POLITECNICO DI TORINO

Facoltà di ingegneria

Corso di Laurea Magistrale in Ingegneria per l'ambiente ed il territorio:

rischi naturali e protezione civile

Tesi di Laurea Magistrale

L'influenza degli incendi boschivi sull'occorrenza delle frane superficiali e correlati meccanismi di innesco

The influence of wildfires on the occurrence of shallow landslides and related triggering mechanisms

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1 Abstract

Gravitational phenomena, like shallow landslides and debris flows, are very common in Italy due to the orographic and geological features of the territory, two mountain chains go all across the nation indeed (Alps and Apennines).

It has already been demonstrated that it is impossible to avoid them all occurring; that is why prevention measures and studies are needed to decrease the damages and victims that such phenomena could cause. Exploiting the database of the Piemonte Region and Regional Agency for Environmental Protection of Piemonte (ARPA Piemonte), an attempt has been made to investigate the variations of soils affected by wildfires.

Numerous studies have demonstrated that hydrological characteristics' variations due to wildfire have to be examined. Whether these correlations have been sufficiently demonstrated for debris flows around the world, as analyzed in a recent article by Tiranti et al. (2021) in Piemonte, for the shallow landslides have not been made many studies in this regard and it is not yet clear how a wildfire could predispose shallow landslides.

Critical rainfall values are usually one of the main triggering factors to consider, but as it is presented in this thesis, a significant and long-term predisposing factor able to increase the effect of rainfall in triggering shallow landslides must be considered: the dead vegetation that remains on the slope even several years after the passage of wildfires.

To obtain useful information for the aim of the thesis project, considering the lack in complete information in public data available at regional scale, it was necessary to search for new data (unpublished data) by field surveys focused on some case studies. The research work was conducted by contacting various professionals and public administrations in order to acquire technical reports on wildfire and landslide events and carry out field investigation in the areas of interest.

2 Introduction

2.1 Scope of work

The work's objective, defined with the ARPA Piemonte's tutor, was to investigate if demonstrable relationships exist in Piemonte between the occurrence of wildfires and the triggering of shallow landslide. The thesis work focused on finding relevant case studies within the entire Piemonte area to justify the thesis theory using information, documentation, and making considerations about it.

Numerous studies have demonstrated that slopes' hydrological characteristics' variations due to wildfire have to be investigated.

Wildfires can increase the frequency and intensity of debris flows, mobilizing loose material and altering the slopes' hydrological characteristics, ultimately affecting the triggering of shallow landslides. However, the relationship between wildfires and shallow landslides is not yet well understood, with critical rainfall values being a major parameter to consider, along with the presence of dead vegetation that remains on slopes for several years after a wildfire. Each sector of Piemonte is characterized by various characteristics, such as hydrogeology, morphology, geology, soil cover, and vegetation type, that can influence the triggering of shallow landslides. Wildfires can also alter the starting hydrological conditions, soil permeability, and vegetation damping effect, ultimately increasing the availability of mobilizable material as reported by Tiranti et al. (2021).

A very schematic approach was used to tackle the work. Initially, the available data was entered into the Quantum QGis software and Microsoft Excel, with the spatial delimitation of the investigation being the Piemonte region, divided into provinces to facilitate calculation operations. Similar problems have been found for all the shallow landslide data, expressed a really and punctually, from the official and unpublished databases of ARPA Piemonte and other sources.

During these first elaborations, the data's different structuring and modus operandi in cataloguing the wildfire events were immediately noticed. In fact, for some, there is an approximation of the perimeters, while in other cases, information on event timing was missing.

At this point, a first exploratory approach was attempted to see if there was a spatial overlap between the distribution of shallow landslides and wildfires without considering the temporal component at this stage of the work. Spatial data have been processed with Quantum QGis software to conduct an exploratory analysis of the spatial overlap between shallow landslides and wildfires. A considerable number of correlations were found in which the overlap of the geometries representing shallow landslides (points) and wildfires (polygons) was verified.

However, when the spatial correlation took place in MS Excel, it became apparent that satisfactory results could not be obtained.

