Versilia River valley. The catchment area is characterized by the presence of two main torrents (Cardoso and Vezza) that converge to form the Vezza River (Figure 1), which in turn forms the Versilia River further downstream.

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2.1 Geological and morpho-climatic setting

The Versilia River valley is located in the southern sector of the Alpi Apuane tectonic window, where a metamorphic complex (the “Autoctono” and Massa units) and the Tuscan Nappe crop out [12].

The upper Versilia River catchment has a mountain morphology characterized by narrow, deeply incised valleys, and steep slopes, clearly influenced by the structural-geological arrangement of the Alpi Apuane area [6]. In general, the higher portion of the basins is divided by ridges composed of carbonate/dolomite rocks, often with slopes greater than 60°. Usually, these areas are rocky, or with a very thin soil layer, and are connected to the lower slopes by talus and scree deposits. On the other hand, these slopes are moderately steep (between 25° and 40°) and are often made up of metamorphic sandstone and phyllite schist rocks, which in turn are covered by thicker soils (0.3-2 m) where a dense chestnut forest develops.

The morphoclimatic conditions of the Alpi Apuane, which run parallel to the Tyrrhenian coast (Ligurian Sea), and the rapid rise of the relief (about 2,000 m a.s.l. in less than 10 km) favour the rapid cooling of humid air masses of Atlantic or Mediterranean origin [5], causing intense precipitation and, in some cases, extreme rains that trigger floods, landslides, and debris flows.

2.2 Flood and debris flow events in the Vezza catchment

During the last four centuries, numerous geo-hydrological events have occurred in the study area, some of which have been classified as "very high intensity" (catastrophic phenomena with very severe damage and fatalities): May 7, 1636; September 27, 1774; September 18-19, 1846; September 25-26, 1885; October 11, 1902; and June 19, 1996 [13].

The most recent and catastrophic event occurred on June 19, 1996, in the Cardoso sub-catchment. In this case, the observed maximum rainfall amount in 10 h was 460 mm, with a maximum hourly intensity of 160 mm. Hundreds of shallow landslides and hillslopes and in-channel debris flows were triggered, mobilising 1,400,000 m^3 of debris [5]. Most of the solid material was deposited along the main Cardoso valley, partially destroying the village, and resulting in twelve fatalities.

2.3 Available data

A hydrometric station (Ruosina station) is located at the outlet of the catchment under study, while three rain gauges are positioned at Retignano (1), Cardoso (2), and Pomezzana (3) (Figure 1). Rain gauges 1 and 3 have been in operation since 1996, while gauge 2 since 1998. Discharge data from the Ruosina hydrometric station have been available since 2004.

In addition, a detailed engineering geological study based on field measurements and laboratory determinations was conducted in the Vezza catchment by some of the authors of the Department of Earth, Environmental and Physical Sciences of the University of Siena, to evaluate both the saturated hydraulic conductivity and the depth of the soil. Then, morphometric clustering methods [14, 15] provided the continuous maps of the above parameters used for the subsequent numerical modelling.

