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New technology in debris-flow modelling: A WebGIS integrated solution for TRENT2D

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ABSTRACT: Successful debris-flow hazard management in mountain regions is often based on the use of mathematical models. However, advanced models are generally quite complex to be applied, not entirely user-friendly and require high-performing hardware. Overcoming these drawbacks can lead to a wider diffusion of advanced modelling tools. In this work, a smart and easy-to-use modelling solution is proposed for the model TRENT2D, which simulates debris flows and hyperconcentrated flows over a mobile bed with a two-phase approach. TRENT2D was re-developed as a service and equipped with WebGIS technology. This solution transfers computational burden from local computers to a server and simplifies the management of georeferenced inputs and outputs of the model. In addition, the new infrastructure was enriched with a BUWAL-type hazard-mapping procedure, allowing to model and evaluate hazard scenarios in a unique and complete working environment.

1 INTRODUCTION

In the last years, frequency and intensity of extreme rainfall events have risen, especially in Europe and North America, because of climate change (IPCC 2014). This trend has led to an increase in the number of debris-flow events and areas subjected to these phenomena and to a consequent growth in the vulnerability of urbanised mountain regions. Therefore, incisive planning of protection and mitigation measures has become an undeniable need.

In the last decade, several 2D models simulating debris flows and hyperconcentrated flows have been developed, with increasing accuracy and reliability (see Iverson & Ouyang 2015 for an overview). Some of them have already been used to perform back analysis, assess hazard and evaluate the efficacy of safeguard actions, with encouraging results. These applications suggest that mathematical models can support hazard assessment and management effectively.

The UE Flood Directive (2007/60/CE) invites UE Member States to base assessment and management of flood risks on "appropriate best practice and best available technologies not entailing excessive costs". Similar recommendations are given in the Stafford Act (U.S.C. 5121-5207), where the use of "the most cost-effective and efficient technology available" is demanded. These directions suggest that the most advanced models should be used in planning reliable safeguard strategy. However, high reliability in modelling involves increasing physical complexity, which seems to represent currently a limit to the diffusion of state-of-the-art tools between practitioners and stakeholders. Complex models imply large computational burden, requiring high-performing hardware and long computation time. Moreover, several state-of-the-art models are not user-friendly and multiple stand-alone software are needed to pre—and post-process input data and results. All these drawbacks hinder the diffusion of advanced models and, often, practitioners prefer simpler tools and methods, possibly leading to unreliable or inaccurate results (see e.g. Lanni et al. 2014 or Stancanelli & Foti 2015). Therefore, some effort to enhance attractiveness of advanced models seems to be necessary, to support practitioners also in keeping up with progresses in the research field.

In this work, we propose a smart strategy to encourage the diffusion of the model TRENT2D (Armanini et al. 2009, Rosatti & Begnudelli 2013), a mathematical and numerical model simulating debris flows and hyperconcentrated flows. TRENT2D was converted into a service and equipped with a WebGIS technology. This solution is intended to overcome some of the typical drawbacks of desktop applications, benefitting from the SaaS (Software as a Service) approach and from WebGIS technology.

The new system turns up to be an innovative Spatial Data Infrastructure (SDI) with data-processing services, able to manage and display geographic data and offering a flexible and user-friendly working environment. Furthermore, the same infrastructure was equipped also with a BUWAL-type hazard-mapping procedure (Heinimann et al. 1998), for the purpose of obtaining a complete and versatile tool for hazard assessment.

This paper is organised as follows. In Section 2 the model TRENT2D is introduced. Section 3 presents the strengths of the SaaS approach and of WebGIS technology. Both were capitalised on the development of a new SDI, which is introduced in Section 4. Then, in Section 5, the BUWAL hazard-mapping procedure implemented in the SDI is presented and applied to a real case study.

2 THE MODEL TRENT2D

TRENT2D (*Transport in Rapidly Evolutive Natural Torrent*) is a 2D shallow-flow model that simulates debris flows and hyperconcentrated flows (see Armanini et al. 2009, Rosatti & Begnudelli 2013). TRENT2D describes the solid-liquid mixture with a two-phase approach, without velocity-lag between phases. Moreover, it is a mobile-bed model, i.e. bed elevation may vary, according to the dynamics of the mixture. In this way, morphological evolution and mixture dynamics are fully coupled, leading to a proper representation of erosion and deposition processes.