The completeness of available databases and the lack of crucial information, such as the date of occurrence, pose significant challenges to achieving comprehensive results. To address these limitations, a new case studies research was conducted by contacting various professional figures and public administrations, with the objective of investigating the existence of demonstrable relationships between wildfires and shallow landslides in Piemonte.

Relevant case studies were found by reading available documentation, contacting communal administrations, barracks of the Firefighters, sections of the Club Alpino

Italiano (CAI) and Antincendio Boschivo (AIB), and several professional geologists and engineers.

Finally, improving the quality and accuracy of available data is crucial to developing a more accurate early warning system and achieving a better understanding of the relationship between wildfires and shallow landslides' occurrence.

2.2 Study areas

2.2.1 Context

Piemonte is a region of north-western Italy with 4'240'791 inhabitants, with the main town the Torino city.

Piemonte borders France to the west (Auvergne-Rhône-Alps and Provence-Alpes-Côte d'Azur regions), Valle d'Aosta to the north-west, Switzerland to the north, Lombardia to the east, a short stretch with Emilia Romagna to the south-east and Liguria to the south.

It is the second Italian region for extension and municipalities' number, and, seventh for inhabitants number.

It is also the fourth region for exports, with a share of 10 % of the national total, and fifth for the value of Gross Domestic Product (GDP) with a total of around 143 billion euros.

As it is a highly productive and populated region, it is important to analyze the various risks present, such as shallow landslides, which can cause damage to both production and the population.

2.2.2 Orography

Piemonte's leading mountain chains constitute a natural border on three sides of the region, the Western Alps on the north-west and Ligurian Apennines on the south.

Schematizing the region territory, it is divisible into three concentric zones. The main and external one is mountainous, formed by the Alps and Apennines (43% of the regional territory). Inside is the hilly zone (31% of the territory), which encloses the lowland (26% of the territory).

Piemonte's physic configuration highlights the absence of a pronounced foothill zone leaning against the Alps, as in other Italian regions. The mountains alternate with the plain in most of the region indeed.

The great variety of landscapes and geographical-environmental unity translates into a complex territory: from the Alpine environment, where 4000 m a.l.s. are exceeded, to the humid rice fields of the Vercelli and Novarese areas located about 100 m a.s.l. From the hilly slopes of Monferrato and the Langhe to the plain riches in industrial and agricultural activities.

The aspect of Piemonte's mountains is harsh and massive: the peaks above three thousand meters fall rapidly towards the plain, a phenomenon particularly marked in Val Susa.

The mountains that embrace the territory of Piemonte are pretty steep and high on the west and north sides, which is evident with Punta Nordend (4'609 m) representing the maximum regional elevation.

Below the mountains, pasturelands and extensive coniferous forests proliferate.

The valleys are a nerve centre of Piemonte, thanks to the hydroelectric plants, dams, local tourist centres and the international road and railway routes that pass through them.

The predominant hilly areas are the Langhe, the Roero (Tertiary Piemonte Basin), the Monferrato and the Torino Hill. Ancient marine sediments forming the southern hill of

Langhe and Monferrato, where the surficial water modelled valleys due to the hill's low resistance to water erosion.

Cereals are grown above the hillsides, grapevine and fodder either. These are also the places where orchards and hazelnuts extend, while farming is concentrated in the flats.

The Po River Valley forms a large semicircle around the hilly area, generated by the action of the Alpine watercourses. Despite the numerous reclamations works, the plain still has a pebbly and permeable appearance in the highest part, less permeable and very fertile in the lower one. Furthermore, the flat area between the provinces of Vercelli and Novara has been widely cultivated with rice paddies thanks to the large amount of water brought in by the work of artificial channels such as Canale Cavour.

