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The use of BIM for hydrogeological risk analysis in Cervo Valley: an innovative perspective

Supervisors:
Anna Osello
Ruben Verstraeten
Davide Lorenzo Dino Aschieri

Student:
Noemi Sobrino

To my mother, Valentina

To my father, Gianni

To my brother, Omar

'Nothing happens unless first a dream.'

Carl Sandburg

Abstract

The primary objective of this thesis is to develop innovative web maps in both 2D and 3D formats, offering static and dynamic (real-time) information. They are adopted to demonstrate their potential application in conducting hydrogeological risk analyses, especially in regions with high risk due to dense urbanization.

The main area of interest is the Cervo Valley, situated in the Piedmont Region, Italy. This Valley is cyclically affected by catastrophic natural events due to its orographic and hydrographic characteristics.

To achieve this final purpose, a series of QGIS Python-based tools and Python scripts are utilized to create the web maps. Additionally, initial comments are provided on the features of two culturally and historically significant infrastructures in the Valley: the Sain Giovanni Andorno Sanctuary and the ex-wool mill Maurizio Sella.

This study uses QGIS, an open-source Geographic Information System (GIS) software, due to its flexibility and compatibility with Python. Initial geographic data from Geoportale Piemonte and ARPA Piemonte websites are processed in QGIS to create simplified web maps. Python scripts generate additional static layers, while API calls to ARPA Piemonte website introduce dynamic updates. The finalized maps can made public.

Hydrogeological risks identified include landslide susceptibility for Saint Giovanni Andorno Sanctuary and flooding for the ex-wool mill Maurizio Sella. Static layers effectively show vulnerable areas in the Cervo Valley, while dynamic data integration emphasizes the need for real-time updates. Further Python script optimization and additional data on terrain conditions are necessary for a complete analysis.

Overall, this thesis aims to showcase the practical applications of innovative web maps in conducting hydrogeological risk assessments. It uses the Cervo Valley and its infrastructures as a case study.

Keywords: Web maps; Hydrogeological risk analysis; GIS-BIM Digital Twin; QGIS; Python.

Extended abstract

Introduction

The Italian peninsula is one of the European regions most affected by landslides and flood risks. Nine out of twenty Italian regions have 100% of their municipalities at risk of either landslides or floods, and another six regions have more than 90% of their municipalities at risk. This makes hydrogeological risk assessment a crucial topic of focus in Italy.
Despite the high risk, the country presents lacks in the introduction of comprehensive Digital Twins able to provide detailed information for the areas frequently affected by these hazards. While some websites offer relevant data, they often fail to graphically represent the territory of interest, which limits their effectiveness in developing robust risk management plans.

The introduction of innovative and interactive web maps (in 2D and 3D) that can define hydrogeological risks in real-time – incorporating both static and dynamic information – could significantly enhance risk management strategies. These strategies aim to reduce the risk to human lives and minimize structural damage to buildings.

The proposed study focuses on the Cervo Valley, one of the most affected areas in the Piedmont region, in Italy. This Valley experiences recurrent catastrophic natural events, posing serious threats to structures and, in the worst cases, resulting in loss of human lives. Two historically and culturally significant infrastructures of the Valley are then taken into account to discuss about the different possible hydrogeological risk in various areas.

By providing a detailed and interactive graphical representation of the territory, these new web maps could greatly improve the efficiency of risk management plans. This would be particularly beneficial from a hydrogeological perspective.
The ability to visualize and assess risks in real time would be of crucial importance for local authorities and emergency responders, allowing for more timely and effective interventions. Ultimately, this tool could help mitigate the impacts of natural disasters and protect communities in the Cervo Valley and beyond.

Goal

The main objective of this thesis is to demonstrate the critical importance of creating a Digital Twin for the most vulnerable areas prone to hydrogeological risks. This includes not only highlighting the necessity and benefits of such a digital tool but also exploring in detail the potential and critical aspects of the various technologies and methodologies employed. Furthermore, the thesis will delve into the possible future applications and enhancements of web maps in the context of risk management and disaster prevention.

A small section of the thesis is devoted to investigating the interoperability between Geographic Information Systems (GIS) and Building Information Modeling (BIM) software. This examination holds the potential to substantially improve the functionality and precision of Digital Twins.

The goal of the web maps developed in this project is to effectively represent both static and dynamic information. Static information is in the form of layers, offering a comprehensive depiction of the geographical and structural landscape. Then, dynamic information is presented via interactive pop-ups, providing real-time updates and data. This design aims to enhance the ability to efficiently monitor hydrogeological risks.

The structure of the thesis to achieve this goal proceeds as follows:

The first section introduces the characteristics of the Cervo Valley, accompanied by initial comments on the two infrastructures and the software adopted for the research.
Following that, a detailed description of the QGIS tools and Python scripts developed for creating the 2D web maps is provided.
A subsequent chapter mirrors the previous one, focusing on the creation of the 3D web maps.
Afterwards, comments on the applicability of these maps for the hydrogeological risk analysis of the two infrastructures are provided.
Subsequently, the potential and critical aspects of each tool adopted are described, offering a comprehensive overview of the research.
Before concluding, an exploration of possible future applications of the web maps is undertaken, followed by a chapter where limitations and specific conclusions are discussed. In this chapter, a critic analysis on the interoperability between GIS and BIM software is provided.

Methods

Despite the multitude of Geographic Information System (GIS) software programs available today, this study focuses on the utilization of QGIS. It is adopted for its flexibility, being an open-source software that can be easily adapted for various applications. It can be combined with numerous third-party plugins, and it supports programming languages such as Python or C++.

The study is completed by the development of Python scripts with the aim of creating new static layers to be incorporated into the web maps, as well as for managing dynamic information.

The workflow begins with the acquisition of initial geographic and geometric data from two official Italian websites: Geoportale Piemonte and ARPA Piemonte. These data are then processed in QGIS to create a user-friendly web map and to reduce the number of imported layers. Various tools are used in this process, including layer merging, intersection, and clipping. Subsequently, additional layers generated by specific Python scripts are integrated to enhance the static representation of the map.

Afterwards, dynamic information is introduced by making API calls to the ARPA Piemonte website. This step ensures that the maps are continuously updated with real-time data. Once finalized, the maps are prepared for publication and made available to the public.

Results

The first hypothesis regarding hydrogeological risks associated with the two infrastructures has been confirmed. The Saint Giovanni Andorno Sanctuary is particularly susceptible to landslide hazards, whereas the ex-wool mill Maurizio Sella is prone to recurrent flooding events.

The introduction of various static layers, able to depict areas at hydrogeological risk, has proven to be effective and efficient. These layers offer a comprehensive overview of the hydrogeological situation in the Cervo Valley, including the identification of streets and buildings vulnerable to catastrophic natural hazards.

The incorporation of dynamic information highlights the importance of integrating real-time data with static layers. However, true real-time data are unavailable on the ARPA Piemonte website. Therefore, 2023 data have been utilized as real-time information.

An optimization of the Python script used to provide elevation coordinates to the shapefiles employed in the 3D web map is essential to increase the graphical representation of the Valley. Furthermore, improvements are needed in the development and management of the exporting plugin. It is necessary to face up existing graphic visualization errors in the 3D web map.

The comprehensiveness of hydrogeological analysis requires additional data. Specifically, information regarding terrain evapotranspiration characteristics, geological conditions, and water content will further enrich and refine the assessment process.

Conclusions

The development of interactive maps has highlighted the necessity of creating a Digital Twin for the targeted area, allowing the prediction and prevention of natural catastrophic events through effective risk management planning. Using existing static information concerning flooding events, landslide areas, and hazard cones it is possible to understand the terrain's behavior across various return periods.

The differentiation of terrain slopes aims in understanding the land's inclination and facilitates the identification of associated landslide risks. Furthermore, integrating dynamic precipitation data into the maps allows real-time monitoring of meteorological events in the area.

This system empowers municipalities to identify property owners and notify them of potential risks to their assets. Moreover, these maps can integrate with emergency evacuation systems, facilitating the planning of evacuation routes during imminent catastrophic events. In addition, these maps can also support sensibilization programs for both the public and institutional stakeholders, including fire and police departments.

Despite these advancements, current limitations in interoperability between Geographic Information Systems (GIS) and modeling software are present. Specifically, efforts to improve QGIS-BIM format interoperability are crucial. Such advancements would simplify the creation of Digital Twins for structures, infrastructures, and terrain areas increasing the adoption of these software programs.

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1. Introduction

1.1. Hydrogeological risk analysis: the research question

The hydrogeological risk is linked to slope instability due to specific geological and geomorphological characteristics, as well as river instability caused by adverse environmental, meteorological, and climatic conditions. This is translated into the risk of loss of human lives and lack of security for services and infrastructures located in the territory.

The Italian peninsula is one of the European countries mostly affected by both landslides and floods risks.

According to the *Landslides and floods in Italy 2018* report, 620,808 landslides affect an area of 23,700 km^2 that corresponds to the 7.9% of the national territory. While, for what concerns the flooding events, they are considered as the water temporary covering of land not normally covered by it. They include floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas.

Considering the total amount of municipalities present in the Italian territory, the 91.1% of them are considered located in landslide hazard zones (high and very high hazard) and/or flood hazard zones (medium probability scenario, return period of 100-200 years). This is geographically translated into the 16.6% of the whole national territory. Considering these data, 9 Regions (Valle d'Aosta, Liguria, Emilia Romagna, Toscana, Umbria, Marche, Molise, Basilicata, and Calabria) have 100% of municipalities affected by high and very high landslide hazard and/or medium flood hazard zones. In addition, the Province of Trento, Abruzzo, Lazio, Piemonte, Campania and Sicilia Regions have percentages greater than 90% (Triglia & Iadanza, 2018) [Figure 1.]. *(1)*

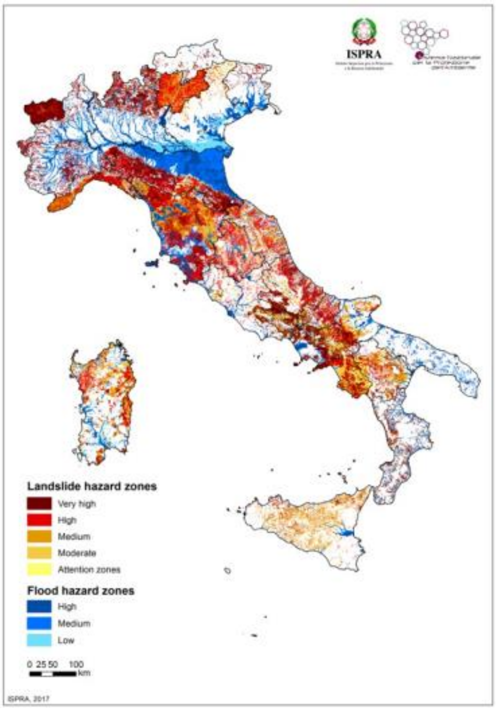

Figure 1. National mosaic of landslide and flood hazard zones.

Therefore, the definition of a proper risk management plan for these two types of calamities can help in the prevention, protection and preparedness of both population and territory. With accurate forecasting of possible catastrophic events, it is possible to activate early warning systems in time and reduce the overall impact of destructive consequences. At the same time, they could become useful to promote sustainable land use practices and to improve the water retention techniques.

As already described, the Piedmont region is one of the most affected areas in the national territory. With 1,201 municipalities, 1,133 of them – that corresponds to 94.3% of the total – are affected by high and very high landslide hazard zones and/or medium flood hazard zones. It means that 3,217.8 km^2 out of 25,387 km^2 – the 12.7% of the territory – is the area under these types of risk (Triglia & Iadanza, 2018). *(1)*

Consequently, the introduction of an innovative web map from where it is possible to define the hydrogeological risk in real time by considering both static and dynamic information, can fully meet the requirements of a proper risk management plan. This has the final purpose to reduce the loss of human lives risk and structural risks for the buildings.

The study is focused on Cervo Valley that is one of the mostly affected Piedmont's areas.

1.2. Introduction to the Cervo Valley

The Biella province, in the northern area of Italy, is a territory composed of 910 square kilometers. It borders with the Aoste Valley, the Vercelli province, and the Turin province. It consists of 74 municipalities and 9 unions of municipalities. At a first glance, because of its orography and its relevant altitude range, the area seems to be characterized by an opposition of mountains and plain. At the same time, paying attention to the development of the territory, there are distinguishable three different environmental frameworks: the Valleys, the Hills and the Plain.

Cervo Valley – the one of interest for the development of the thesis – is a mountain territory developed all along the Cervo Stream. It is also known as 'Andorno Valley' that is the name given by the Community of residential villages guided by the Andorno Cacciorna center. The Valley is extended from North-West where it is located the Cervo Stream origin – in Piedicavallo village – to its floor and to the city of Biella. The High Valley is poorly populated and narrow, characterized by the presence of a series of huts and pastures; while the Low Valley is delineable as the area where most of the residential and industrial settlements are present. In this latter part of the territory, the mountainous landscape gives the stage on a wooded one. At the same time, all along the area there are some important villages of historical and cultural heritages. This is the case of Rosazza, Piedicavallo and Campiglia Cervo.

1.2.1. Cervo Valley History

On the official Cervo Valley website, there is some historical information available.

Cervo Valley has served for centuries as a transit zone for herd and populations. From the high valleys of Lys and Sesia, heading towards the markets of Biella and Cacciorna, the Sanctuary of Oropa, or high-altitude grazing areas.

The first historical documents where it is present are dated to before the year 1000, when the territory was donated from emperor Ottone I to Aimone, Vercelli count.

Then, in 1379 the whole area was dominated by Amedeo VI of Savoia (Green count) who ended the period of violence exercised by Giovanni Fieschi bishop.

During the 1621 year, Carlo Emanuele I of Savoia duke created the Andorno Marquisate and in 1649 the whole territory was invaded by Spanish troops at war with Piedmont. In this situation, the Cervo Valley inhabitants paid money and gave up fodder, food, and cattle to avoid looting events.

Starting from 1722, the entire Community was divided in different administrative entities. In 1782 all the fiefs were agglomerated under the power of the vassals.

The disintegration of the Marquisate began in the year 1694, when the Callabiana, Selve Marcone municipalities and the Valle canton became autonomous.

Afterwards, during the XVIII century, the canton was further divided into the municipalities of Campiglia, San Paolo, Quittengo and Piedicavallo; with Rosazza separating from the latter in 1906. Different other municipalities became autonomous from 1720 to 1948.

In 1973 the two mountain communities of Upper and Lower Valley were formed, even if toady they are considered merged into a single entity.

Today, the Mountain Union 'Valle del Cervo-La Bürsch' comprises 12 municipalities: Andorno Micca, Campiglia Cervo, Miagliano, Piedicavallo, Pralungo, Ronco Biellese, Rosazza, Sagliano Micca, Tavigliano, Ternengo, Tollegno, and Zumaglia. (2)

1.2.2. Buildings and geological configuration

From a structural perspective, the stone is the main construction material adopted, especially in the northern areas from Campiglia Cervo municipality. Villages like Rosazza and Sassaia are entirely composed of stone buildings. This stone is properly defined as syenite, a granite with exceptional durability and resistance characteristics, widely used for creating monuments, constructions, and urban furnishings.

On the other hand, the geological configuration of the Valley is quite complex. A walk along the bed of the Cervo Stream between Sagliano Micca and Passobreve reveals the complexity of the evolution of the Alpine chain, with the interaction of many intricate geological processes narrated by the rocks exposed along the Stream.
Starting from Sagliano Micca, it is observable the outcrop of rocks like granite, called tonalites, representing the solidification of magma in the Earth's depths. The deformations undergone by these rocks in the last 30 million years are evident, highlighted by visible fractures in the outcrops.
At Passobreve, the first rocks emerging in the streambed are still granites predating the Alpine chain, which have been intensely deformed by the processes of Alpine chain formation.

Travelling through the Valley, the paths taken by the magma, called dikes, are visible both in the streambed and along the Panoramic Zegna Road. The magma that formed these flows ascended along the fault, called the 'Canavese Line', which represents the point of connection between two different worlds. The first has been passively affected by the processes of Alpine chain formation. The second, in the north of the Canavese Line, consists of rocks from the so-called Sesia Lanzo Zone, representing one of the fundamental geological units of the Alpine chain.(3)

1.2.3. Hydrographic configuration

Focusing the attention to the hydrographic characterization of the region, the distribution of surface waters falls almost entirely within the two basins of the Cervo and Sessera rivers. Both are tributaries of Sesia that characterizes the territory.

Among the main streams in the province of Biella, 17 belong to the Cervo basin, while only 2 flows into the Sessera.

For what concerns the Cervo basin, in the Valley of interest and above Biella, there are different confluences. The bigger one is the so-called Rio Valdescola, while among the others are recognizable the so-called Mologna and Irogna streams.

As regards the confluences below the city of Biella and therefore out of the Valley of interest, there are 14 confluences depicted below.

Cervo basin [Figure 2.]:

1. Cervo (65,48 km)
2. Oropa (13,49 km)
3. Strona di Mosso (26,81 km)
   - 3.1. Quargnasca (12,54 km)
     - 3.1.1. Chiebbia (12,11 km)
4. Ostola (23,51 km)
   - 4.1. Bisingana (14,70 km)
5. Guarabione (20,47 km)
6. Rovasenda (37,83 km)
7. Marchiazza (34,67 km)
8. Elvo (58,46 km)
   - 8.1. Ingagna (18,50 km)
     - 8.1.1. Viona (16,50 km)
   - 8.2. Oremo (16,21 km)
   - 8.3. Olobbia (15,22 km)

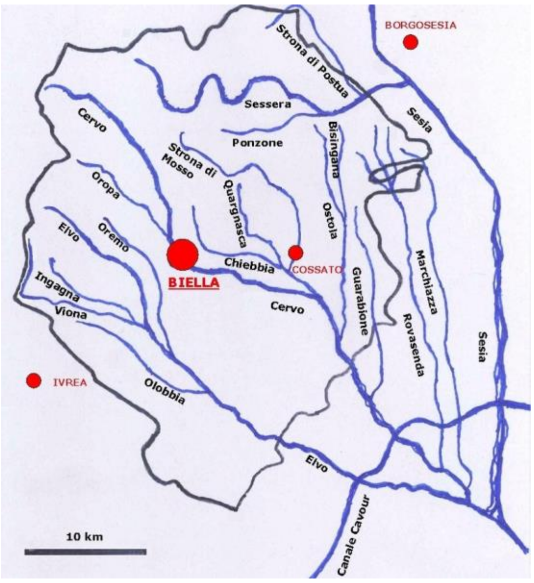

Figure 2. Representation of the Cervo basin and its confluences. [4]

The Biella province streams have been subjected to devastating floods that over time have caused numerous damages to properties and people. [4]

1.2.4. Hydrogeological risk analysis – The infrastructures of interest

Considering the subjectivity of the region to floods and landslides, the final purpose of the thesis is related to the realization of a tool for the hydrogeological risk analysis of the whole Cervo Valley, focusing the attention on two different historically and culturally fundamental infrastructures for the region.

The first one – the so-called Saint Giovanni Andorno Sanctuary – is in the High Valley and it has monumental dimensions with a clear devotional significance. It is also considered an architectural and environmental complex with a distinct community character. Placed in Campiglia Cervo municipality on the edge of the national road Rosazza–Oropa, it requires a careful analysis because of the mountainous characteristics of the terrain where it has been built and the corresponding landslides risks.

The second building of interest – the Ex-wool mill Maurizio Sella – is placed in Via Corradino Sella, Biella. The complex is situated on the left bank of the Cervo Stream, extending for a length of approximately 500 meters. It includes the original buildings of Quintino Sella's residence, paper mills, and wool processing facilities (spinning, weaving, dyeing) constructed between the 1700s and the 1930s. Structural interventions involve a variety of new constructions and consolidations using different construction techniques. Because of the vicinity of the structure to the Cervo Stream, it is considered necessary a proper analysis of the hydrogeological risks associated with flooding events.

1.3. Historical hydrogeological background

The flood events that have affected Piedmont in recent decades, have highlighted the need for a modern and proper river area planning policy. On one hand, this policy should define and safeguard the areas under the jurisdiction of the watercourse. On the other hand, it should lead to the protection of urban settlements and existing infrastructures in this area.

The processes associated with river dynamics, demonstrate their activity not only within the active riverbed but also in a lateral zone which extension depends on the type of riverbed present. This affects lands that have been subject to an increasingly widespread human occupation over time.

The Biella territory, due to its orographic and hydrographic features, is cyclically affected by hydrogeological instability, which occurs during rainfall events of a certain intensity. Often, these storm cells localize over a single basin, while at other times, entire valleys are involved. The risk is consistently high due to the dense concentration of urbanized areas.

For what concerns the hydrogeological risk in Cervo Valley, it is something that has been always existed during the years. This is also because of the human-historical occupation of the territory in the past decades.

1.3.1. Geological characterization and hydrometric level of Cervo stream basin

A proper description of the geological characterization and of the water level of the Cervo Stream is necessary to delineate the context of analysis.

The Cervo Stream, a right tributary of the Sesia River – drains a basin of 9.943 square kilometers – is approximately 64 km long and has an overall average slope of 0.5% (SERTEC S.p.A., 1976).

The mountainous basin practically closes at Biella, where it receives the Oropa Stream. In this area, it traverses lithologies from the Sesia-Val di Lanzo Series (light mica gneiss, biotite gneiss, eclogitic mica schists, etc.) from upstream to downstream. It also encounters rocks from the Cervo Valley Pluton (granites, syenites, monzonites, etc.) and, near Tollegno, lithotypes from the Dioritic-Kinzigitiga Series (diorites, biotite-sillimanite gneiss with garnet and graphite, etc.).

The Cervo Stream, concerning its hydraulic behavior, exhibits a typical torrential regime. In a study for the 'Hydraulic Arrangement of the Cervo River,' commissioned by the Piedmont Region and the Provincial Administration of Vercelli (BUTERA, 1980), an investigation was conducted to contextualize the floods of the Cervo Stream. This was done within the broader context of peak flows of Piedmont's watercourses in the mountainous and foothill sections.

Through mathematical relationships considering contributions from a specific area, flows of approximately 900 cubic meters per second were predicted at the Silit cross-section (Biella) for a 100-year return period. A comprehensive investigation of the upper basin of the Cervo Stream conducted by STUDIO STIGE (1982), for the Mountain Community Alta Valle del Cervo, suggests maximum flood flows of 961 and 1047 cubic meters per second, respectively calculated for return periods of 100 and 200 years in correspondence of Passobreve hydrometric station. This calculation utilized hydrological data from the Oropa Station, compared with data from other stations, and employed the method of calculating the travel time or the kinematic method (Ramasco & Rossanigo, 1988). [(5)]

1.3.2. Historical flooding events associated with Cervo Stream

From Arpa Piemonte data and other sources, it is possible to trace several historical flooding and landslide events occurred in the territory of interest. A brief introduction to them is delineated below.

The first recorded landslide occurred on September 26, 1666: the overflowing Cervo River swept away and destroyed about twenty buildings without causing any casualties (Cattaneo, 2018). [(6)]

Another flooding event occurred in November 1951, when an Atlantic anticyclone was followed by an African anticyclone and leaded to an extraordinary flood of the Po River. The amount of information available in this regard is low, but the whole Piedmont region was subjected to extraordinary rainy events and flooding ones. Focusing the attention on the Cervo Valley, the event produces many landslides with some victims (ARPA Piemonte, s.d.).[(7)]

The second and most important catastrophic event in the territory occurred in November 1968 (Ramasco, et al., 1997).[(8)] In that situation, along the course of the Sesia River from Borgosesia to the confluence with the Cervo Stream, significant sediment mobilizations have been identified. This includes the partial or complete removal of islands and river bars, deep erosions along the banks, and the redeposition of the materials that were eroded [Figure 3., Figure 4., Figure 5., Figure 6., Figure 7., Figure 8.]. Examination of aerial photographs from the 1968 event revealed that in many sections, the Cervo Stream embankments already present at the time of the flooding event were not functional. Breaches and overflows were frequent on both the right and left banks. More in detail, the breach of the embankment on the left bank was the cause of extensive flooding in the areas behind it. The riverbed represented in 1882 consists in the first reference for the analysis of the historical evolution of the Cervo Stream.

In October 1979, a flooding event affected the whole Valley with major attention to the municipalities of Campiglia Cervo and Piedicavallo. [(10)]

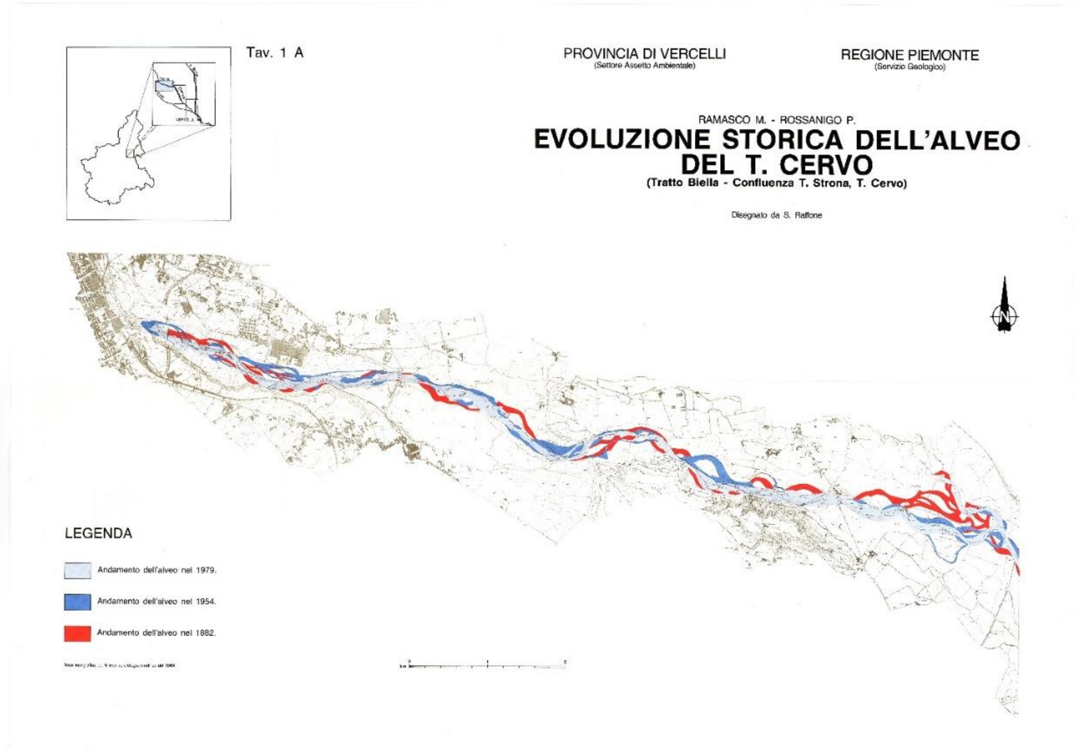

Figure 3. Board 1A of Arpa Piemonte – Historical evolution of Cervo Stream riverbed: 1882 in red, 1954 in blue and 1979 in light blue. [9]

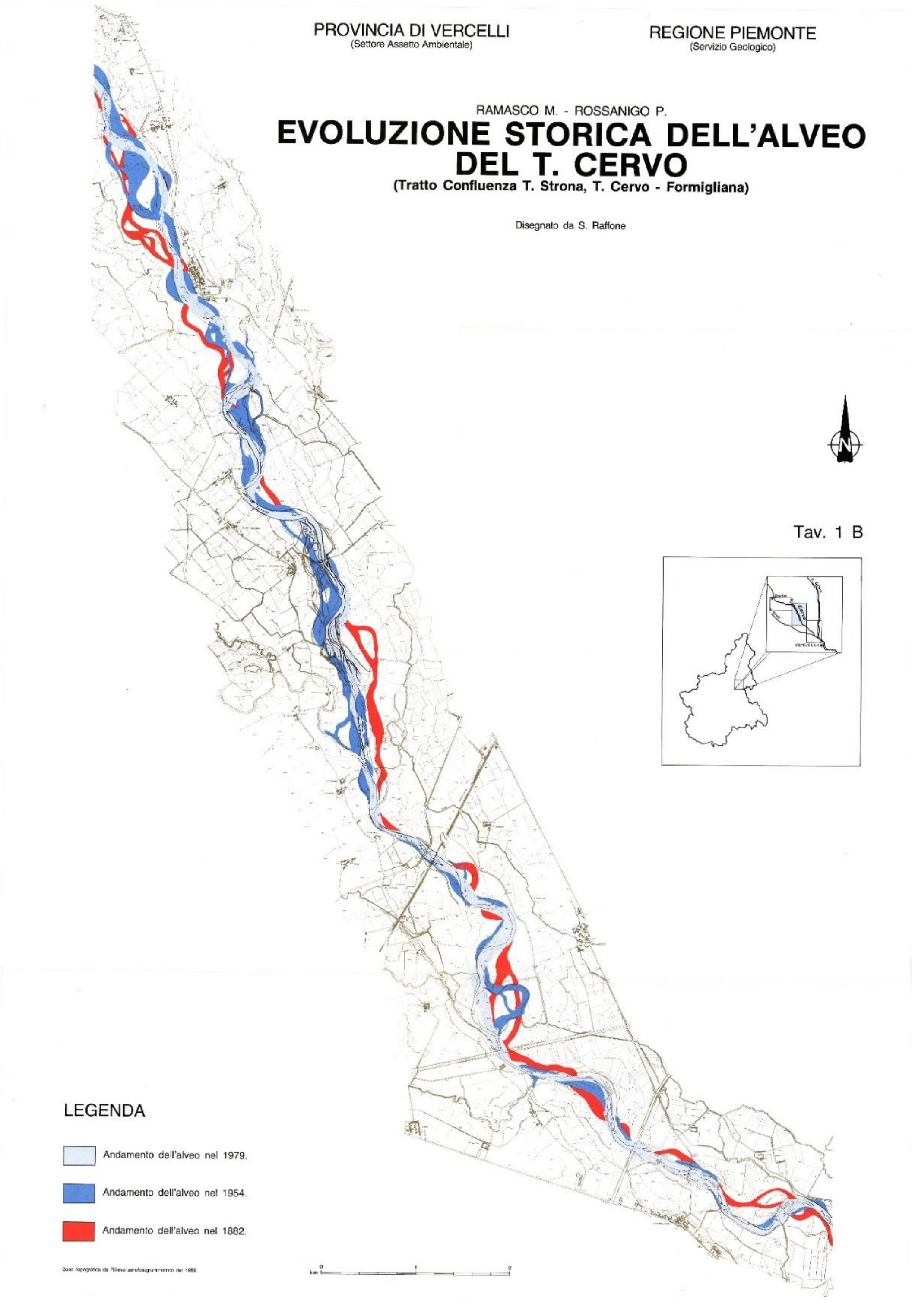

Figure 4. Board 1B of Arpa Piemonte - Historical evolution of Cervo Stream riverbed: 1882 in red, 1954 in blue and 1979 in light blue. [9]

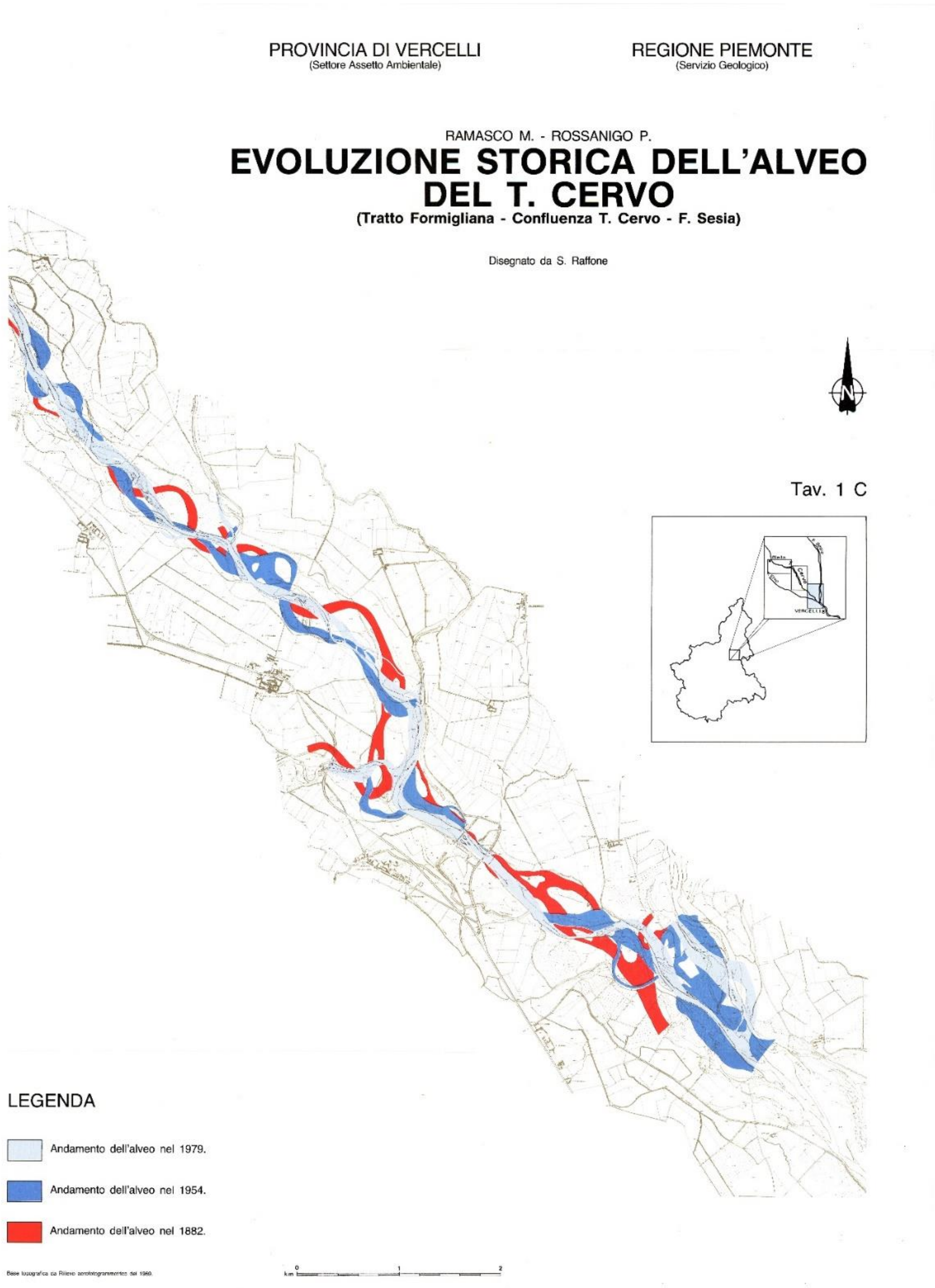

Figure 5. Board 1C of Arpa Piemonte - Historical development of Cervo Stream riverbed: 1882 in red, 1954 in blue and 1979 in light blue. (9)

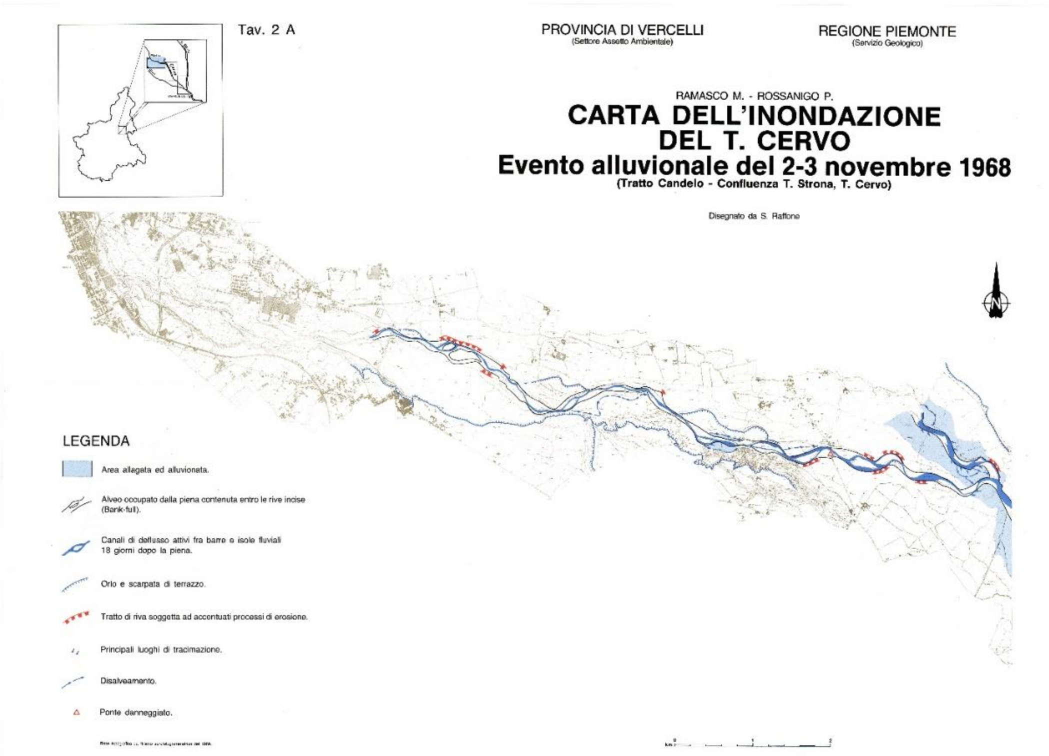

Figure 6. Board 2A of Arpa Piemonte - Flooding interested area in light blue. [9]