The system 1 of depth-integrated governing equations consists of four PDEs: a mass balance for the mixture, a mass balance for the solid phase and two mixture-momentum balances in x and y directions,

$$\begin{cases} \frac{\partial}{\partial t}\left(z_b + h\right) + \frac{\partial}{\partial x}\left(hu_x\right) + \frac{\partial}{\partial y}\left(hu_y\right) = 0 \\ \frac{\partial}{\partial t}\left(c_b z_b + ch\right) + \frac{\partial}{\partial x}\left(chu_x\right) + \frac{\partial}{\partial y}\left(chu_y\right) = 0 \\ \frac{\partial}{\partial t}\left(\delta hu_x\right) + \frac{\partial}{\partial x}\left[\delta\left(hu_x^2 + \frac{1}{2}gh^2\right)\right] \\ \qquad + \delta gh\frac{\partial z_b}{\partial x} + \frac{\partial}{\partial y}\left(\delta hu_x u_y\right) = -\frac{\tau_{bx}}{\rho_w} \\ \frac{\partial}{\partial t}\left(\delta hu_y\right) + \frac{\partial}{\partial x}\left(\delta hu_x u_y\right) \\ \qquad + \frac{\partial}{\partial y}\left[\delta\left(hu_x^2 + \frac{1}{2}gh^2\right)\right] \\ \qquad + \delta gh\frac{\partial z_b}{\partial y} = -\frac{\tau_{by}}{\rho_w} \end{cases} \tag{1}$$

where z_b = elevation of the mobile bed; h = flow depth; u_x and u_y = components of the depth-averaged velocity vector $\mathbf{u}$; c_b = maximum packing concentration of the solid material of the bed, c = depth-averaged concentration, $\delta = 1 + c\Delta$ with $\Delta = (\rho_s - \rho_w)/\rho_w$, where ρ_s = density of the solid phase and ρ_w = density of the interstitial fluid; g = gravitational acceleration; τ_{bx} and τ_{by} = components of the bed shear stress τ.

The unknowns of the system are (z_b, h, u_x, u_y), while two further relations are necessary to close the problem and define the concentration c and the shear stresses τ_{bx} and τ_{by}.

The depth-averaged concentration c is expressed as a function of the Froude number $Fr = |\boldsymbol{u}|(gh)^{-1/2}$, through the non-dimensional transport parameter β (Equation 2).

$$c = c_b \beta Fr^2 \tag{2}$$

The shear stress τ is described through a suitable relation for grain-inertial regime, recalled in Equation 3. This relation was proposed by Bagnold (1954) and modified by Takahashi (1978):

$$\boldsymbol{\tau} = \frac{25}{4} a\rho_s \sin\phi \frac{\lambda^2}{Y^2}|\mathbf{u}|\mathbf{u} \tag{3}$$

where $a = 0.32$ (constant), ϕ = friction angle of the solid-phase material, $Y = h/d$ is the relative submergence, d = sediments grain size and λ = linear concentration is defined by Equation 4:

$$\lambda = \left[\left(c_b / c\right)^{1/3} - 1\right]^{-1} \tag{4}$$

The Equations 1 are solved over a regular Cartesian mesh, with a finite-volume method with Godunov-type fluxes. The accuracy is second order in space and time, by means of a MUSCL-Hancock approach. See Rosatti & Begnudelli (2013) for further details.

The complexity of TRENT2D, due to the high non-linearity of the system of PDEs and the presence of non-conservative terms, affects also the use of the model, introducing high computational costs and requiring high-performing hardware.

2.1 *TRENT2D input and output data*

TRENT2D needs two kinds of input data: geographic data (maps) and hydrological data (hydrographs). Then, it produces geographic data also as outputs.

The Digital Terrain Model (DTM) of the study area represents the essential geographic input. In addition, geographic information could be enhanced profitably with further maps, such as orthophotos or thematic shapefiles. All these geographic data can be managed and organised efficiently by means of a Geographic Information System (GIS). However, TRENT2D does not provide native GIS functionalities.

The second basic model input is the hydrological datum, characterising the scenario to be modelled. As hydrological information, TRENT2D requires a hydrograph of the liquid discharge, which is used to compute model boundary conditions. Liquid hydrographs are easily available if stream gauges are installed in the study area. However, frequently debris flows are observed in small non-instrumented basins, so discharge values are usually obtained starting from rainfall data and applying a suitable rainfall-runoff model. In anticipatory studies, typically in hazard mapping, rainfall data are commonly estimated from Intensity-Duration-Frequency (IDF) curves.