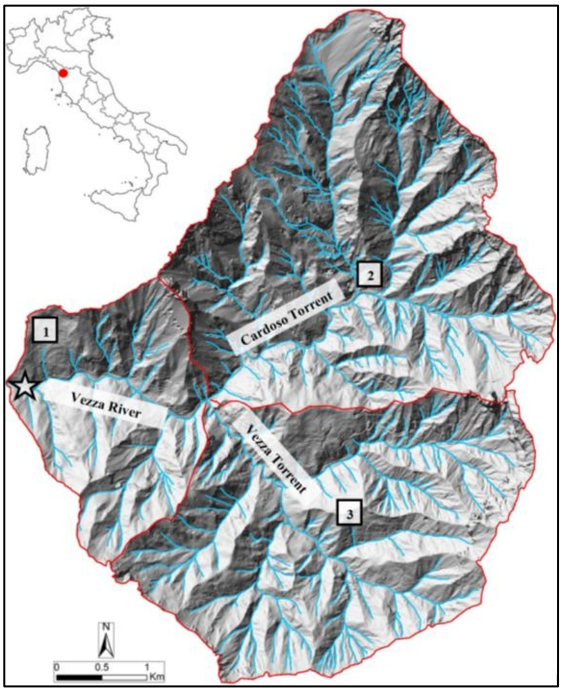

Fig. 1. Location of the Vezza catchment and its morphology. Red lines: borders between the sub-catchments of the Cardoso and Vezza torrents. White boxes (1-3) and white star: rain gauges and hydrometric station, respectively.

3 Rainfall-runoff modelling of recent rainstorms in the Vezza catchment

Ten rainfall events that caused a rapid increase in the flow of the Vezza River were selected (Table 1). These events differ in the season they occur, duration, and intensity. In no case did flooding of inhabited areas or significant erosion processes occur.

Table 1. Maximum rainfall peak and associated maximum peak discharge of the selected rainfall events recorded by the gauges in the study area. *Maximum rainfall peak and maximum peak discharge of the 1996 debris flow event [4].

Event	Max Peak Rain (mm/15’)	Max Peak Discharge (m^3/s)
19/6/2010	15	171
21-22/12/2010	5.8	58
25-26/10/2011	23	148
30/3/2013	7.8	98
21/10/2013	21.8	175
15-16/3/2018	8.4	33
1-2/2/2019	12.2	94
2-3/3/2020	6.8	78
4/6/2020	31	149
4-5/12/2020	15.4	92
*19/6/1996	61.8	381

Numerical modelling of these events was performed using the well-established software FLO-2D, a hydrologic-hydraulic and distributed model that continuously calculates rainfall-runoff volumes from the catchment area according to the digital elevation model, rainfall amount and intensity, land use, and soil type. Precipitation loss (interception) and infiltration are also considered and spatially allocated within the computational domain. The G-A approach was used to estimate the infiltration processes. In this model approach, the saturated wetting front is assumed to move vertically downward from the ground surface as a single piston-like displacement. Horizontal subsurface flow is not considered in the FLO-2D model. The matching between the simulated and measured discharges was satisfactory, confirming the reliability of the engineering geological survey data and related model.

4 Rainfall-runoff and debris flow modelling of the June 19, 1996, Cardoso event

Two numerical modelling approaches were considered for the simulation of the 1996 catastrophic debris flow event that destroyed the village of Cardoso (Figure 2), namely the FLO-2D model and the experimental TRENT2D-based, rainfall-runoff mobile bed model. Their main features are presented in the following sections.

Fig. 2. Destruction of the Cardoso village caused by severe debris flows deposition [16].

To validate the models, since no direct discharge measurements were available for the Cardoso catchment, the liquid discharge values were compared with those of [4], which were calibrated considering the amount of water flowing in and out of a dam near the Cardoso catchment during the event. Moreover, to compare the debris flow modelling results, we used the maps of both eroded and inundated areas obtained from the post-event orthophotos interpretation, as well as the maximum heights of deposition obtained by interpreting archive photos of the event.

4.1 The FLO-2D model approach

As with the simulation of recent precipitation events, the rainfall-runoff modelling of the 1996 event is based on the G-A approach to determine runoff values along the hydrographic network.

Following the liquid forcing evaluation, a back-analysis of debris flow propagation and deposition was performed. Since FLO-2D is a fixed bed model, erosive processes were not considered. For this reason, specific inflow sections of the flow mixture were selected along the hydrographic network. In addition, various rheological parameters and different amplification factor formulas were evaluated to estimate the volumetric concentration of sediment.