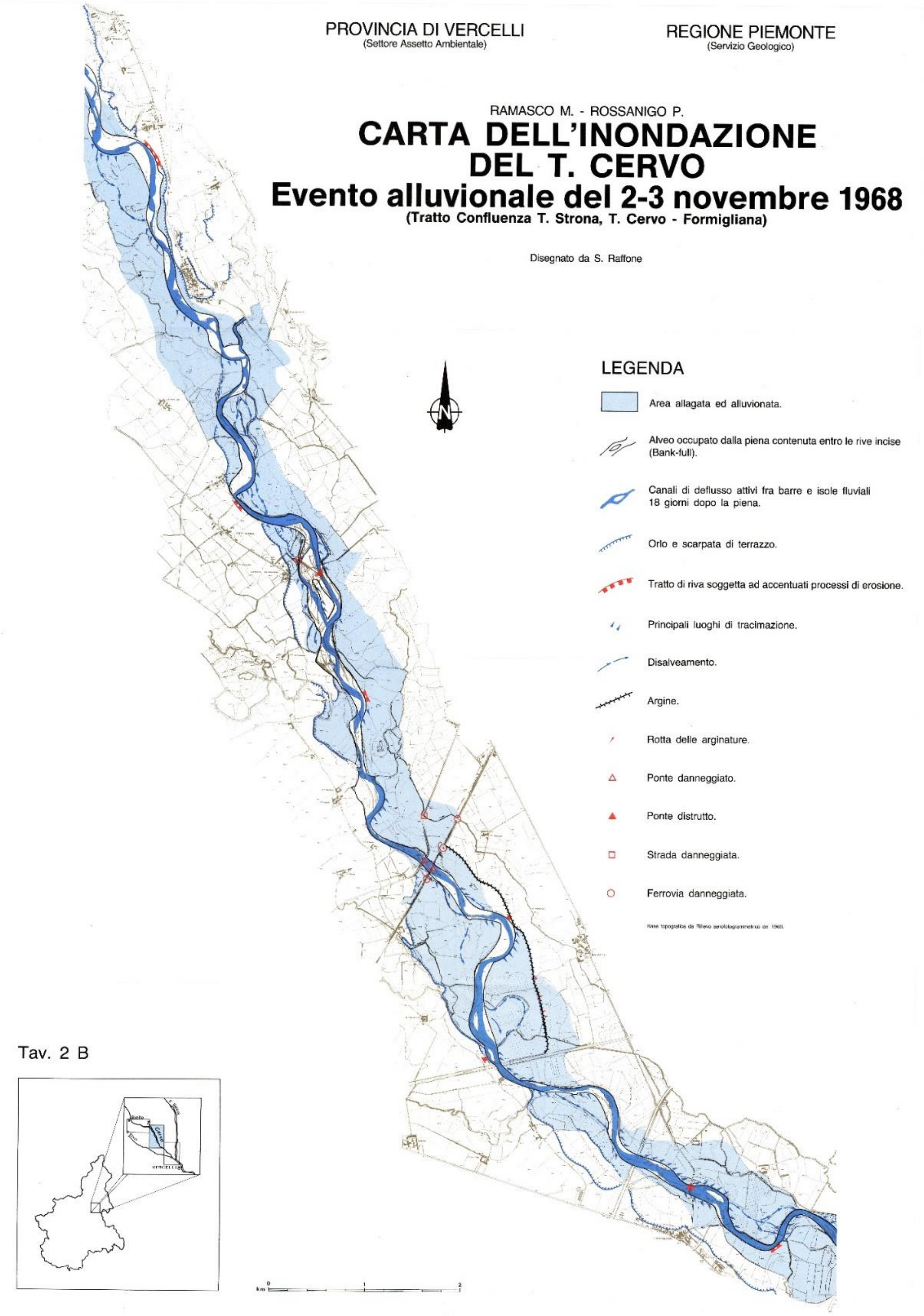

Figure 7. Board 2B of Arpa Piemonte – Flooding interested area in light blue. [9]

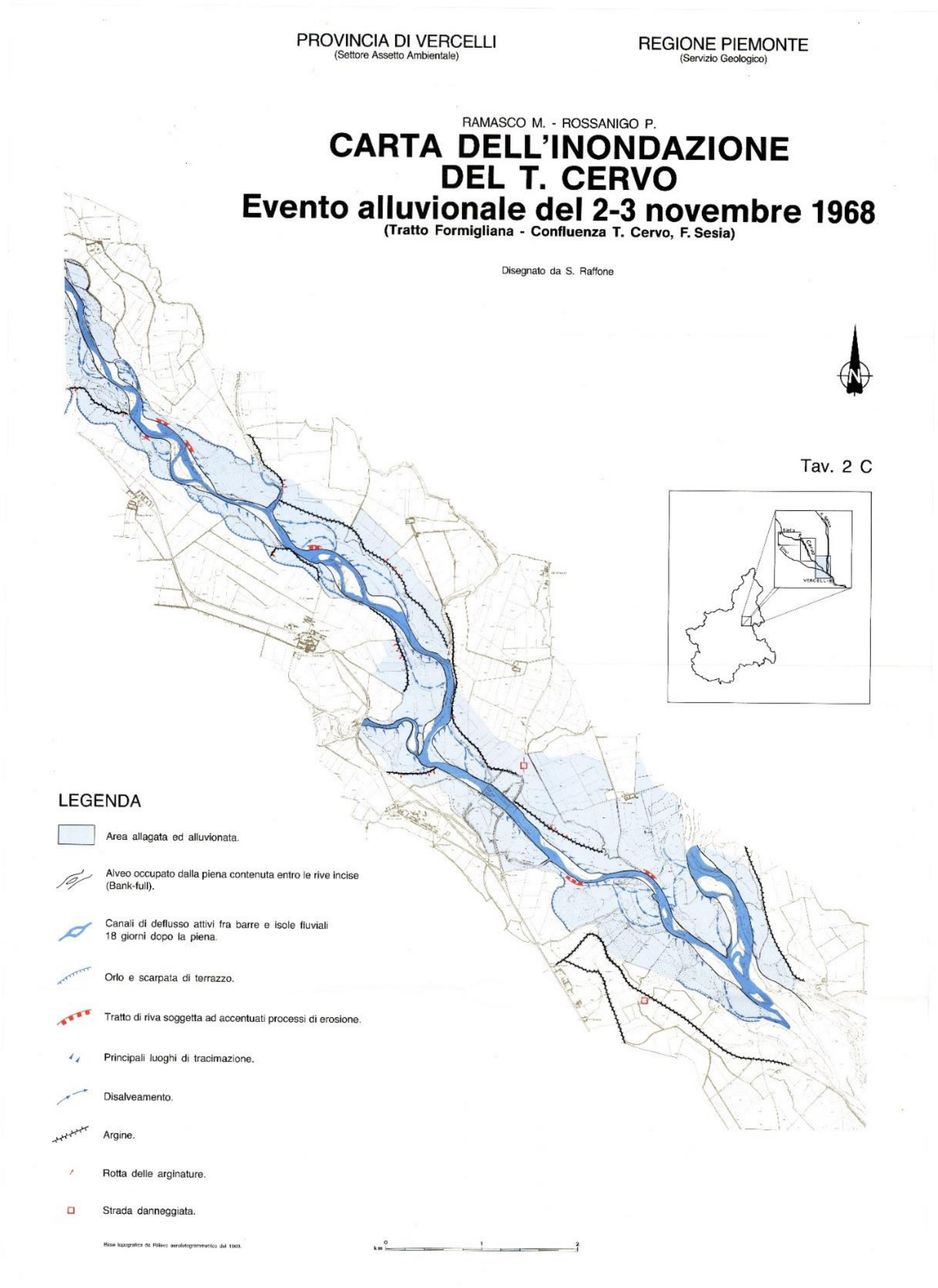

Figure 8. Board 1C of Arpa Piemonte - Flooding interested area in light blue. [9]

The 1993 event mainly affected the watercourse in the mountainous stretch (RAMASCO, 1996). While the flood of 1994 manifested with greater intensity in the river's terminal section (from Vercelli to the confluence with the Po) due to the significant contribution of the Cervo Stream. The flood of November 4-6, 1994, thus occupied a riverbed already shaped by the previous year's event without causing severe damages upstream but exerting more significant effects in the terminal part of the watercourse [Figure 9.]. From Romagnano to the confluence with the Cervo

Stream, the effects of the flood were primarily observed within the embanked river strip, particularly with erosions of the riverbank (Ramasco, et al., 1997). [9]

Il Cervo travolge la tangenziale

L'allarme è scattato alle 18 di venerdì e il viadotto per Chiavazza e Cossato è stato chiuso alle aut
Poi il boato e un'enorme voragine. La struttura era stata costruita dall'Anas e inaugurata nel '68

BIELLA. Due campate del viadotto sul Cervo della tangenziale sono crollate, travolte dalla furia del torrente in piena. I danni sono gravissimi, ma per fortuna non ci sono state vittime: il ponte era appena stato chiuso al traffico.

E' accaduto venerdì sera verso le 18,30. Il maltempo che da 36 ore imperversava anche sul Biellese aveva fatto ingrossare tutti i corsi d'acqua. Già a mezzogiorno il livello del Cervo era sopra il livello di guardia e i vigili del fuoco controllavano ogni ora tutti i ponti della zona. Nel caso della tangenziale poi, i tecnici dall'impresa Lys da mesi impegnata nei lavori di rin-

LE PREVISIONI

In arrivo altra pioggia

Era dal marzo dell'81 che nel Biellese non si verificavano d
precipitazioni così intense. L'Osservatorio di Oropa segnala
tra giovedì e venerdì sono caduti in totale 384 millimetri di p
gia. Il momento più difficile è stato tra le 20 di giovedì e le 8 di
nerdì quando il pluviometro ha raccolto 170 millimetri di ac
accompagnati da raffiche di vento a quasi 60 chilometri all'ora
scroscio più intenso ha riversato in 60 minuti 40 millimetr
pioggia. Dati già ragguardevoli, ma nulla in confronto a quelli
gistrati da una delle stazioni meteo di Genova dove in una
mattinata sono caduti più di 300 millimetri di acqua piovan
tempo per oggi resta perturbato: l'osservatorio metereosismic
segnala la possibilità di nuovi rovesci che si alterneranno a b
schiarite. E c'è già una nuova perturbazione all'orizzonte che
terà ancora maltempo anche se con piogge meno intense.

Figure 9. La Stampa journal - The destruction of a viaduct by the Cervo Stream in 1993. [11]

In June 2002, the Biella region was struck by a severe hydrometeorological event that caused widespread damage to the area, particularly in the Cervo Valley. In Biella territory, the meteorological event primarily affected the western sector, particularly impacting the upper basins of the Viona, Ingagna, Elvo, Oremo, Cervo, and Sessera streams. The intense rains resulted in cumulative amounts of 300 to 400 mm within a 24-hour period, notably reaching 395 mm in Trivero, 340 mm in Piedicavallo, and 300 mm in Oropa. The extremely intense downpours, with peaks of 100 mm per hour, completely disrupted the slopes and the hydrographic network. Concerning the estimation of flow rates, in the upper basin of the Cervo River, the flood processes affected the entire hydrographic network. There was a significant peak flow value on the Cervo River at Passobreve, reaching approximately 400-500 m^3/s. This value is comparable to a flow rate associated with a return period of 20 years. The peak intensity levels of the rains primarily affected the middle to upper sectors of the mentioned basins, triggering numerous shallow landslides on the surface debris and eluvial coverings. The combination of processes occurring on the slopes and those along the hydrographic network has resulted in quite severe effects, especially along the watercourses in the valley bottoms. In many cases, the damages resulting from these phenomena were exacerbated due to the interference of human-made structures with the natural water flow (bridges with insufficient clearance, inadequate water regulation structures, and a dense network of secondary mid-slope roads). A portion of these landslides directly affected buildings and roads, causing severe structural damage [Figure 10. and Figure 11.]. Others, channeling into the steep valleys of smaller streams, tributaries of the main watercourses, triggered debris flows reaching the valley floor, sweeping away everything in their path. Along the course of the Cervo River, in particular, these events led to bed mobilization phenomena of such intensity that there is no historical memory of a flood event of such proportions (ARPA Piemonte, s.d.). [12]

Figure 10. Partial destruction of a residential building in High Cervo Valley. [13]

Figure 11. Rescue after the tragedy in High Cervo Valley. [13]

In October 2020 exceptional intensity precipitation affected the entire region, with particular emphasis on the areas of the upper Tanaro Valley, Biella, Vercelli, and Verbano. The most intense precipitation occurred on October 2nd. The heavily affected area appears to be the Upper Cervo Valley. In the municipality of Piedicavallo out of seven bridges, only one remained intact. The other six either collapsed or were seriously damaged. Provincial and municipal roads were interrupted in multiple points due to landslides and flooding. In the municipality of Campiglia Cervo (BI), the flooding of the Cervo River has eroded and removed a long stretch of the SP100 road in the Malpensà hamlet [Figure 12.]. In that occasion, also the San Giovanni Andorno Sanctuary was hit by a landslide. [14]

Figure 12. Campiglia Cervo: Malpensà locality. Erosion of the riversides. [14]

Between May 19 and May 21, 2023, a large low-pressure area lingered over the Mediterranean basin, blocked to the east by the presence of a high-pressure ridge that prevented its natural eastward movement. The formation of upper-level and surface lows within the disturbance continued to channel intense southerly flows at higher altitudes and northeastern flows in the lower layers, resulting in widespread adverse weather conditions in our region. The most intense and prolonged precipitation was recorded in the mountainous and foothill areas of the Alps. Small disruptions in Biella pre-Alps region have occurred. The SP 115 road to Bielmonte was temporarily blocked by debris fallen in the Campiglia Cervo area, between the Piaro and Forgnengo hamlets. In the Cervo Valley, a collapse landslide affected the construction site next to the Sanctuary of San Giovanni, which was severely damaged by the flood in October 2020.

1.4. The software

To complete the introduction, a specific mention should be done in terms of software adopted to create both the bi-dimensional and three-dimensional maps of the Cervo Valley.

A variety of software can be used with this final purpose, some of them are ArcGIS Pro, a complete closed source suite with advanced GIS tools; Cesium, a web-based platform to visualize in an interactive way geographical data; Mapbox, a platform used to create and personalize maps; InfraWorks, a planning and modelling software; and QGIS, an open-source Geographic Information System (GIS) software with a variety of functions.

Thanks to the high flexibility and the interactive user interface of the latter one, the core of the study is based on QGIS. It is used to visualize, organize, analyze, and represent spatial data. Then, it supports both vectorial data and raster files, but also other spatial databases as PostgreSQL or Spatialite. In addition, it integrates processing algorithms like GRASS GIS and SAGA GIS, and it supports code languages as C++ and Python.

This latter code language is indeed used to complete the whole thesis work as a support and a programming tool. With it, specific vectorial data integrable into the GIS software are created. In addition, it is also adopted to carry out double checks for the accuracy of data directly modified into the GIS software. In conclusion, it completes the web maps through the application of additional graphs in them.

2. 2D Map

2.1. Initial data and websites of reference

The first step for the realization of the 2D map is the import of the geographical data – provided in the official Italian and Regional websites – into the QGIS software. The websites of reference in this case are Geoportale Piemonte and ARPA Piemonte. The former is an online platform that allows to download and to visualize geographic and cartographic data related to the Piedmont Region. The latter is the regional agency online platform for the Piedmonts environment protection. It provides information related to the environment monitoring tools and data, environment emergencies, historical and real time environmental data as well as the meteorological ones.

The 2D map concept is based on two different exports: the Piedmont map and the Cervo Valley one. The first one has the final purpose to represent a general overview of the Piedmonts hydrographic network, flooded areas, landslide ones and cones. For what concerns the second one, it is the principal map, and it only shows the Cervo Valley area.

In the Piedmont map a Digital Terrain Model (DTM) with a precision of 25 m is used, while in the second case the DTM has a precision of 5 m. The difference is necessary to limit the dimensions of the exported files once the first map is ended. In both cases, the DTMs are the base layers, and both are downloaded from the Geoportale Piemonte website. Both are obtained with LIDAR (Light Detection and Ranging) uniform standard method of level 4. The LIDAR technology uses laser impulses to perform a remote detection of the terrain; the uniform standardized method allows to efficiently collect, elaborate, and analyze LIDAR data guaranteeing their high interoperability and possibility of comparison, independently from the place and time of detection; the level 4 defines the quality of detection: it represents the highest level of precision – from 1 to 4 – in the detected data. The DTMs are imported into the QGIS software as raster files (.tiff).

Over the DTMs, different vectorial data are overlapped in QGIS. These data are the hydrographic network that includes rivers, canals, and lakes. And the vectorial dataset of the Geo-Topographic database obtained from the Reference Spatial Database (BDTRE) updated on the 28th of February 2023. These are imported from Geoportale Piemonte website into QGIS as vector shape files (.shp).
Two different hydrographic networks are imported into the QGIS software. The one from ARPA Piemonte website representing information regarding the classification of rivers and identification of water bodies in Piedmont (2015-2020). This is obtained in accordance with the European Directive 2000/60/EC (Water Framework Directive - WFD) establishing a framework for community action in the field of water [Figure 13.]. The other one is the historical hydrographic network from Geoportale Piemonte website obtained from the Military Geographic Institute (IGM) cartography (1952-1966) in scale 1:100.000 [Figure 14.].

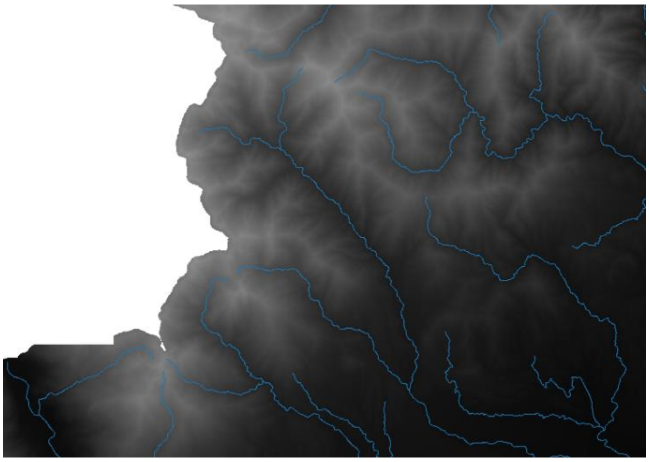

Figure 13. ARPA Piemonte Cervo Valley hydrographic network representation.

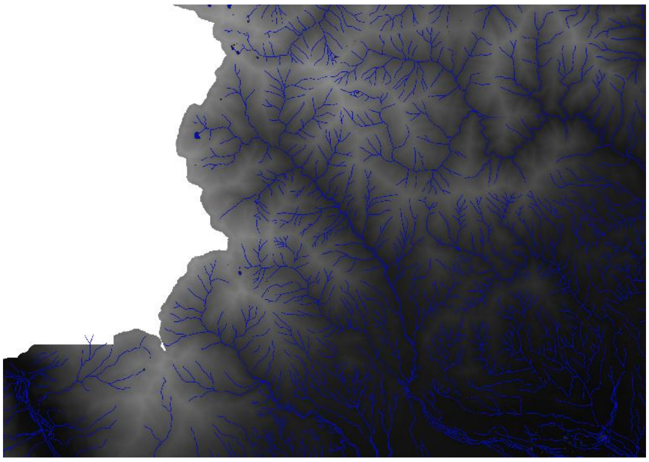

Figure 14. Geoportale Piemonte Cervo Valley hydrographic network representation.

The final purpose of this double import is to verify the variation of the main channel of the Cervo stream over the years [Figure 15.]. The image below represented is a zoom in correspondence of the Upper Valley. It is noticeable a quite small variation of the main river channel.

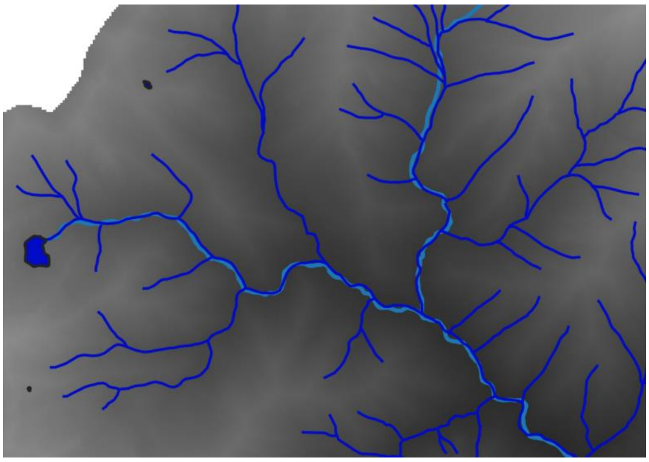

Figure 15. The overlap between the two hydrographic networks in correspondence of the Upper Cervo Valley.

For what concerns the vectorial dataset of the Geo-Topographic database, they are obtained from the Reference Spatial Database (BDTRE). They are related to the streets, the buildings, and the green areas, but also to the hydrographic network of the whole Cervo Valley and to the perimeter of its municipalities [Figure 16.]. These data are available on a municipal basis. A careful distinction between different types of buildings and streets are available: in terms of streets there are provided the vehicles areas, the mixed secondary traffic roads, the pedestrian areas, and the transportation infrastructures; in the buildings category there are included general buildings, sport equipment, minor buildings, covering elements, industries, and monuments. At the same time, lakes and rivers are categorized in the hydrographic network.

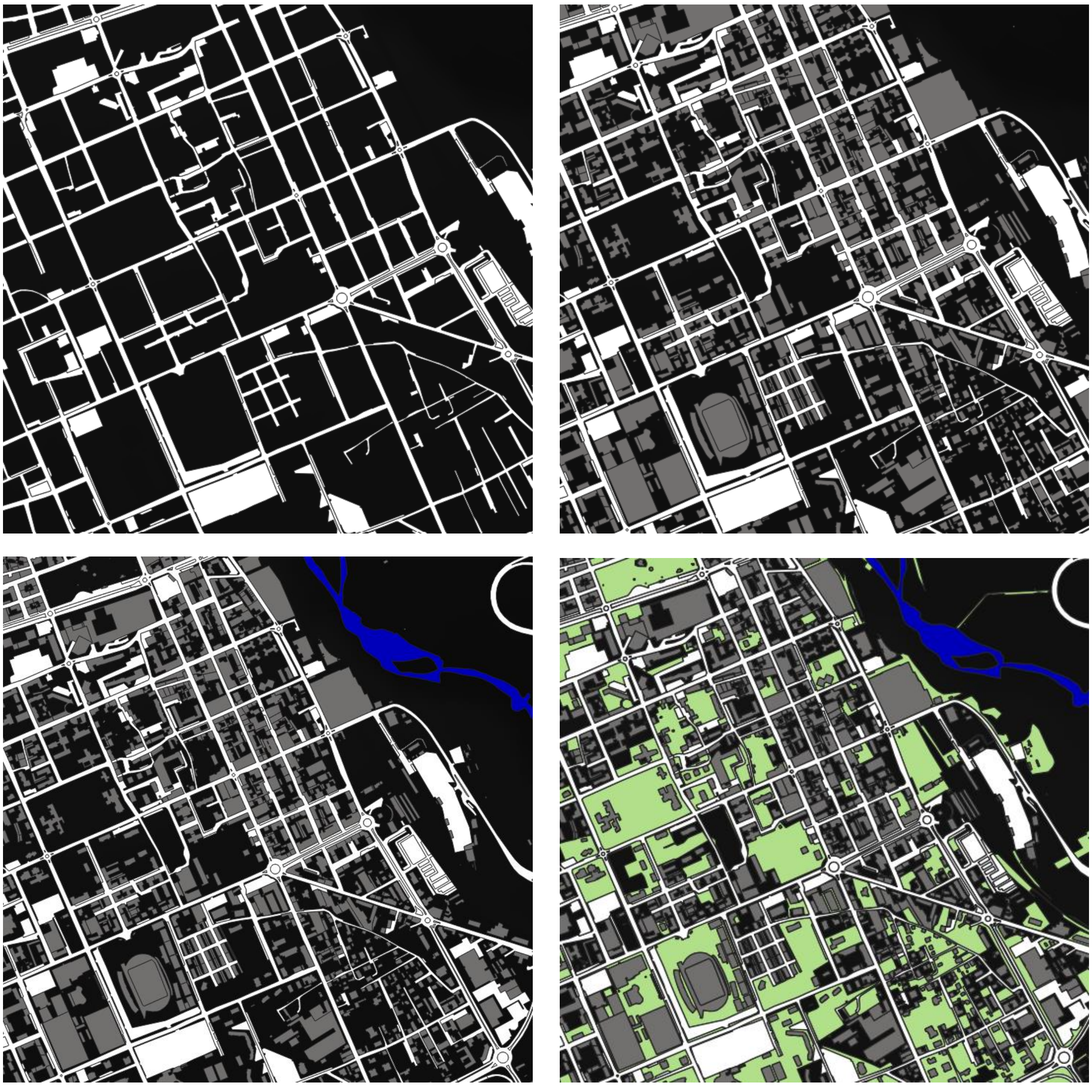

Figure 16. A representation of the different data imported in QGIS. In gray the buildings, in white the streets, in blue the river and in green the green areas.

In addition to these datasets, a layer representing the information related to the framework of disaster described in Annex 2 (Atlas of hydraulic and hydrogeological risks) of the Strategic Plan for Hydrogeological Planning – PAI – is used. It is approved by Decree of the President of the Council of Ministers (DPCM) on May 24, 2001, and updated through urban planning instruments (General Regulatory Plans - PRG). It describes the landslide areas, the flooded ones, the cones, and the avalanches areas of the whole Piedmonts Region [Figure 17., Figure 18., Figure 19., Figure 20.]. Since the study is not focused on the avalanche's risks correlated, they are uniquely showed in the general Piedmonts map for completeness, but they are not included into the Cervo Valley 2D map. These data are again downloaded from Geoportale Piemonte website and imported as vectorial data (.shp file format).

Thanks to the flexibility of both the software adopted and the map realized, it is also possible to import other types of data. The requirements that need to be satisfied in that case are related to the use of data importable in the software (among the others .tiff and/or .shp) and the attachment of a summary report able to describe the different risks represented in the files.

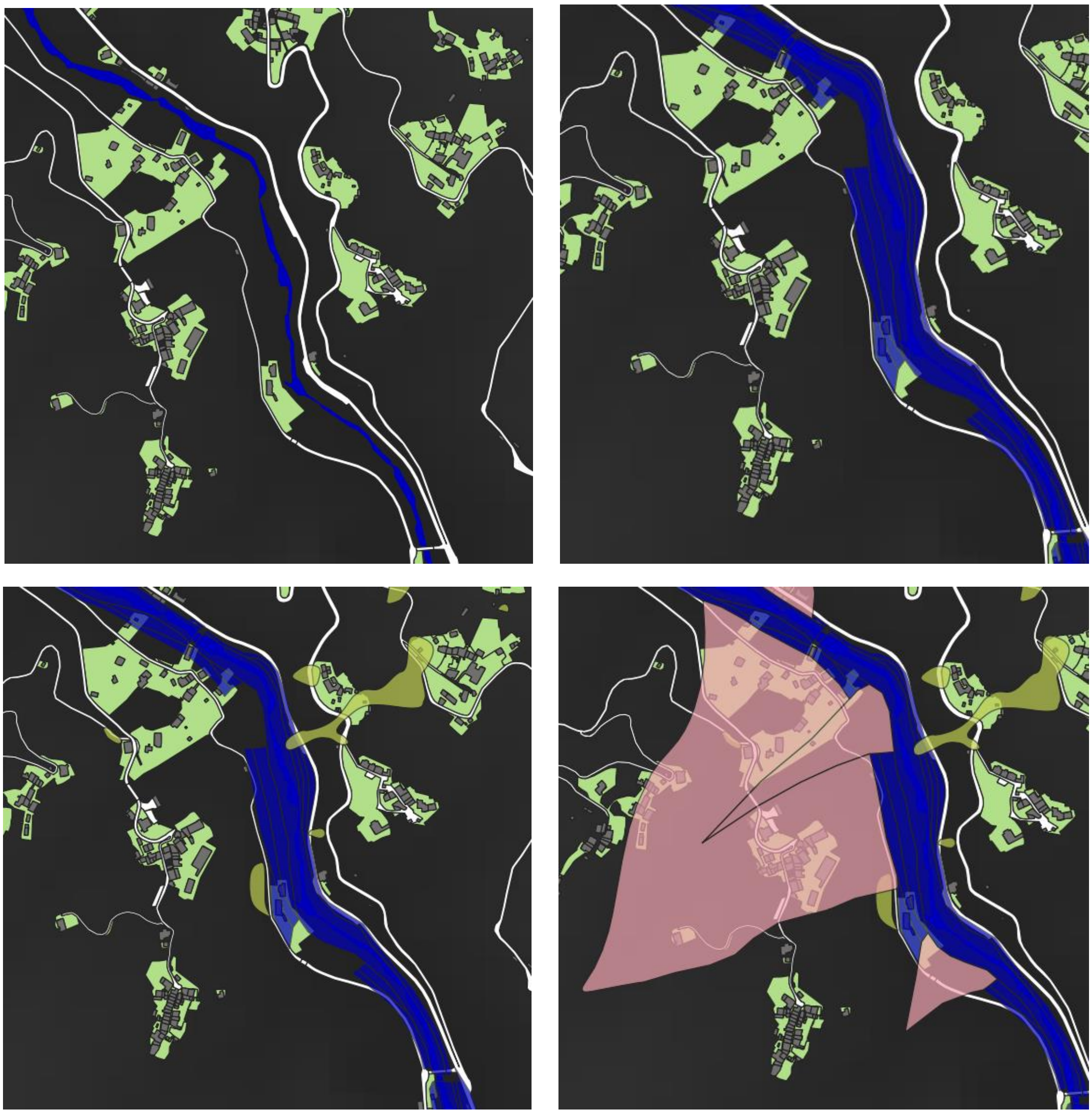

Figure 17. A representation of the Campiglia Cervo flooded areas (blue), of the landslide areas (dark green) and of the cones (pink) from PAI assessment.

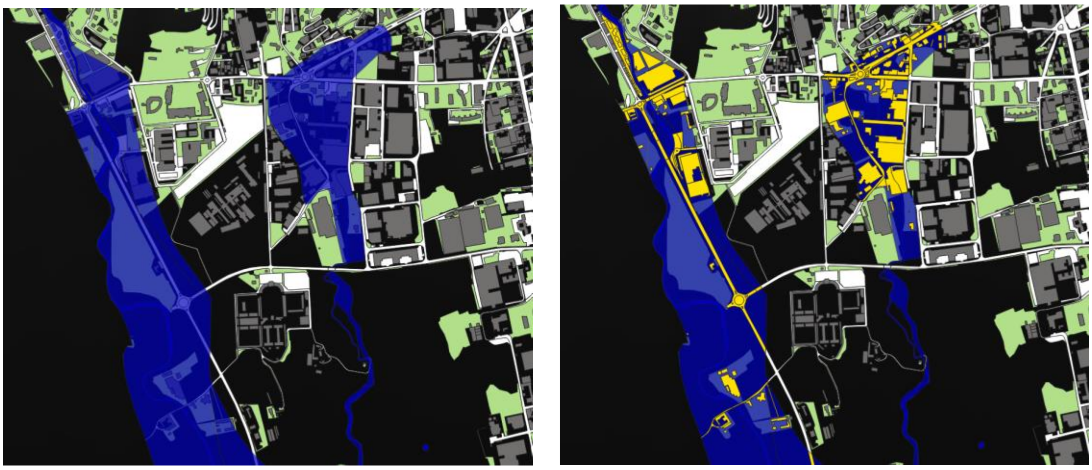

Figure 18. On the left, the representation of flooded areas in Biella municipality. On the right, buildings and streets at floods risk in Biella municipality.

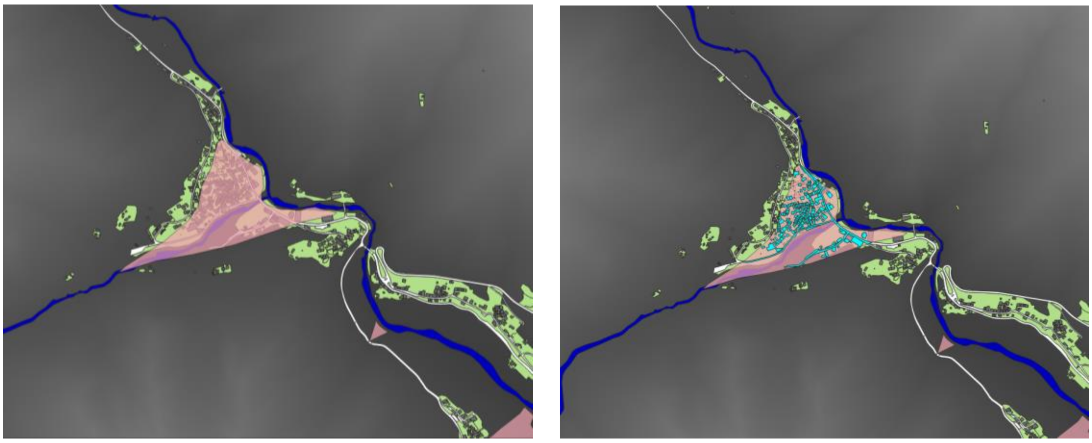

Figure 19. On the left the representation of cone area in Rosazza municipality. On the right, buildings and streets at cone risk.

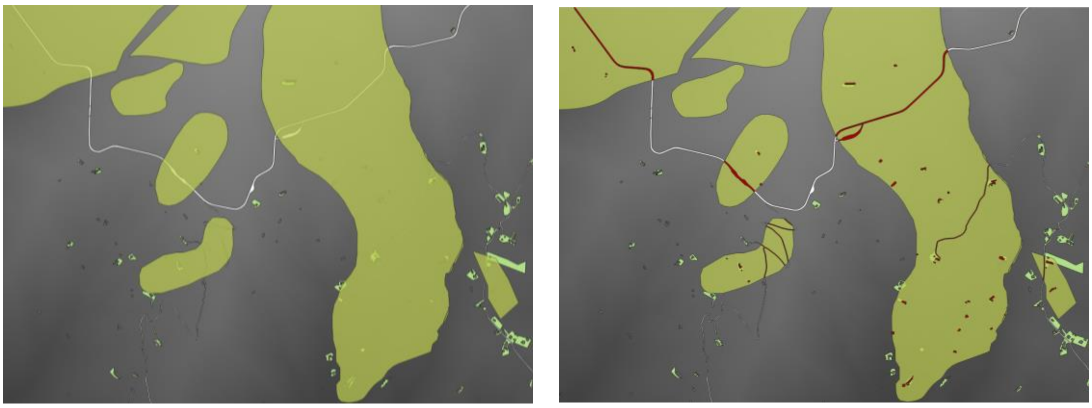

Figure 20. On the left the representation of landslide areas in Sagliano Micca municipality. On the right, buildings and streets at risk landslides.

The PAI framework of disasters consists of the set of hydraulic and hydrogeological phenomena that determine conditions of hazard at various levels of intensity. The acquisition and the georeferencing of available data concerning the spatial distribution of ongoing and past disaster processes and situations, allow the definition of a proper representative cartography. It describes the distribution pattern of instability phenomena across the entire basin territory. For the main watercourses both in the plain and mountain valley sections, the assigned return periods for floods are set as 20, 100, 200 and 500 years (Progetto di Piano stralcio per l'Assetto Idrogeologico (PAI), s.d.). (15)

The final map is obtained from the manipulation of all the graphic data downloaded and imported in QGIS. But also, from the introduction of new shape files created through Python scripts and then imported again in the software. Therefore, the modification and analysis of them is carried out and described in the following paragraphs.

2.1.1. The file formats

As already described, the TIFF file format is used for the raster import, while for what concerns the other geometrical data, they are imported as shape files.

In the first case, the Tagged Image File Format (TIFF) is an image file format for storing raster graphics images. In terms of file structure, it contains a header that includes information about the TIFF file: byte order, version number, and image data layout. Then, the so-called Image File Directory (IFD): a table of pointers to the image data and metadata. For what concerns the Image Data, it contains the image information like pixel values, compressed or not-compressed format. Then, the End of File is a marker that indicates the end of the TIFF file. (16)
It is flexible, adaptive and it includes different tags like size, definition, image-data arrangement, and applied image compression that describe the whole image's geometry. (17)
Different are the positive aspects of managing TIFF files, one of them is to store image data in a lossless format. It means that the file can be edited and re-saved without losing image quality.

When georeferenced, the raster file can be saved and exported as GeoTIFF file format. It represents a public domain metadata standard that allows georeferencing information to be included in a TIFF file. The additional information in this case is related to map projection information, coordinate system, ellipsoids, datums and anything else necessary to provide an exact spatial reference for the file. (18)

In terms of shapefile, it is a vector data file format normally used in the case of geospatial analysis. Indeed, it is one of the most common file formats for geospatial data and it includes location, geometry and attribution of points, lines, and polygon features. Points can be used to represent addresses, points of interests, and parcels; lines are normally defining road networks or waterways; and polygons can represent neighborhoods, geofences and anything with a boundary.
Another important aspect of this format is represented by the possibility of storing additional information of the point/line/polygon. For example, not only the geographic coordinates of the geometric data, but also the name of the element, the height of the building – if the element is a structure – and so on. (19)
The shapefile import must be done as vector layers, otherwise it is not correctly read by the software and it is not visible.

2.2. QGIS tools

Different internal QGIS python-based tools are used with the final purpose of creating a 2D map ready for the web. Some of them are adopted to increase the quality of the result visualization, while some others are fundamental for the analysis of the data and the introduction of different static information in the map.

Before the application of any tool, the georeferencing check of the raster file must be carried out. In this case, it is done by clicking on the properties of the raster layer created in QGIS, selecting 'sources' and then by defining the correct reference system – WGS 84 / UTM zone 32N – if it is not yet properly set.

The same georeferencing check must be done for the shape files imported [Figure 21.].

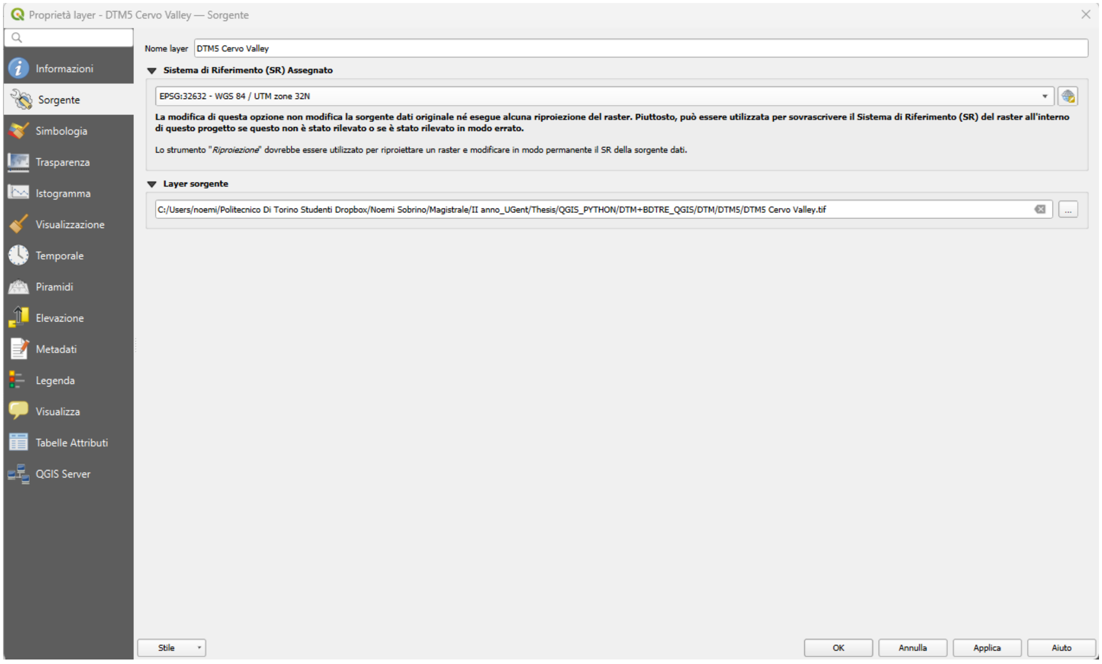

Figure 21. Check of the proper reference system for each imported layer.