With these input data, the model is able to simulate the dynamics of the phenomenon, producing geographic data as output. These maps describe the evolution in space and time of the governing variables (e.g., flow depth, velocity, erosion depth, deposition depth, concentration…). Therefore, also in this case GIS tools turn out to be useful, in order to manage, overlay and analyse model results. This necessity obliges the user to fragment his work, employing different applications for different purposes and dealing with different file formats, with clear operative disadvantages.

3 SAAS APPROACH AND WEBGIS TECHNOLOGY: A PROMISING SOLUTION

In the last decade, the software-delivering model SaaS (Software as a Service) reached a wide diffusion, becoming competitive with standalone-software logic. In a SaaS solution, applications are hosted on a server and made accessible over a network, through a suitable Graphic User Interface (GUI). This approach could be rather promising in the modelling field, opening new prospects, not available with the traditional model of software distribution, based on installation.

At the same time and with the same logic, advances in GIS and web technology have led to Web-based GIS (or WebGIS) solutions, i.e. web applications able to display, manage and process geographic and economic data (Plewe 1997). An example of WebGIS is described in Section 3.1, where the client Terra3 is introduced. Thanks to their high flexibility and usability, Web-based GISs have already been used in risk assessment and management, in the form of accessible historic flood databases (Miller & Han 2009), decision-supporting tools (Andrienko & Andrienko 2001) or communication media (Hagemeier-Klose & Wagner 2009). However, systems combining mathematical models and WebGIS technology are still quite rare and limited to particular applications (see for instance Kulkarni et al. 2014), despite the wide potential of WebGIS (De Amicis et al. 2009).

In this work, we propose an integrated solution for debris flows modelling, developed blending the SaaS approach with WebGIS technology. Namely, the basic idea is to convert model software into services and make them accessible over the World Wide Web. This purpose can be reached by using a Web-based interface, which could be also a WebGIS interface. In this way, not only modelling services but also geodata repositories and GIS functionalities could be invoked and accessed from a unique user interface.

This infrastructure introduces several advantages for the user, in comparison with stand-alone models, i.e. models as desktop applications.

Firstly, the computational core of a SaaS solution is located in a suitably equipped server. Therefore, users do not need any high-performing hardware to access and use the services, since all computational burdens are charged to the server. In this way, services can be used from any device, almost independently of device properties. Moreover, computation time can be extremely short, if a high-performing server is available.

Also data storage can take advantage of the use of a server, which can be the same supporting services. There all the data can be saved and organized, so the user is not required to have any local storage capacity. Consequently, physical damages to hardware can be excluded, together with blackouts and virus attacks, increasing physical and logical security.

Furthermore, administration and maintenance are centralized, hence continuous and systematic technological transfer is facilitated. Moreover, server-side maintenance makes updates available at the same time for all the users and simplifies processes of debug and upgrade.

In addition to these advantages, mainly related to the centralised nature of a SaaS solution, others can be introduced by using the interface of a WebGIS client to access different kinds of services, including modelling services.

A WebGIS client is a Web-based client, which does not need any installation or configuration. Simply, it is available from any Internet browser, without limitation on the Operating System. Moreover, it can be accessed from any device connected to Internet. In this way, the user can login wherever a connection is available. Because of its nature, a WebGIS client is designed to make available also GIS functionalities, useful to organise and manage geographic data, required and produced by models.

In addition, other functionalities supporting data-processing can be added easily in this kind of systems, thanks to the high level of customisation and the characteristic flexibility of the infrastructure.

All these features make the coupling of the SaaS approach and the WebGIS technology an interesting framework for the development of easy-to-use modelling integrated systems.

3.1 *Terra3: a Web-based GIS application*

Terra3 is a WebGIS client developed by Trilogis as a tool for practitioners and stakeholders, to interact with web geodata through a user-friendly GUI. It is able to access many different repositories of geographical data, exploiting interoperable standards of the Open Geospatial Consortium (OGC©).

Terra3 was developed in HTML5, CSS3 and Javascript, according to a modular software structure. Moreover, it supports several OGC standards, such as WMS (Web Map Service 1.1.0 and 1.3.0) and WFS (Web Feature Service).