4.2 The Experimental TRENT2D-based, Rainfall-Runoff Mobile Bed model approach

Initially, the rainfall-runoff model was used in its non-erodible bed mode, to evaluate the sole liquid runoff and results were compared with those of FLO-2D. In this mode, the model uses a two-dimensional, coupled surface and subsurface flow description in which the surface flow occurs over a fixed bed. Like the FLO-2D model, infiltration is based on the G-A equation while in contrast, the TRENT2D model considers sub-surface flow and possible upwelling fluxes.

After this phase, we switched to the mobile bed mode to study the impact of the debris flow formation on the runoff response of the basin. In this mode, the model uses, as surface flow, a mobile bed debris-flow model which interacts dynamically with the subsurface model in terms of liquid flux exchanges and variation of the relevant soil depth available for the subsurface flow. Possible non-erodible zones can be considered as well.

The full model was applied in some sub-basins of the Cardoso catchment, where erosion processes were particularly severe during the 1996 event, and where the importance of the coupling was relevant in the formation of the debris flow and the runoff response of the basin.

5 Preliminary Results

The most relevant results that were obtained can be summarized as follows:

- The hydrological analysis in the Vezza catchment provided quantitative information on infiltration and runoff processes in response to rainfall events of varying intensity and duration. Moreover, the modelled hydrographs were consistent with those observed.
- The experimental rainfall-runoff mobile bed model allowed us to simulate some key processes connected to the widespread debris flows affecting hillslopes, first-order streams, and the main hydrographic network during the June 19, 1996 event in the Cardoso sub-catchment. Namely, it was possible to model: (i) the variation of the hydrological response of the catchment caused by morphological changes; (ii) the widespread debris flows processes (an example is depicted in Figure 3); (iii) the temporary deposition and subsequent erosion of solid material causing the development of impulsive waves typical of debris flows.

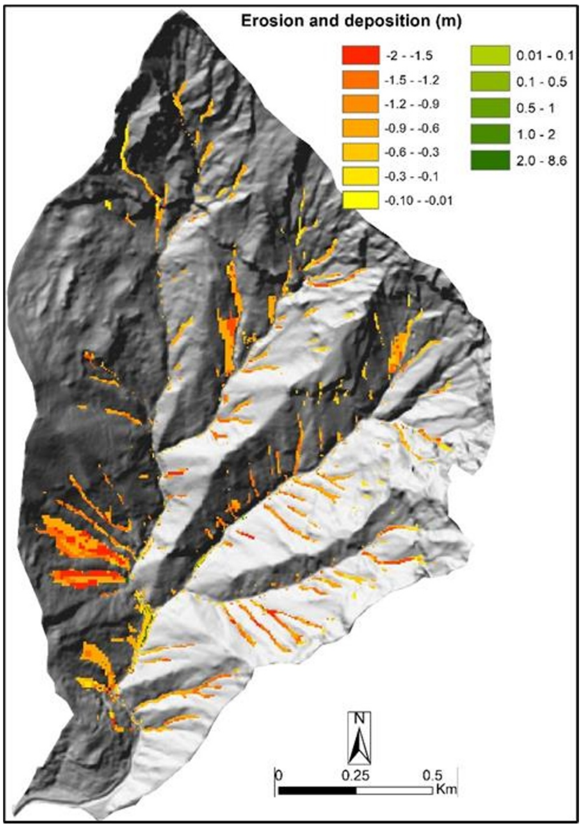

Fig. 3. Dynamics of erosion and deposition (m) debris flow processes occurred on June 19, 1996, within a portion of the Cardoso sub-catchment.

6 Concluding remarks

An adequate knowledge of the engineering geological framework, based on the integration of detailed mapping and specific field investigations, is a fundamental prerequisite for further accurate rainfall-runoff and debris flow modelling using physically based approaches.

Starting from this framework, the modelling tools used allowed us to improve our knowledge of the hydrological behaviour and its modification connected to debris flow processes in the Vezza catchment, an area particularly prone to such extreme-precipitation-induced geo-hydrological events.

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