Equipping the TRENT2D model with a WebGIS infrastructure: a smart tool for hazard management in mountain regions

N. Zorzi, G. Rosatti & D. Zugliani
Department of Civil, Environmental and Mechanical Engineering
University of Trento, Trento, Italy

A. Rizzi & S. Piffer
Trilogis Srl, Rovereto, Italy

ABSTRACT: Mountain regions are naturally exposed to extreme floods and climate change has worsened this exposure. Therefore, incisive actions and strategies to safeguard urbanized areas are always more undeniable. In recent years, reliable mathematical models for hyperconcentrated flows and debris flows have been developed and used to plan hazard protection and mitigation strategies successfully. However, the increasing trustworthiness of advanced modelling implies higher complexity and larger computational burdens, with a greater request of high-performing hardware. Therefore, new solutions should be found, in order to overcome these drawbacks and encourage a widespread diffusion of best practices and best available technologies not entailing excessive costs in risk-management field, as the UE Flood Directive (2007/60/EC) requires. In this work, a smart and easy-to-use solution is proposed and applied to the TRENT2D model, which is a state-of-the-art 2D model, simulating debris flows and hyperconcentrated flows. This model was converted into a service and equipped with WebGIS technology, developing a complete, flexible and user-friendly working environment. This solution allows geographically referenced input and output to be managed straightforwardly. Moreover, computational burdens are transferred from the user hardware to a high-performing server, also enhancing model accessibility. To avoid work fragmentation, also a GIS-based BUWAL-type hazard-mapping procedure was implemented in the same working environment. In this way, research activity and professional needs are brought significantly closer, encouraging the diffusion of good practices.

1 INTRODUCTION

In the last years, extreme rainfall events have become more frequent and intense, especially in Europe and in North America (IPCC 2014). In mountain regions, which are naturally exposed to paroxystic events, this trend has caused an increase in the number of extreme floods and geomorphic flows. Moreover, climate change has revealed an increased vulnerability of urbanised mountain areas, highlighting the necessity of effective protection and mitigation strategies, able to safeguard population, settlements and infrastructures.

In Europe, guidelines for flood-risk assessment and management are stated by the UE Flood Directive (2007/60/CE), which recommends the application of ”appropriate best practice and best available technologies not entailing excessive costs” in the field of risk management.

In the last decades, impressive strides have been made in the field of mountain flood modelling, especially with regards to hyperconcentrated and debris flows (see Iverson & Ouyang 2015 for an overview), and recent applications have shown that advanced models can support hazard assessment and management effectively (see for instance Rosatti et al. 2015). However, the increasing physical complexity of most state-of-the-art models often implies large computational burdens and long computation time, if standard computers are used. This issue still discourages a wide diffusion of the most cutting-edge models between practitioners and stakeholders, which prefer simpler but untrustworthy approaches and tools. Moreover, advanced models are generally not easy-to-use and require several other stand-alone software to prepare input data and analyse model results. Also complexity and fragmentation of working environments and file formats seem to limit significantly the diffusion of advanced models, hindering an effective management of flood hazard and risk.

In this work, a new smart tool supporting mountain hazard management is presented. This infrastructure, called TRENT2D WG, was developed for the purpose of enhancing and simplifying the use of TRENT2D (Armanini et al. 2009, Rosatti and Begnudelli 2013), a state-of-the-art model which simulates hyperconcentrated flows and debris flows. TRENT2D WG is a web solution developed according to the SaaS (Software as a Service) approach, with the model converted into a service and equipped with WebGIS technology. This new infrastructure offers an innovative and complete working environment, where simulations can be performed easily and input and output geographic data can be processed, organised and displayed straightforwardly. Moreover, also a BUWAL-type hazard-mapping procedure (Heinimann et al. 1998), devoted to assess debris-flow hazard, was introduced in the same working environment, taking advantage of the large flexibility of the web infrastructure. In this way, the procedure can be applied directly starting from model results.

The paper is organised as follows. In Section 2 the TRENT2D model is presented. Section 3 is devoted to the innovative technology applied to build the system TRENT2D WG. Then, in Section 4 the system TRENT2D WG, its architecture and its functionalities are presented, while in Section 5 the integrated BUWAL-type hazard-mapping procedure is described and applied in an educational example.

2 THE TRENT2D MODEL

TRENT2D (*Transport in Rapidly Evolutive Natural Torrent*) is a 2D model to simulate debris flows and hyperconcentrated flows. Its main properties are shortly described here below (for further details see Armanini et al. 2009 and Rosatti and Begnudelli 2013). Then, data required as input of the model and produced as results are also presented.