A 2D interactive map (based on OpenLayer 2.0) is the main entrance of the application, where geographical information is displayed and the user can interact with the system. In addition, a 3D view has been integrated in the system, through the Java-based NASA World Wind visualisation engine, enriching visualisation possibilities.

Terra3 is compatible with the most common Internet browsers and offers all the advantages typical of Web-based GIS. All these characteristics make Terra3 a suitable candidate for the development of integrated solution for modelling.

4 TRENT2D WG: AN INTEGRATED SOLUTION FOR DEBRIS-FLOW MODELLING

The strategy described in Section 3 was applied with the purpose of encouraging the diffusion of the model TRENT2D, attempting to overcome several of the typical drawbacks of stand-alone software for advanced modelling.

Firstly, TRENT2D was converted into a service, according to the SaaS approach. This application was exposed as a processing service on a cloud server, the same hosting the WebGIS client Terra3. Besides, also other ancillary services has been exposed on the same server. They are useful functionalities devoted to process model inputs and results. Some of these functionalities are presented in Section 4.1.

However, these services could be accessed by the user only if some graphic interface was available.

Besides, a web user interface was required in order to make TRENT2D accessible over the World Wide Web. Therefore, a suitable web interface has been developed, starting from the GUI that the WebGIS client Terra3 was equipped with. This new interface is able to invoke all the services available on the cloud server, offering a complete and easy-to-use working environment (Fig. 1).

The whole system (which architecture is described shortly in Section 4.2) was developed following an iterative and incremental approach, which turned out to be particularly suitable to improve and refine both services and interface design, tailoring the solution to TRENT2D requirements.

The new infrastructure was called TRENT2D WG. Joining the SaaS approach and WebGIS technology, TRENT2D WG allows to simulate debris flows and hyperconcentrated flows, to process model results and to manage, display and overlay geodata straightforwardly.

4.1 *Some functionalities of TRENT2D WG*

TRENT2D WG was equipped not only with the most typical GIS functionalities, but also with some new specific functionality, implemented to facilitate pre—and post-processing.

Thanks to pre-processing tools, DTM ASCII GRID files can be uploaded and merged in the SDI. Widespread editing can be performed by means of suitable Shapefiles, while pointwise values can be modified with a specific visual editor.

Other specific functionalities, based on WMS and WFS services, allow to draw the computational domain and to locate inflow boundaries accurately.

Moreover, a guided procedure was introduced to prepare input data, to compute boundary conditions and to define model parameters. With these data, model runs can be performed easily, benefitting from server capacity and allowing the user to verify and analyse in-progress simulation results.

Model results can be displayed and inspected with different post-processing functionalities. Three displaying options are available:

- a 2D view for in-depth analysis, with the opportunity to draw, display and export profile and section charts;
- a 2D view (Fig. 2) with wide overlaying possibilities, addressed to display model results in a georeferenced context. This view permits an overview of the phenomenon dynamics, thanks also to time animations;
- a 3D view (Fig. 3), conceived as a communication media, able to display simulations in a realistic way, also by means of WMS layers. This

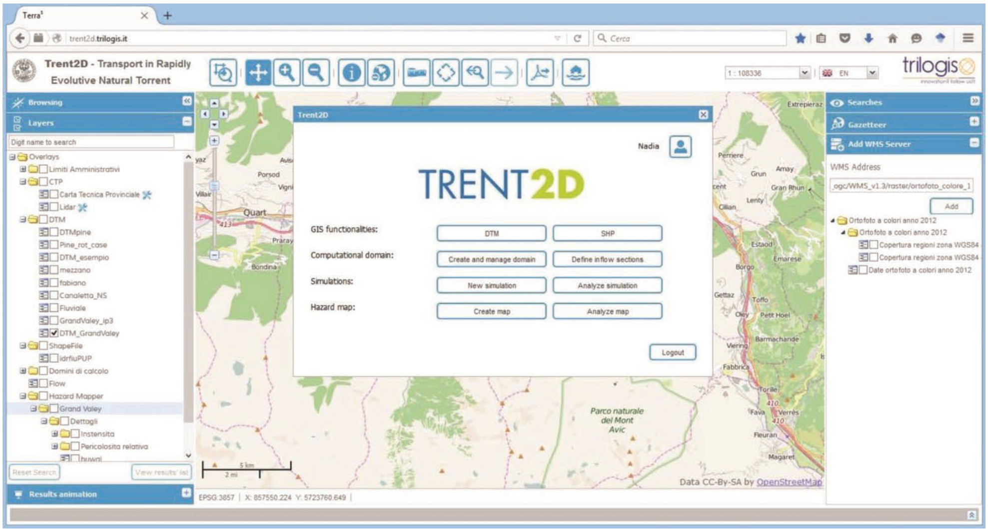

Figure 1. TRENT2D WG workspace.