2.2.1. Hill-shade

To better comprehend the digital terrain model once imported in QGIS, it is processed with the QGIS command *Raster analysis – Hill-shade*.

This is an operation that produces a visual representation of shading on the DTM. It shows areas shaded in relation to the position of the sun or a simulated light source. In this case, a simulated light source is used. A proper application of this command can help in giving a first idea of the third dimension of the terrain.

In this case, the processing is obtained by defining different parameters listed below:

- The input raster file. In function of the different raster files, it is obtained a completely different result. This is mainly due to the precision of the raster itself.
- The color band number. For gray band the number is 1.
- The factor Z. It represents the vertical exaggeration of the raster file. It is set as 1.
- The scale. It is defined as the ratio between horizontal and vertical units. Again, defined equal to 1.
- The Azimuth value of the light. It refers to the horizontal angle between the north direction and the light direction projected onto the horizontal plane. It is measured in degrees clockwise from the North. In this case has a value of 315°, therefore the light comes from Noth-West.

- The altitude of the light. It refers to the vertical angle between the horizontal plane and the direction of sunlight. It is measured in degrees above the horizon. An altitude of 0° corresponds to the horizon, while an altitude of 90° corresponds to the point where the sun is directly above the observation point. In this case, an altitude of 45° is selected.

These values are set with the final purpose of obtaining a clear result for the user [Figure 22.].

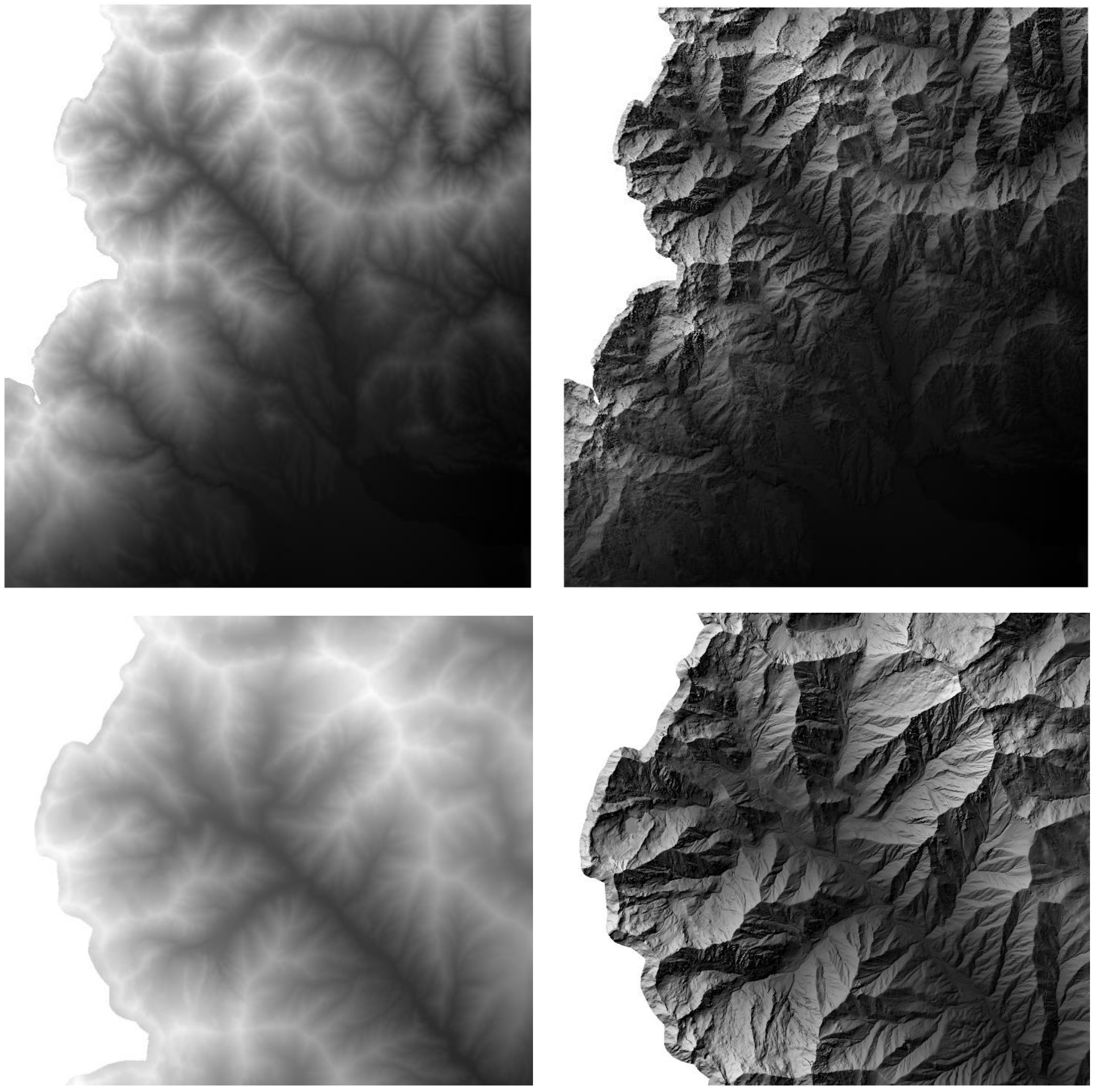

Figure 22. On the left the DTM5 imported in QGIS, on the right the DTM5 processed with the Hill-shade QGIS command.

2.2.2. Geometric tools: union, intersection, difference, and clip

After the graphical improvement of the raster file, the first real modifications of the shape ones are performed.

The different structures and infrastructures as well as the water systems are imported as single layers. Therefore, to reduce their number in the QGIS project, the vectorial geoprocessing tool *union* is used. For each municipality all the streets – vehicles areas, mixed secondary traffic roads, pedestrian areas, and transportation infrastructures – are collected in the *Name of the municipality_Viability* layer. At the same time, all the buildings – general buildings, sport equipment, minor buildings, covering elements, industries, and monuments – are collected in the *Municipality name_Structures* layer. Then, all the BDTRE rivers, canals and lakes are unified in the *Name of the municipality_Water* layer [Figure 23.].

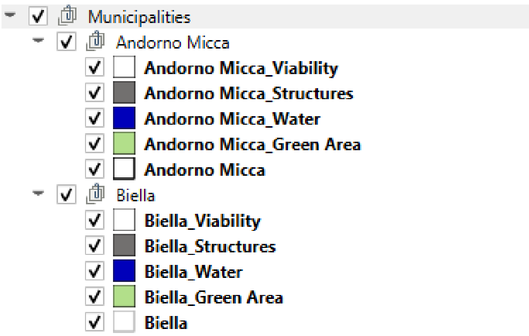

Figure 23. An example of the different layers obtained.

In addition, the whole street layers are collected into *Cervo Valley_Viability* one. The same process is performed for both structures and water layers [Figure 24.].

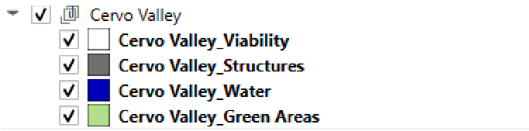

Figure 24. The Cervo Valley unified layers.

In this way, a user-friendly map can be exported. The user can choose to turn on and off different municipality layers or opt to view the entire valley at once.

For the other modifications, a distinction between the Piedmont map and the Cervo Valley one must be done. The first one has the primary goal of representing the territory on a large scale and provide a comprehensive overview of the map's potential. In this case, it is not necessary to use data with high acquisition precision. For the latter map, higher precision is necessary to provide a reliable tool for conducting a proper hydrogeological risk analysis.

2.2.2.1. Piedmont map

In the QGIS vectorial geoprocessing tools, the *intersection* command is used to represent the streets and the buildings that are at risk of floods, cones, or landslides according to the PAI imported layers. Indeed, looking at figures from Figure 17. to Figure 20., it is noticeable the presence of structures and infrastructures overlapped to the PAI layers. According to this overlap, it is indeed possible to use the *intersection* command and understand what structures and infrastructures are potentially subjected respectively to flood risks [Figure 25.], cone risks [Figure 26.], and landslide risks [Figure 27.]. This tool only requires the selection of an input layer and an overlapping one.

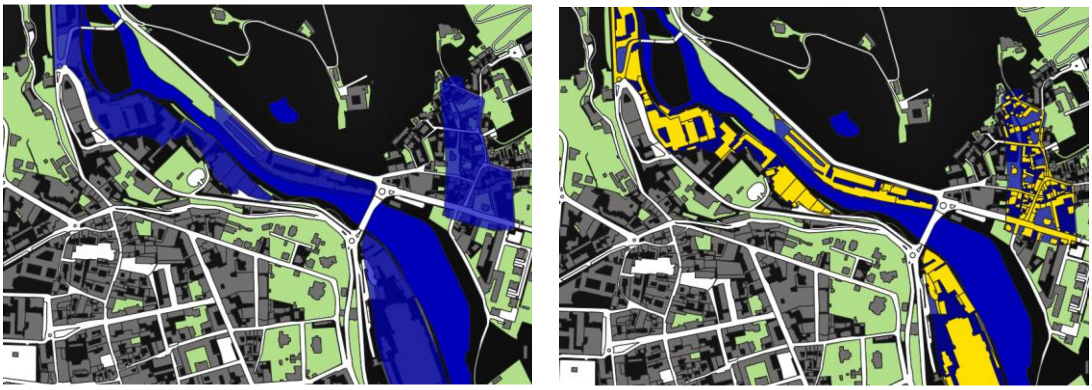

Figure 25. On the left the representation of a flooded area in Biella; on the right streets and buildings at flood risk depicted in yellow.

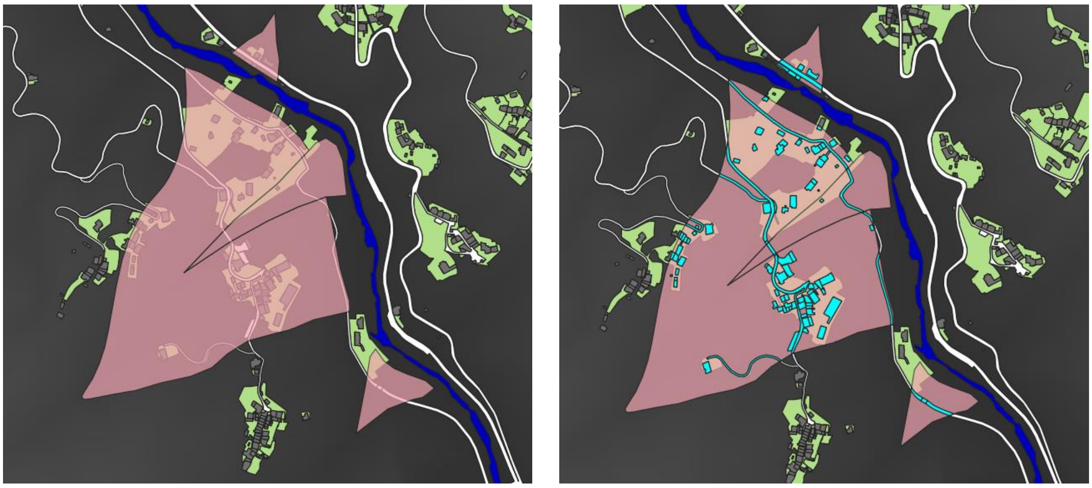

Figure 26. On the left the Campiglia Cervo cones areas; on the right streets and buildings at cones risk colored in light blue.

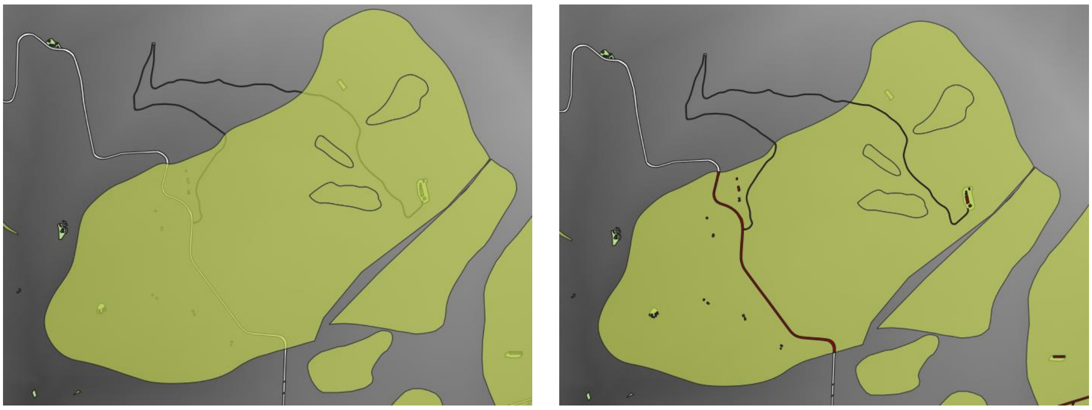

Figure 27. On the left the Campiglia Cervo landslide areas; on the right streets and buildings at landslide risk drawn in red.

This process is performed separately for all the Cervo Valley municipalities and risks. To make the map user-friendly, a different color for each risk is used.

2.2.2.2. Cervo Valley map

The final purpose of the Cervo Valley map with respect to the Piedmont one, is to provide a more precise overview of the Valley hydrogeological situation. This is done by introducing a more precise Digital Terrain Model – with a precision of 5 m – and

by making a closing-up on the Valley area. This area is obtained by considering the perimeter of the Cervo Valley municipalities.
According to that, before using the vectorial intersection command, it is necessary to clip the DTM5 in the area of interest. To do so, the raster tool named *extraction – clip raster from extension* is used. The requirement is to define the input raster and to draw in the QGIS project the extension of the new raster file. The following result is obtained [Figure 28.].

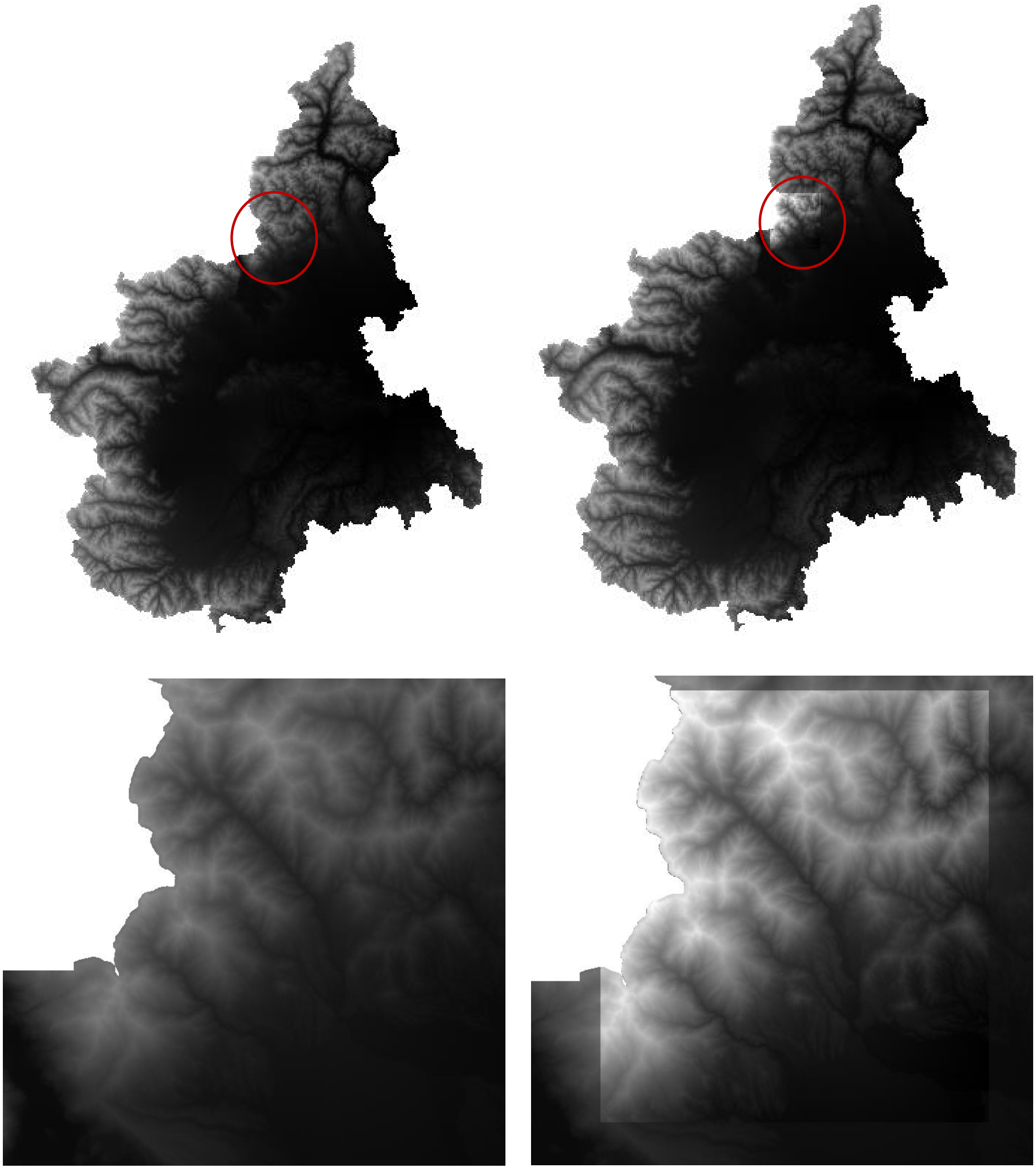

Figure 28. On the top the Piedmont Region DTM5 with and without clipped raster overlap. On the bottom the zoom-in on the Cervo Valley with and without the clipped raster overlapped.

Afterwards, the clip of the PAI risks layer is performed.
Since they are vector data, a different Python-based QGIS command should be used. In the vectorial geoprocessing tools, the *difference* command is therefore adopted. By placing the municipality layer in input and the PAI ones as overlapped layers, it is possible to clip the second ones along the perimeter of each Cervo Valley municipality. Since in QGIS is not possible to intersect and/or clip raster layers with

vector ones and vice-versa, the solution of using the municipalities as areas of PAI layers extension resulted the most logic one.

On the opposite, in some cases where the municipality region is in correspondence of the Valley watersheds, this solution can result useless. Therefore, to figure out that aspect, the clip of the raster file can be done exactly in correspondence of the Valley watersheds.

Subsequently, the same *intersection* command is used as before to get the structures and infrastructures at flood risks, cones, and landslide ones.

At the end of the process, a variety of layers is produced. Considering:

- Three different PAI areas: floods, cones, and landslides
- Fourteen municipalities: twelve Cervo Valley municipalities, Biella and the total Cervo Valley layers
- One traffic road layer for each municipality
- One structures layer for each municipality

a total amount of 84 different intersected layers is produced. Therefore, with the final purpose of making the map user-friendly, the necessity of merge them together is real.

From now on, the Cervo Valley map is the one of reference. In the Piedmont map a copy of the Cervo Valley layers is performed. Indeed, the latter has the final purpose to provide a general overview of the Cervo Valley hydrogeological situation at a larger scale.

2.2.3. MMQGIS plugin: merge different layers

The *union* QGIS tool joins different layers one by one. But the procedure with this command can be time consuming. Therefore, the MMQGIS plugin is considered the best alternative solution to reach the set goal.

It is a Python based plugin focused on the base operations necessary to unify different data. It is more direct with respect to the software processing toolbox. It has an intuitive user interface and can be used to create/modify animations, combine layers, create Voronoi diagrams, import/export CSV files and to produce some other additional elements. In this case, the one of interest is the so-called *combine – merge layers* tool. By activating it, the necessity is to simply select the different layers that should be merged and save the new shapefile into a specific folder. After that, an automatic import in the QGIS project is done with the shapefile produced by the plugin.

The different attributes and features of the layers are all listed in the new layer field. In this way, no attributes are lost. If some layers have the same features name, the plugin will save them with an automatic nomination (*feature name1, feature name2* and so on). Therefore, after the joining of the different shapefiles, it is necessary to check and select the useful attributes by removing the useless ones.

With it, streets and buildings – of all the municipalities – subjected to floods risk are collected in one single layer. The same is done for cones risks and landslide risks.

2.2.4. GRASS process algorithm: the drainage area calculation

The drainage area definition of the river basins in different points of interests is possible according to the use of the GRASS process algorithm.

A watershed is a land area delineated by topographic ridges where all rainfall and/or runoff drains into a single drainage system such as rivers, streams, and creeks, toward a common outlet. A distinction must be done between drainage basin and hydrogeological basin. In the first case the analysis is performed by considering the area of the drainage system that only collects surface water; in the second case, the analysis is done by calculating the area of the drainage system including both surface water and groundwater. (20)

The drainage area analysis is useful to know the river flow in a specific point of the Valley, but also to understand if a point is in a particular drainage surface or not. (21) According to that, the definition of the watershed is useful to understand how the drainage basin changes along the river path into the whole Valley. Then, it can help in the definition of a proper water resource planning and management. But also, since its size affects the amount of water it can collect, it helps in the hydrogeological risk assessment and in the definition of potential for damage and flooding.

In QGIS, the watershed is calculated in four different points:

- In correspondence with Piedicavallo, the first village of the Upper Valley.
- Where the Saint Giovanni Andorno Sanctuary is located, in Campiglia Cervo municipality.
- In Biella, at the end of the Cervo Valley.
- In the point of location of the Ex-wool mill Maurizio Sella, situated in Biella.

They are considered interesting point to understand the variation of the drainage basin at the beginning and the end of the Valley. In addition, with the other two points, the two infrastructures of interest can be easily monitored.

To do so, the Geographic Resources Analysis Support System (GRASS) processing algorithm is implemented into the QGIS software. It allows to elaborate raster and vectorial data for their management, geoprocessing, spatial modelling, and visualization. It is an open-source algorithm that can connect spatial databases and interface with a variety of third-party systems and libraries. (22) In this case study, it is uniquely used to carry out the basin areas analysis in the points previously cited.

To get the result, different steps are considered.
Firstly, it is necessary to check if the DTM presents specific sinks. They might be caused by errors during the data acquisition, but also natural terrain features, and processing errors. Therefore, it is always a good procedure to control the different input data before any analysis. In these terms, by opening the processing toolbox in QGIS and selecting the GRASS algorithm, it is possible to activate the so-called *r.fill.dir*. command. In the command dialogue, the input layer must be the raster file and no other considerations must be done. It is possible to directly save the depression-less DTM as a GeoTIFF file, run the process and close the dialogue window. This command filters and generates a depression-less terrain map from a given raster elevation map. It takes an elevation layer as input and initially fills all the depressions with one pass across the layer. The method adopted to filter the elevation map and rectify it is based on the paper "Extracting topographic structure from digital elevation model data for geographic information system analysis" by S.K. Jenson and J.O. Domingue (1988). (23) The filled raster file is the base layer for the drainage area analysis [Figure 29.].

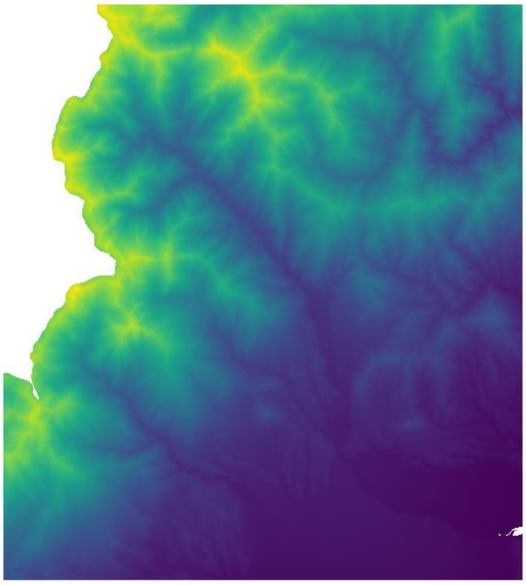

Figure 29. A representation of the filled DTM.

Then, the flow accumulation and flow direction calculations must be carried out. They represent the amount of water and its direction when collected. Then, it flows into an outlet point as the result of precipitation and/or runoff from surrounding areas. The GRASS tool used in this case is named *r.watershed* and in the dialogue window it is necessary to set the minimum size of exterior watershed basin and the single flow direction (D8). The first parameter is a threshold only relevant for those watersheds with a single stream having at least the threshold of cells flowing into it. This means that the threshold parameter defines the minimum size of the watersheds and considers only the ones within this specific value. (24) In this case study, it is set as 500 considering it as a logic dimension for a proper first drainage area analysis.

For what concerns the single flow direction (D8), at each raster cell the code determines the slope to each of the 8 surrounding cells and assigns the flow direction to the highest slope for each cell. In case of more than one equal, non-zero slope, the code picks one direction based on preferences hard coded into the program. In case the highest slope is flat and in more than one direction, the code tries to select an alternative based on flow directions in the adjacent cells. (23) The zero value represents a depression area, while negative values indicate that the surface runoff is leaving the boundaries of the current geographic region. Therefore, the absolute value of these negative cells indicates the direction of flow. Consequently, the conversion of these negative values into absolute ones is necessary after running the process.

To do so, it is possible to enable the *raster calculator* command in QGIS and compose the following equation:

$$(\text{"FLOWDIR"} < 0) \cdot -1 \cdot \text{"FLOWDIR"} + (\text{"FLOWDIR"} \geq 0) \cdot \text{"FLOWDIR"}$$

Where FLOWDIR is an arbitrary name given to the flow direction exported file through the previous process. With this equation, if the flow direction values are less than zero, then the results are Boolean True (1), else Boolean False (0). In case of Boolean True, it is necessary to multiply it with -1 and the flow direction. So then, the first part of the equation results in the absolute values of the negative flow directions. Then, it is considered the addition of having cells with values equal or larger than 0.

In this case the multiplication is done only with the flow direction values. Which means that a non-negative flow direction value will keep its original condition.
After that, the new absolute flow direction file must be saved as TIFF file [Figure 30.].

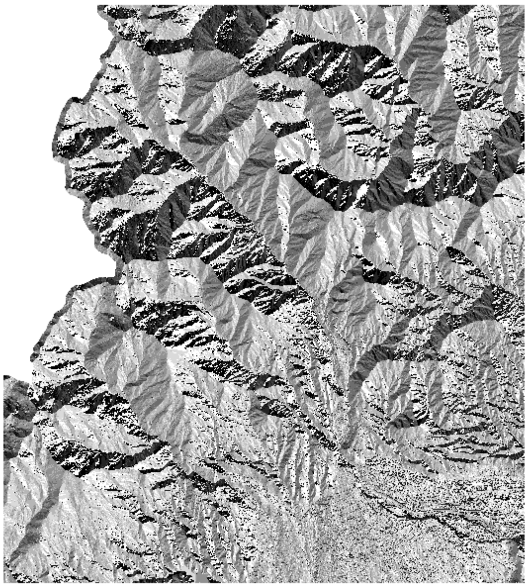

Figure 30. The flow direction exported TIFF file.

At this point, each cell of the Cervo Valley study area has a value for flow accumulation, but not all of them are considered as part of a river channel. Therefore, the determination of a threshold flow accumulation above which the pixel is considered as part of a river channel is necessary. In this case, by opening again the QGIS *raster calculator* tool, it is necessary to define the following equation:

$$\text{"Accumulation"} > 500$$

That means: if flow accumulation file is larger than 500 cells, then give Boolean True (1), else give Boolean False (0).
The value of 500 is completely arbitrary and it is defined as the threshold value that better represents the development of the rivers in the area of interest in function of a reference map. In this case, the reference map used is the OSM (Open Street Map) standard map directly implemented in QGIS [Figure 31.].

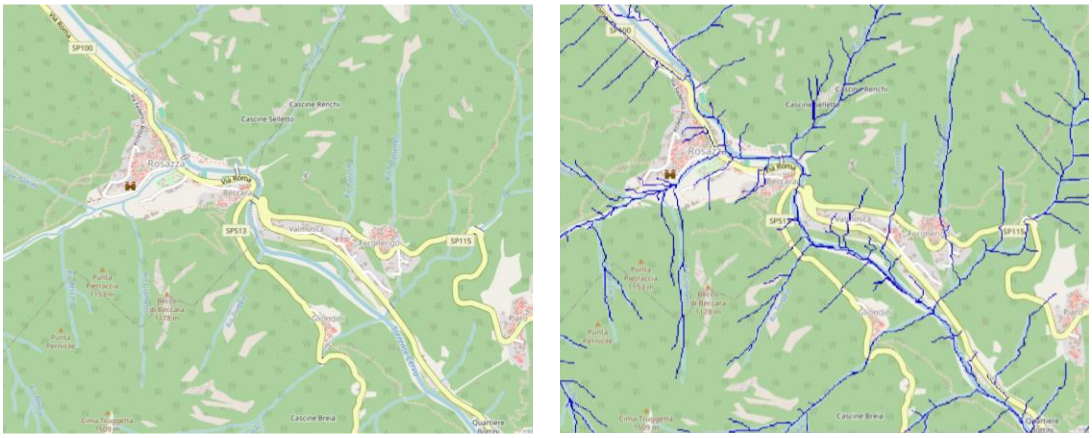

Figure 31. The OSM reference map on the left. The overlapped channel layer and OSM reference map on the right.

By using this threshold value, the determination of the streams is now possible.
The GRASS command named *r.stream.extract* is used with this final purpose and can be adopted in both raster and vector formats. In this case the filled DTM and the accumulation map are considered as input maps. The minimum flow accumulation for streams is defined as the threshold already set for the accumulation map, so 500. It represents the minimum flow accumulation value that will initiate a new stream. If this threshold is reached or exceeded, a new stream is initiated. Then, in the advanced parameters the GeoPackage output format should be selected as line vector, otherwise the result is an empty layer [Figure 32.].

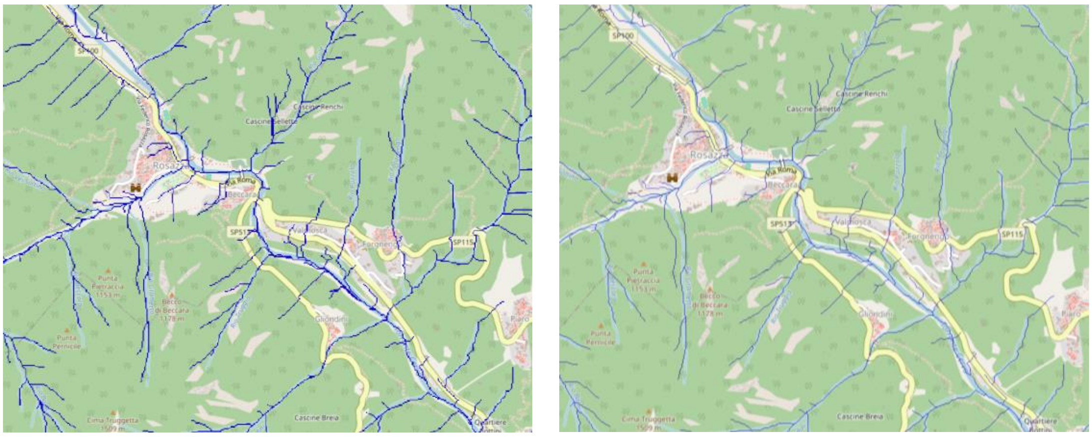

Figure 32. In the left-hand side the channel layer on the OSM reference map. In the right-hand side the stream layer overlapped to the OSM reference map.

After the stream definition, it is possible to select the outlet point. It is the reference location for the drainage area calculation. By clicking on the *r.water.outlet* GRASS tool, it is possible to insert the absolute flow direction file in input and then select directly on the OSM reference map the outlet point. Its coordinates are automatically detected by the tool and reported into the command dialogue window. Consequently, the basin layer is automatically saved as TIFF file after the running of the process. Therefore, it must be converted into a polygon. This step is performed by using the *r.to.vect* command and by placing in input the basin TIFF file and selecting the area as feature type. Before running the process, the output file selected is the vectorized one [Figure 33.].

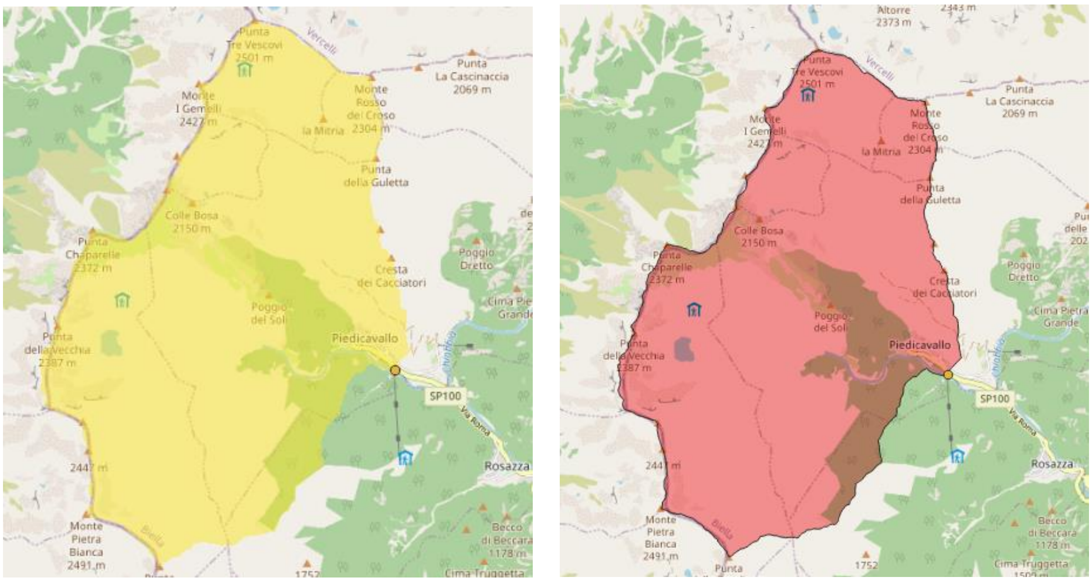

Figure 33. *In yellow the TIFF file of the catchment area; in pink the correspondent polygon.*

By doing right-click on the polygonal watershed basin layer and opening the attributes field, it is possible define the calculation on the polygon area. The *field calculator* must be opened and in the geometry field, the *area* function is selected [Figure 34.]. In that way, the drainage area is calculated, and the analysis is concluded.

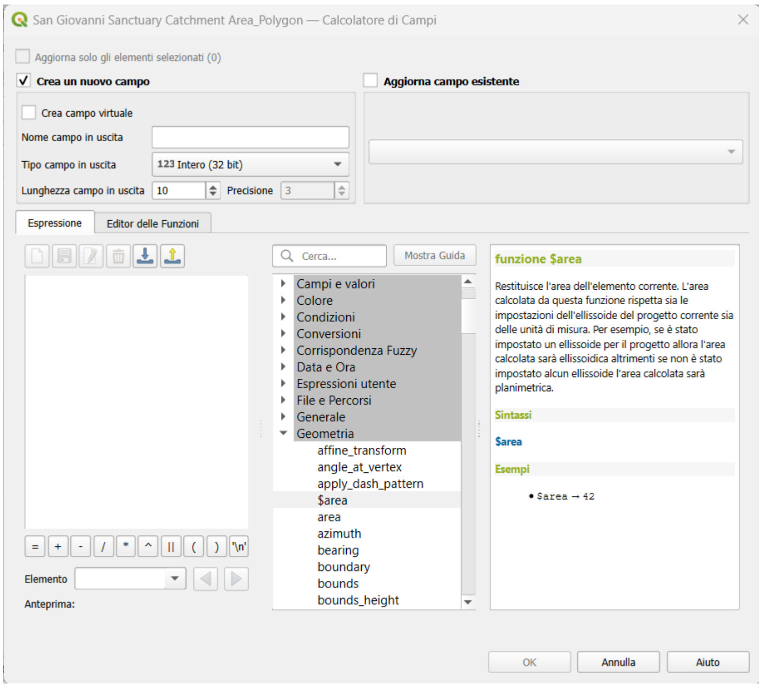

Figure 34. *The calculator field user interface.*

Depicted below, the different watershed basins and their respective area in square kilometers are represented:

- Piedicavallo – Upper Valley, drainage area of 18,076 km^2 [Figure 35.]
- Saint Giovanni Andorno Sanctuary, drainage area of 0,37 km^2 [Figure 36.]
- Biella – End of the Valley, drainage area of 99,047 km^2 [Figure 37.]
- Ex-wool mill Maurizio Sella, drainage area of 124,713 km^2 [Figure 38.]

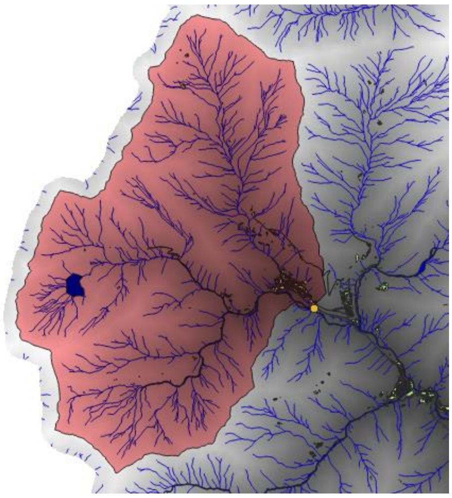

Figure 35. Piedicavallo drainage area.

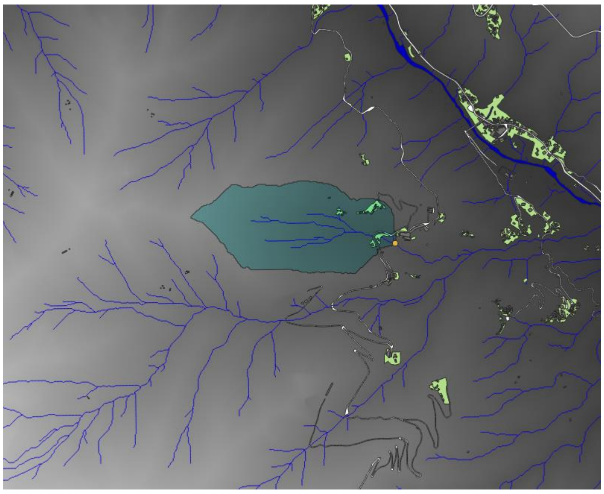

Figure 36. Saint Giovanni Andorno Sanctuary drainage area.