2.1 *The mathematical and numerical model*

TRENT2D is a shallow-flow model, based on a two-phase description of the mixture of water and sediments. No velocity lag is assumed between the solid phase and the liquid phase. The model adopts a mobile-bed approach to represent properly erosion and deposition, which are characteristic processes of the modelled phenomena. Variations of the bed elevation are fully-coupled with the mixture dynamics and derive directly from the system of governing equations and from the two-phase approach. The bed elevation z_b is one of the unknowns of the system, just like the flow depth h and the x and y components of the depth-average velocity vector $\vec{u} = (u_x, u_y)$. The values of the unknowns are obtained straightforwardly from the system integration.

Model governing equations describe the conservation of the mixture mass (Equation 1a), the conservation of the solid mass (Equation 1b) and the conservation of the mixture momentum along the x and y directions (Equations 1c and 1d). Two further relations define the relationship between the unknowns, the concentration c and the shear stresses τ_{bx} and τ_{by}.

The system of governing equations can be written as:

$$\left\{\begin{aligned}
&\frac{\partial}{\partial t}(z_b + h) + \frac{\partial}{\partial x}(hu_x) + \frac{\partial}{\partial y}(hu_y) = 0 && \text{(1a)}\\
&\frac{\partial}{\partial t}(c_b z_b + ch) + \frac{\partial}{\partial x}(chu_x) + \frac{\partial}{\partial y}(chu_y) = 0 && \text{(1b)}\\
&\frac{\partial}{\partial t}(\delta h u_x) + \frac{\partial}{\partial x}\left[\delta\left(hu_x^2 + \frac{1}{2}gh^2\right)\right] + \\
&\qquad + \delta g h \frac{\partial z_b}{\partial x} + \frac{\partial}{\partial y}(\delta h u_x u_y) = -\frac{\tau_{bx}}{\rho_w} && \text{(1c)}\\
&\frac{\partial}{\partial t}(\delta h u_y) + \frac{\partial}{\partial x}(\delta h u_x u_y) + \\
&\qquad + \frac{\partial}{\partial y}\left[\delta\left(hu_y^2 + \frac{1}{2}gh^2\right)\right] + \delta g h \frac{\partial z_b}{\partial y} = -\frac{\tau_{by}}{\rho_w}. && \text{(1d)}
\end{aligned}\right.$$

where c_b is the maximum packing concentration of the bed solid material, c is the depth-averaged concentration, $\delta = 1 + c\Delta$ with $\Delta = (\rho_s - \rho_w)/\rho_w$, where ρ_s is the density of the solid phase and ρ_w is the density of the liquid phase, g is the gravitational acceleration and τ_{bx} and τ_{by} are the x and y components of the bed shear stress $\vec{\tau}$.

The concentration c is expressed as a function of the Froude number $Fr = \|\vec{u}\|/\sqrt{gh}$, by means of the Equation 2, originally proposed by Rosatti & Fraccarollo (2006). The non-dimensional parameter β is called transport parameter and depends on sediment shape and diameter. In the model, it is assumed to be constant. A particular approach to estimate β is presented in Rosatti et al. (2015).

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

Equation 3 describes the shear stress $\vec{\tau}$ in the grain-inertial regime.

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

It was proposed originally by Bagnold (1954) and modified by Takahashi (1978), with $a = 0.32$ (constant). ϕ is the friction angle of the material of the solid phase, λ is the linear concentration, defined as

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

and Y is the relative submergence, defined as

$$Y = \frac{h}{d} \tag{5}$$

where d is the sediment grain size.

The high non-linearity of the governing equations and the presence of non-conservative terms require a sophisticated numerical model. In this model, the governing equations are solved over a regular Cartesian mesh, by a finite-volume method with Godunov-type fluxes. A MUSCL-Hancock approach allows to obtain second order accuracy in space and time. Further details about the numerical model are available in Rosatti & Begnudelli (2013).

The complexity of the mathematical and numerical model leads to high computational burdens, which should be supported by suitable high-performing (and expensive) hardware in order to limit computational time.

2.2 *TRENT2D input and output data*

TRENT2D simulations can be performed starting from two classes of input data: geographic data and hydrological data. With these data, the model produces geographic data also as results.

The fundamental input geographic datum is represented by the Digital Terrain Model (DTM) of the study area, in ASCII GRID format. DTMs with high resolution are recommended in order to obtain highly reliable results. Then, geographic information could be enriched also by other maps, as for instance orthophotos or thematic layers. All these data can be managed suitably by means of Geographic Information Systems (GISs), which are conceived to display, organise and analyse geographically referenced maps. However, TRENT2D does not support itself the management of geographic data, forcing the user to make the use of stand-alone GIS applications, with consequent work fragmentation.