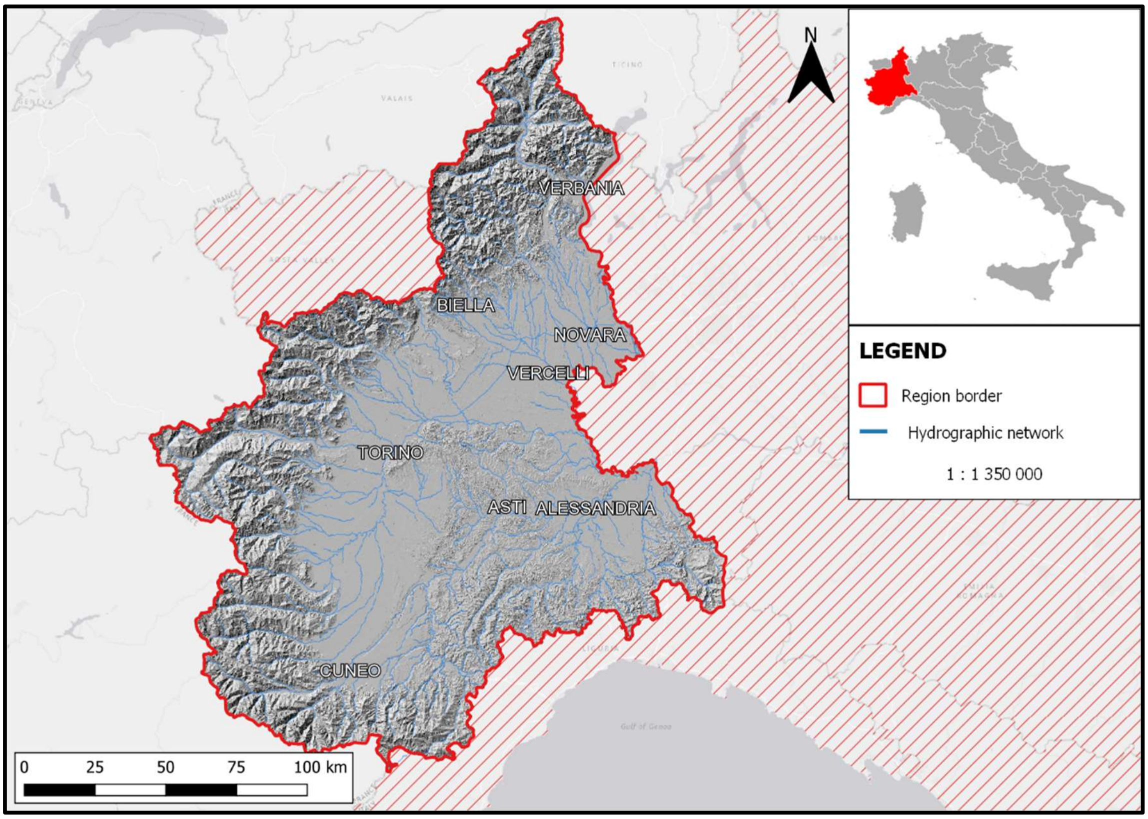


Figure 2-1 Overview of the area of interest - Piemonte

2.3 Geological setting of the region

The geomorphological framework of Piemonte shows several orographic features: the Alps and Apennines Mountain ranges, the hills of Monferrato and Langhe, the end-moraine systems and fluvio-glacial or alluvial fan at the outlet of major Alpine and Apennine valleys, major glacial lakes in the northern part of the region and the wide alluvial plains of Po River. This highly variable geomorphological framework mirrors an equally complex geologic and tectonic context, almost unique for its large variety of lithological and structural features. This has induced enormous scientific interest, promoting a large quantity of multidisciplinary scientific papers and maps.

The geological setting of Piemonte ideally encompasses an almost complete section of the Earth's crust, ranging from deep lithospheric mantle rocks to oceanic basalts and relevant sedimentary covers, from the plutonic and volcanic continental rocks to the overlying carbonate and siliciclastic sedimentary covers, as well as to many kinds of metamorphic rocks formed in different geodynamic contexts and at different pressure and temperature conditions. Several Palaeozoic to Cenozoic and Quaternary associations of rocks, referred to a long sequence of magmatic, metamorphic and sedimentary events, can be recognised. All this variety of geological units can be considered (as discussed below) as parts of the 'Alps–Apennines orogenic system'.