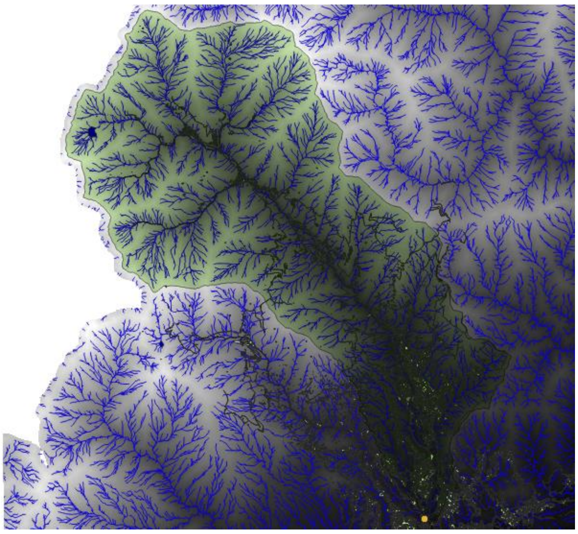

Figure 37. Biella drainage area.

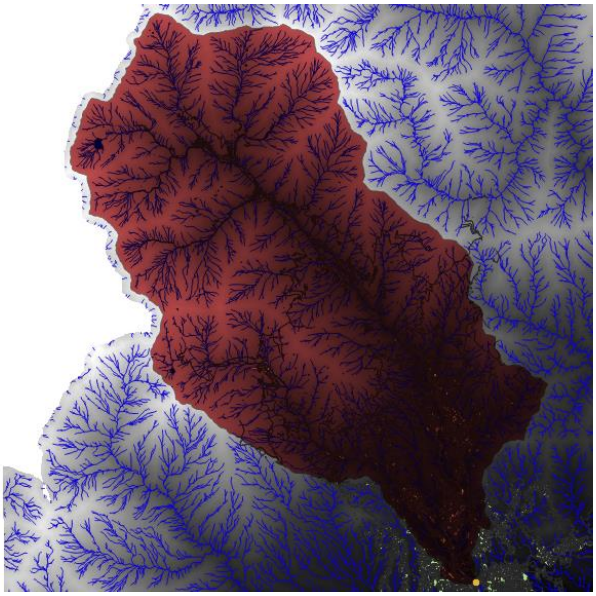

Figure 38. Ex-wool mill Maurizio Sella drainage area.

The pictures above clearly show the Cervo Valley area interested in the collection of the water due to precipitations and/or runoff in different specific points.

The smallest drainage area is calculated in correspondence of the Saint Giovanni Andorno Sanctuary watershed analysis. The biggest problem in this case is probably related to the landslide risk.
On the opposite, looking at the Ex-wool mill Maurizio Sella infrastructure, the drainage area also includes another Valley, the so-called Oropa Valley. This is an initial confirmation that the biggest hydrogeological risk associated with this infrastructure is probably the flooding one.

In general, the bigger the catchment area of the river basin, the higher the risk of cadastral events like floods, landslides, ground erosions and so on.

2.2.5. qgis2web plugin: export of the map for the web

Since the data previously described and managed are not variable in time, they are considered static ones. One additional static data added to the map is obtained through the application of a Python script able to calculate the terrain percentage of slope and create new shape files with different ranges of percentages. After the creation of these files from Python, they are imported in the QGIS project before the map export. This script is fully described in *section 2.3.3. Percentage of slope calculation* of this document.

Afterwards, once all the static data are included in the map, it is ready for the export. The QGIS plugin named *qgis2web* is used to obtain it. This is a plugin used to export the QGIS project to a Leaflet web map. It replicates layers, extent and styles used in the project and it does not require a server-side software. [(25)]
Leaflet is the open-source JavaScript library used to create mobile-friendly interactive maps. [(26)]

Each layer used in the QGIS project presents specific attributes. Some of them are fundamental for the comprehension of the static data, while some other are additional information not useful to the final purpose of the case study. Examples of the first category are the municipalities names, the catchment area of the river basins, the name of the river represented in the hydrographic network and so on. In the second group of attributes, it is possible to list the day of data acquisition, the upgrade data day, the responsible institution of the data etc. Therefore, before the application of this plugin, a careful management of the project layers must be considered and for the useless attributes a hidden widget should be selected [Figure 39.]. At the same time, for the necessary ones, the widget should be selected in the form of *modify text* and an attribute name – *alias* – can be realized [Figure 40.].

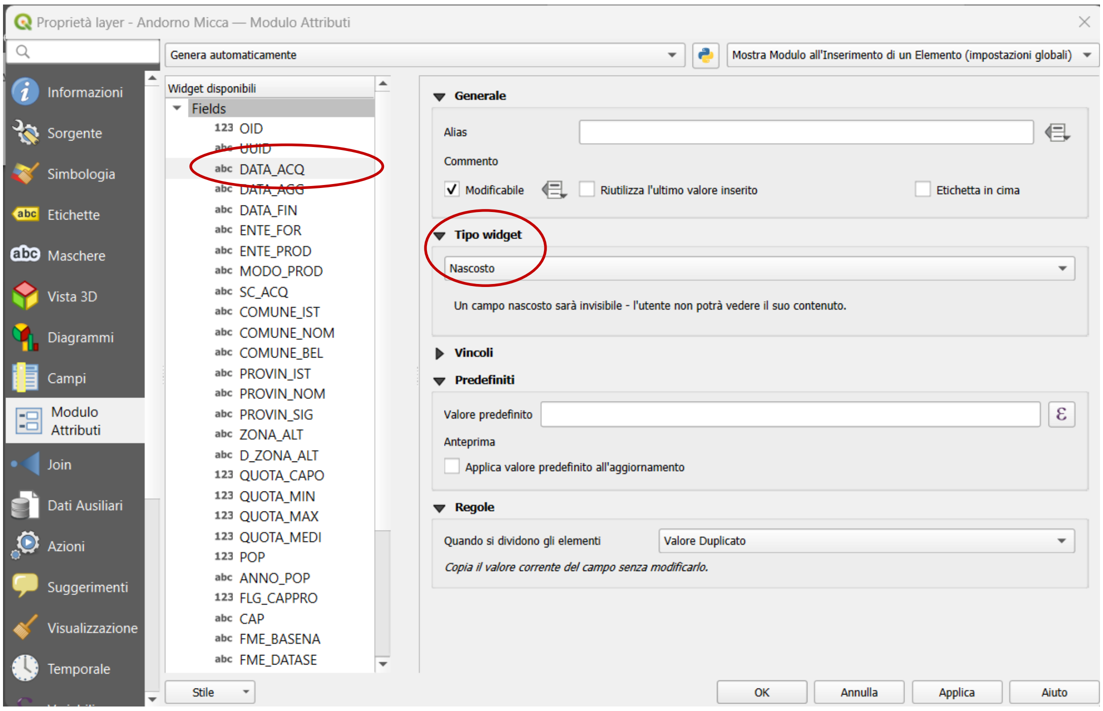

Figure 39. An example of useless attribute. DATA_ACQ stands for acquisition day. The widget is set as Nascosto, that means hidden.

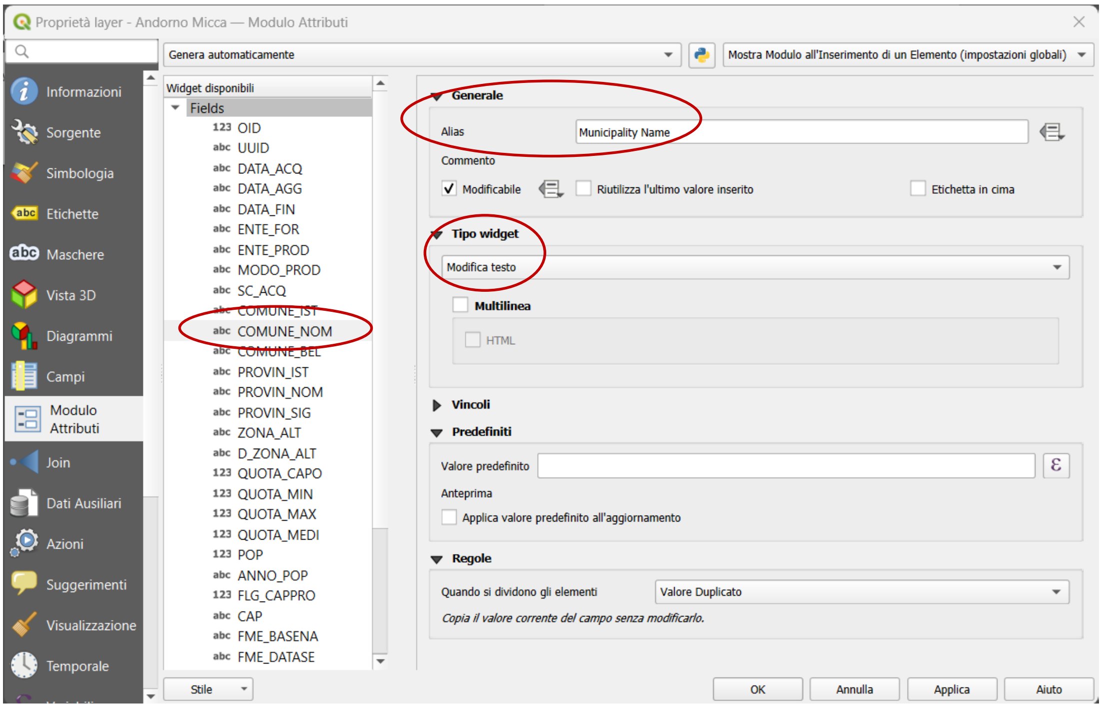

Figure 40. An example of useful attribute. COMUNE_NOM stands for municipality name. The widget is set as Modifica testo, that means modify text. An Alias is provided.

After the definition of the necessary attributes, it is possible to open the plugin dialogue window. In it, the selection of the Leaflet library is done. Consequently, the different layers available are selected and turned on. For the ones that specific attributes widgets previously defined are present, it is produced a pop-up visible when the data is available [Figure 41.].

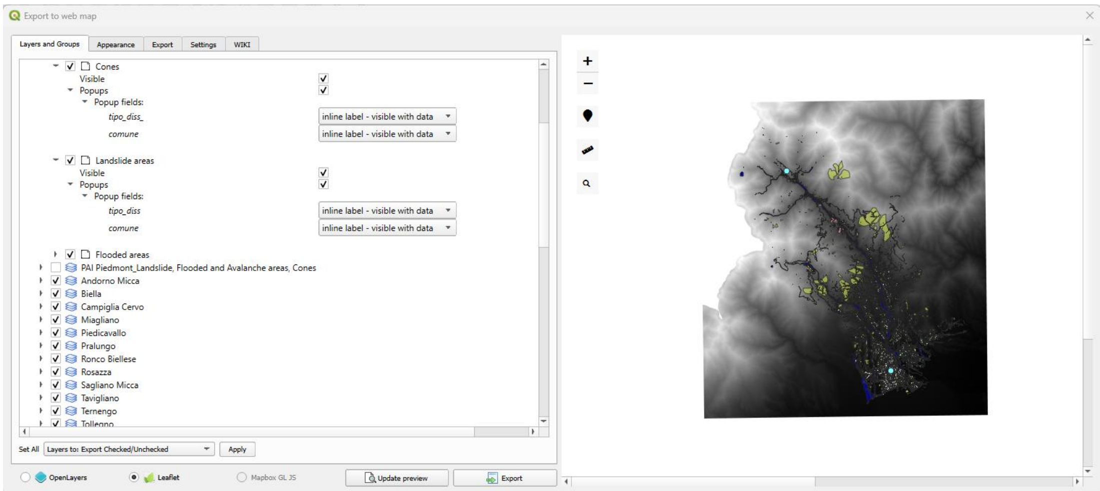

Figure 41. The representation of the plugin dialogue window. Selection of the layers and the Leaflet map. On the right-hand side of the dialogue window the map preview.

In the *appearance* page the address search tool, the attribute filter, the user geolocation, and the possibility of highlighting the layers over which the mouse is placed are selected [Figure 42.]. For what concerns the attribute filter, the municipality name is selected. In that way – once the map is exported – by clicking on a specific municipality in this filter, a direct zoom on it is performed.

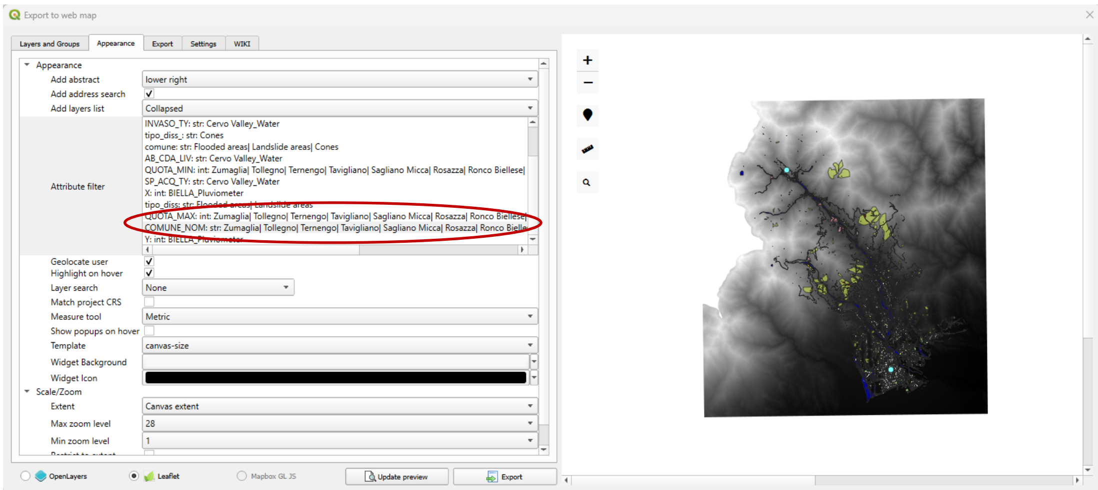

Figure 42. *The representation of the appearance page. Circled in red the municipality name selected in the attribute filter.*

The map is now ready to be exported, therefore in the export plugin dialogue the folder of export is selected, and the plugin is run.

The same procedure is adopted for both the Cervo Valley map and the Piedmont one.

Since the dynamic precipitation data are still missing, the exported map is not yet ready for the web.
Some representative pictures of the export are depicted below [Figure 43 and Figure 44.]; however, in *section 2.4. 2D Map: ready for the web* a complete representation of them is provided.

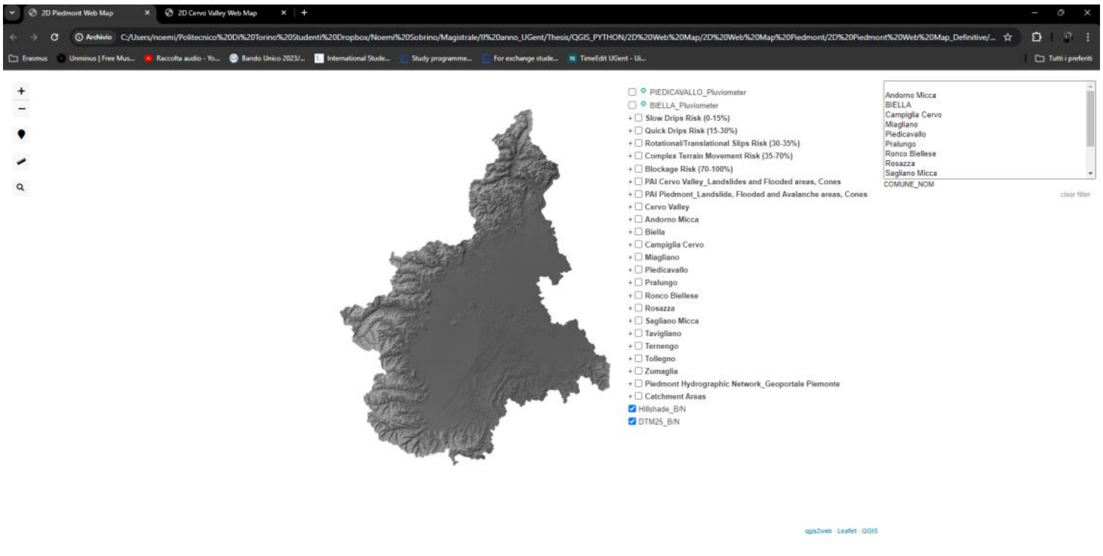

Figure 43. *The 2D Piedmont map. On the left of the map: zoom tool, user geolocation, measure tool and search bar. On the right: map layers and attribute filter.*

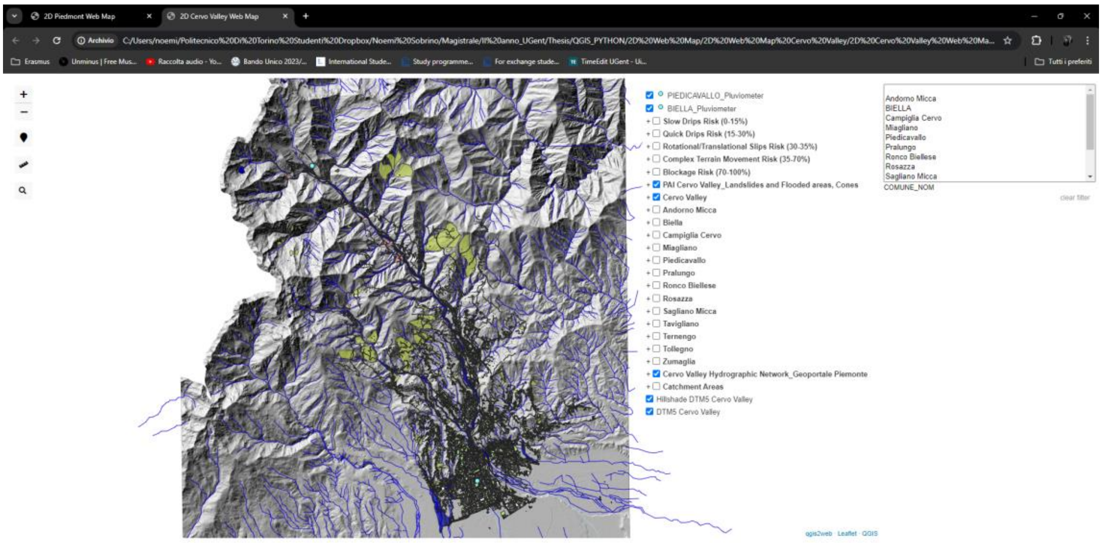

Figure 44. *The 2D Cervo Valley map. On the left of the map: zoom tool, user geolocation, measure tool and search bar. On the right: map layers and attribute filter.*

2.3. Python scripts

Additional static and dynamic hydrogeological information are obtained by implementing different Python scripts. Thanks to them it is therefore possible to increase the number of information available in the Valley map and use them for a proper hydrogeological risk analysis. These scripts are initially generated with the help of Chat GPT, an Artificial Intelligence (AI) chatbot that uses generative AI and machine learning to engage in written dialogue with human end-users. [27] Then, they are modified accordingly to the different requirements.

With this final purpose, the Anaconda distribution is adopted. It is a distribution of the Python and R programming languages for scientific computing that aims to simplify package management and deployment. [28]

To make the program process smoother, it is defined a new Python environment.

All the scripts are available in the personal GitHub account. [29]

2.3.1. Differences between raster files

The first real implementation of a Python script in the Cervo Valley project regards a script able to understand the differences between the raster files. More specifically, the two DTM with precision of respectively 25m and 5m are studied. The final purpose is to understand what the data differences between the two digital terrain models are: raster dimensions, pixel dimensions, data type and amount of data per every cell.

In this case, the *rasterio* library is necessary. It is designed to work with raster data; therefore, it can open, read, and write raster files in different formats as GeoTIFF, JPEG and others. It has full access to the raster file metadata, and it can clip, project, transform and extract statistics from raster information. For this reason, it is used to analyze the TIFF files and compare their characteristics.
At the same time, to plot the different raster files, the *matplotlib* library is used.

The import of the raster files is done by defining the file path in the script itself. Then, the analysis of the raster dimensions is performed as well as the definition of data in every cell.

Firstly, the function *read_array* of script *Differences between raster files* [(30)] is used to read the input files and return the associated arrays. Then, a function called *dimensions_analysis* is described. Starting from the file path, it opens it through the rasterio library and gives feedback about the dimensions, the pixels resolutions, the data type, and the amount of data per cell.

Afterwards, all these information are saved in their corresponding variables for each raster file and the plot is performed [Figure 45.].

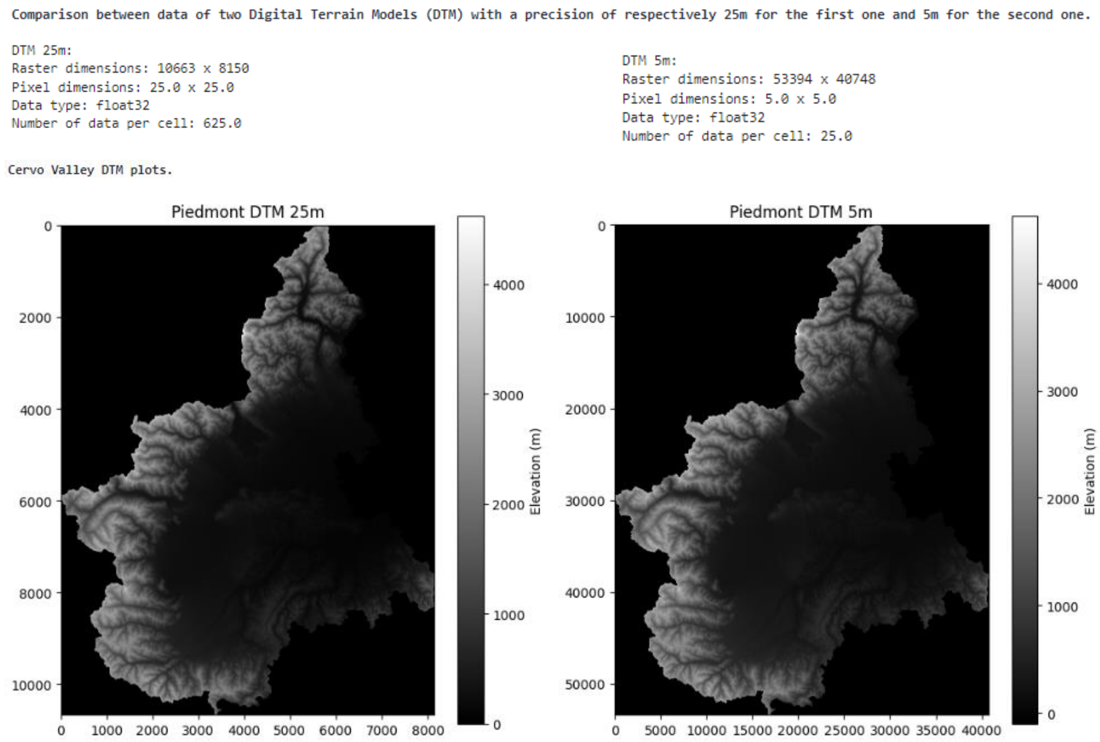

Figure 45. The Python script output.

Looking at the results obtained, it is clearly noticeable the bigger dimensions of the raster file with precision of 5m. Indeed, the lower the pixels dimensions, the bigger the raster dimensions. At the same time, smaller pixels allow to have a higher resolution of the image and to represent more details, but their collection requires bigger computer memory.

For what concerns the data type *float32*, it is the common name for Single-precision floating-point format. It is a computer number format that usually occupies 32 bits in computer memory.

In terms of amount of data per cell, it represents the number of information that each cell in the raster file contains. In the case of DTM with a precision of 25m, the number of information is greatly higher than the one of the DTM5. They are respectively 625 in the first case and 25 in the second one. This is mostly due to the extension of the area that every cell represents: in the DTM 25, each cell represents a length of 25 m per side; therefore, the amount of data collected per cell is higher than the DTM 5 where the length represented is 5 m per cell side.

On the x and y axes the raster dimensions are represented, while the color-bar on the right-hand side of the plot allows to understand the elevation of the different Piedmonts areas.

This is an initial analysis considered useful in understanding the computational requirements for each raster file. In conclusion, the higher the precision of the raster file, the bigger the raster file dimensions and the higher the computational requirements. This might be considered for the further data analysis.

2.3.2. Percentage of slopes calculation

Another type of static data analysis is performed by creating a Python script with the final purpose of producing several shape files representing all the DTM5 raster cells with their slope percentages.

The idea is to produce different shape files – to be imported in QGIS as layers – representing various categories of terrain slopes.

From literature, it is possible to make a classification of the characteristic landslides in Piedmonts Region. They are slow and quick drips (also known as debris flows); rotational/translational slips; complex terrain movements and rockfalls (Ramasco & Colombo, s.d.). [(31)]
The debris flows are type of landslides where a downhill movement of debris occurred. They are often accompanied by a significant amount of water. Their danger lies in their propagation speed and their possible impact on populated areas. [(32)]
Translational slips are terrain movements able to affect a big area of bedrock. They can reach depth of around 15-20 meters, and they often affect slopes oriented to North-West. At the same time, for what concerns the rotational slips, they are normally present at the bottom of previous landslides, and they can reach a depth of around 2m. [(33)]
In terms of complex terrain movements, they are types of landslides derived from the combination of some of the previous ones. Their main characteristic represents the area of terrain involved in the landslide. The bigger the area, the bigger the probability of a combination of two or more landslides and therefore the higher the probability of having complex terrain movements (Inventario dei Fenomeni Franosi in Italia, s.d.). [(34)]
In conclusion, for what concerns the rockfalls, they represent a portion of terrain that presents a quasi-vertical slope from where it falls. Also, rocks can fall from this slope and their falling trajectory is often free fall with rolling and/or bouncing. [(35)]

Factors that influence the occurrence of a landslide include geological conditions, slope gradient, water content, vegetation cover, and human activities. The slope gradient is particularly significant and according to it, a differentiation of five layers can be carried out in the Cervo Valley case study. [(36)] They are defined through the calculation of the slope gradient, and they are listed below:

- Slow drips (0-15%)
- Quick drips (15-30%)
- Rotational/Translational slips (30-35%)
- Complex terrain movements (35-70%)
- Rockfalls (70-100%)

These percentages are arbitrary set and defined according to the terrain characteristics descripted in the literature general classification of the landslides. [(36)]

The first slope range – from 0 to 15% – is representing possible minor phenomena risks for streets and buildings. Since most of structures and infrastructures are in areas within this slope percentage, it is not possible to identify all the risks and damages to which they are subjected. Therefore, a marginal representation of them is provided in the 2D maps.

2.3.2.1. Main script

The script *Slope Shapefile* (37) is composed of two main parts: the first one where the slope gradient is calculated and each cell that is within the slope thresholds are represented as polygons; the second one where the cell polygons are unified to create a unique layer. In that way, the layer has reduced dimensions, but the information maintains a high quality of representation.

To obtain the higher quality possible in the layer representation, the DTM5 is used as input raster file.

The different libraries in this case used are *numpy* for the data elaboration, *gdal* to manage raster data, *ogr* and *osr* for the vectorial data management and the spatial projection, *fiona* for the shape files management, *shapely.geometry* to create and manage the vectorial geometries.

Then, the terrain slope is firstly calculated in radians and converted in degrees. Furthermore, the slope is calculated as a percentage value. Afterwards, the polygons within the already specified slopes ranges are created. In conclusion, they are converted into a unique polygon.

Depicted below the representation of the Python function that calculates the terrain percentage slope.

```
# Slope calculation function
def calculate_slope(dtm_array, cell_size):
    dzdx = np.gradient(dtm_array, axis=1) / cell_size
    dzdy = np.gradient(dtm_array, axis=0) / cell_size
    slope_radians = np.arctan(np.sqrt(dzdx ** 2 + dzdy ** 2))
    slope_degrees = np.degrees(slope_radians)
    slope_percent = np.sqrt(dzdx ** 2 + dzdy ** 2) * 100
    return slope_percent
```

Where *dtm_array* is a variable defined once the DTM data are read and saved as an array; and *cell_size* is the cell dimension variable. In this regard, a proper distinction between the cell size in the x and y direction is normally done. At the same time, since in this case the pixel dimensions are the same in both directions, a unique variable can be used. Then, *dzdx* and *dzdy* are the DTM gradients respectively calculated along the x and y directions. In conclusion, three different formats of slopes are provided: slope in radians, in degrees and in a percentage value. The function returns the latter one while the other two are provided for completeness of the script. In that way, if the will is to create a shapefile representing different slopes in degrees, it is easily possible to switch the return data result.

In terms of shape file for the different ranges of slope, they are saved following a specific structure showed as follows:

```
# Save polygons into a Shapefile
def save_polygons_to_shapefile(polygons, output_shapefile):
    schema = {'geometry': 'Polygon', 'properties': {'id': 'int'}}
    with fiona.open(output_shapefile, 'w', 'ESRI Shapefile', schema) as c:
        for i, polygon in enumerate(polygons):
            c.write({
                'geometry': mapping(polygon),
                'properties': {'id': i}
            })
```

Indeed, the schema represents the structure of the shape file – geometry type and properties – and the command *fiona.open* creates it with the specified name (*output_shapefile*, written modality) and structure (*ESRI Shapefile*).

In general, the realization of Python scripts is also useful to maintain a parallelism (QGIS-Python) among the graphic results. An example of plot is performed with the terrain slope between 70 and 100% – the most difficult layer to be visualized compared to the other areas of diffusion – where it is directly overlapped to the raster file [Figure 46.].

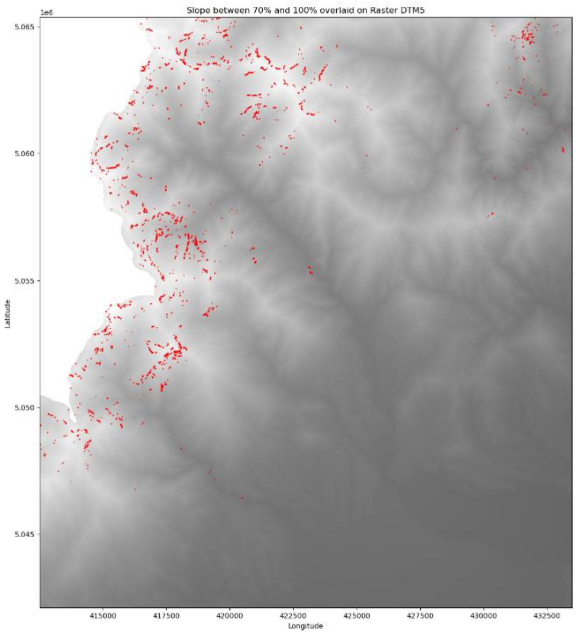

Figure 46. Slope between 70 and 100% overlaid on raster DTM5. In red the shapefile.

To verify the accuracy of the exported data, a double check is defined.

2.3.2.2. Slope check: coordinates

A twin script that takes two different random points coordinates in input and calculates the percentage of slopes between them is realized. It is called *First slope check.* [(38)]

In this case, the latitude and longitude are converted from degrees to radians. Then, the Haversine formula is used to calculate the horizontal distance and the points altitude variation. Indeed, this formula allows to determine the great-circle distance between two points on a sphere given their longitudes and latitudes. [39]

Then, the slope percentage is calculated as the ratio between the altitude difference among the points and their horizontal distance.

2.3.2.3. Slope check: color map

The script-named *Color map slope check* [40] represents the second check performed on the produced shape files. Since the previous script does not provide a general overview of the raster file, an iterative process introducing all the raster cell coordinates is considered useless and time consuming. Therefore, to face up the problem and provide a parallel way of visualizing the shape file produced, two color maps are considered useful. They represent the different areas of the DTM with the various percentages of slope.

The first color map shows the whole Cervo Valley providing a general overview of the terrain inclination in a 2D representation. It is showed below [Figure 47.].

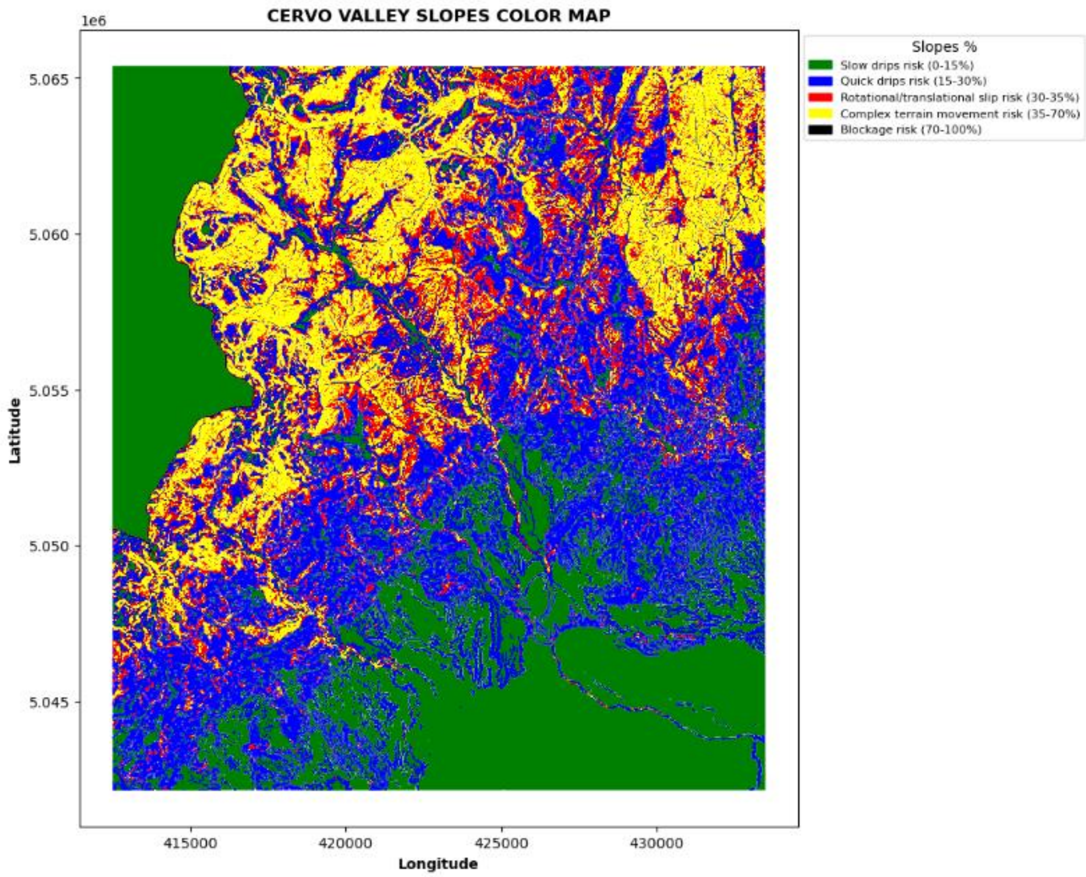

Figure 47. Cervo Valley slopes color map.

The different color used are green for slopes within 15% where the risk is related to slow drips; blue for quick drips risk with a percentage of slope from 15 to 30%; red representing the rotational and translational slips risk where the terrain slope percentage is between 30 and 35%; yellow for the complex terrain movements risk from 35 to 70% of slope and in black the rockfalls risk where the terrain is almost vertical and has a percentage of slope from 70 to 100%.

The second one represents a zoom in correspondence of the so-called Mologna Hill, one of the mountain peaks in the Valley that has the most variations in slope. The Python plot is depicted in Figure 48.

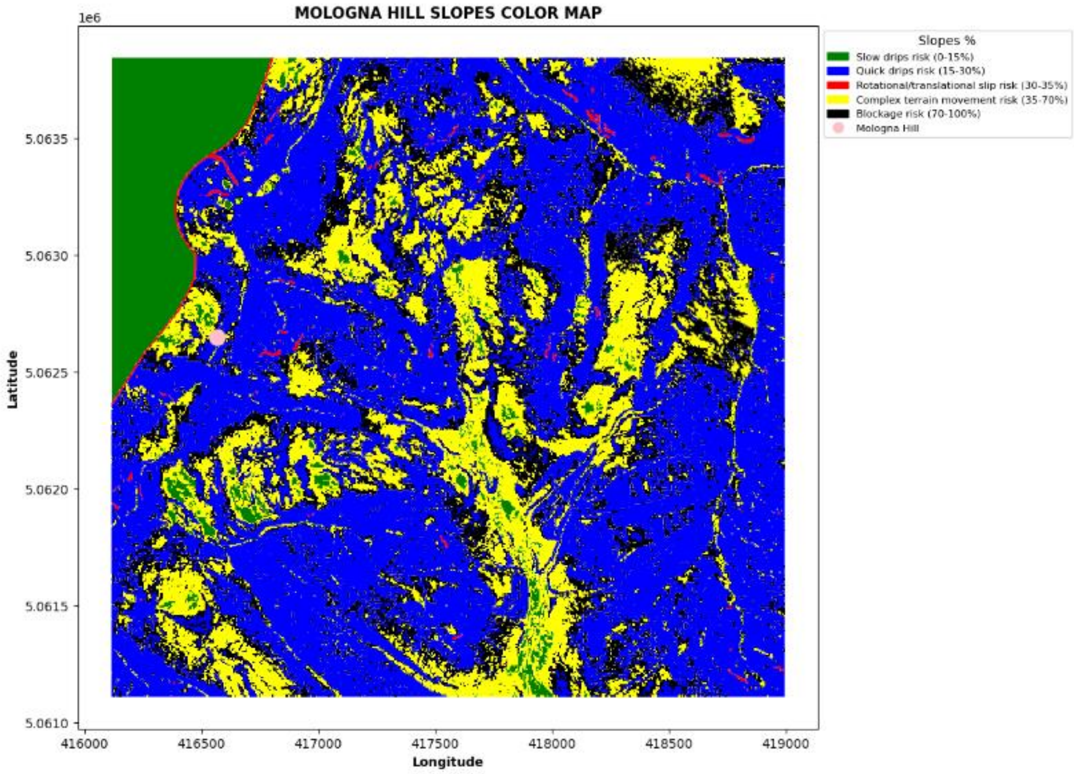

Figure 48. Mologna hill slopes color map.

2.3.3. ARPA Piemonte API calls: create a new pop-up for the 2D maps

The introduction of dynamic data help in the hydrogeological analysis with the final purpose of creating and adopting a proper territory management plan. In this regard, the idea is to realize pop-ups in both the Piedmont and Cervo Valley maps representing real-time precipitation data. This is done after the qgis2web plugin export of the two maps.