The other category of input data involves hydrological information, which is essential to compute model boundary conditions. For each inflow section, a hydrograph of the liquid phase is required. Notice that this hydrograph represent the distinguishing characteristic of each scenario to be modelled. Generally, this information is quite simple to obtain in instrumented basins. However, geomorphic flows are observed usually in small non-instrumented basins. Therefore, liquid hydrograph should be obtained applying an appropriate rainfall-runoff model, i.e. starting from rainfall data. If a past event is back-analysed, some measured or interpolated rainfall data could be used, while, in anticipatory study, rainfall data can be estimated from Instensity-Duration-Frequency (IDF) curves.

Once liquid hydrographs are defined, boundary conditions are computed applying model closure relations. Assuming the local uniform flow condition in the upstream section of the study area, it is possible to define suitable a-priori values of the model parameters, which turn out to be reliable when the study area is located far enough from the debris-flow triggering point (Rosatti et al. 2015). Thereafter, mixture discharge can be computed straightforwardly.

Supplying these data, hyperconcentrated- and debris-flow dynamics can be modelled, producing geographic data as results. These maps describe space and time evolution of the governing variables (i.e. flow depth, deposition depth, erosion depth, velocity, concentration...). Therefore, GIS applications could be used conveniently also to manage and analyse model results.

3 SAAS APPROACH AND WEBGIS TECHNOLOGY

The basic ingredients of TRENT2D WG are two: a particular software-delivering approach, called Software as a Service (SaaS), and the technology of Web-based GIS. Both are presented shortly hereafter.

3.1 *The SaaS approach*

The software-delivering approach SaaS represents a promising alternative to the traditional standalone-software logic. According to SaaS, software is developed as a service and hosted by a cloud server. Therefore, applications can be accessed through a suitable Graphic User Interface (GUI) by means a common Internet browser, without limitation on the Operating System and without installation.

This approach offers several advantages, in comparison with standalone-software logic.

First, the whole computational burden is supported by a suitably equipped server, presumably reducing computational time. Moreover, software can be accessed through the World Wide Web, by a simple login from any Internet-connected device. Furthermore, the service can be used almost independently of device properties. This solution shrinks user burdens significantly, since no high-performing local hardware is needed.

In SaaS, multiple users access a single infrastructure, which is centrally maintained and administered. Therefore, all users can access the same software version, making updates available for all the users at the same time and simplifying debug processes. Moreover, this approach brings innovation closer to users, facilitating connections between researchers, specialists, practitioners and stakeholders.

Advantages offered by a SaaS solution turn out to be useful also for data storage, since data processed by software can be saved and organized on the same cloud server hosting the service. In this way, the user does not need large local storage capacity. Furthermore, hardware physical damages, virus attacks and blackouts can be excluded, since physical and logical security is ensured by the service provider.