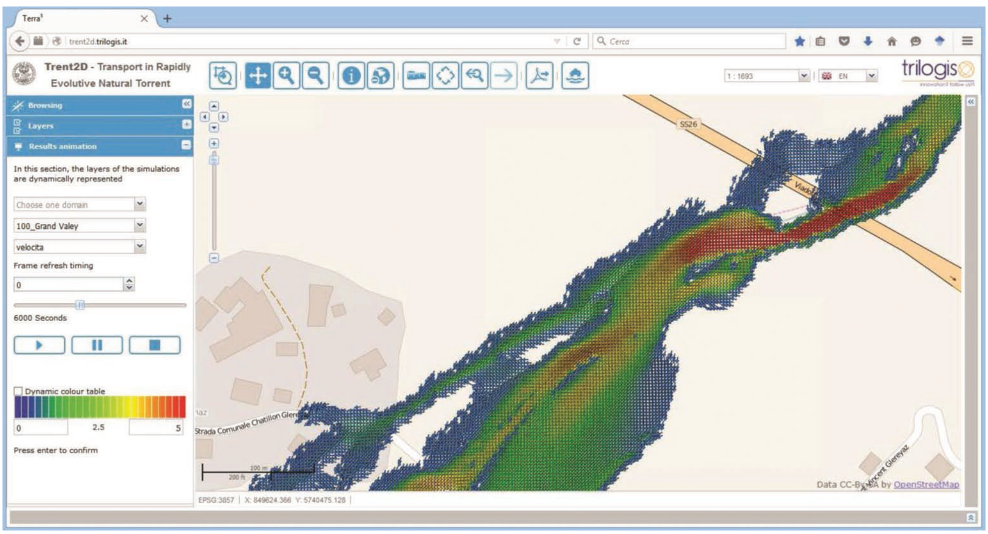

Figure 2. 2D view in TRENT2D WG.

tool was realised through modern web technology and without plug-in installation.

Moreover, all the model results can be easily downloaded or plotted.

4.2 *Architecture of the solution*

The infrastructure was developed with a multi-tier architecture, where different functionalities are physically separated in distinct, but interconnected, software layers.

In this solution, there are three layers, as shown in Figure 4:

- a presentation tier (or Application Layer), allowing information to be displayed;
- a logic tier (or Middleware Layer), which provides functionalities and supports complex processing. For example, it contains the model TRENT2D and some modules for data display, based on a GeoServer solution;
- a data tier (or Data Layer), devoted to data storage and retrieving and improves scalability and