This involves the use of a Python script adopting Application Programming Interface (API) calls. These API are specific mechanisms that allow two software to communicate one another by using a series of definitions and protocols. Different types of API are present nowadays, but in this case study only the API REST category is adopted. It represents the client requests sent in the form of data requests. The word REST stands for Representational State Transfer and it defines a series of functions (GET, PUT, DELETE etc.) used to have the client access on the server data. This category does not save the client data among the requests. The specific function used in this case study is the GET one. (41) This method is used to read data or retrieve information about a resource. (42)

ARPA Piemonte is the website of reference for the collection of the Cervo Valley data. It directly provides API data from its website. Among the variety of data available, the ones of interest in this case study are related to the precipitation measurements of the two pluviometers present in the Valley. The first one is placed in Piedicavallo – at the beginning of the Upper Valley – while the second one is in Biella, at the end of the Cervo Valley. However, the data provided in the API documentation refers to the year 2023. Therefore, the initial idea of using the API documentation to introduce dynamic pop-ups updated in real time is modified. Specifically, the 2023 data will be considered as real-time data.

The 2D maps are created and exported from QGIS through the adoption of the qgis2web plugin. It is properly described in *section 2.2.5. qgis2web plugin: export of the map for the web* of this document. According to it, the main script of the map realization adopts the JavaScript language.

2.3.3.1. Piedicavallo pluviometer

The Piedicavallo pluviometer has the following characteristics:

- x-coordinate. UTM x – ED50: 418813
- y-coordinate. UTM y – ED50: 5060264
- Elevation. 1040 m over the sea level
- Station code. 191

And the GET request is performed in the script as follows:

```
https://utility.arpa.piemonte.it/meteoidro/dati_giornalieri_meteo/?fk_id_punto_misura_meteo=PIE-002095-900
```

2.3.3.2. Biella pluviometer

The Biella pluviometer has the following characteristics:

- x-coordinate. UTM x – ED50: 426445
- y-coordinate. UTM y – ED50: 5045652
- Elevation. 405 m over the sea level
- Station code. S2566

And the GET request is performed in the script as follows:

```
https://utility.arpa.piemonte.it/meteoidro/dati_giornalieri_meteo/?fk_id_punto_misura_meteo=PIE-002012-901
```

2.3.3.3. The Cross-Origin Resource Sharing (CORS) mechanism

The Cross-Origin Resource Sharing (CORS) is a mechanism used to share resources from different origins. This functionality defines a way with which the client applications in a specific domain can interact with different resources from different domains. This is useful whenever the client application refers to API documentations from third parties in the script client-side. *(43)*

At the same time, the Same Origin Policy (SOP) limits the data usage from another server when a website is used. All the data information should come from the same server. Since JavaScript and CSS files can load data from different server – included the dangerous ones – without the client consent, the SOP regulates the type of data that could be used. *(44)* This is a policy used for browser webs.

In this case study, since the map is created by using the JavaScript language, the CORS problem is present. Indeed, the ARPA Piemonte Same Origin Policy does not recognize the HTML file of the exported map because its server is not the same of the website. Consequently, the request is locked and the data are not provided.

To face up this problem, an intermediate step is done.
Considering that Python does not work in a browser, the Cross-Origin Resource Sharing problem is not present. Therefore, a Python script is used to make the API

call to the Arpa Piemonte website. Then, in the same script a specific library – better explained in *section 2.3.3.4. Creation of Python script to make the API request* – called *Flask* is used. It creates a virtual server without the CORS mechanism and the SOP. Thanks to it, it is possible the creation of a direct link between the Python virtual server and a JavaScript file where the pop-up graph is realized.
Afterwards, the JavaScript file is included in the HTML script of the map making available the dynamic information.

2.3.3.4. Creation of Python script to make the API request

In this section, a proper description of the Python script is provided. It represents the starting point for the introduction of dynamic data in the map exported from QGIS. It makes possible the connection between the ARPA Piemonte website precipitation data and the 2D web maps.

The general purpose of the Python script – named *PluviometerAPI* [(45)] – is to consider the real-time day and refer it to a year before (from 2024 to 2023); create a new virtual server without the CORS mechanism; make the API call with the converted date and activate the debug modality.

The first step of the script regards the realization of the virtual server by using the *flask* library and by removing the Same Origin Policy de-activating the CORS mechanism.

In terms of days, as already mentioned in the first section of *chapter 2.3.4. ARPA Piemonte API calls: create a new pop-up for the 2D maps*, the ARPA Piemonte website only provides API documentations up to the 31st of December 2023. Therefore, the dynamic data are related to the past year, but they are considered as real-time information. Indeed, the script takes three different days: the actual day referred to a year before, and the two previous days with respect to that date. In that way, the pop-up shows a graph with the precipitations of these three selected days.

For what concerns the API call, the script uses the previously described links for the two pluviometers. This part of the script is showed below:

```
# Make the API call to the ARPA Piemonte website
def call_API():
  # Take today's date
  today = datetime.now()
  # Refer today's date to a year before. Relativedelta avoids values = 0. Use 'yearS' and not 'year' otherwise
the year is defined as 1.
  one_year_ago = today - relativedelta(years=1)
  # Dates format 'YYYY-MM-DD' to decide for how many days I want the rain information ans use
relativedelta to come back to the previous month in case of values <= 0.
  reqDates = {
    'min_date': (one_year_ago - relativedelta(days=2)).strftime('%Y-%m-%d'),
    'max_date': one_year_ago.strftime('%Y-%m-%d')
  }
```

```python
# URL API ARPA Piemonte website
  # By using 'f' I can create a binding and make the call dynamic based on the date parameters
  arpa_api_url =
f"https://utility.arpa.piemonte.it/meteoidro/dati_giornalieri_meteo/?fk_id_punto_misura_meteo={request.args.get('fk_id_punto_misura_meteo')}&data_min={reqDates['min_date']}&data_max={reqDates['max_date']}"

  # Make the GET request to the ARPA Piemonte API documentation
  try:
    response = requests.get(arpa_api_url) # take the response from the API call made in ARPA Piemonte website
    response.raise_for_status()  # create an exception if the request has a negative result
    data = response.json()  # conversion of the JSON response into a Python dictionary
    # Plot the data
    if 'results' in data:
      location = request.args.get('location')
      return {'data': data, 'location': location, 'dates': reqDates}, 200
    else:
      # Create an error if no rainy days data are found
      print(f"No precipitation (ptot) data found from {reqDates['min_date']} to: {reqDates['max_date']}")
  # For any error (with the exception of missing ptot data) give a feedback about the type of the error
  except requests.exceptions.RequestException as e:
    print("Request error:", e)
```

Afterwards, the activation of the flask server is made in debug modality.

2.3.3.5. Creation of JavaScript API call database

The second step for the realization of the web map pop-up is made in JavaScript (JS). Two different JavaScript files are realized.

The first one named *Chart* (46) is a JavaScript library already programmed by third parties. (47) This is used to realize the pop-up graph and its file is placed in the JS folder automatically created by the QGIS plugin during the maps export.

The second one is called *Pluviometer*. (48) In this case, the API call is done from the JavaScript file to the virtual server previously created with Python. This request uses the fetch method with a GET request and uses the pluviometer parameters *fk_id_punto_misura_meteo* – that represents the identification parameter of each pluviometer – and *location* that considers the pluviometer location.

The JavaScript function used to obtain the precipitation data – *ptot* – from the API call is represented as follows:

```javascript
// Function that obtain the precipitation data for a set day
async function getPtotDataForDate(fk_id_punto_misura_meteo, location) {
 // API call to Python virtual server by using fk_id_punto_misura_meteo and location with GET method
 try {
  const response = await fetch(
   `http://127.0.0.1:5000/get_pluviometer?` + // This is the server of the map
    new URLSearchParams({ // This is a JavaScript class able to work with URL links. In this case it considers the following two specific parameters
     fk_id_punto_misura_meteo, // Identification code of the pluviometer (Biella or Piedicavallo)
     location, // Name of the pluviometer location (Biella or Piedicavallo)
```

```
    }),
    { method: "GET" }
  );
  // Save the response and converts it into a JSON object. This conversion is necessary to make possible
the interpretation of the data into the JS
  const res = JSON.parse((await response.text()).toString());
  if (res.data.results) { // res should have an attribute 'data' that should have an attribute 'results' in the
API call
    // If a response is available, I give it to the function caller
    return res;
  } else {
    // No response = error
    console.log(`No data founded`);
    return null;
  }
 } catch (error) {
  // Service error = error
  console.error("Error during the API call:", error);
  return null;
 }
}
```

In the second part of the script, a function for the realization of the graph with the specific API data is used. Here there is the connection between the two JavaScript files: *Chart* and *Pluviometer*.

2.3.3.6. Modification of HTML script for the web (2D)

Once all the preparation files are ready, the modification of the HTML script representing the web maps is done. In these terms, all the files and modifications of the two web maps – *2D Cervo Valley Web Map* [(49)] and *2D Piedmont Web Map* [(50)] – are the same.

The modifications are performed in the points where the comment */*TODO: Add */* is placed. By making internal research (CTRL + F) and digiting the previous comment, the script shows all the variations. For completeness, they are showed below.

First, the increment of the graph dimension is done to make it clearer once the web map is used.

```
/*TODO: Add */
    /* Modify graph dimensions */
    .leaflet-popup-content {
      min-width: 500px;
      min-height: 300px;
    }
    /* Modify pop-up image dimensions in case of error */
    .image-size {
      max-width: 500px;
    }
```

Then, the introduction of the sources chart and pluviometer is necessary to create the link between all the files previously realized.

```html
<script src="js/Chart.js"></script>
<script src="data/Pluviometer.js"></script>
```

Afterwards, the modification of the pop-ups in correspondence of both the Biella and Piedicavallo pluviometers is performed. Since the modified function is the same for both the pluviometers, just one of them is following described.

```javascript
// TODO: Add
  function pop_BIELLA_Pluviometer_98(feature, layer) {
    //Canvas creation where there will be the graph
    var popupContent = `<canvas id="BIELLA"></canvas>`;
    //Highlight the level when I have the mouse over it
    //mouseout: function activated when the mouse comes out from the level
    //mouseover: function activated when the mouse comes over the level
    layer.on({
      mouseout: function (e) {
        for (var i in e.target._eventParents) {
          if (typeof e.target._eventParents[i].resetStyle === "function") {
            e.target._eventParents[i].resetStyle(e.target);
          }
        }
      },
      mouseover: highlightFeature,
    });
    //Pop-up creation
    layer.bindPopup(popupContent);
    //Save of the created pop-up
    var popup = layer.getPopup();
    //Saving of pop-up content
    var content = popup.getContent();
    //Saving the filtered pop-up without the non-populated leaflet contents
    var updatedContent = removeEmptyRowsFromPopupContent(content, feature);
    //Upgrade of pop-up data
    popup.setContent(updatedContent);
    //API call when I click on the level
    layer.on("click", function (e) {
       //Call of the function described in Pluviometer.js in entrance: fk_id_punto_misura_meteo and
      location name
      getPtotDataForDate("PIE-002012-901", "BIELLA").then((response) => {
        if (response != null) {
          //Saving of the response
          //var responseData = response;
          //Method esecution to obtain the graph with the entrance response
          plotPtotDataForDate(response);
        } else {
          //Error feedback if present
          layer.bindPopup(
            '<img class="image-size" src="./images/404-error.png">'
          );
        }
```

```
            });
        });
    }
```

In green all the script comments are provided.

The web maps are now ready to be published in the web. In the following paragraphs, a deep representation of them is provided.

2.4. 2D Map: ready for the web

In this chapter, the representative pictures of the maps are provided. In addition, by clicking on the GitHub account, a representative video is present. [51]

2.4.1. 2D Piedmont web map

As already described, the Piedmont map is used to provide a general overview of the Cervo Valley hydrogeological situation in a bigger environment. In addition, it is also used to demonstrate the possibility of spreading the Cervo Valley analysis in the whole region and reach bigger scales of representation.

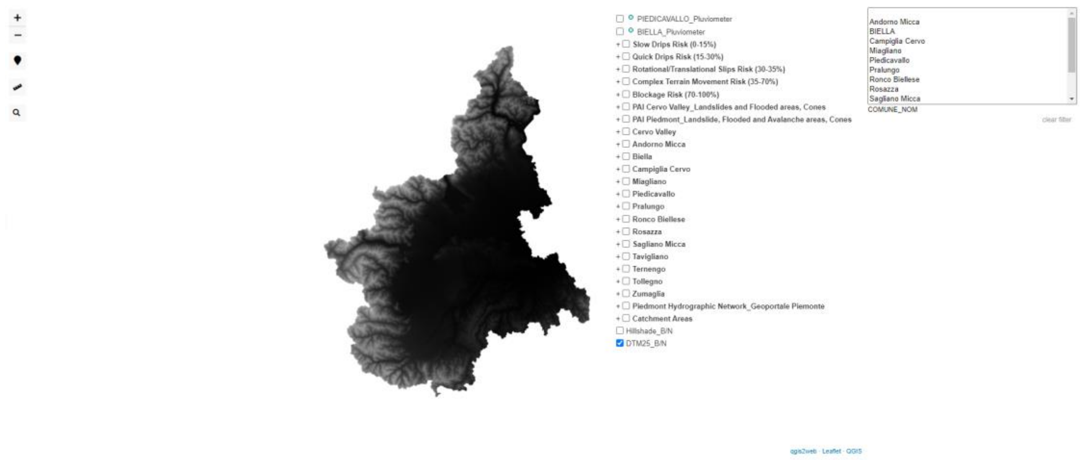

Figure 49. Piedmont web map. DTM25 raster layer.

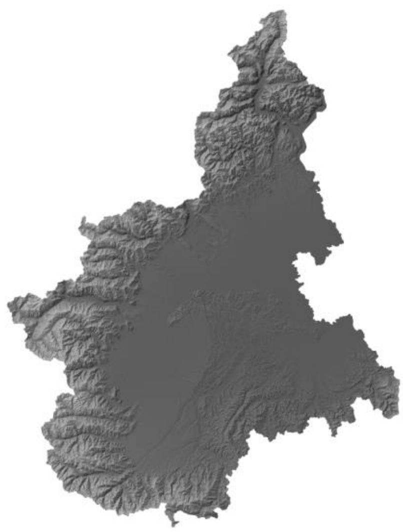

Figure 50. Hill-shade of DTM5 raster layer.

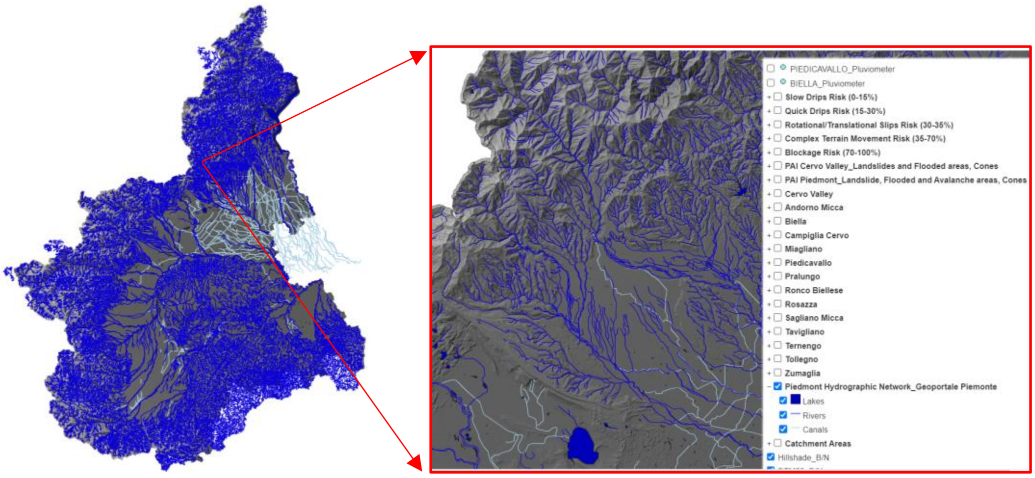

Figure 51. *On the left Piedmonts historic hydrographic network layer from Geoportale Piemonte. On the right a zoom of the hydrographic network layer with the representation of lakes and rivers in blue and canals in light blue.*

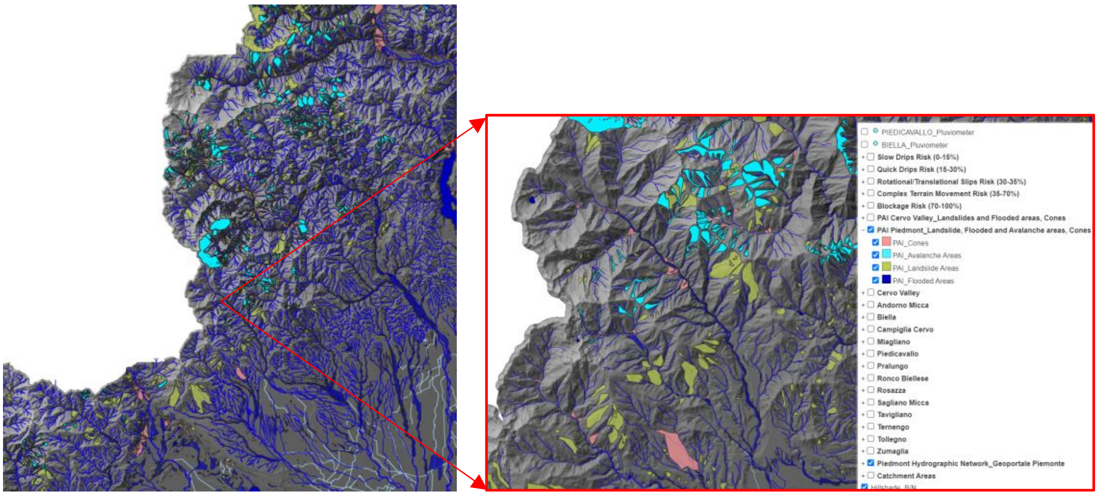

Figure 52. *On the left Piedmonts representation of PAI Annex 2 – cones (pink), flooded areas (blue), landslides (green) and avalanches (light blue). On the right the Cervo Valley zoom of the PAI Annex 2 – cones, flooded areas, landslides, avalanches.*

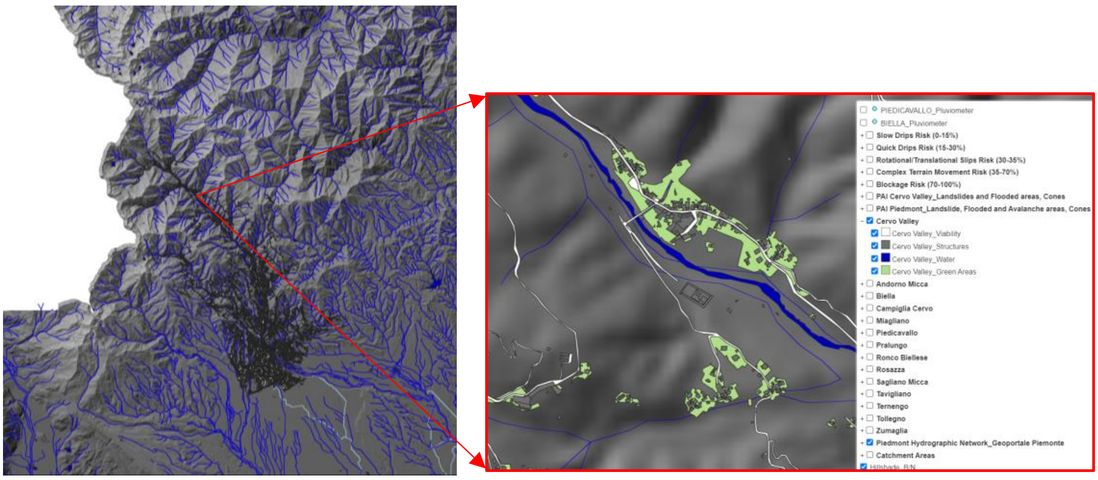

Figure 53. *On the left an overview of the Cervo Valley BDTRE layers: structures, streets, hydrographic network, and green areas. On the right a zoom on Campiglia Cervo municipality.*

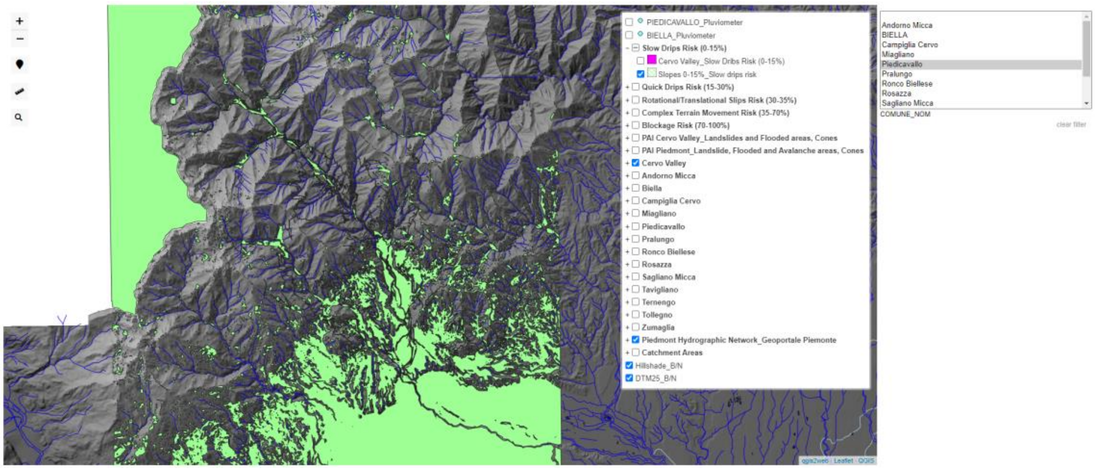

Figure 54. *Slope terrain layer between 0 and 15%.*

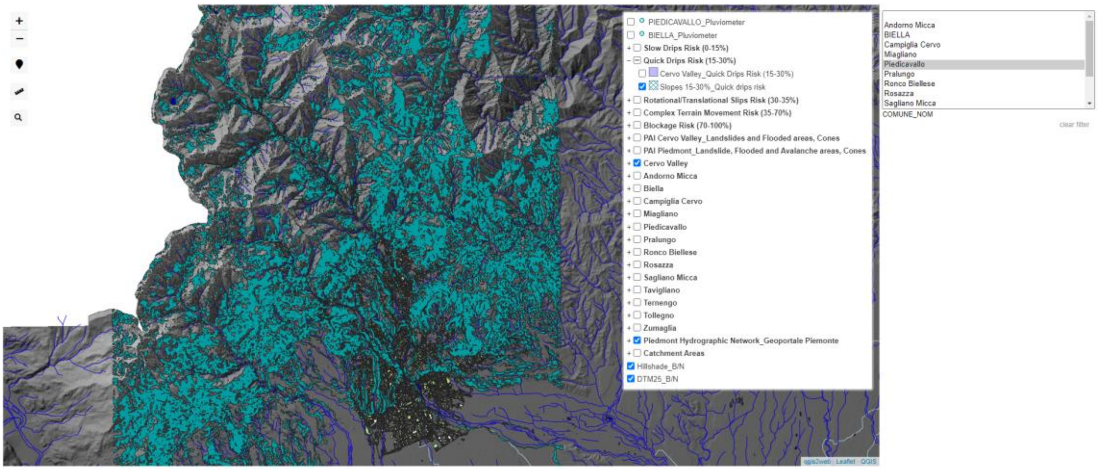

Figure 55. *Slope terrain layer between 15 and 30%. Quick drips risk events.*

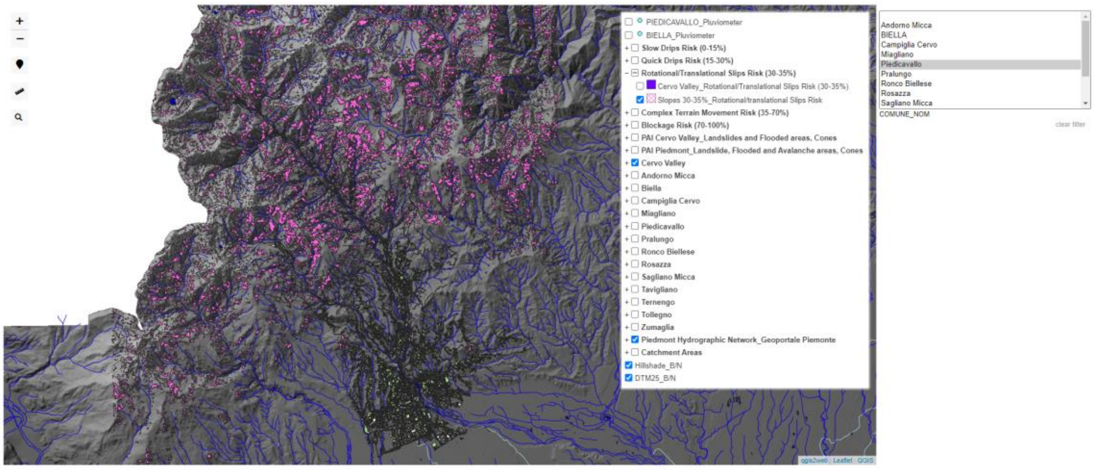

Figure 56. *Slope terrain layer between 30 and 35%. Rotational/Translational slips risk events.*

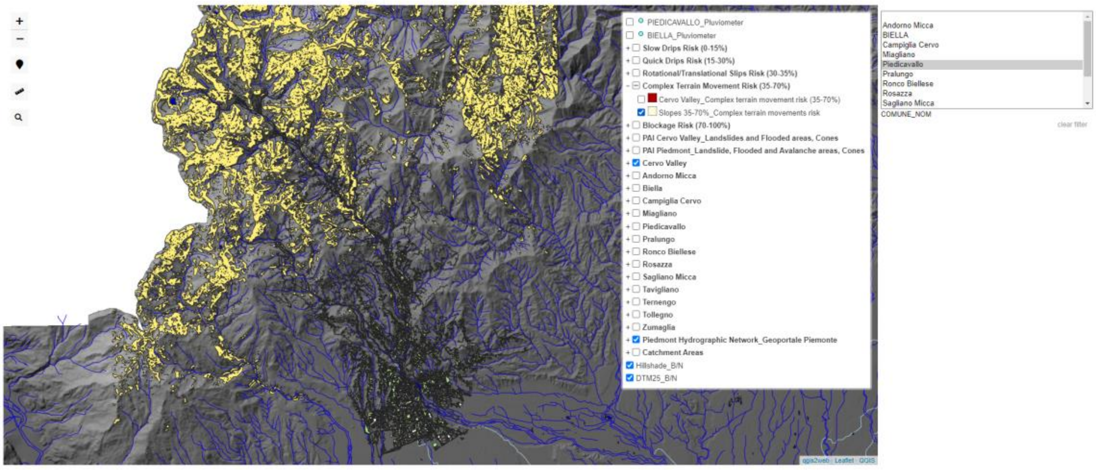

Figure 57. *Slope terrain layer between 35 and 70%. Complex terrain movements risk events.*

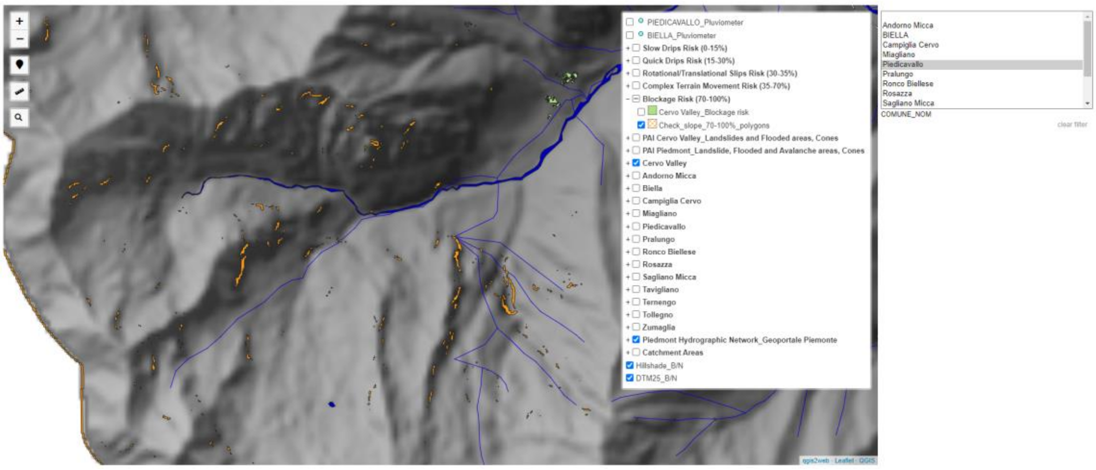

Figure 58. *Slope terrain layer between 70 and 100%. Rockfalls risk events.*

Figure 59. *Drainage area Piedicavallo basin and the pop-up zoomed representation: 18,076 km^2.*

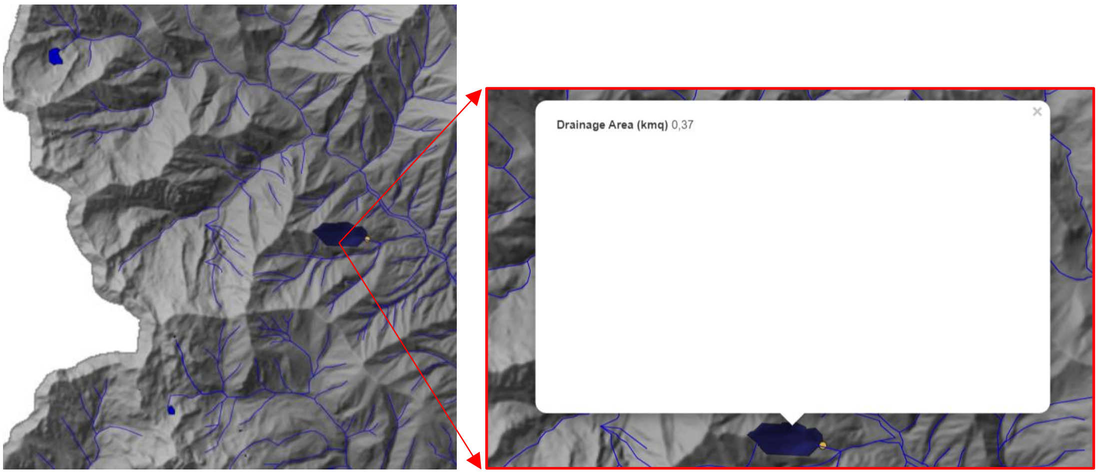

Figure 60. *Drainage area Saint Giovanni Andorno Sanctuary basin and pop-up zoomed representation: 0,37 km^2.*

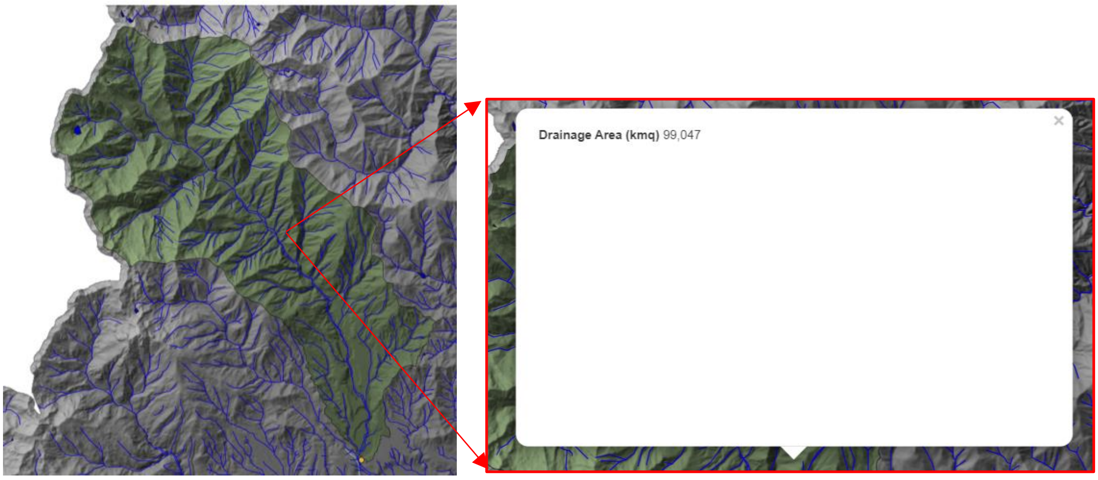

Figure 61. *Drainage area Biella basin and pop-up zoomed representation: 99,047 km^2.*

Figure 62. *Drainage area Ex-wool mill Maurizio Sella basin and pop-up zoomed representation: 124,713 km^2.*

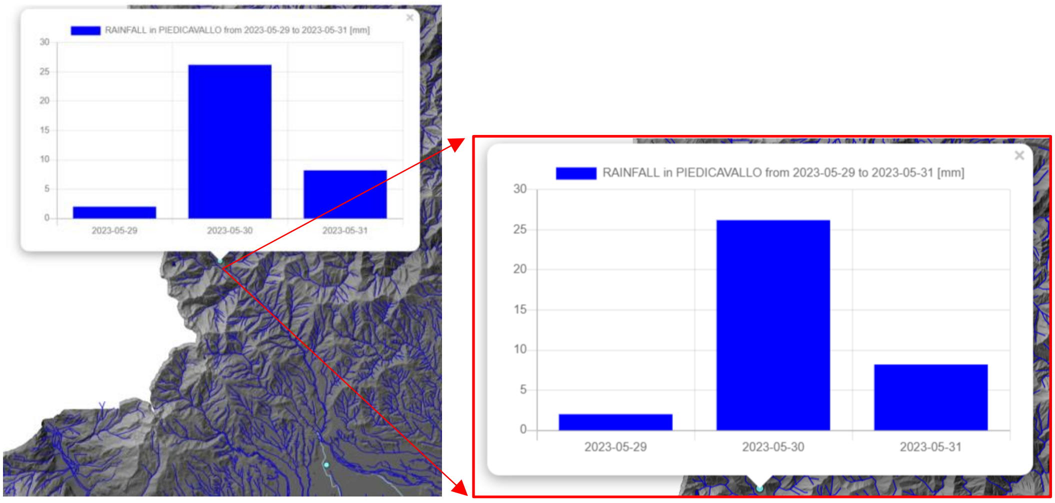

Figure 63. Piedicavallo pluviometer. Dynamic pop-up representation.

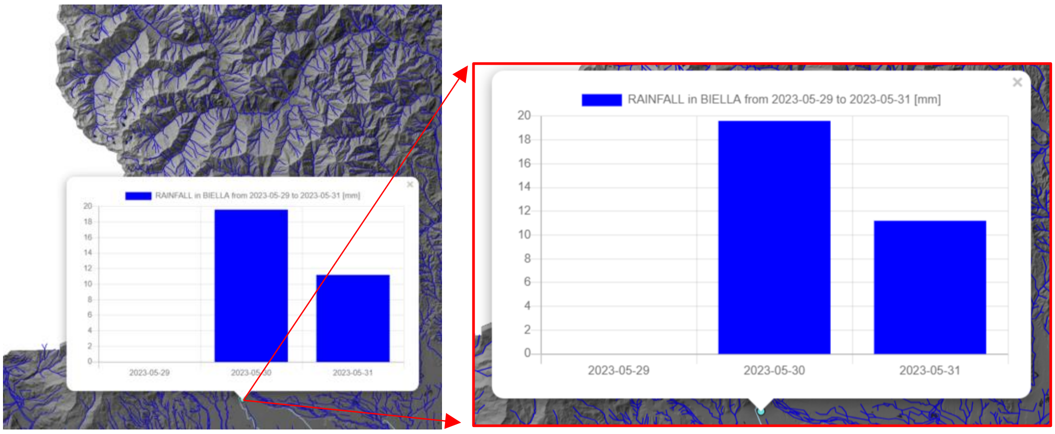

Figure 64. Biella pluviometer. Dynamic pop-up representation.

2.4.3. 2D Cervo Valley web map

To avoid repetitions, in this section only specific zooms are provided. They have the final purpose of giving a better comprehension of the different layers present in the map. Thank to them, it is clear the representation of structures and streets that could be affected by the different types of risk.

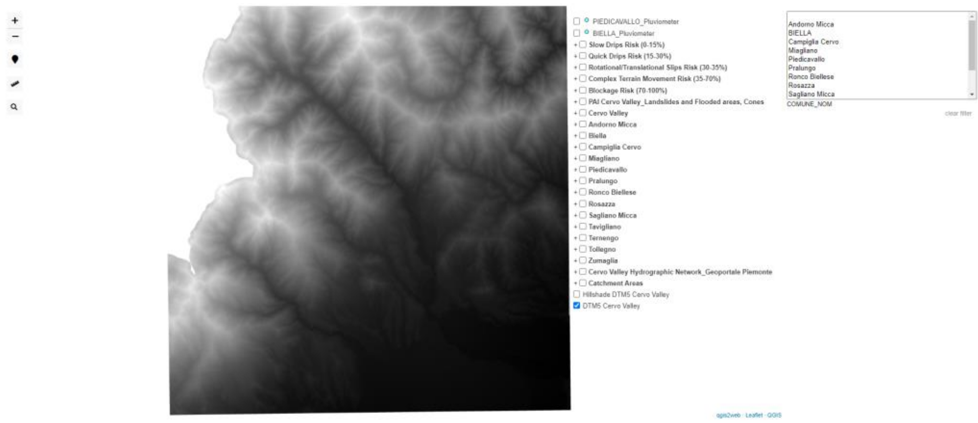

Figure 65. Cervo Valley web map. DTM5 raster layer.

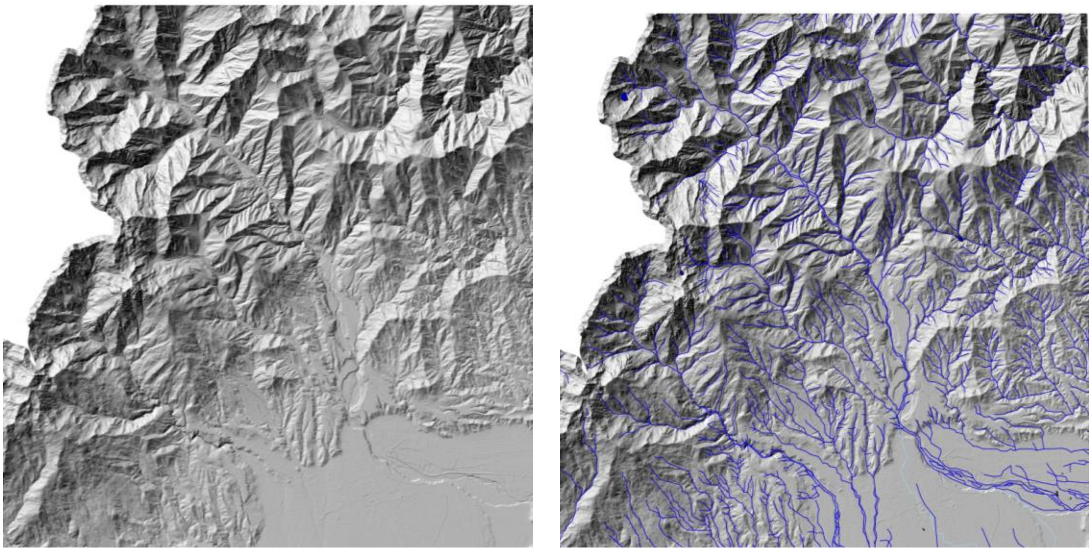

Figure 66. Hill-shade of raster layer and Cervo Valley historic hydrographic network layer from Geoportale Piemonte.