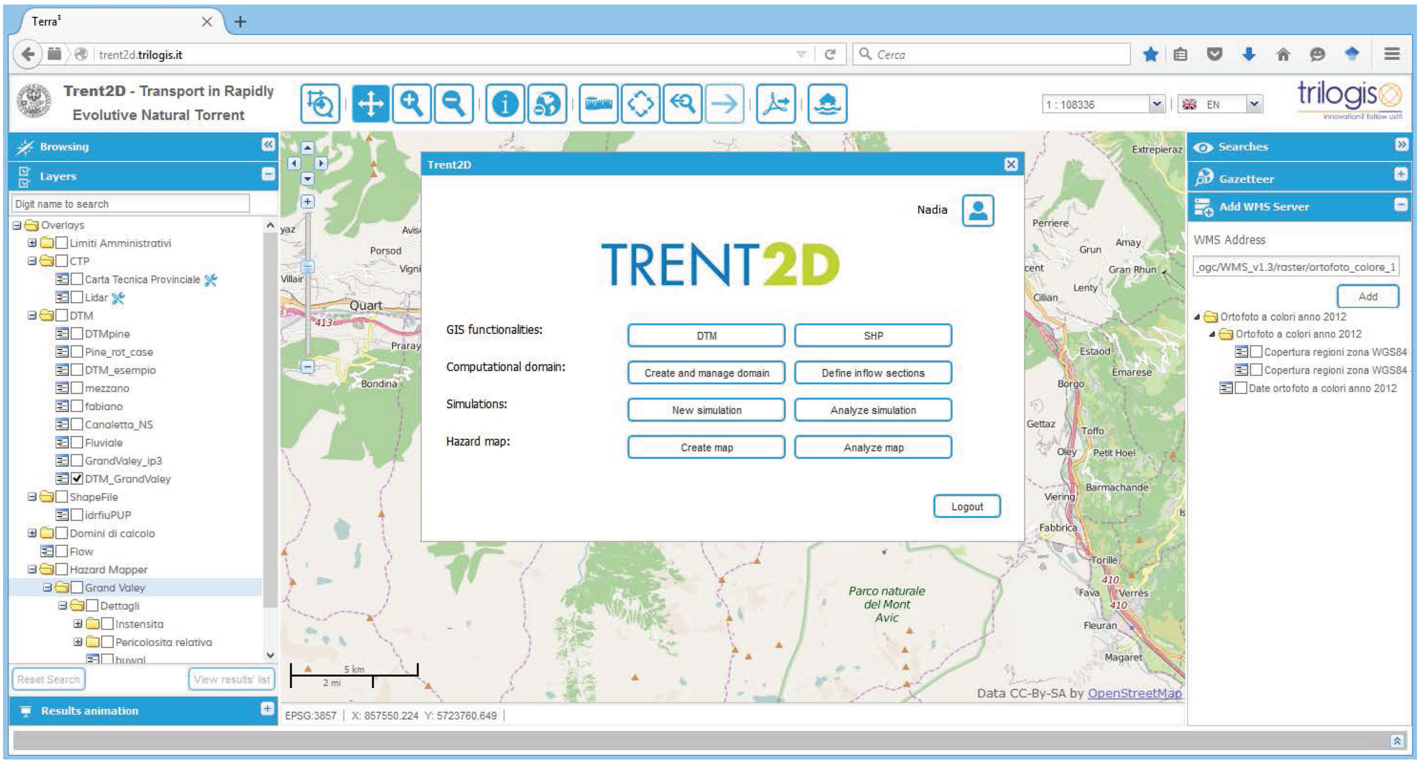

Figure 1: Main menu of the TRENT2D WG workspace

3.2 *WebGIS technology*

The SaaS approach represents the basis also of Web-based GIS (or WebGIS) technology. WebGIS solutions are web applications able to display, organise and process geographic and economic data (Plewe 1997). Clearly, they offer GIS functionalities, which can be accessed through a suitable web GUI.

WebGIS technology has already been employed in hazard management, in the form of communication media (see for instance Hagemeier-Klose & Wagner 2009), decision-supporting tool (e.g. Andrienko & Andrienko 2001) or historic flood database (Miller & Han 2009). However, the huge potential of WebGIS technology (De Amicis et al. 2009) has still to be totally exploited in this field. For example, only few existing applications combine WebGIS functionalities and modelling services and most of them were developed for particular and limited applications (see for instance Kulkarni et al. 2014).

In this work, we try to take advantage of WebGIS technology and its characteristic flexibility, which allows easily to create custom applications, hosting multiple services.

4 TRENT2D WG: AN INTEGRATED SOLUTION FOR HAZARD MODELLING

Complying with the SaaS approach, the TRENT2D model was converted into a service and equipped with WebGIS technology, with the purpose of obtaining a web smart modelling tool supporting debris- and hyperconcentrated-flow hazard assessment. This new integrated solution is called TRENT2D WG and aims to overcome some of the drawbacks typical of advanced modelling. The new solution allows to simulate debris flows and hyperconcentrated flow in a user-friendly working environment (Fig. 1) , where input data and results can be displayed, organised, overlaid, processed and analysed straightforwardly.

The WebGIS client chosen for the integration is called Terra3 and is presented in Section 4.1. Then, the integration strategy is described in Section 4.2, together with the architecture of the solution, while Section 4.3 lists some significant functionalities of TRENT2D WG.

4.1 *Terra3: a WebGIS application*

Terra3 is a WebGIS client developed by Trilogis Srl to allow practitioners and stakeholders to deal with geographically referenced data in a user-friendly web environment. It can be accessed from the most common Internet browsers and offers all the advantages typical of a WebGIS solution.

Terra3 is built in HTML5, CSS3 and Javascript and employs the interoperable standards of the Open Geospatial Consortium (OGC ©). Thanks to WMS (Web Map Service 1.1.0 and 1.3.0) and WFS (Web Feature Service), it is able to access many geo-data repositories.

The application was developed with a modular architecture and was equipped with an intuitive web GUI. The main entrance of the application is a 2D interactive map based on OpenLayer 2.0. Also a 3D view is available, thanks to the Java-based NASA World Wind engine.