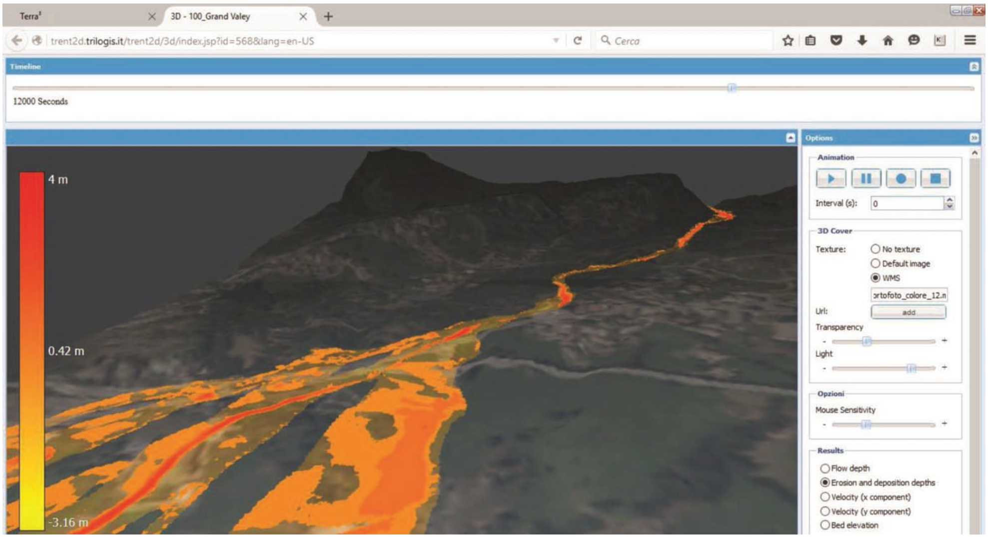

Figure 3. 3D view in TRENT2D WG.

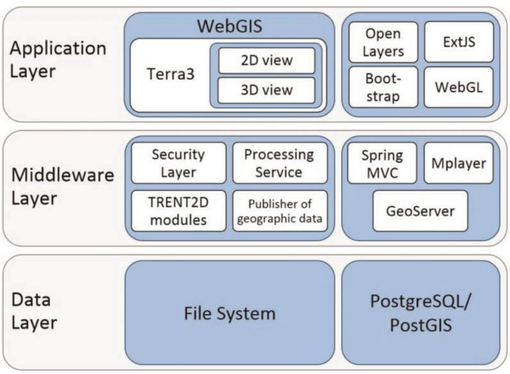

Figure 4. Multitier-architecture outline of TRENT2D WG.

performance. Data remain independent of server application or business logic and are managed through File System. Geodata are organised according to a DBMS (Database Management System) solution.

5 INTEGRATING HAZARD ASSESSMENT IN TRENT2D WG

Mathematical and numerical models can be used effectively in hazard assessment. In practice, a model allows to simulate and characterise different hazard scenarios that can be then classified, leading to the assessment of local hazard levels.

The original version of TRENT2D has already been used in hazard-mapping procedures, with encouraging results (see Rosatti et al. 2015).

For these reasons, TRENT2D WG was equipped also with a service for hazard assessment, taking advantage of the great opportunities of customisation offered by the SaaS approach (see Section 5.2 for details about the integration).

In this service, a hazard-mapping procedure complying with BUWAL standards (Heinimann et al. 1998) was implemented. The key points of the procedure are described in Section 5.1. The integrated hazard-mapping procedure was also applied to a real case study, as shown in Section 5.3.

5.1 *BUWAL-type hazard-mapping procedure*

Hazard is a function the probability of occurrence of an event and of its intensity in a certain area. It follows that information about both probability and intensity is necessary to map the hazard.

According to BUWAL approach, probability can be taken into account by considering three relevant scenarios, each characterised by a different probability of occurrence.

Each scenario is classified locally in terms of phenomenon intensity, through thresholds criteria, usually supplied by local authorities. As an example, thresholds provided by the Autonomous Province of Trento (Italy) to classify debris-flow intensity of are shown in Table 1.

Data about intensity and probability are then merged and interpreted through a key-matrix (the BUWAL matrix), which represents hazard as a stepwise function. In this way, hazard turns out to be assessed according to a probabilistic approach.

Information about scenarios intensity can be obtained profitably by modelling, since models allow to reproduce time and space evolution of the characteristic variables of the phenomenon. For this purpose, advanced models describing thoroughly physical complexity should be chosen, in order to take into account all the fundamental physical processes thoroughly. For instance, in the case of debris flows, scenarios should be simulated with models able to reproduce erosion and deposition processes.

Therefore, accuracy and reliability of hazard assessment depend widely on reliability and forecasting capabilities of the model.

5.2 *A BUWAL-type hazard-mapping procedure integrated in TRENT2D WG as a service*

Debris-flow modelling and hazard mapping can be matched usefully to assess debris-flow hazard. For this reason, a hazard-mapping procedure complying with BUWAL standards was integrated in TRENT2D WG as a new functionality, or rather as a service hosted by the Middleware Layer. In this way the model TRENT2D and the hazard-mapping procedure are made available in the same working environment. Moreover, they can be used easily in succession: hazard scenarios can be simulated by the model, then model results can be used as input of the procedure, which produces a hazard map as output, classifying probability, intensity and hazard automatically.