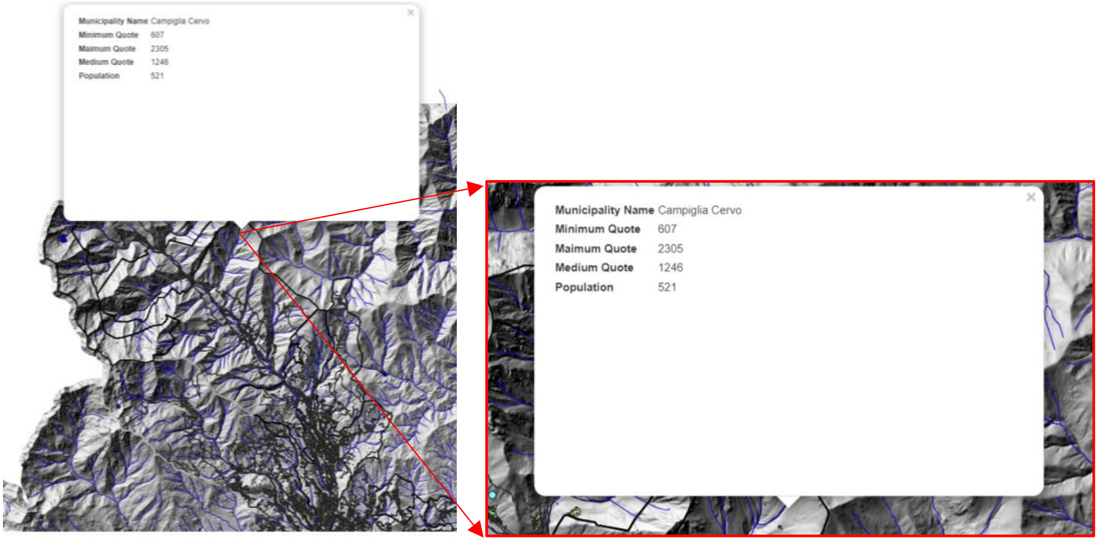

Figure 67. Municipalities pop-ups.

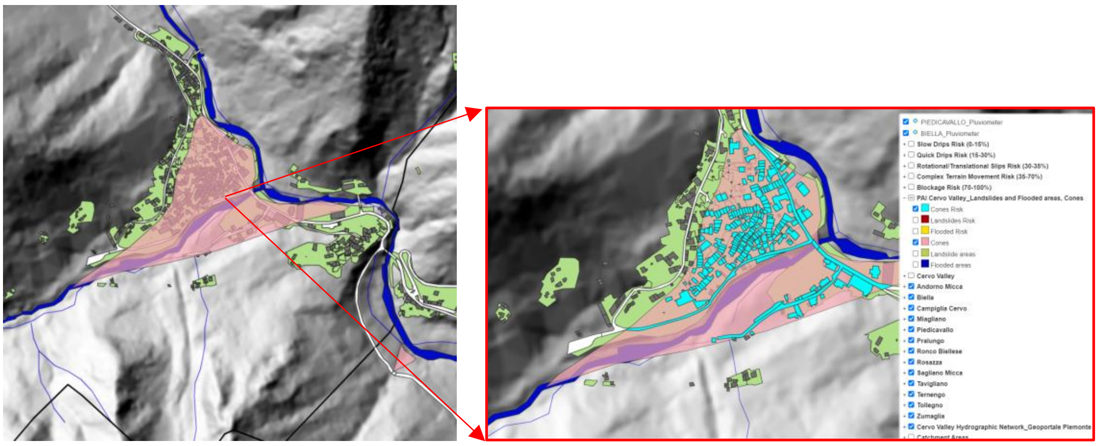

Figure 68. PAI Annex 2: cones areas in pink. Buildings and streets under the cones risk in light blue.

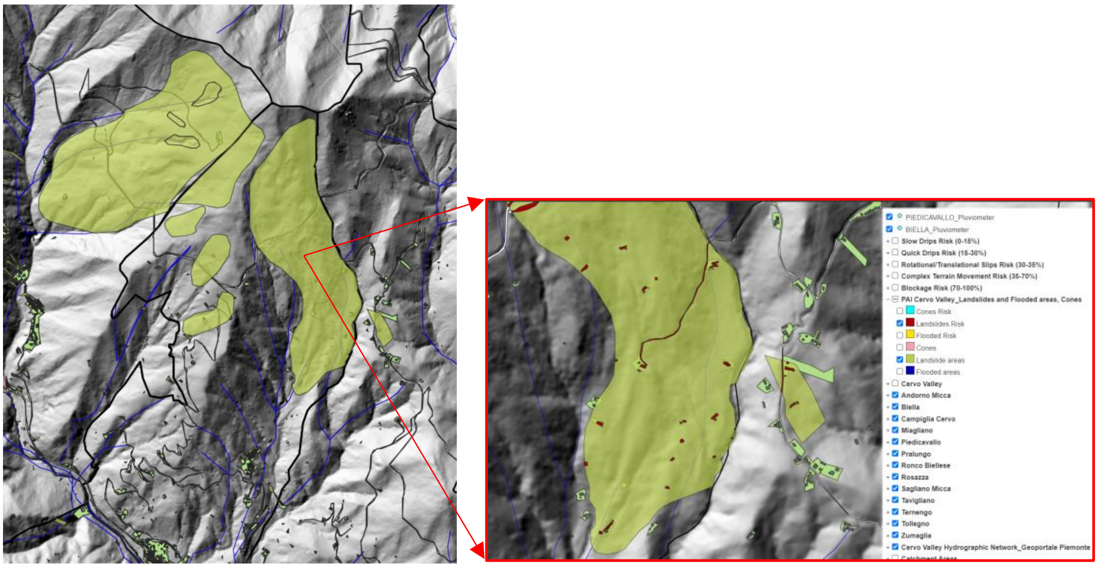

Figure 69. PAI Annex 2: landslide areas in green. Buildings and streets under the landslide risk in red.

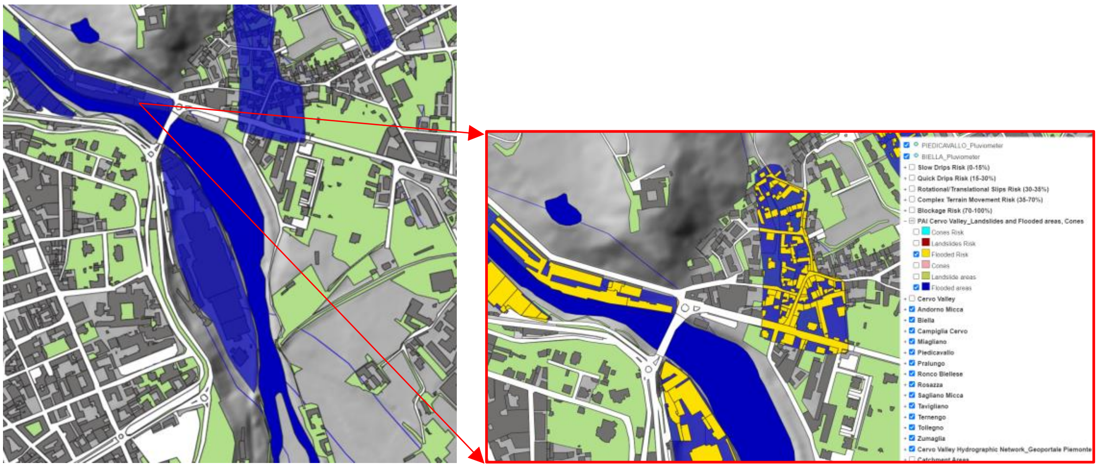

Figure 70. PAI Annex 2: flooded areas in blue. Buildings and streets under the floods risk in yellow.

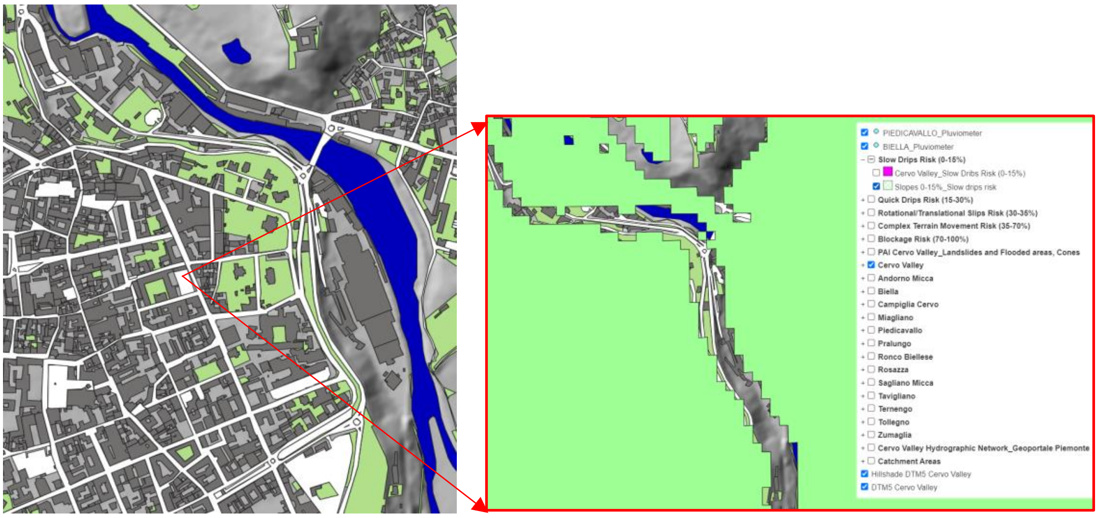

Figure 71. A part of Biella municipality area over which the slope terrain 0-15% layer is applied.

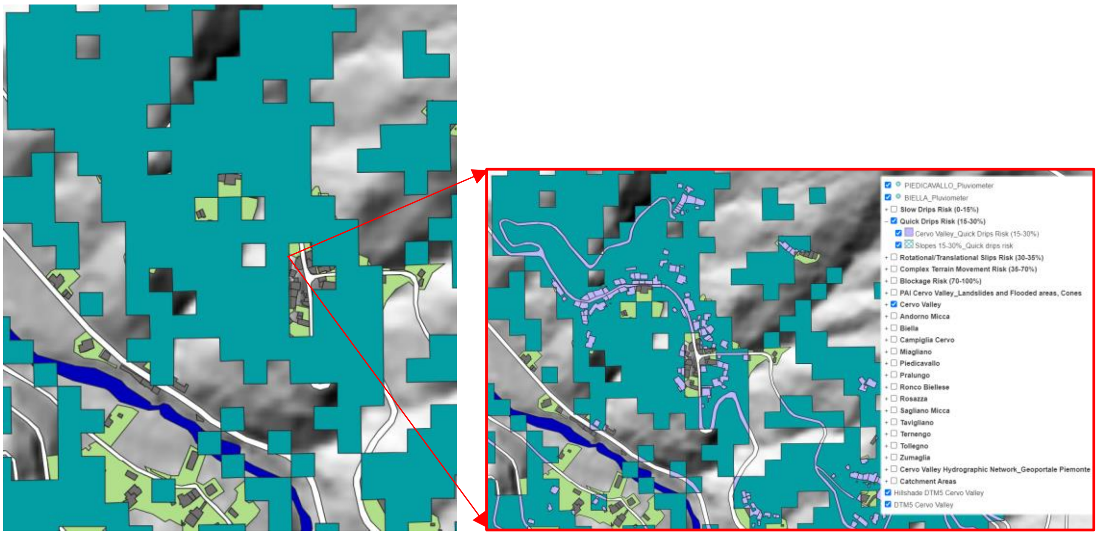

Figure 72. An area of Campiglia Cervo municipality over which the slope terrain 15-30% layer is applied. Structures and infrastructures at risk of quick drips.

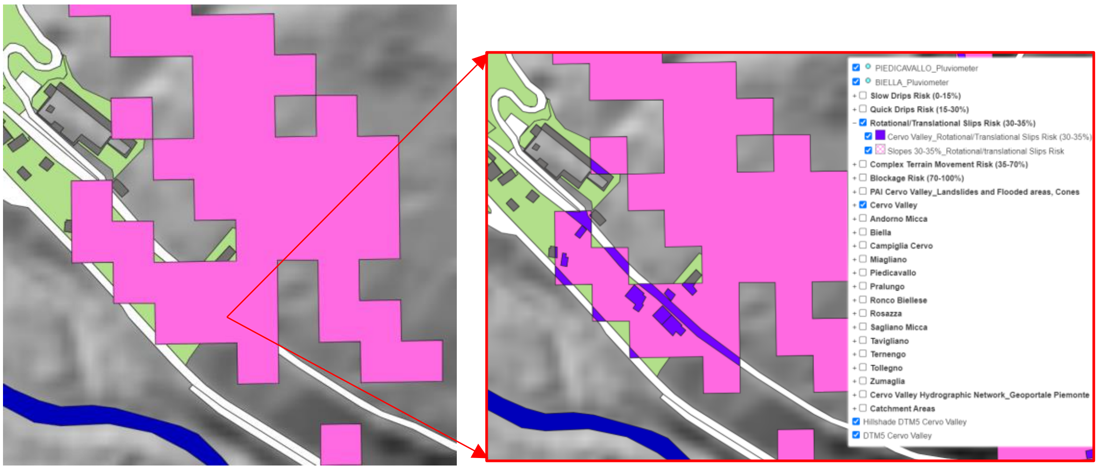

Figure 73. An area of Piedicavallo municipality over which the slope terrain 30-35% layer is applied. Structures and infrastructures at risk of rotational/translational slips.

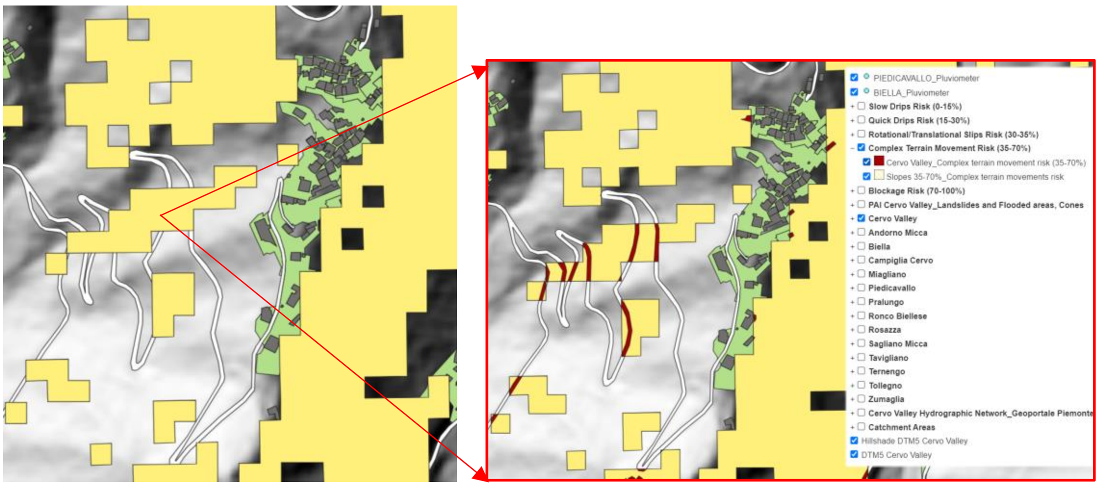

Figure 74. The same Campiglia Cervo municipality areas over which the slope terrain 35-70% layer is applied. Structures and infrastructures at risk of complex terrain movement.

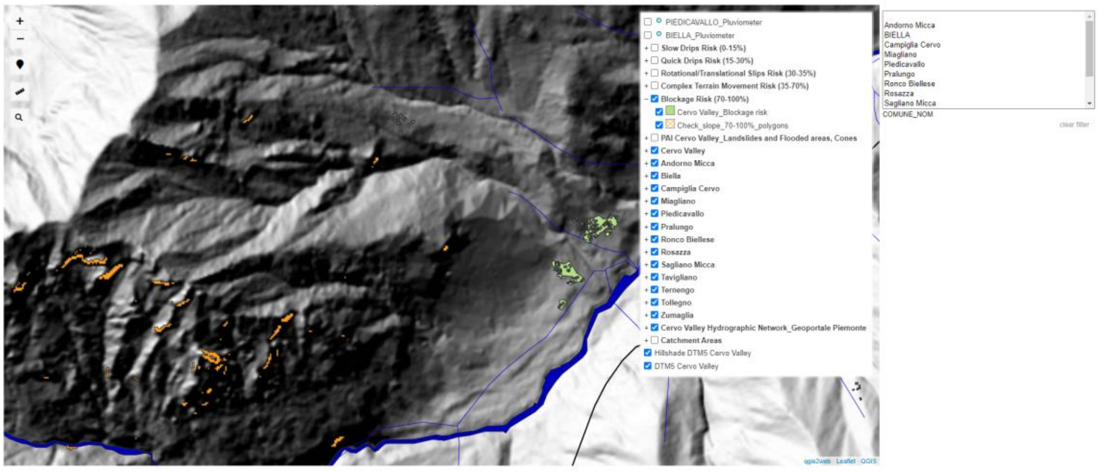

Figure 75. A Piedicavallo municipality area where the slope terrain 70-100% layer is switched on.

For what concerns the slope terrain 70-100% layer, it is important to represent it even if it does not directly overlap any structure or infrastructure in the Cervo Valley. The rockfall event can affect different areas of the Valley and not only the place where the terrain has an almost vertical inclination. Some rocks can fall for many meters and they can always reach populated areas.

3. 3D Map

The 3D map only represents the Cervo Valley area. Therefore, it is no more necessary to make a comparison between the regions of analysis as already done for the 2D Piedmont map with respect to the Cervo Valley one.

In any case, two maps are provided, the first one that represents the whole Cervo Valley and the second one that shows a restricted area in correspondence of Piedicavallo. In this way, with the second map it is possible to limit the file dimensions.

The following sections will focus on the Cervo Valley map realization. The Piedicavallo one is only different in terms of extension of exported area.

3.1. Initial data and their uses

The same raster and shape files already imported and modified in the *2D Cervo Valley map* are used in the 3D map. At the same time, all the shape files imported do not have the elevation information that is fundamental for the 3D plot. To face up the problem a specific Python script is used. It provides the third coordinate, and it will be properly described in *section 3.3.1. Adding elevation to the shapefiles*.

The DTM used for the Cervo Valley is the same of the 2D map, therefore it has a precision of 5m. For completeness of representation, one additional raster file is provided. It represents the DTM of a part of the Aosta Valley Region adjacent to the Valley of interest. Thanks to it, a better result can be achieved. This raster file is imported from the Aosta Valley Geoportal. [(52)] Since it is only used for completeness and it does not influence the static and dynamic data, to reduce the file dimensions it has a precision of 25m.

3.2. QGIS tools

Since all the files are already modified for the 2D map, the only one additional QGIS tool that is used in this case is the plugin necessary for the 3D map export.

3.2.1. qgis2threejs plugin: export of the map for the web

As already mentioned for the 2D map, this plugin is used once all the static data are imported. Therefore, it is adopted only after the import of the new shape files with the elevation information.

The plugin *qgis2threejs* visualizes raster data and vectorial ones in 3D on web browsers. Thanks to it, it is possible to build different 3D objects and generate files for web publishing. In addition, it also allows to save the 3D model in glTF format for 3DCG or 3D printing. [(53)]

The attributes of each layer in this case are not visible. On the opposite, each layer property must be properly defined to obtain the best graphic result.

Starting from the DTM raster files, the following properties are selected [Figure 76.]:

- Resampling level. This represents the geometry resampling of the DTM layer, and it is set as level 3. This allows to reach a good balance between quality and memory requirement.
- Image width (px). It is defined as 1024.
- Image format is PNG.
- Opacity of visualization is 70%. This helps with the visualization of the overlapped shape files.

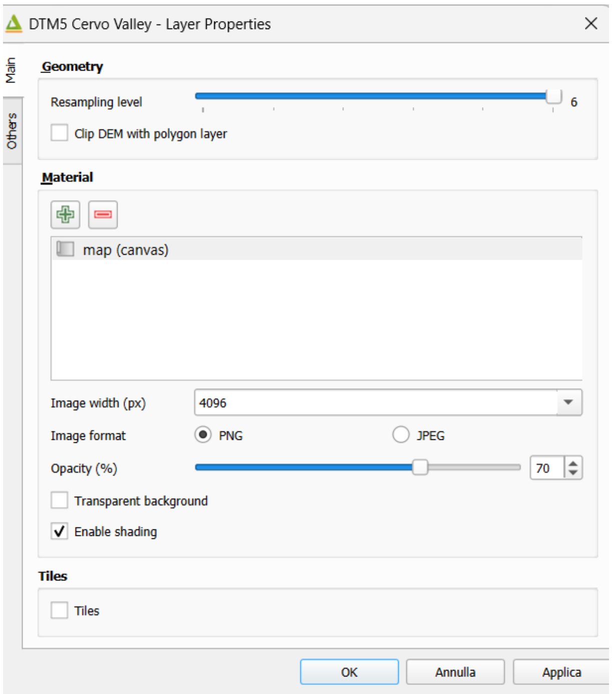

Figure 76. The dialogue window for the DTM properties.

Then, for what concerns the Piedicavallo and Biella pluviometers, they are represented in 3D as spheres and overlapped to the DTM file.

For all the other shape files, they are represented as lines – Geoportale Piemonte historic hydrographic network – and polygons – all the other shape files – overlapped to the DTM file.

After the definition of the layer properties, the map is ready for the export. In this case, after the selection of the output directory and the HTML file name, it is important to enable the viewer to run locally the map [Figure 77.]. In that way, the map is locally visible to everyone.

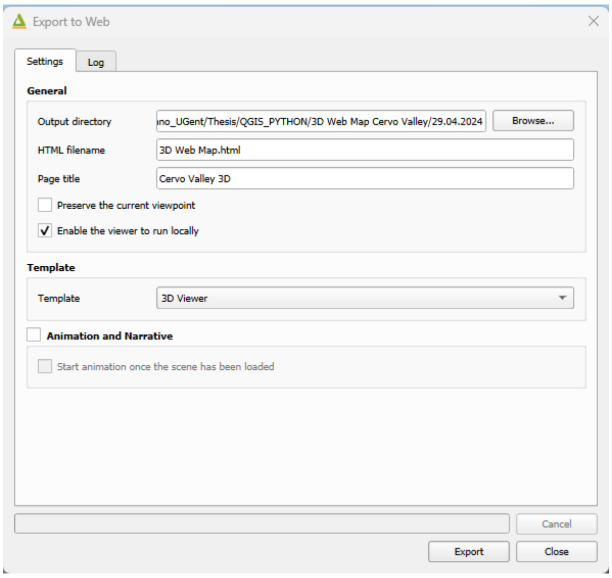

Figure 77. The dialogue window for the 3D map export.

Since the dynamic precipitation data are still missing, the exported map is not yet ready for the web. Consequently, two representative pictures of the exports are depicted below [Figure 78. and Figure 79.]; however, in *section 3.4. 3D Map: ready for the web* a complete representation of them is provided.

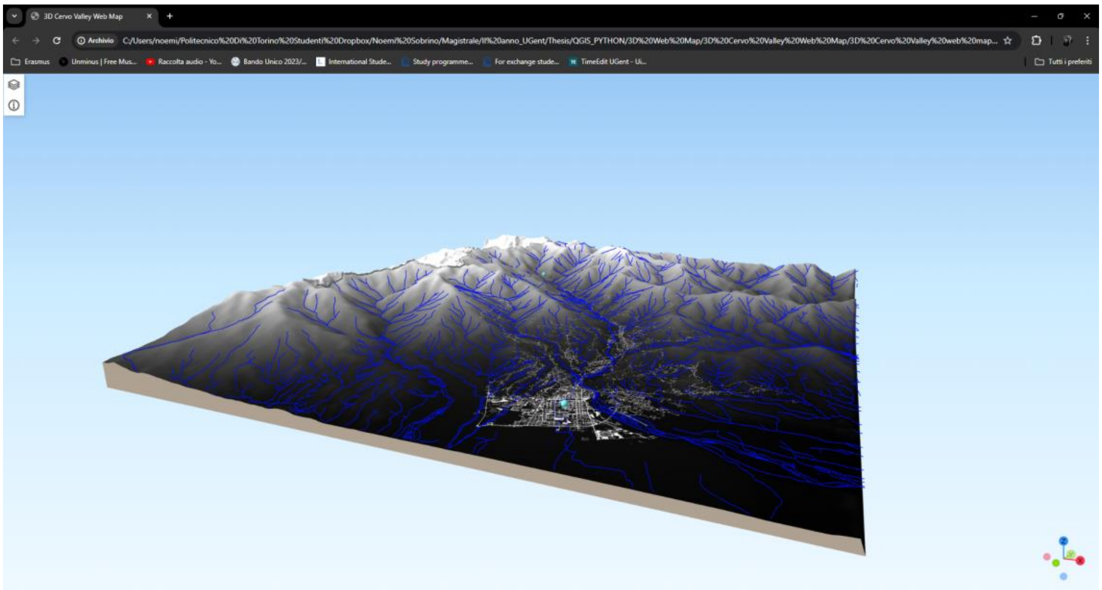

Figure 78. A first representation of the 3D Cervo Valley web map with only static data.

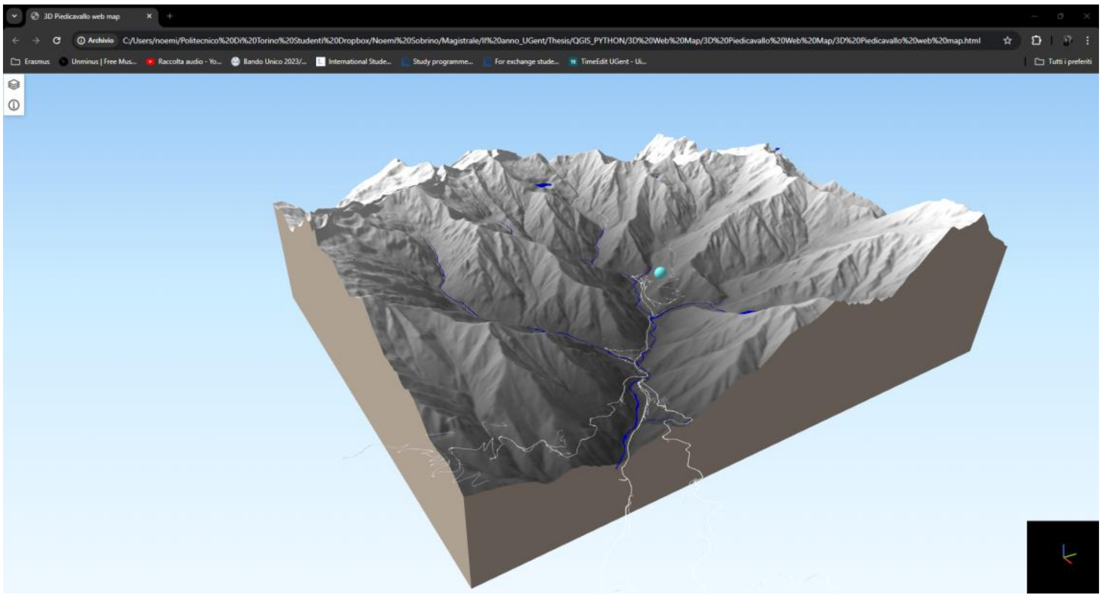

Figure 79. A first representation of the 3D Piedicavallo web map with only static data.

3.3. Python scripts

Again, in the 3D map both static and dynamic data are present.

For what concerns the static data, a Python script is developed to provide the third coordinate to each shape file layer. While, in terms of dynamic data, the same scripts and files used for the 2D maps are again adopted. However, in this case the Pluviometer JavaScript file is now directly implemented into a file previously created by the QGIS plugin.

Again, these scripts are initially generated with the help of Chat GPT [27] and then modified accordingly to the different requirements.

All the scripts are available in the personal GitHub account. [29]

3.3.1. Add elevation to the shapefiles

As already mentioned, the 2D map layers do not have the information in elevation. This is because the downloaded files do not include this attribute. However, this information is fundamental to create the 3D map.

The problem is solved by creating a Python script able to read in input all the 2D shape files layers – adopted in the 2D Cervo Valley map – and the DTM 5 raster file. Then, it assigns to the shape files the same elevation of the raster. Afterwards, a double check is provided. Before the new shape files import in QGIS, a three-dimensional map of a Cervo Valley small area is plot in Python. According to it, it is possible to check the accuracy of realization of the new shape files.

3.3.1.1. Main script

This script is named *Add Elevation to Shapefile.* [54]

Described below the two functions of the first part of the script.
A first function named *sample_raster* is used to sample the raster along a geometry. This geometry is the one of the 2D shape files. Starting from the raster and the geometry in input, the function returns the raster values correspondent to the input geometry.

```
# Function to sample the raster along a geometry
def sample_raster(raster, geom):
    # Transform the geometry into a boolean matrix (mask)
    mask = geometry_mask([geom], out_shape=raster.shape, transform=raster.transform, invert=False)
    # Sample the raster using the mask
    values = raster.read(1, masked=True)
    sampled_values = values[mask]
    return sampled_values
```

The second one overlaps the shape files to the raster one. Then, it uses the sampling function to sample the raster according to the different shape files geometry. Furthermore, it calculates the average altitudes for every raster geometry and gives them to the shape files as new attribute.

```
# Function to assign elevations to a shapefile
def assign_elevations(shapefile_path, raster):
    # Load the shapefile into a GeoDataFrame
    gdf = gpd.read_file(shapefile_path)

    # Sample the raster along the geometries of the shapefile
    elevations = []
    for idx, row in gdf.iterrows(): # Iteration through the GeoDataFrame rows
        geom = row['geometry'] # Extract the geometry from the current row
        sampled_values = sample_raster(raster, geom) # Sample the raster values accordingly to the
extracted geometry
        if len(sampled_values) > 0:
            # Calculate the mean of the sampled values
```

```
            elevation = np.nanmean(sampled_values) # Calculates the mean value of the sample values without NaN
            elevations.append(elevation) # Add the calculated elevation in the list 'elevation'
        else:
            elevations.append(np.nan) # Add a NaN (=Not a Number -> missing value or not valid) to the list 'elevation'

    # Add the elevations to the shapefile dataframe
    gdf['elevation'] = elevations

    # Save the new shapefile with the assigned elevations
    output_shapefile_path = os.path.splitext(shapefile_path)[0] + '_with_elevations.shp' # Creates the path of the new file in the Shapefile format and with the assigned elevations
    gdf.to_file(output_shapefile_path) # Save the GeoDataFrame as a new Shapefile

    print(f"Elevation assignment for {shapefile_path} completed and file saved successfully.")
```

3.3.1.2. *Check shape files elevation*

Afterwards, it is possible to plot in 3D the shape files overlapped to the raster one. In this case, a small part of the Cervo Valley is used to limit the script file dimensions. In particular, the Zumaglia municipality area is used. It represents a small area of the Valley, but at the same time in this surface the raster elevation is different point by point. In addition, a good number of streets and buildings are present. Indeed, no green areas or hydrographic networks are included in the plot. This is only due to the will of limitation of the file dimensions. The script is named *Check Shapefile Elevation*. [55]

A new library is used in this case: plotly.graph. It is an interactive, Open-Source, and browser-based graphing library for Python. It contains more than 30 chart types, including scientific charts, 3D graphs, statistical charts and so on. [56]

The 3D plot is provided in Figure 80.

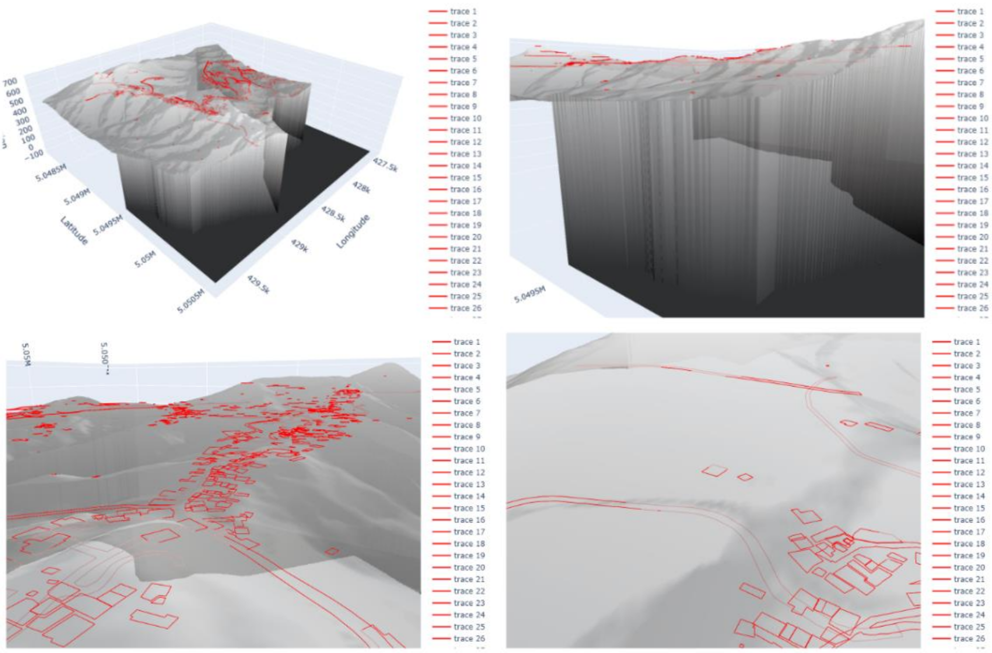

Figure 80. The 3D Python plot representation.

Looking at the picture, it is noticeable a small error in the elevation shape files. In some cases, the street or the building does not perfectly suit the raster slope. This is due to the way of realization of the main Python script. Indeed, the function *assign_elevations* calculates the average altitude of each raster geometry and assign it to the shape files as new attribute.

Even if the error is limited compared to all the Cervo Valley shape files, in a future possible application of the script, it could be useful to improve it and further limit the spreading of this error.

3.3.2. Arpa Piemonte API calls: create a new pop-up for the 3D maps

In the 3D map the dynamic precipitation information is introduced in the form of pop-up as already described for the 2D maps.

This is done after the qgis2threejs plugin export of the two maps (the whole Cervo Valley map and the Piedicavallo area).

The same considerations done in *section 2.3.3. ARPA Piemonte API calls: create a new pop-up for the 2D maps* are still valid. The files realized are the same: a Python script able to make the API call to the ARPA Piemonte website through the GET method; the Chart JavaScript file representing the library necessary for the realization of the graph; the Pluviometer JavaScript file to activate the Python service in its virtual server and connect its response to the HTML script of the 3D map.

However, some small variations in the management of these files are performed in this case. The biggest one represents the implementation of the Pluviometer JavaScript file into the Qgis2threejs one following described.

3.3.2.1. The Python script to make the API request

The general purpose of the Python script – named *PluviometerAPI* [(45)] – is to consider the real-time day and refer it to a year before (from 2024 to 2023); create a new virtual server without the CORS mechanism; make the API call with the converted date and activate the debug modality.

The first step of the script regards the realization of the virtual server by using the *flask* library and by removing the Same Origin Policy de-activating the CORS mechanism.

In terms of days, the same considerations are done. Therefore, the dynamic data are related to the past year, but they are considered as real-time information. Indeed, the script takes three different days: the actual day referred to a year before, and the two previous days with respect to that date. In that way, the pop-up shows a graph with the precipitations of these three selected days.

This file is the same adopted for the realization of the 2D web map.

3.3.2.2. The JavaScript API call database

The second step for the realization of the web map pop-up is made in JavaScript. In this case, one JavaScript file is realized – *Chart* – and one already created by the QGIS plugin – *Qgis2threejs* – is modified.

The first one named *Chart* [(46)] is the same JavaScript library used in the 2D maps and already programmed by third parties. [(47)] This is used to realize the pop-up graph and its file is placed in the JS folder of the 3D exported map.

For what concerns the second one – *Qgis2threejs* [(57)] – it is already created by the QGIS plugin and then modified. In this case, the Pluviometer JavaScript file of

section 2.3.3.5. Creation of JavaScript API call database is directly implemented here. Therefore, the GET request to the Python service of the virtual server is done from the Qgis2threejs file. This request uses again the pluviometer parameters *fk_id_punto_misura_meteo* – that represents the identification parameter of each pluviometer – and *location* that considers the pluviometer location.
In addition, the graph is hidden when the clicks are done in another point. In that way, it is avoided the overlap among different graphs.
Then, another modification is related to the API response and the graph creation.

In the second part of the script, a function for the realization of the graph with the specific API data is used. Here there is the connection between the two JavaScript files: *Chart* and *Qgis2threejs*.

All these modifications are findable by making the internal research of the script and by digiting the comment *Add*. They are anyway showed below.

The first modification is related to the graph hidden to avoid overlapped showed data.

```
// Add: Hide the graph to avoid overlapped data
    document.getElementById("canvas-container").innerHTML = "";
```

The second modification regards the introduction of the API call response in the graph.

```
// Add: API call and graph response
    // Create the canvas from zero to avoid overlaps
    document.getElementById("canvas-container").innerHTML =
      '<canvas id="PLUVIOMETER"></canvas>';
    switch (layer.properties.name) {
      case "PIEDICAVALLO_Pluviometer":
        getPtotDataForDate("PIE-002095-900", "PIEDICAVALLO").then(
          (response) => {
            if (response != null) {
              // Save the response from API call
              // var responseData = response;
              // Method that created the graph starting from the response
              plotPtotDataForDate(response);
            }
          }
        );
        break;
      case "BIELLA_Pluviometer":
        getPtotDataForDate("PIE-002012-901", "BIELLA").then((response) => {
          if (response != null) {
            // Save the response from API call
            // var responseData = response;
            // Method that created the graph starting from the response
            plotPtotDataForDate(response);
          }
        });
        break;
```

```
            default:
              // Clean the canvas in case other points are selected
              document.getElementById("canvas-container").innerHTML = "";
              break;
          }
```

The last one represents the introduction of the Pluviometer JavaScript file directly in the Qgisthreejs one. It represents the part of the script that contacts the service of the Python virtual server.

```
// Add: The Pluviometer.js file used for the 2D web map is here inserted
// Function that obtain the precipitation data for a set day
async function getPtotDataForDate(fk_id_punto_misura_meteo, location) {
  // API call to Python virtual server by using fk_id_punto_misura_meteo and location with GET method
  try {
    const response = await fetch(
      `http://127.0.0.1:5000/get_pluviometer?` + // This is the server of the map
       new URLSearchParams({ // This is a JavaScript class able to work with URL links. In this case it
considers the following two specific parameters
        fk_id_punto_misura_meteo, // Identification code of the pluviometer (Biella or Piedicavallo)
        location, // Name of the pluviometer location (Biella or Piedicavallo)
       }),
      { method: "GET" }
    );
    // Save the response and converts it into a JSON object. This conversion is necessary to make possible
the interpretation of the data into the JS
    const res = JSON.parse((await response.text()).toString());
    if (res.data.results) { // res should have an attribute 'data' that should have an attribute 'results' in the
API call
      // If a response is available, I give it to the function caller
      return res;
    } else {
      // No response = error
      console.log(`No data founded`);
      return null;
    }
  } catch (error) {
    // Service error = error
    console.error("Error during the API call:", error);
    return null;
  }
}
```

3.3.2.3. Modification of HTML script for the web (3D)

Once all the preparation files are ready, the modification of the HTML script representing the web maps is modified. In these terms, all the files and modifications of the two web maps – Cervo Valley and Piedicavallo – are the same.