4.2 *Integration methodology and system architecture*

The TRENT2D model was exposed as a service on a cloud server hosting the WebGIS Terra3. On the same server also other useful functionalities were exposed, devoted to pre- and post-process TRENT2D input and output data.

Then, all these services were made available and accessible through the World Wide Web by means of an intuitive web GUI, developed starting from the Terra3 interface.

The system shows a multi-tier architecture (Figure 2), where different, but interconnected, software layers support different tasks. The layers of the solution are three:

- a presentation tier (or Application Layer), which allows information to be displayed;
- a logic tier (or Middleware Layer), which is based on a GeoServer solution and supports services, as TRENT2D, some modules for data displaying and other processing functionalities;
- a data tier (or Data Layer), which supports data storage and retrieving and improves scalability and performance. A Database Management System (DBMS) solution is used to organise geodata, which are managed by File System, remaining independent of server application or business logic.

The infrastructure was developed according to an iterative and incremental approach, which led to a continuous enhancement of the system, with cyclic refinements of the service offering and of the interface design. In this way, the system was tailored to the requirements of TRENT2D.

4.3 *Some functionalities of TRENT2D WG*

In addition to the most typical GIS functionalities, TRENT2D WG offers also some other tools, intended to pre- and post-process modelling data.

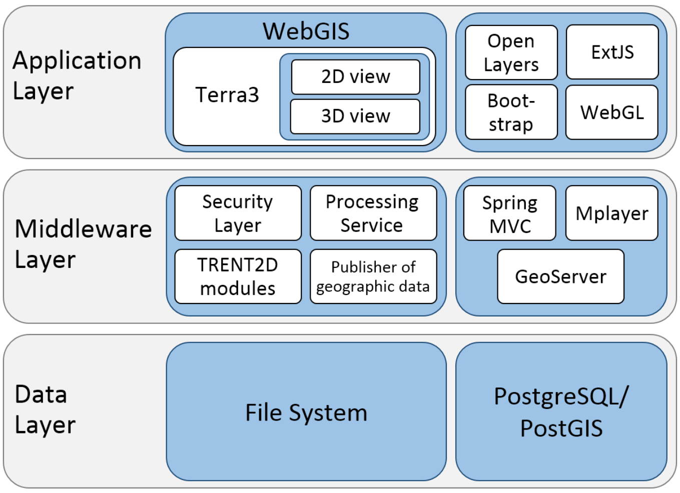

Figure 2: Multitier architecture of TRENT2D WG

First, pre-processing functionalities allow the user to upload and merge DTM ASCII GRID files. Also DTM editing is supported: widespread editing can be performed by means of suitable Shapefiles, while a specific display allows to modify DTM cells point-wise.

Other functionalities allow to draw the computational domain and to locate the inflow boundary sections, taking advantage of WMS and WFS services.

Once the computational domain is defined, a wizard procedure guides the user in the evaluation of the boundary conditions for the model and in the definition of the model parameters. In this way, the model can be run easily. In addition, the user can verify simulations progress and analyse partial results while a run is underway.

Three different displaying frameworks can be used to analyse model results:

- a 2D view, designed for in-depth analysis. Here, results can be analysed point-wise and section and profile charts can be displayed and exported.
- A 2D view, introducing model results in a geographically referenced context. This view allows to overview the global dynamics of the phenomena. Time animation is supported.
- A 3D view (Figure 3), which operates effectively as communication medium, displaying model runs in a context that is closer to reality, thanks to WMS layers.

Furthermore, specific functionalities support download and plot of model results.

5 ASSESSING DEBRIS-FLOW HAZARD WITH TRENT2D WG

Hazard assessment can take significant advantage by the use of sophisticated modelling tools. Models allow to reproduce and analyse many different hazard scenarios and represent a precious support in evaluating effectiveness of protection and mitigation measures. Moreover, model results can be used to draw up hazard maps.

The TRENT2D model has already been used in debris-flow hazard assessment, with reliable results (e.g., Rosatti et al. 2015). For this reason, the system TRENT2D WG has been enriched with a service devoted to debris-flow hazard mapping. The hazard-mapping procedure implemented in the system abides by BUWAL standards (Heinimann et al. 1998) and is based on GIS, as described in Sections 5.1 and 5.2.

In Section 5.3, the procedure is applied to an educational case study, showing opportunities offered by the integrated procedure.