This service, called Hazard Mapper, was made accessible once the user has simulated at least three scenarios with different probability of occurrence. Once scenarios are available, intensity classification criteria are applied automatically to the local highest values of the governing variables, giving the local intensity of each scenario. Intensity and probability information are then merged and classified according to the BUWAL matrix, producing a single, effective and easy-to-use hazard map.

Because of the huge volume of geodata involved, this hazard-mapping procedure would be a long and laborious task, if no automatic procedure is available.

Table 1. Threshold criteria provided by the Autonomous Province of Trento (Italy) in the DGP 2759/2006 to classify the intensity of a debris flow scenario

Intensity class	Flow depth [m]		Velocity [m/s]		Deposition depth [m]
High	$h>1$	or	$\|\mathbf{v}\|>1$	or	$M>1$
Medium	$0.5<h<1$	or	$0.5<\|\mathbf{v}\|<1$	or	$0.5<M<1$
Low	$h<0.5$	or	$\|\mathbf{v}\|<0.5$	or	$M<0.5$

5.3 *A realistic case study: hazard mapping in Saint Vincent (Italy)*

TRENT2D WG was used to map debris-flow hazard in Saint Vincent, in Aosta Valley (Italy, South-Western Alps). The village of Saint Vincent is located on the alluvial fan of the Grand Valey, a small and steep stream where debris-flow events have been observed quite often (about ten events in last ten years), triggered by intense thunderstorms. Some characteristics of the Grand Valey basin are listed in Table 2.

This study was carried out only as a realistic exercise, since no protection or mitigation measures present in the study area were considered.

Applying the BUWAL approach, three different debris-flow scenarios were defined, starting from probabilistic observations on rainfall, according to the most common practice. In this case study, rainfall scenarios with return periods of 20, 100 and 200 years were considered. These values correspond respectively to high, medium and low probability of occurrence.

Table 2. Characteristics of the Grand Valey basin

Characteristic	Value
Basin area	5.66 km^2
Minimum elevation	680 m
Maximum elevation	2680 m
Stream length	3.76 km
Average stream slope	29.0%
Average slope on the alluvial fan	12.0%

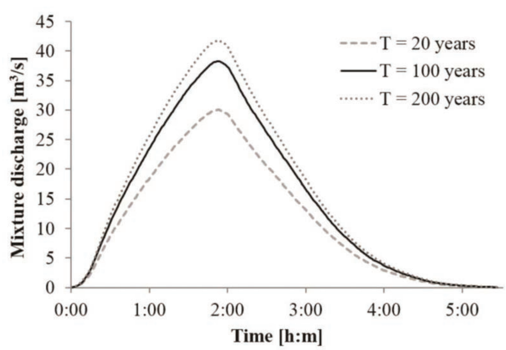

Figure 5. Mixture hydrographs used as boundary conditions to model three debris-flow scenarios in Grand Valey stream. Each hydrograph is representative of a particular return period *T*.

Figure 6. TRENT2D WG hazard map for the Saint Vincent fan.

Starting from Intensity-Duration-Frequency curves relevant for the study area, the rainfall-runoff model Peakflow (Rigon et al. 2011) was applied, in order to obtain liquid hydrographs, i.e. hydrographs of the debris-flow liquid phase. For each return period, the hydrograph with the highest peak discharge was chosen, since the purpose is to map the hazard. These hydrographs were employed to define the mixture hydrographs shown in Figure 5, representing TRENT2D boundary conditions. Thereafter, the model was applied to simulate the different scenarios, each characterised by a mixture hydrograph.

Model results were then used to map the debris-flow hazard on the alluvial fan, by means of the Hazard Mapper integrated in TRENT2D WG. Hazard maps produced by the automated procedure are shown in Figure 6.

CONCLUSIONS

In this work, a smart solution for debris-flow modelling was proposed and implemented. Joining the SaaS approach and the WebGIS technology, a new infrastructure, called TRENT2D WG, was developed. TRENT2D WG is intended to overcome several of the typical limits of complex modelling tools.

With this infrastructure, several services can be accessed from a single, user-friendly, web working environment, which allows to simulate debris flows, to pre—and post-process model input and output, to manage and display geographic information and to map the debris-flow hazard.

This new system was applied to map the hazard in a realistic case study, with considerable operative advantages from the user point of view.

Moreover, in future also other models, e.g. rainfall-runoff models or avalanche models, could be integrated in the same infrastructure, thanks to the flexibility of the SaaS approach.

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