Again, the HTML scripts named *3D Cervo Valley Web Map* [(58)] and 3D *Piedicavallo Web Map* [(59)] are only present in the GitHub account due to their dimensions. The modification is performed in the points where the comment */* Add */* is placed. By making internal research and digiting the previous comment, the script shows the variation. For completeness, it is anyway described.

```
<!-- Add canvas where the graph is showed -->
<div id="canvas-container">
<canvas id="PLUVIOMETER"></canvas>
</div>
```

The maps are now ready to be published in the web. In the following paragraphs, a deep representation of them is provided.

3.4. 3D Map: ready for the web

In this chapter, the representative pictures of the maps are provided. In addition, by clicking on the GitHub account, a representative video is present. (60)

3.4.1. 3D Cervo Valley web map

The whole Cervo Valley is three-dimensionally represented here. Some overlapping errors are visible, but they are only visualization problems.

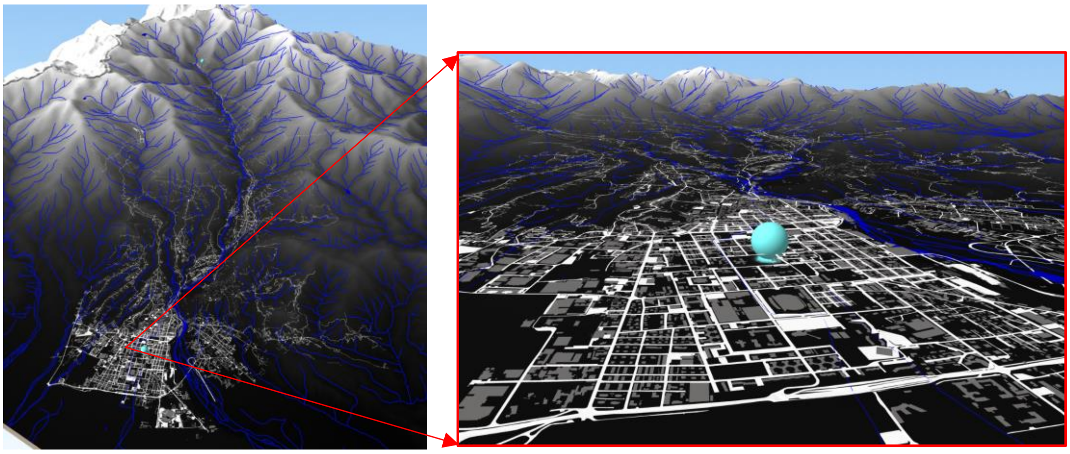

Figure 81. A general representation of the 3D Cervo Valley web map and zoom in Biella municipality. The light blue sphere represents the Biella pluviometer.

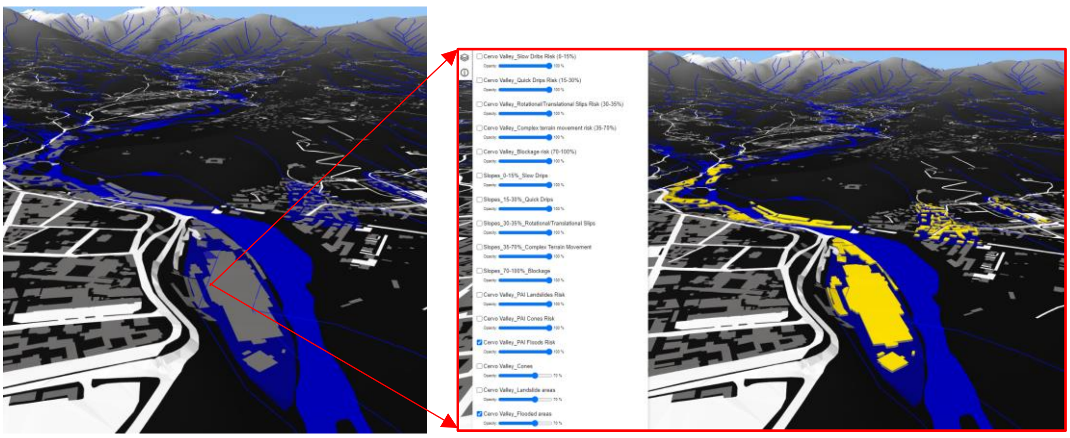

Figure 82. Some flooded areas in Biella municipality. Structures and infrastructures at flood risks in yellow.

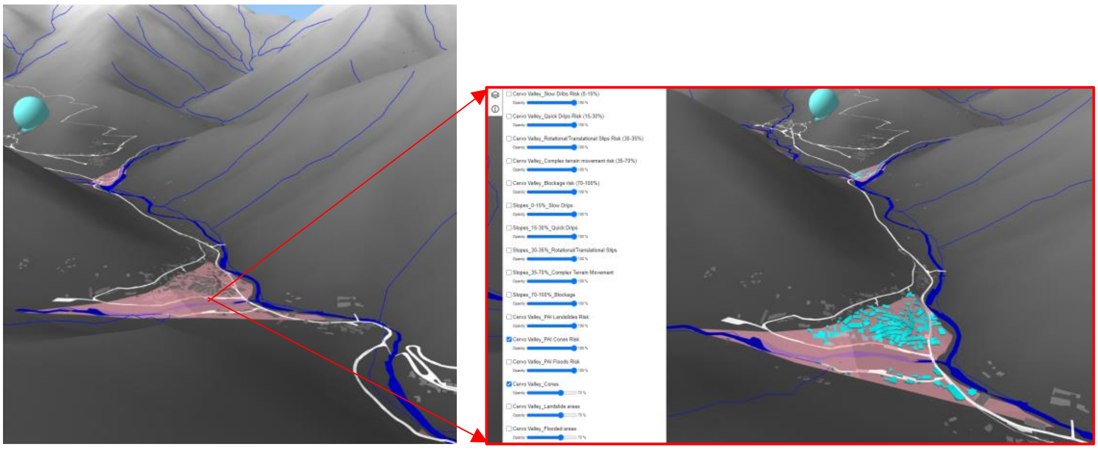

Figure 83. Cone areas in Rosazza municipality. Structures and infrastructures at cone risks in light blue.

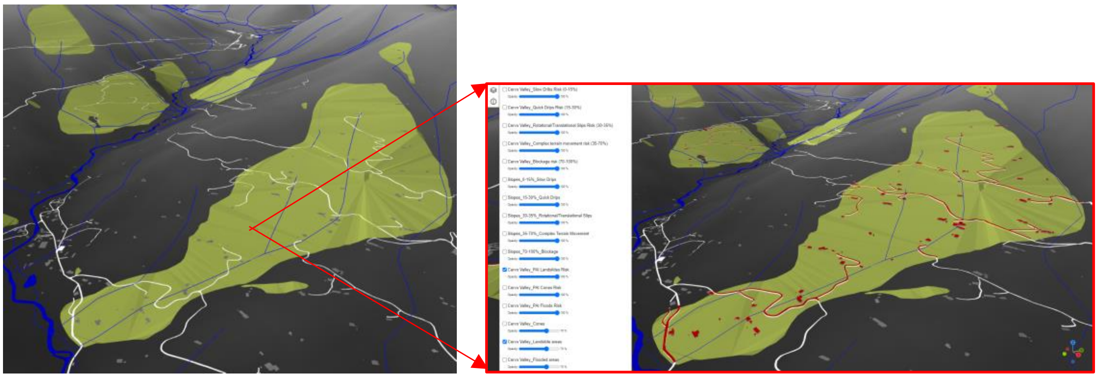

Figure 84. Landslide areas in Pralungo municipality. Structures and infrastructures at landslide risks in red.

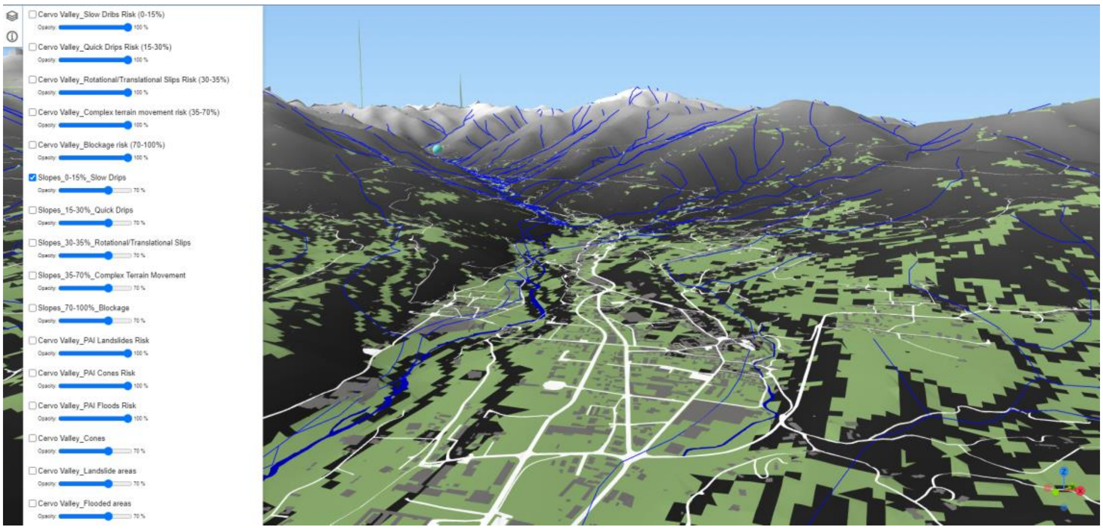

Figure 85. Slope terrain percentage between 0 and 15%.

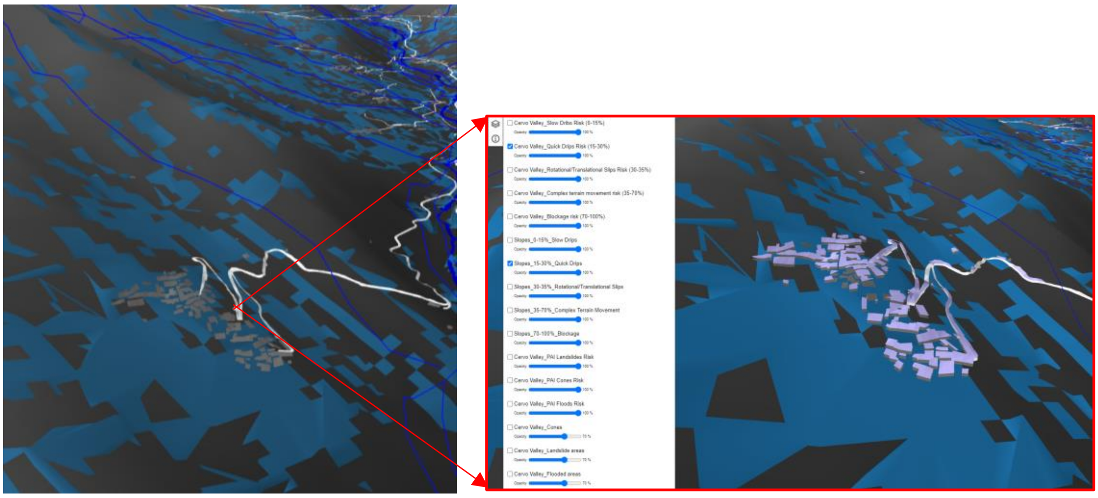

Figure 86. *Slope terrain percentage between 15 and 30%. Streets and buildings at risk of quick drips (15-30%) in pink.*

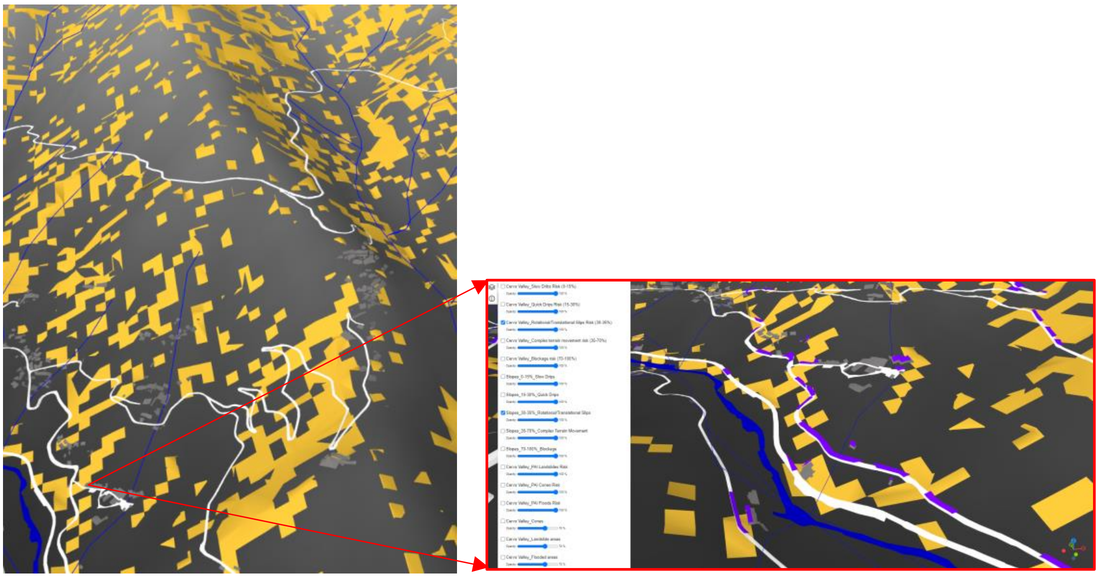

Figure 87. *Slope terrain percentage between 30 and 35%. Streets and buildings at risk of rotational/translational slips (30-35%) in purple.*

Figure 88. *Slope terrain percentage between 35 and 70%. Streets and buildings at risk of complex terrain movements (35-70%) in red.*

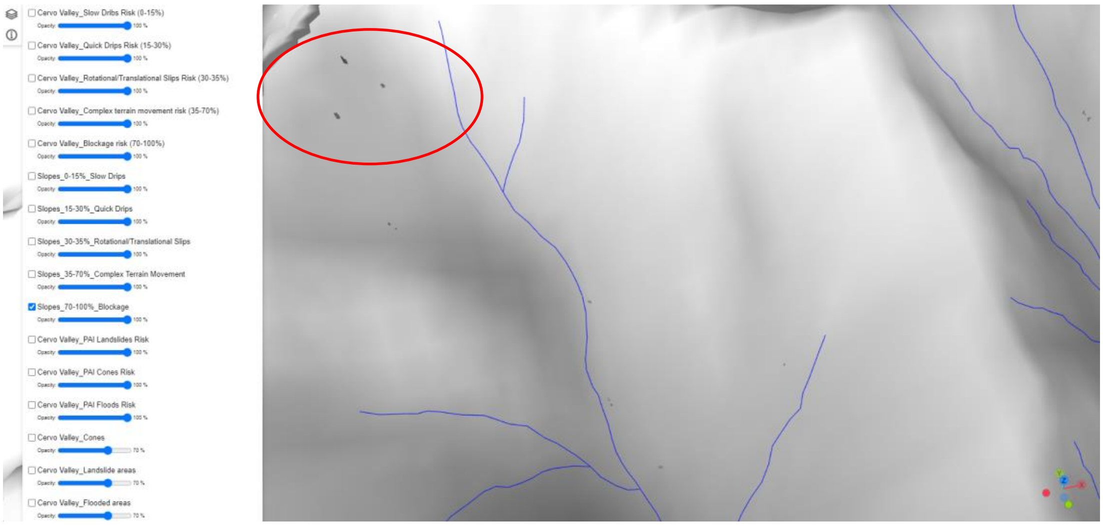

Figure 89. Slope terrain percentage between 70 and 100%.

3.4.2. 3D Piedicavallo web map

This map has the final purpose of creating a smaller and faster 3D map once loaded in the browser. Again, some exporting errors are present and they are properly defined in *section 5.5 qgis2threejs: 3D map export*.

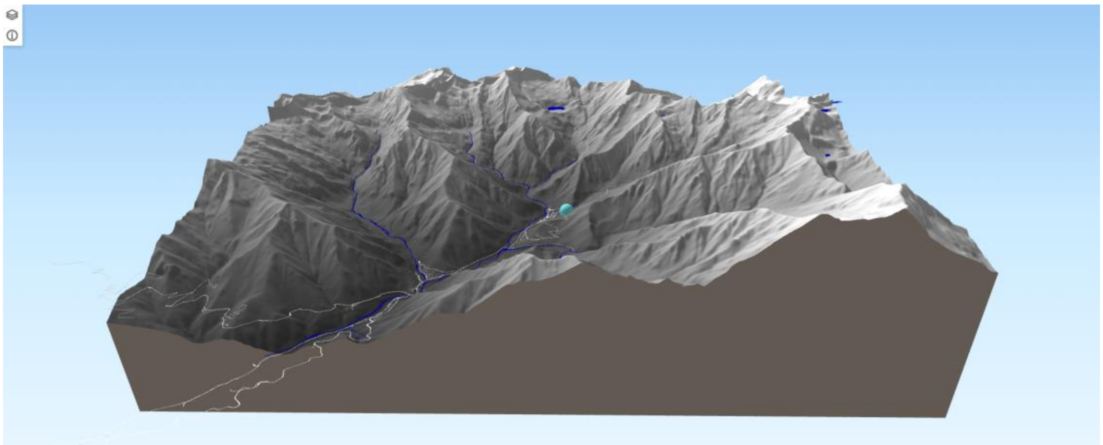

Figure 90. 3D Piedicavallo municipality area.

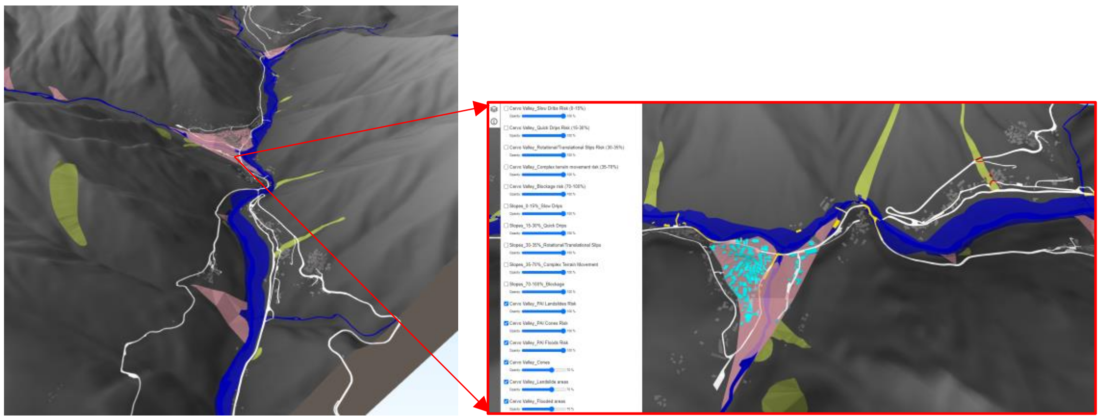

Figure 91. Flooded areas, cones, and landslide areas. Structures and infrastructures at risk floods (yellow), cones (light blue), and landslides (red).

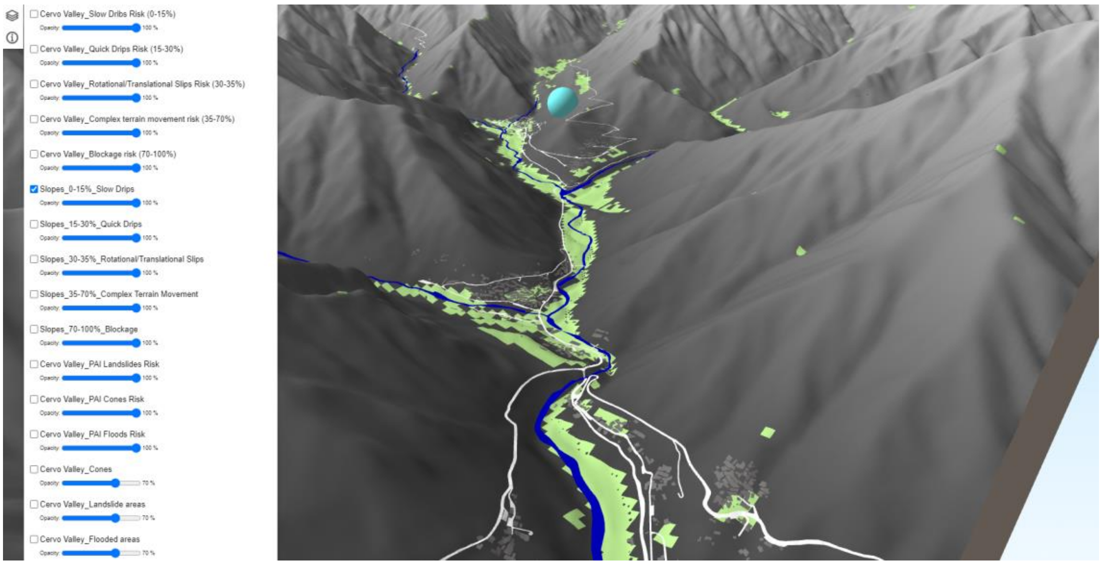

Figure 92. Terrain slope between 0 and 15%.

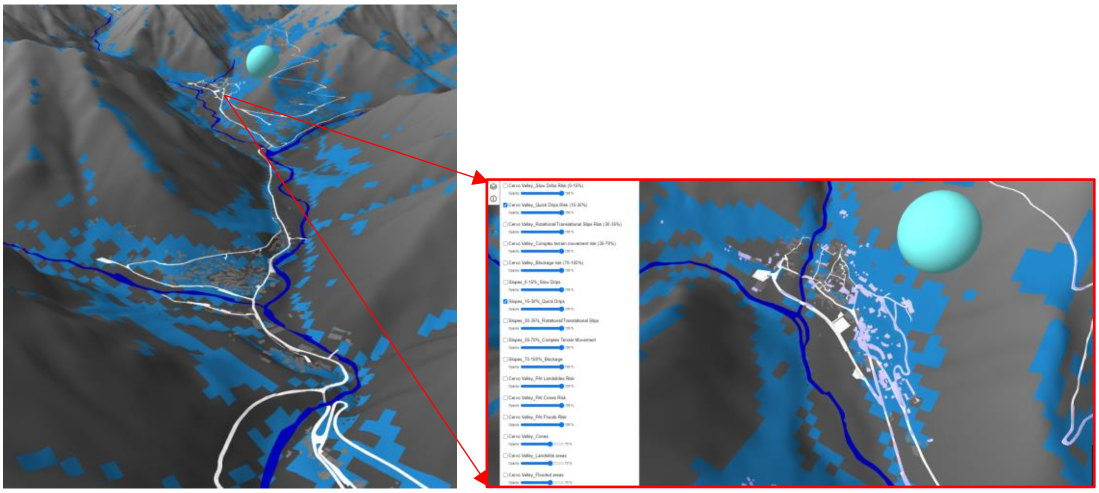

Figure 93. Streets and buildings at risk of quick drips (slope terrain 15-30%).

Figure 94. Streets and buildings at risk of rotational/translational slips (slope terrain 30-35%).

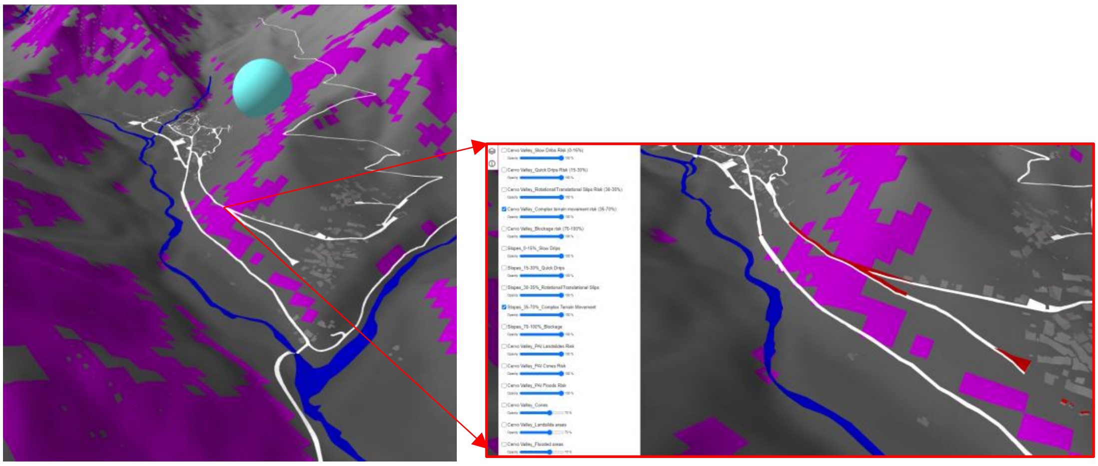

Figure 95. Streets and buildings at risk of complex terrain movements (slope terrain 35-70%).

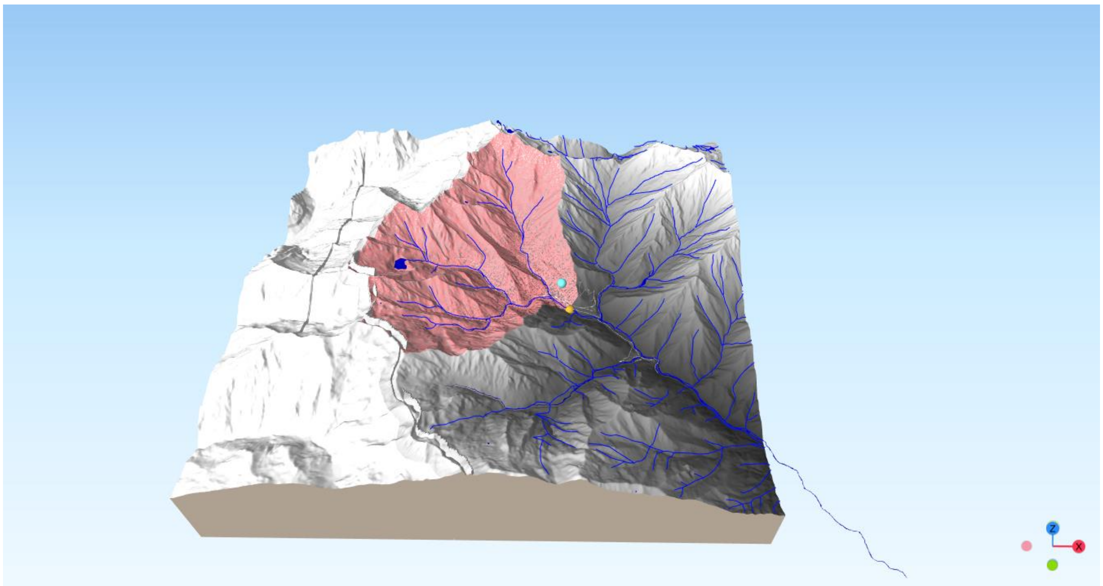

Figure 96. Piedicavallo basin area.

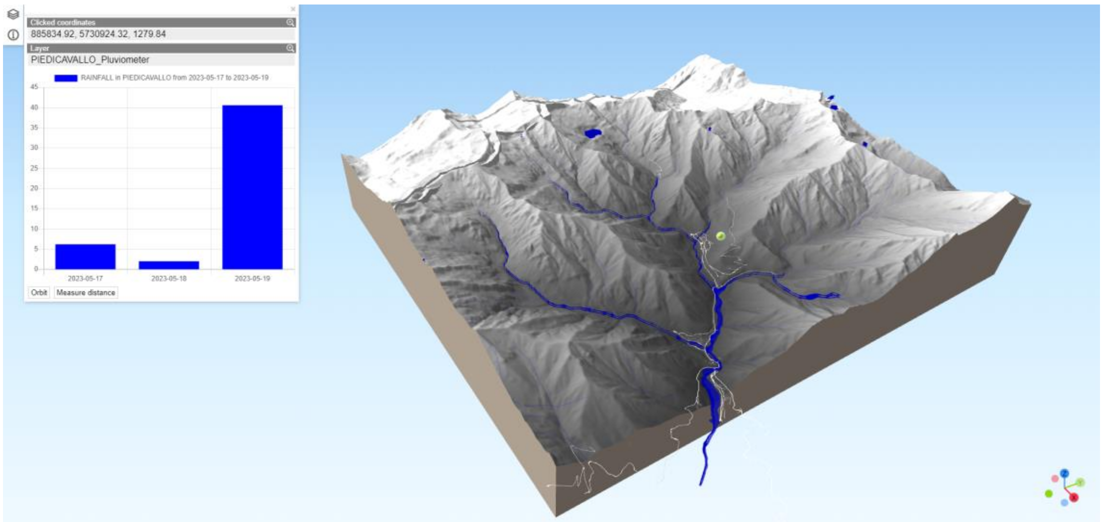

Figure 97. Representation of the dynamic information from Piedicavallo pluviometer.

4. Comments on the infrastructures of interest

Two historically and culturally fundamental infrastructures for the Cervo Valley region are considered useful to confirm the utility of the maps for the hydrogeological risk analysis.

To carry out the hydrogeological analysis in its completeness some additional information like the amount of infiltrated water into the ground; the water flow in springs and/or artesian wells; the water losses to the bed of non-impermeable layers; and the amount of water directly withdrawn from the aquifer (e.g., extraction wells) should be considered. [61] Therefore, only general comments can be performed at this point of the study.

In any case, the two infrastructures are useful to comprehend the variability of risks in this Valley and understand the importance of a proper monitoring and management plan.

4.1. Saint Giovanni Andorno Sanctuary

As already mentioned, the Saint Giovanni Andorno Sanctuary [Figure 98. and Figure 99.] is placed in Campiglia Cervo Municipality, therefore in correspondence with the final part of the Upper Valley.

Figure 98. The 2D representation of the Saint Giovanni Andorno Sanctuary.

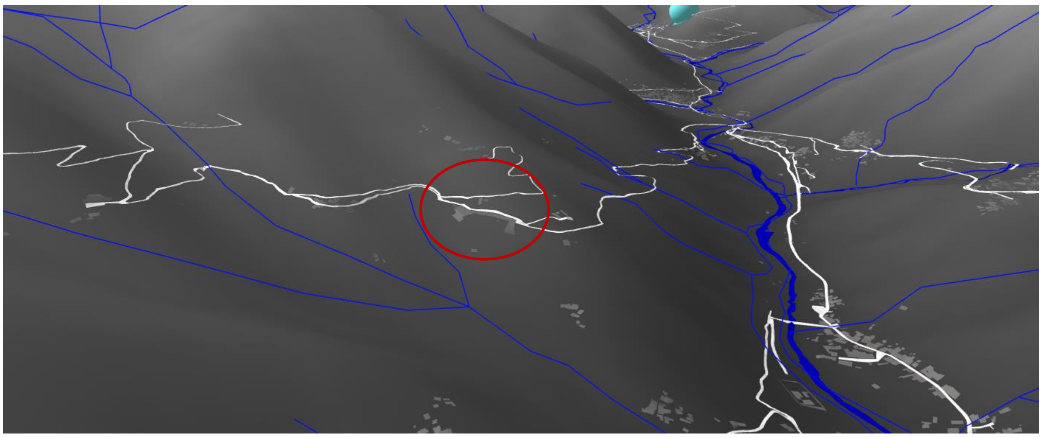

Figure 99. The 3D representation of the Saint Giovanni Andorno Sanctuary.

In this area, the biggest problem is related to the terrain slope. Indeed, by selecting the different layers representing the inclination of the terrain, it is noticeable the combination of different landslide risks in the same area [Figure 100.].

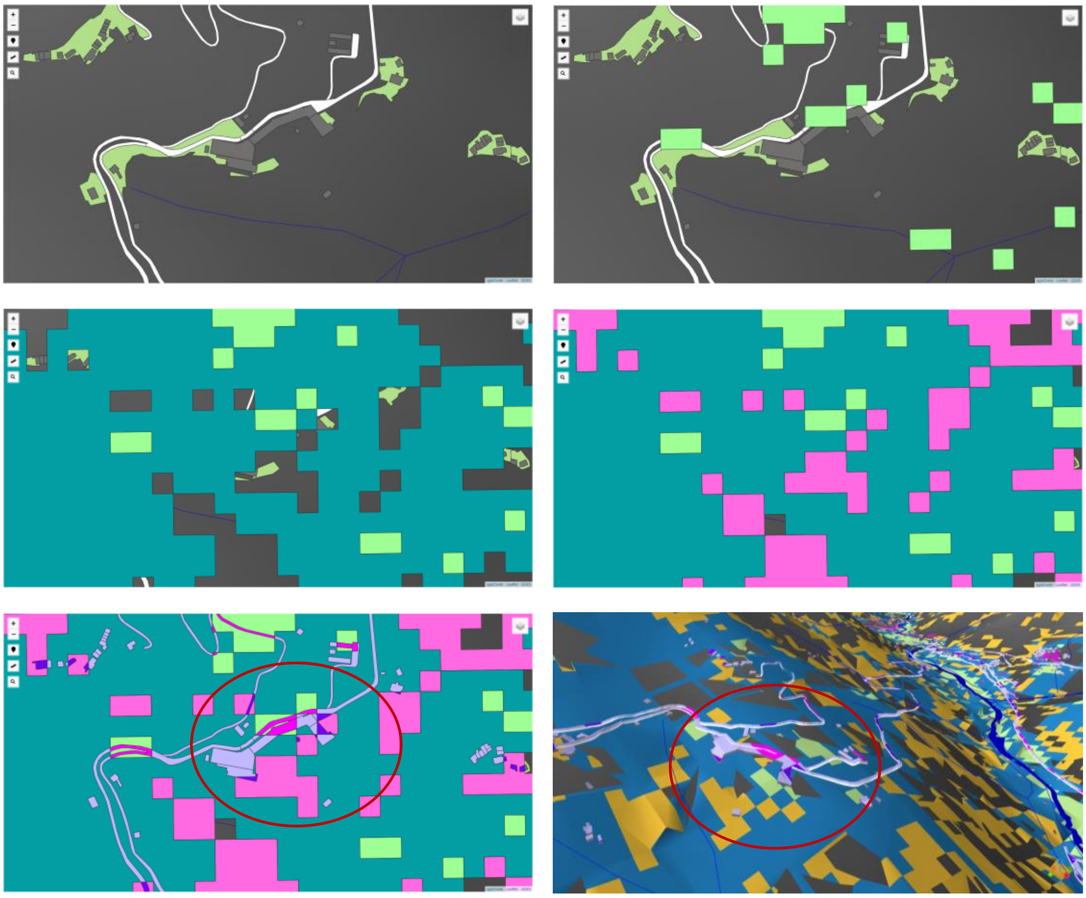

Figure 100. The 2D and 3D representation of the percentages of terrain slopes. From left to right: slow drips 0-15%; quick drips 15-30%; rotational/translational slips 30-35%; the building in 2D and 3D at risk of different landslides.

In these regards, an additional consideration should be done. Despite the good precision of the digital terrain model, this is not enough to represent a vertical terrain slope placed in the backside of the infrastructure. In this position, a terrain slope higher than 70% is present but looking at the previous image [Figure 100.] it is not showed in the map. This is due to the height of the terrain in this location. This is not higher than 5 meters and therefore the DTM cannot represent it. A representative image of the terrain slope is depicted in Figure 101.

Figure 101. Top view and street view of the terrain slope from Google Maps.

Furthermore, looking at Figure 98. and Figure 99. it is noticeable the presence of a small stream branch represented according to the historical hydrographic network downloaded from the Geoportale Piemonte. By making a comparison with Google Maps – a geographic internet service developed from Google [62] – this small stream is not visible today [Figure 102.]. At the same time, it is clearly noticeable the stream branch underneath it. It corresponds to a dried-up stream that could activate during rainy days. Indeed, it happened during the flooding event in October 2020.

It for sure influences both the hydrographic and the hydrologic situation of the area, with a possible influence on landslides risks of different nature.

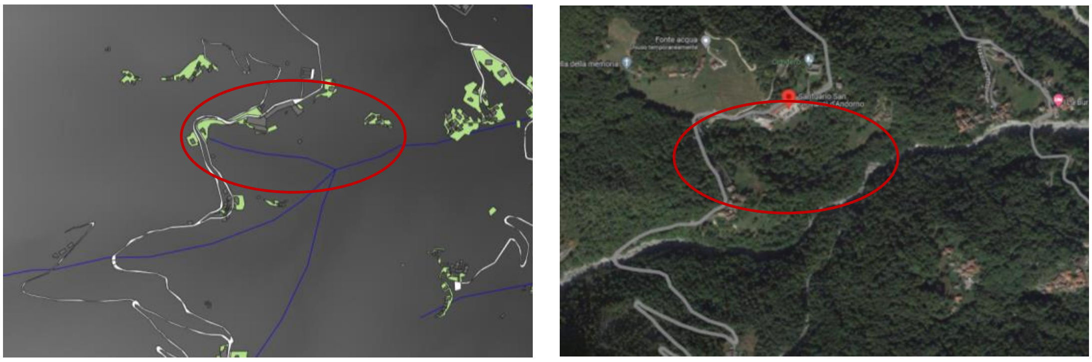

Figure 102. Comparison between the 2D web map and Google Maps in the Sanctuary representation.

In conclusion, by looking – for completeness of analysis – at the static information provided by the PAI associated layers, since no cones/floods/landslides areas are showed, no specific comments are necessary.

4.2. Ex-wool mill Maurizio Sella

For what concerns the ex-wool mill Maurizio Sella, as already described in the first paragraphs of the thesis work, the structure is placed in Biella, next to the end of the Cervo Valley region [Figure 103. and Figure 104.].