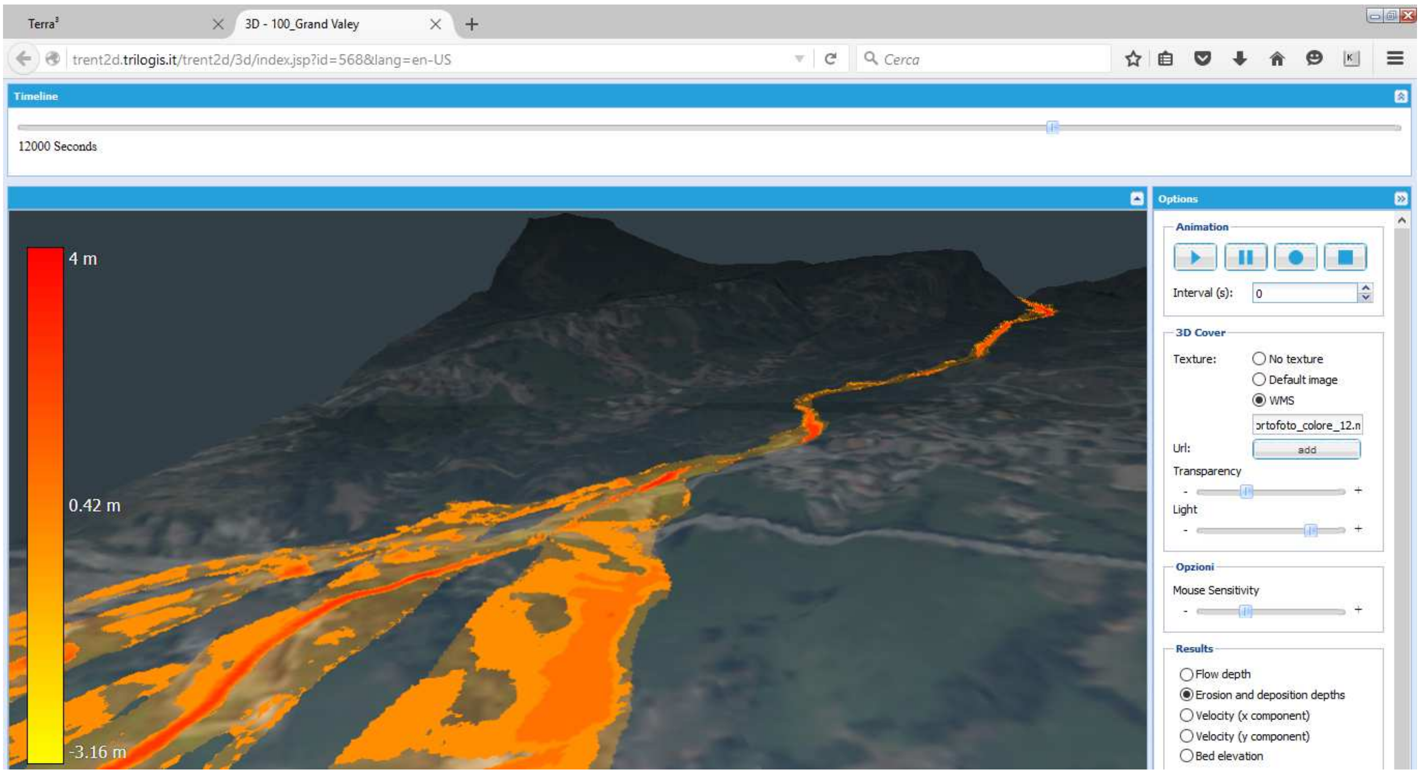

Figure 3: 3D view in TRENT2D WG

5.1 *A BUWAL-type hazard-mapping procedure*

Hazard-level maps, or hazard maps, should be drawn up considering both probability and intensity data, since hazard levels depend on both the occurrence probability of an event and its local intensity.

Following the BUWAL approach, the occurrence probability can be taken into account by considering different forcing events, each one characterised by a particular size, i.e. by a significant value of the return period. Commonly, three forcing events, respectively with high, medium and low values of the return period, are considered.

On the other hand, local intensity can be defined for each forcing event if some information about the time and space evolution of the phenomenon is provided, namely considering some characteristic physical quantities (e.g. flow depth, velocity, deposition and erosion depths). Comparing local maximum values of these variables with suitable threshold criteria, it is possible to classify the phenomenon local intensity, usually by using three levels (high, medium and low). Generally, intensity criteria are established by national or local authorities. Table 1 shows criteria provided by the Autonomous Province of Trento (Italy) to classify debris-flow intensity.

Then, hazard levels are evaluated by means of a key-matrix, called BUWAL matrix, which is a stepwise function depending on probability and intensity.