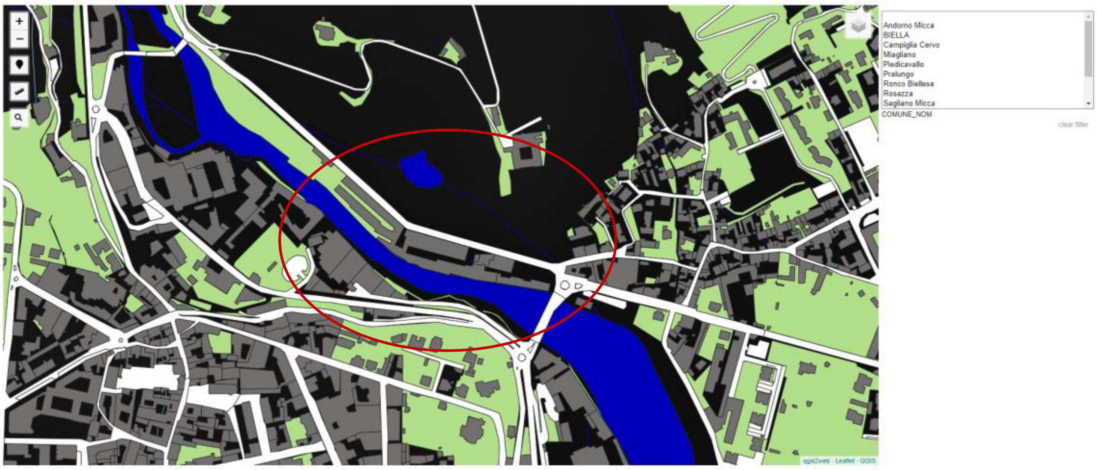

Figure 103. The 2D representation of the ex-wool mill Maurizio Sella.

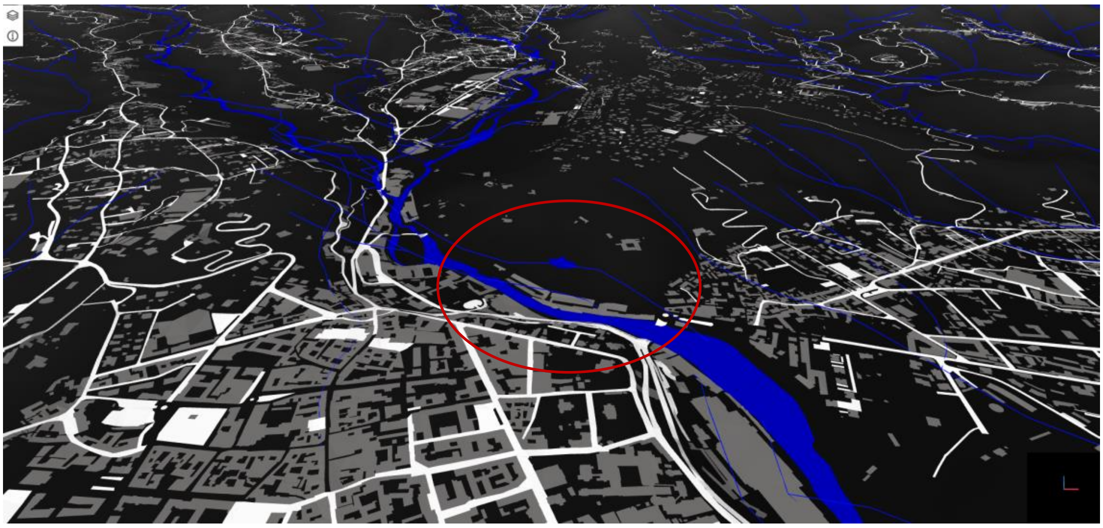

Figure 104. The 3D representation of the ex-wool mill Maurizio Sella.

Because of the vicinity of the building with the Cervo Stream, it is plausible that the biggest problem in this case is related to flooding events [Figure 105.].

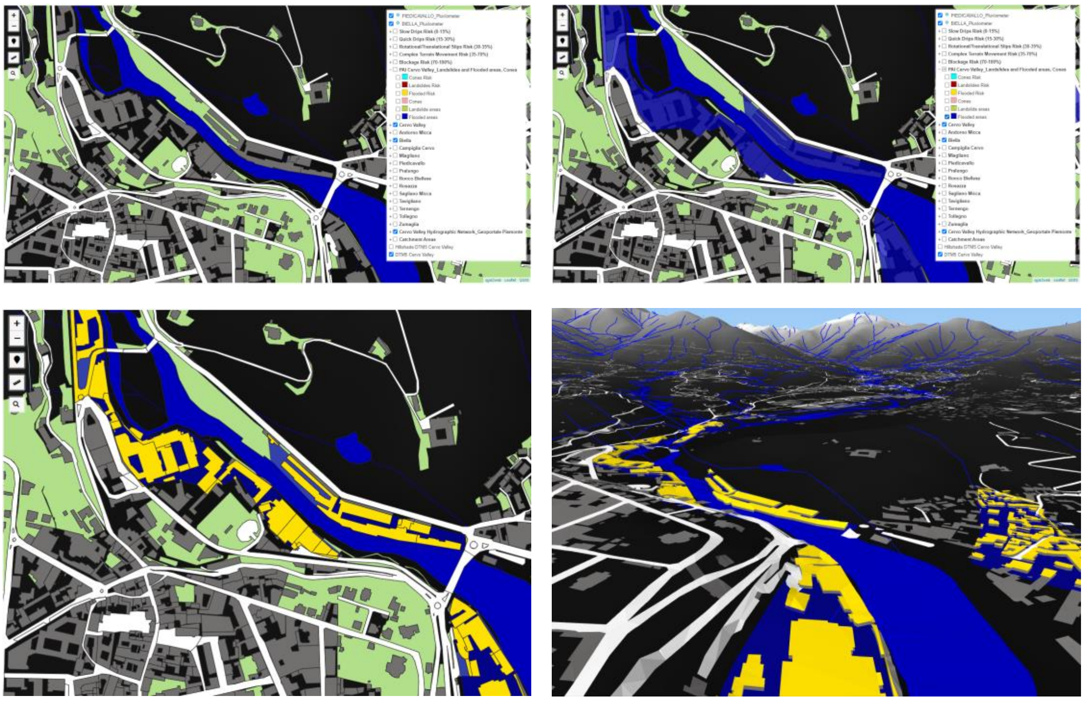

Figure 105. The 2D and 3D representation of the floods risk according to Annex 2 of PAI.

Even if according to the PAI document the return period of this flooding event is 500 years, it is useful to consider the vicinity of the infrastructure with the stream and actuate a proper management plan.

5. Software interoperability

In this section, a brief description of the investigation performed in terms of software interoperability among them is carried out.

At the beginning of the thesis work, some different software programs are cited as applicable to create the user-friendly and interactive maps. None of them presents a full interoperability with QGIS. More in detail, the QGIS project cannot be exported and directly imported in ArcGIS pro, Cesium, Mapbox or Infraworks without losing information. Indeed, the QGIS project can only be directly exported as an image, as a PDF and in DWG or DXF file formats.

In ArcGIS Pro the data format allowed are the shape files, GeoJSON, KML and GeoTIFF.
A possible connection between the two software can be defined by the export of both vectorial and raster data in the GeoPackage format. This is an open platform-independent and standards-based data format for geographic information systems built as a set of conventions over an SQLite database. (63)
To store all the data in a unique file, a plugin is necessary and it is called QConsolidate. Even if it has not been directly tested during this case study, it is used to copy raster files and convert vector layers to GeoPakage or ESRI ShapeFile storing all the project files in a zip one.
In these terms, some considerations are anyway necessary. Firstly, the symbology supported in QGIS is not always supported in ArcGIS Pro, therefore some layer styles and colors can be lost during the sharing process. Information about metadata and print layouts of the QGIS project can be lost at all after the import of the GeoPackage file.
On the opposite side, from ArcGIS pro to QGIS, things are easier. The GeoPackage file is directly exportable from the first software and no additional plugins are necessary.
Both the software programs support the Python language; therefore, the different scripts are perfectly interchangeable, and they can be used to automatize the export process.

For what concerns Mapbox, the interoperability between the software is limited to the possibility of automatic sharing of vectorial data in the GeoJSON format. (64) This is an open standard format designed for representing simple geographical features. In this case, the limit is also related to the necessity of exporting and importing the layers one-by-one.
For what concerns the shape file format, it must be pre-processed creating a zip file of the vectorial data and then imported in Mapbox. A variation or loss of information in terms of symbology and pop-ups may happens. In terms of TIFF, again a pre-processing of the files should be performed. The raster file should be geo-referenced before the import in Mapbox.
The same problems are present in the opposite direction: from Mapbox to QGIS. Therefore, the interoperability is considered almost null.

In Cesium no shape files can be imported. The logic thread is always the same: it is not possible a direct export of QGIS project in Cesium software. All the layers should be imported one-by-one.
An additional problem is represented by the possibility of conversion and export of 3D data from QGIS to Cesium. In this case, this process is complex and requires additional tool to maintain the data integrity. One of them is the so-called plugin Cesium ion. By the creation of a Cesium token and the activation of the plugin, it is

possible to make a direct connection between the two software programs and use it to show a three-dimensional perspective in QGIS. The Cesium map is directly imported as a layer in QGIS and used in the same way of the vectorial data. Therefore, the interoperability is higher from Cesium to QGIS than vice versa.

The interoperability between QGIS and InfraWorks is again quite low. The possibility of sharing vectorial and raster format does not include the possibility of sharing the whole QGIS project. This means that in InfraWorks the project should be restarted from the beginning. The managed shape files imported in QGIS are re-imported from zero in Infraworks. Therefore, a concept of full non-interoperability is nowadays defined.

Despite this low interoperability among the different software, a notable strength of them is related to the possibility of easily import already modified data from QGIS. This avoid the necessity of starting from the beginning whenever there is a variation in the software used and reduces the time required for the modification and management of the data.

Depicted below, a graphic representation of the interoperability study [Figure 106.].

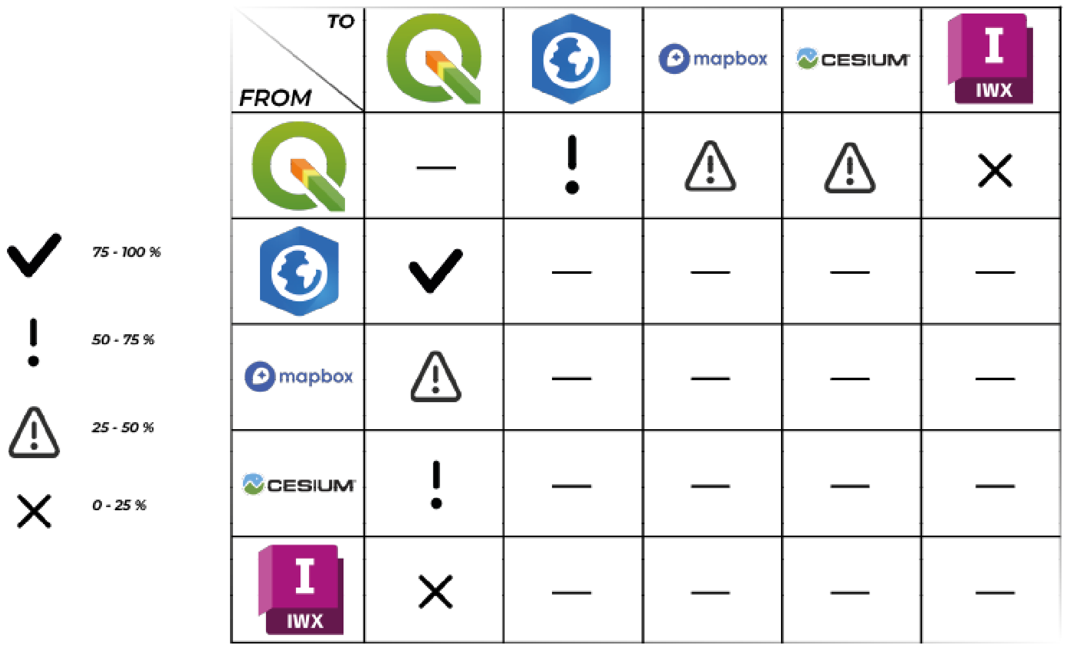

Figure 106. A graphic representation of the interoperability among the different software programs studied.

In this thesis context, only the interoperability between the different software programs considering QGIS as the base of investigation is performed. That is why the interoperability among the other software programs between each other's is not represented in the graphic.

6. Potentialities and criticalities of each tool

In this chapter, each QGIS tool is analyzed to provide a general overview of their positive and negative aspects.

Since the Python scripts are created from the beginning and to meet specific requirements, it is not necessary to consider either their potentiality or criticality. At the same time, in the consideration of their use for future possible application, their optimization could be useful.

6.1. Hill-shade

The hill-shade QGIS tool allows to represent shading effects on the raster files. In this way, a clear representation of the raster third dimension is provided. It allows to personalize the final output, by manipulating parameters like the light altitude, the shade intensity etc.

The hill-shaded maps can be integrated with other analysis tools enhancing their utility during the geo-spatial data management process. They can also be implemented in 3D maps.

Among the other limitations, the most important one is related to the quality of the DTM adopted for the hill-shade process. The lower the DTM precision, the lower the quality output after processing.
Then, a small variation of the light parameters and characteristics can produce a huge impact on the result.
In addition, the bigger the dimensions of the raster file, the higher the computational time required.

6.2. Union, intersection, difference, and clip

6.2.1. Union

Potentialities

- Different layers are joined together simplifying the data analysis in QGIS project.
- It is useful in joining different information from various layers increasing the information available in the new dataset.

Criticalities

- Overlapped areas are duplicated, increasing the time required for the correct management of the layers.
- To efficiently realize the union of more than two layers, the process should be done one-by-one.

6.2.2. Intersection

Potentialities

- It allows the determination of common areas with different layers.
- It enhances the understanding of the geographic data providing new features based on intersected areas among different input layers.

Criticalities

- A loss of information can be obtained; therefore, a careful management of the input data should be performed.
- It is complex when more than one layers are managed together. To simplify the process, it is again necessary to work one-by-one.

6.2.3. Difference

Potentialities

- It is useful to represent and analyze the spatial variations between two different geographic datasets.
- It is used to remove useless features from a specific dataset.

Criticality

- The layer orientation can have an influence on the results.

6.2.4. Clip

Potentialities

- It allows to clip an input layer starting from a specific geometry.
- It is useful to perform specific analysis in determined geographical areas.

Criticalities

- Loss of information can be done.
- Some errors can be obtained in the case of complex geometries management.

6.3. Slopes

In this case study, for the calculation and analysis of the terrain slopes, a specific Python script is used. Since this is not the unique way of slope calculation, a comment on the QGIS tool is considered necessary.

To properly understand the difference between the tools, the arithmetical concept of slope must be considered. There are two different ways of slope calculation: the surface gradient and the tangent of the angle.

In the first case the percentage of slope is calculated as the surface gradient.

$$slope(\%) = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \cdot 100$$

The gradient represents the altitude variation with respect to the horizontal distance of two points. By multiplying it by 100, the slope value assumes a percentage form.

On the opposite, in the second case the slope [Figure 107.] is defined in function of the angle of inclination of the terrain (purple line in the picture). Arithmetically speaking, it is described as:

$$\tan\theta = \frac{opposite\ cathet}{adjacent\ cathet}$$

Where θ represents the angle of the terrain inclination and the two cathects are the horizontal and vertical lengths of the slope.

Then, the terrain slope is evaluated as a percentage value multiplying the tangent of θ by 100.

$$slope(\%) = \tan\theta \cdot 100$$

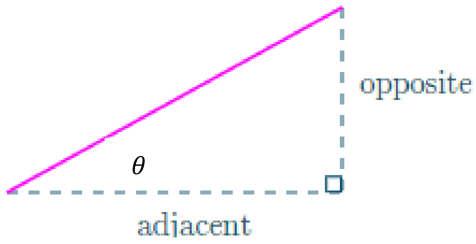

Figure 107. The graphic representation of the slope calculation.

This second procedure is the one adopted by QGIS and following described.

6.3.1. Slopes in QGIS

In QGIS the slope analysis is normally performed by adopting the GDAL tool named *slope*. It takes the DTM raster file in input and it provides the slope calculated output in a TIFF format.

In the dialogue window, it is possible to select the definition of percentage slope instead of the degrees output [Figure 108.].

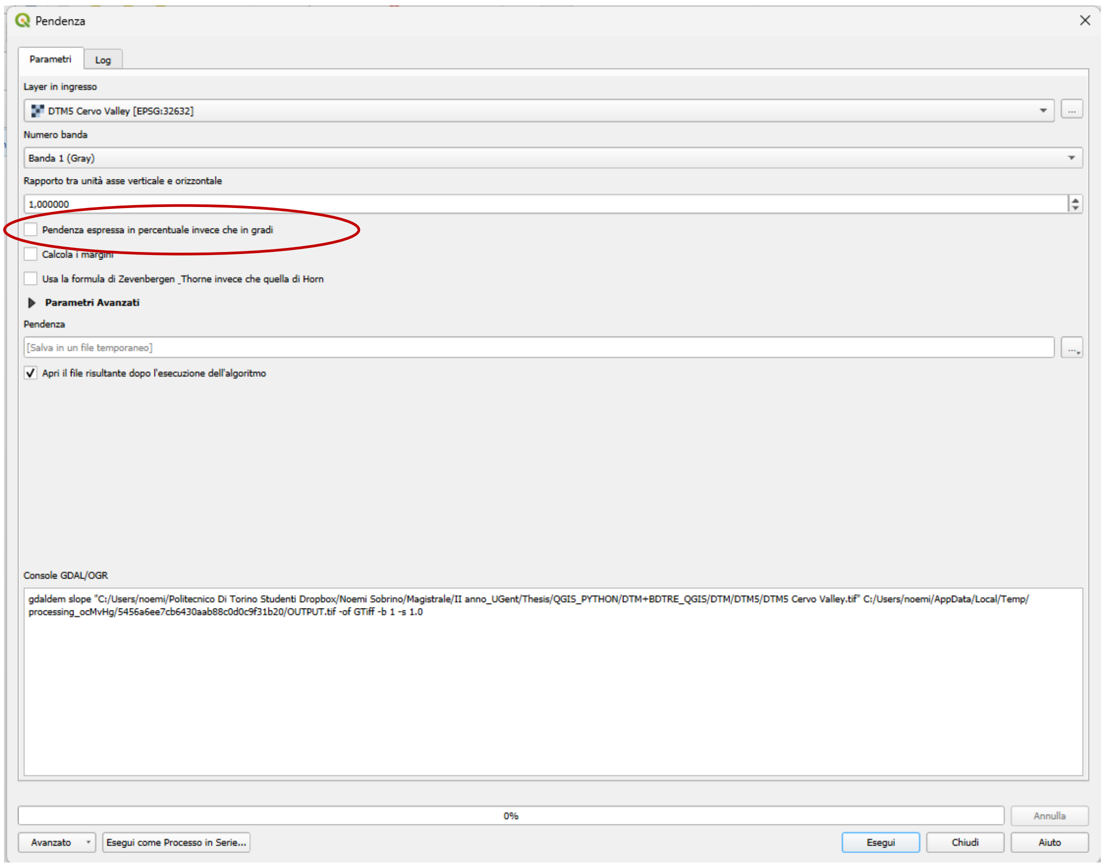

Figure 108. The dialogue window in QGIS-GDAL slope analysis.

After selecting the percentage value and running the tool, the raster output is automatically opened in QGIS. By looking at the values associated with the color band, it is clearly noticeable that they are within a range higher than 0 and 100% [Figure 109.].

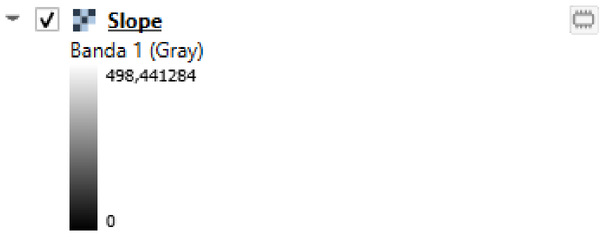

Figure 109. The terrain slope percentage values obtained by using QGIS-GDAL tool.

This is because the tool calculates the terrain slope in degrees by default – therefore as an angle – and then it converts the angle from the tangent. This happens because the angle measures the slope with respect to the horizontal direction. Therefore, it may be higher than 45 degrees (the value that provides a slope of 100%). Consequently, the higher the angle, the higher the percentage value.

Even if this analysis is considered correct, this does not meet the requirements of the maps. In fact, the goal is to create different layers with different slope ranges and graphically analyze the risks correlated to these slopes. With percentages values converted from the angle calculation, the realization of the different ranges of slope and the visual analysis is not easy. That's why the Python script uses the surface gradient calculation and substitute the QGIS tool.

6.4. Drainage area

6.4.1. GRASS process algorithm in QGIS

The GRASS process algorithm is necessary to figure out the definition of drainage areas in the Cervo Valley.

Different commands are used and each of them presents specific positive and negative aspects represented below.

6.4.1.1. r.fill.dir

Potentialities

- It is essential for the DTM processing for hydrogeological analysis.
- It fills the depression areas of a Digital Terrain Model to create a proper terrain surface for the hydrogeologic analysis.
- It can generate a map of the water flows directions based on the terrain topography.

Criticalities

- The precision and quality of filling depends on the DTM precision.
- It can be a time-consuming process in the case of big DTM with high resolutions.
- It can overestimate the filling of depression areas in the DTM modifying the terrain morphology in the most extreme cases.

6.4.1.2. *r.watershed*

Potentialities

- It can make a total hydrogeological analysis. Some of them are the hydrographic basin analysis and water flows directions.
- It determines the water accumulation areas.
- The different results are dependent on the precision of the raster files provided. The higher the precision, the better the result.

Criticalities

- It requires a depression-less DTM, therefore it can be used only after the application of the *r.fill.dir* command.
- The definition of the necessary parameters for this command is often complex and not precise. Indeed, in function of the minimum size of the external watershed basin it is possible to obtain a better or worst result. In addition, this value should be carefully selected. A too low value can lead to the definition of a bigger number of basins with an increment in the computational time. Then, the distinction between total basins and half-basins is harder.
- The computational time is often large, and it highly increases with high-resolution files.

6.4.1.3. *r.stream.extract*

Potentialities

- It identifies and extract the water flows starting from a DTM.
- These data can be used to perform different hydrogeological analysis.
- By the application of different thresholds, the precision of representation may vary.

Criticalities

- Also in this case, the result quality depends on the DTM precision.
- The threshold definition influences a lot the result obtained. The lower the threshold value, the higher the number of detected streams. At the same time, a high value of stream extracted may result a problem in the comprehension of the result.
- It can require a big memory use if adopted in case of big areas and high precisions.

6.4.1.4. *r.water.outlet*

Potentialities

- It identifies and defines a basin area considering a specific outlet point.
- It only uses a depression-less DTM file in input and a specific point. Therefore, it is quite easy to be used.

Criticalities

- The precision of the basin area depends on the DTM resolution. It can lose precision in case of basin areas with low terrain slopes.
- It requires a pre-processing of the DTM, therefore the application of all the different tools previously described.
- An error in the determination of the outlet basin point can lead to a significant errors in the basin area.

6.4.1.5. r.to.vect

Potentialities

- It has the potential to convert raster file in shape ones. According to that, the vectorial data are more adaptable in terms of style changes and tags.
- Thanks to this export, the vectorial data obtained by the raster ones are easily integrable into other vectorial datasets.

Criticalities

- If from one side the polygon precision is higher than that described in the raster since no cells are considered in the polygon, the quality of the raster has the major influence in the result resolution.
- The NoData raster cells should be adequately filtered before the application of this command, otherwise the result can induce into some visualization and analysis errors.

6.5. MMQGIS: merge different layers

In the case study analyzed, the MMQGIS plugin is used to merge different layers.

For what concerns the positive aspects, it has an easy user interface – also adaptable to non-expert users – and it allows to merge different data all at once. In addition, it supports a wide range of union tools guaranteeing a good versatility for the different QGIS applications.

At the same time, problems related to the union of layers with the elevation information are present. Specifically speaking, once it is necessary to merge layers with the third coordinate Z in the attribute field, the plugin provides an error. This is in the form of: 'it is not possible to merge data in the format multi-polygon Z'. This means that since the z-coordinate represents the altitude of the data geometry, it increases the complexity of the data themselves and the plugin is not able to manage it. This leads to a reduction of the plugin flexibility in the case of 3D data and an increment of the time requirement. Indeed, to face up the problem, all the data managed in the case study are merged as polygons in the 2D map and then processed with the Python script to provide them the elevation coordinate.

6.6. qgis2web: 2D map export

The biggest potential of this plugin is related to the possibility of exporting a web map without any pre-requirement in terms of programming knowledge. It is the plugin that automatically generates the HTML files associated with the JavaScript and CSS ones.
Then, it supports the Leaflet JavaScript library, which is one of the most diffuse libraries for the creation of interactive maps.
The graphic representation of the QGIS project stays the same, indeed the plugin tries to exactly represent each layer feature. It is also able to manage both vectorial and raster data increasing its flexibility to different requirements.

On the opposite, the most complex style features of each layer might be unsupported by the Leaflet library. Therefore, a careful selection and management of the layer style must be done.
Then, the bigger the number of present layers, the higher the computational time requirement. Indeed, it is necessary a pre-processing of the present layers to limit them and reduce the computational time.

In conclusion, the web publication of the 2D maps can be effectively achieved using a free and static hosting service like GitHub. The primary procedure involves creating a new GitHub repository, enabling GitHub Pages, and obtaining the URL link for public access. GitHub offers an accessible and user-friendly platform for hosting static content, making it ideal for sharing interactive maps with a wider audience. However, in this case study, this procedure was not performed due to the limitation of the basic GitHub account, which restricts file uploads to a maximum size of 25MB. The exported 2D scene exceeded this size, highlighting a significant constraint for larger projects.
Alternative hosting solutions that accommodate larger file sizes may be necessary. Examples include the upgrade of GitHub, Amazon S3, Google Cloud Storage and Microsoft's Azure Blob Storage. These platforms can effectively support the hosting and distribution of detailed and interactive geographic visualizations online.

6.7. qgis2threejs: 3D map export

This plugin allows to create web maps visualizing geo-spatial data in 3D and to increase the geographic development comprehension. As it also happens for the qgis2web plugin, it is directly integrated into QGIS software and uses all its layer flexibility and potentiality to create the three-dimensional web map.
In addition, the plugin allows to personalize the map in different ways: it is possible to set the scale of visualization; to regulates the light used, but also the materials and other similar configurations.
It supports different geo-spatial data. Among the others, shape files and raster data are fully supported.
It provides different ways of visualization of the three-dimensional map. The 3D viewer template (this is the one used for the case study representation) that loads all the layers when the map is opened. The 3D viewer with dat-gui panel that also allows the regulation of the layer opacity and visualization and the mobile viewer. This latter one represents the model for mobile phones that also uses an experimental Augmented Reality tool. [(65)]

For what concerns the negative aspects, they are mostly related to the memory usage and to the computational time requirement for the export. Indeed, a careful management of the layers should be conducted to avoid crushes during the plugin use. In addition, the higher the precision and definition of the image, the bigger the amount of time required to export it and the bigger the memory usage once the map is run locally.

Some additional errors may be present in the visualization. For example, in correspondence of the empty cells the slope terrain layers present vertical lines that are not supposed to be present. Then, some small visual intersections among overlapped layers are present and they might reduce the comprehension of the map [Figure 110.].

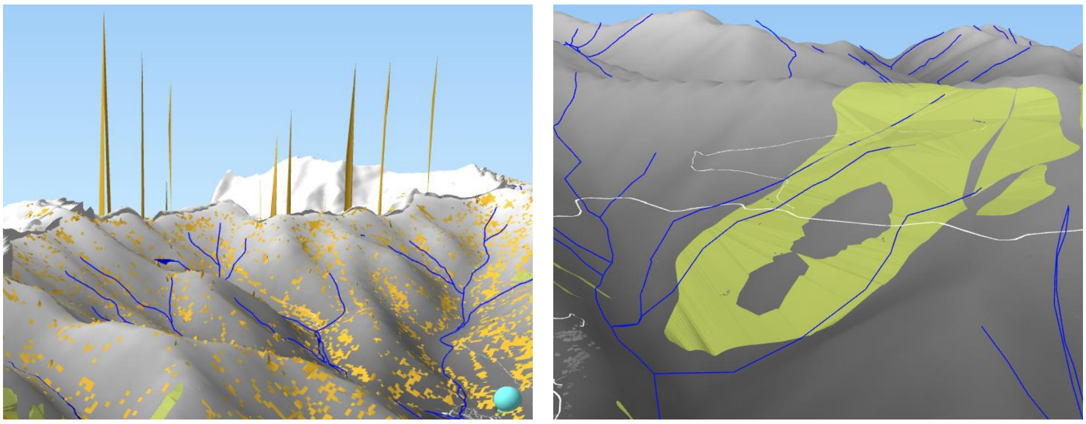

Figure 110. Visual errors in the 3D maps.

As already mentioned for the 2D web map, the web publication of the 3D maps can be effectively achieved using a free and static hosting service like GitHub. The primary procedure involves creating a new GitHub repository, enabling GitHub Pages, and obtaining the URL link for public access. However, also in this case, this procedure was not performed due to the limitation of the basic GitHub account, which restricts file uploads to a maximum size of 25MB. The exported 3D scene exceeded this size, highlighting a significant constraint for larger projects.
Alternative hosting solutions that accommodate larger file sizes may be necessary as already described in *section 6.6 qgis2web: 2D map* export.

7. Possible future applications

7.1. Hydrogeological risk analysis perspective

In the perspective of hydrogeological risk analysis, different possible future applications can be described.

With effective management of both static and dynamic data, the 2D and 3D web maps can be integrated into cadastral environments. This integration facilitates the adoption of comprehensive management plans. Through this system, each municipality can identify building or infrastructure owners and timely inform them about potential risks to their property.

In addition, these maps can be integrated in the use of emergency evacuation systems. By consulting them in real time, it is possible to plan the proper evacuation route for the population in the case of imminent catastrophic events like floods, landslides, and cones.

Then, insurance companies can use them to monitor the territory development and adequate their insurance coverage according to the risks associated with the area of interest. This can lead to a proper risk management also in terms of money invested by the population.

Furthermore, since their realization is done to meet the user-friendly requirements, they can be eventually used to promote sensibilization programs for the population and experts of the institutional departments (fire departments, police ones and so on).

They can also be adopted for a sustainable urban planning. Municipalities can limit the terrain usage if it represents too high risks for both infrastructure and population. This can reduce the damage caused by the hydrogeological catastrophic events and protect the surrounding environment.

7.2. Software perspective

In the software perspective, possible future applications can be related to the height information of the buildings. Indeed, by having a look on the 3D web maps, the buildings are represented as 2D elements. This is because the height information is not included in the shape file attribute layers. Therefore, the implementation of shape files with the building height information included in the attributes can highly improve the graphic and operational management of the map.
At the same time, this is not the only possible three-dimensional additional information to improve the possible future application of the web maps. Other examples include the possibility of introduction in the maps of a BIM model for each relevant structure or infrastructure. However, this might create problems related to the final file dimensions. A possible alternative can be the introduction of one attribute providing a link with an external BIM model. In that way, an additional line in the already present pop-ups will provide the BIM link. By clicking it, the user is also able to easily comprehend the characteristics of the relevant structures and infrastructures.

In addition, nowadays the possibility of exporting the whole QGIS project and import it into another software environment is often not possible. Therefore, a low interoperability among the different Geographic Information Systems and modelling software is present. This lack of interoperability poses significant challenges for professionals who rely on multiple software platforms to manage and analyze geographic and infrastructural data. The fragmentation of data workflows can lead to inefficiencies, increased costs, and potential errors as data is manually transferred and reformatted between systems.

As already cited in *section 5. Software interoperability* of this thesis work, none of the mentioned software presents a full interoperability among them without compromising the managed information. The QGIS project cannot be exported and directly imported in ArcGIS pro, Cesium, Mapbox or Infraworks without losing information. In the following paragraphs, some possible future applications for each software combination (QGIS – software) are described.

Realizing a real-time synchronization among ArcGIS pro and QGIS could increase their flexibility and general usage. In this way, the barrier developed using different software can be deleted all at once.

A direct link between QGIS and Mapbox could help in publishing online the web maps realized. Then, an improvement of the already existing plugins – as qgis2web – could be done.

The development of a QGIS plugin able to directly export the 3D map in a format readable for Cesium could reduce the time required for the management of all the data and limit the loss of information during their conversion.

In the future a better supported environment for the QGIS-BIM formats interoperability should be developed. In this way, the realization of Digital Twins of structures, infrastructures and terrain areas could be easier; the sharing of information smoother and an increment of application of these software programs obtained. Since all the software programs can perform the same analysis done with QGIS by using different commands and plugins, a complete interoperability among them could create a set of complete powerful tools. Moreover, it can be crucial for disaster preparedness and response. Detailed 3D models of buildings and infrastructure can be used to simulate natural disasters such as earthquakes or floods properly represented in the GIS environments. This cooperation helps authorities to better plan and implement effective mitigation strategies. The addition of real-time data can also help in managing and maintaining infrastructure efficiently.

8. Conclusions

The realization of innovative Cervo Valley web maps – both in 2D and 3D – from where the hydrogeological risk analysis can be performed, is the final purpose of the thesis work. The data analysis can be done either in real time or not by simply considering both static and dynamic information.

The development of the interactive maps revealed the importance of introducing a sort of Digital Twin of the interested area to predict and prevent natural catastrophic events developing a proper risk management plan.
The management of already existing static information related to flooding events, cones and landslide areas can improve the comprehension of the territory behavior in function of the different return periods considered.
The distinction between different terrain slopes helps in the comprehension of the terrain inclination. Then, it allows the detection of various landslide risks associated with them.
In conclusion, the introduction of dynamic precipitation data in the two maps allows to obtain real-time feedback of the meteorological events in the area.

All these static and dynamic information represent the base from where to start in performing a deeper and more complete hydrogeological risk analysis. The introduction of additional data related to a better description of human activities and to the terrain characteristics – terrain evapotranspiration capacity; geological conditions and water content – can improve the hydrogeological risk analysis. In addition, they help to understanding the causes of occurrence of possible dangerous events.
According to that, these maps can be used to predict the possible damages for both structures and infrastructures associated with natural dangerous events.

Despite that, this study only represents the first step for the realization of a complete Digital Twin. First, the dynamic data introduced are not properly in real-time. As already mentioned in the previous sections of the thesis work, they are data related to the year 2023 managed as real time ones. Then, no automatic hydrogeological analysis can be performed at this point of the study and a lack of information is present in the perspective of obtaining proper analytic results.
At this stage, the two maps are closer to the definition of a viewer tool than that of a Digital Twin.

However, this demonstrates that a wide range of possible future applications is present. The direction of development requires the introduction of additional information to perform a detailed hydrogeological analysis. Then, the definition of influence of each hydrogeological parameter can help in the description of a proper hydrogeological risk management plan.
By implementing additional tools and/or plugins in the software, it can be possible an increment of interoperability among the software programs with a consequent introduction of automatic analytic analysis.

Furthermore, hydrogeological risk is only one of the possible applications of the web maps. Other risks can be included and analyzed for structures, infrastructures, and territories in these 2D and 3D maps. For instance, they are seismic risks, fire hazards, environmental pollution and industrial accidents. Integrating these additional layers of risk analysis, it can be obtained a comprehensive tool for disaster preparedness and mitigation, offering valuable insights for planners, decision-makers, and the public.

A summary of the tools and scripts used during the study is provided [Figure 111.].

Web Maps	QGIS tools		Python codes		JavaScript codes	
	Name	*Functionality*	*Name*	*Functionality*	*Name*	*Functionality*
2D	Hillshade	Produce visual representation of shading on the DTM	Differences between raster files	Define the differences between DTM25 and DTM5	Pluviometer	Make the API call to the Python code and realize the graph in function of Chart library
	Union	Join different layers				
	Intersection	Intersect different layers visualizing streets and buildings at different risks				
	Difference	Cut shapefile layers				
	Clip	Cut raster layers				
	MMQGIS plugin	Merge different layers all at once				
	GRASS algorithm: basin areas calculation		*Percentages of slope*		Chart	Third parties developed library to create the pop-ups graphs
	r.fill.dir	Create a depression-less raster layer	Main code	Create shapefiles representing different percentage slope ranges		
	r.watershed	Flow accumulation and flow direction analysis	Slope check: coordinates	Check the main code by using the coordinates of a random point		
	r.stream.extract	Streams determination	Slope check: color map	Check the main code by representing detailed color maps for the different percentage slope ranges		
	r.water.outlet	Define the outlet points of basin areas	PluviometerAPI	Make a virtual server and make the API call to ARPA Piemonte website		
	r.to.vect	Convert raster layer into shapefiles				
	qgis2threejs	Export a 2D web map with Leaflet library				
3D	qgis2threejs	Export a 3D web map	*Add elevation to shapefiles*		Chart	Third parties developed library to create the pop-ups graphs
			Main code	Sample the raster along the shp file geometry and provide to the shp file the medium height of the sampled raster		
			Check shape file elevation	Check the main code by making a 3D plot of the raster with the shp files overlapped		
			PluviometerAPI	Make a virtual server and make the API call to ARPA Piemonte website		

Figure 111. The summary of all the tools and scripts used.

In conclusion, the study has the potential to represent an innovative perspective in the definition of the hydrogeological risk analysis at different scales: from a single map to a whole region. The introduction of interactive and user-friendly maps easily readable by everyone, leads to the possibility of their application in different areas and for different final purposes: analytic analysis, visualization of results, sensibilization, sustainability perspectives and so on.
The final goal is to create an innovative perspective adaptable to different risk analysis able to include large representation scales as well as nations.

9. Acknowledgments

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Thank you to the rest of my family for always supporting me. From my grandmother *Renata* to all my uncles and *Ylenia*.

I wish to express my profound gratitude to *Lucia* for her support, her words, her tireless and infectious joy. She is the only one who allowed me to look beyond, seeing engineering as a form of art. I owe to her the courage to somehow combine it with my other passions.

One thought inevitably goes to my lifelong friends, *Marco*, *Mara* and *Raluca*. No matter what part of the world we are in, a red thread will always tie me to you.

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Those mentioned here are aware of the many passions that characterize my life and personality. One of these is undoubtedly the mountains. The opportunity to work on mountainous areas, even in an engineering way, has been a constant source of commitment and interest for me. With this final acknowledgment, I wish you to always be proud of what you do, at any age. If I am, it is also thanks to all of you.

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