In this procedure, models turn out to be very useful, because they allow to reproduce time and space evolution of the characteristic variables for each forcing event, i.e. they supply intensity data. Since we are dealing with complex geomorphic flows, only models accounting for physical complexity should be used for hazard-mapping purposes. For instance, models which are not able to represent correctly erosion and deposition processes should be avoided, while models showing high reliability and good forecasting capabilities should be preferred.

5.2 *Integration of the hazard-mapping procedure in TRENT2D WG*

The model TRENT2D has already been used to assess debris-flow hazard in several real case studies, with encouraging results (see for instance Lanni et al. 2015 or Stancanelli and Foti 2015).

However, a correct application of the procedure requires a lot of geographically referenced maps, which make hazard mapping a long and laborious task. This happens also if a GIS-based environment is used to organize, process and overlay intermediate maps drawn up by the procedure and to produce and display final hazard maps. For these reasons, the procedure was automated and integrated in the system TRENT2D WG as a service. The service is called Hazard Mapper and hosted by the Middleware Layer. In this way, the procedure is made available in the same working environment where TRENT2D can be applied and where GIS functionalities are offered.

By means of the Hazard Mapper, hazard maps can be produced easily, starting from results supplied by TRENT2D. The service classifies intensity, probability and hazard levels automatically, ensuring a right implementation of the procedure and drawing up readable hazard maps. In this way, the hazard-mapping task is made extremely straightforward and

Table 1: Debris-flow intensity criteria provided by the Autonomous Province of Trento (Italy) with DGP 2759/2006

Intensity class	Flow depth h		Velocity $\vec{u}$		Deposition depth M		Erosion depth d
	m		ms^{-1}		m		m
High	$h > 1$	or	$\|\vec{v}\| > 1$	or	$M > 1$	or	$d > 2$
Medium	$0.5 < h < 1$	or	$0.5 < \|\vec{v}\| < 1$	or	$0.5 < M < 1$	or	$0.5 < d < 2$
Low	$h < 0.5$	or	$\|\vec{v}\| < 0.5$	or	$M < 0.5$	or	$d < 0.5$

its reliability is preserved.

5.3 *An educational application: assessing debris-flow hazard in different design scenarios*

The system TRENT2D WG was created as a modelling tool suitable for different purposes. For example, it can support profitably the design of effective protection and mitigation measures. In this case, models can be applied to evaluate the efficiency of such structures, assess their effect on different hazard scenarios or compare multiple design solutions, quantifying hazard variations.

In this work, TRENT2D WG was applied to an educational case study, aiming to evaluate the impact of a designed slit-check dam on debris-flow hazard levels in an urbanised mountain area. For this purpose, a realistic alluvial fan was considered and two different hypothetical configurations compared. In the first configuration, the geographic datum was represented by the original topography of the fan, without any protection structure. In the second configuration, a design solution was introduced, with a slit-check dam located at the fan apex. The dam was supposed to control a suitably designed deposition area, containing a maximum volume of sediments of about $4000\,m^3$. The slit was assumed totally obstructed by debris during the simulated events. All these design characteristics were introduced in the system TRENT2D WG thanks to the DTM-editing functionalities, which allow to modify cell elevations easily.

The Hazard Mapper service was used to produce a hazard map for each configuration, for the purpose of quantifying the effect of the dam on hazard levels on the alluvial fan.

Scenarios required by the hazard-mapping procedure were simulated by means of TRENT2D, considering the same a-priori values of the model parameters and the same boundary conditions for both the configurations. Each scenario was characterised by proper forcing events, i.e. by boundary conditions obtained from liquid hydrographs representative of the required return periods. Liquid hydrographs were generated starting from probabilistic observations on rainfall, i.e. from suitable Intensity-Duration-Frequency curves, and applying the rainfall-runoff model Peakflow (Rigon et al. 2011). Rainfall return periods of 30, 100 and 200 years were considered.

Then, TRENT2D outputs were processed through the Hazard Mapper, which produced the maps shown and compared in Figure 4.

On the whole, both the maps cover approximately the same area, with the map of the basic configuration which is slightly wider. On the contrary, the extension of each hazard level changes between the first configuration and the second. Areas with high hazard level, i.e. red areas, are quite wider in the basic configuration, especially in the upper part of the figure. In the second configuration, some of these areas are classified as medium hazard level areas (in blue). Similarly, some of the blue areas of the basic configuration change into low hazard areas (in yellow) in the design configuration. This is a clear proof of the effect of the design structure, which reduces hazard levels on the alluvial fan, especially in its lower part. This result accounts for the deposition processes induced by the slit check-dam in the deposition area, which reduces the amount of solid material reaching the fan.

Such analyses were performed quite easily by means of TRENT2D WG, taking advantage of the integration of different tools in a unique and smart environment. Of course, also other design solution could be considered and compared, with different results.

6 CONCLUSIONS

In this work, the new modelling infrastructure TRENT2D WG was presented. It was developed as a smart web system, able to overcome most of the issues related to the use of the TRENT2D model. TRENT2D WG allows to simulate debris flows and hyperconcentrated flows, applying a state-of-the-art model in a user-friendly environment. The system offers several pre- and post-processing functionalities and most of them GIS-based. Moreover, model results can be used straightforwardly to assess hazard levels, produce hazard maps and evaluate different hazard scenarios, as shown in the educational application.

Joining SaaS approach and WebGIS technology, this system is intended to introduce significant operative advantages for the user, encouraging the diffusion of state-of-the-art models between practitioners and stakeholders and bringing research targets closer to professional needs.

In the future, the characteristic SaaS flexibility will allow also other models, e.g. rainfall-runoff or avalanche models, to be integrated in the same system, developing a more complete and versatile working environment for hazard management in mountain

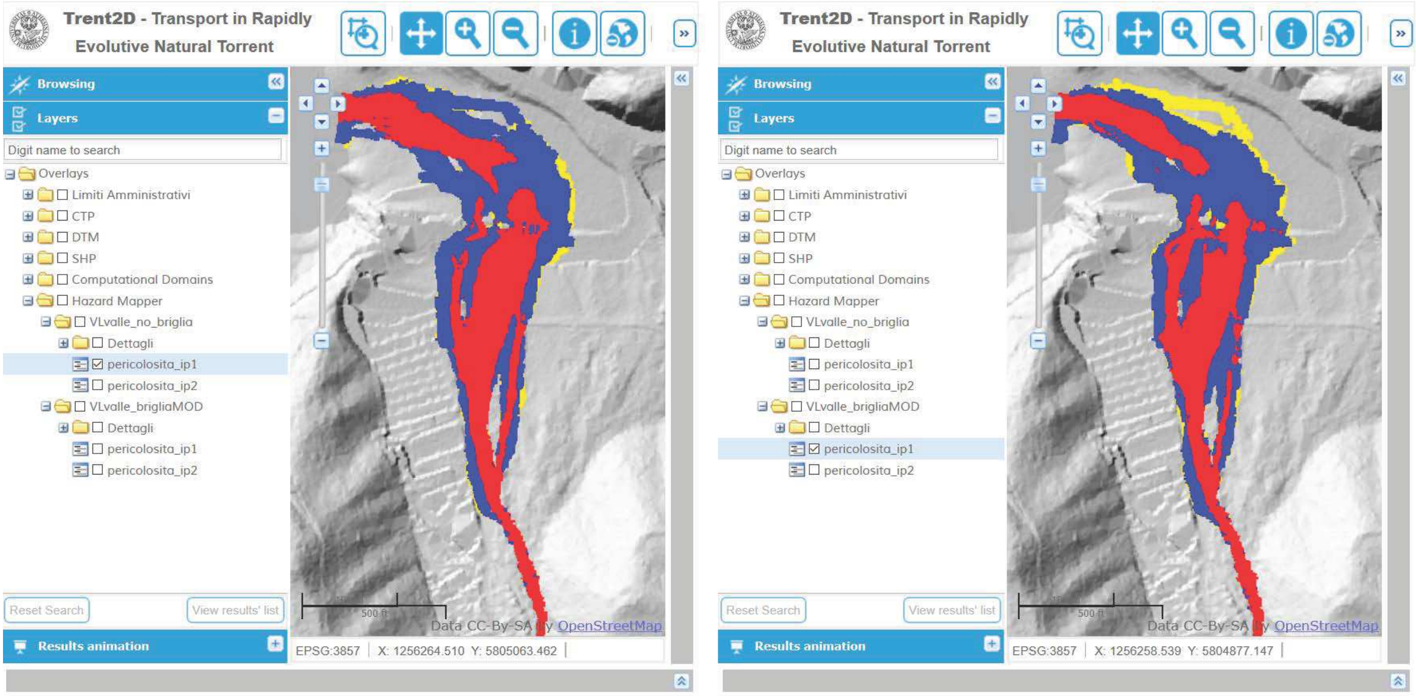

Figure 4: Comparison between the hazard map obtained for the basic configuration (on the left) and the hazard map obtained for the design configuration (on the right). High hazard level areas is represented in red, medium level in blue and low level in yellow

regions.

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