The complexity of Piemonte geology is the result of a continuous geodynamic process which, since the Rhaetian-Hettangian, led to the formation of two continental 'passive' margins: the 'Palaeo-European Margin' and the 'Palaeo-Adriatic Margin', and two oceanic zones: the Liguria–Piemonte Domain and the Valais Domain (Bernoulli & Jenkins (2009); Bertotti et al. (1993); Dal Piaz (1974, 1999); Dal Piaz et al. (1972, 2003);

Dewey and Bird(1970); Dewey et al. (1973); Handy et al. (2010); et al. (2010); Sturani(1975); Trumpy(2001).

Since the Late Cretaceous, the European and Adriatic continental plate margins began to converge (Le Pichon, 1968) inducing the subduction of the interposed oceanic lithosphere. This process led, since the middle-late Eocene, to the collision and mutual indentation of the two plate margins. In this framework, the Alps–Apennines orogenic system originated, involving continental and oceanic crustal units that were affected, at a very different extent, by metamorphic and tectonic reworkings (see Dal Piaz, 2010 for a review). In the early Oligocene, magmatic complexes intruded the orogenic belt as a consequence of the crust subduction (see Alagna et al. 2010, for a review). Contemporaneously, since the middle Eocene, synorogenic sedimentary basins developed: the middle Eocene–early Oligocene Alpine foreland basin in the outer part of the Alpine chain, the Eocene–Messinian Tertiary Piemonte Basin (TPB) and the Pliocene–Quaternary basins in the inner part. The sediments of these basins, which became, in turn, part of the overall orogenic system, recorded the syn-collisional tectonic evolution of the Alps–Apennines orogenic system. From a geographic perspective, the Piemonte Alps– Apennines system can be subdivided into distinct orographic features:

(a) the Western Alps, represented in Piemonte by the Maritime, Cottian and parts of the Graian, Pennine and Lepontine Alps, which display the deeper crustal portions of the Alps–Apennines orogenic system, affected by pre-Alpine and Alpine metamorphism.

Discontinuous portions of the Mesozoic sedimentary covers of the continental and oceanic crusts, metamorphosed at different degrees, as well as Eocene-Rupelian deposits of the Alpine Foreland Basin, are exposed in the Cottian, Maritime and Ligurian Alps. These are, at a minor extent, also exposed in the Ossola sector, in the ‘Lakes district’ and in the Canavese–Biellese area. The Piemonte Alps roughly correspond to the internal and axial sectors of the Western Alps double-vergent orogenic belt (see Beltrando et al. (2010); Dal Piaz et al. (2003); Pfiffner et al. (1997); Rosenbaum et al. (2002); Roure, (1996); Roure et ak. (1990) for a review). The internal sector is bounded by the Periadriatic Lineament (Insubric Fault, Canavese Line) and by the south, southeast- and east-vergent ('retrovergent') thrust fronts on its Padane side. Portions of these sedimentary successions, which did not undergo metamorphic transformations at depth, are now part of the northern Apennines and of the Maritime and Ligurian Alps.

(b) The southern part of Piemonte Alps (represented by the Ligurian Alps between Tenda Pass and Cadibona Pass), which are characterised by polycyclic metamorphic rocks (Ligurian Briançonnais basement) and late Carboniferous to Permian sedimentary-volcaniclastic sequences covered by Mesozoic carbonate successions of the palaeo-European margin, are in turn unconformably covered by Eocene to Pliocene sediments of the synorogenic basins. The southern Piemonte Alps belong to the external sector of the Western Alps orogenic belt, which is bounded by south- and southwest-vergent thrust systems bounding it from the foreland domains (Ford et al. (1999); Jourdon et al. (2014)).

(c) The Apennines mountain range to the East of Cadibona Pass extends in Piemonte up to the boundary with the Emilia-Romagna and Lombardia regions. From Cadibona Pass to the Lemme valley, the Apennines show polycyclic basement rocks and the overlying Mesozoic carbonate successions of the palaeo-European margin, as well as metamorphic rocks derived from the oceanic Liguria–Piemonte Domain (from Erro valley to Lemme valley). In the geological literature, these units are included in the Ligurian Alps, although they belong, from a geographic and orographic perspective to the Apennines. To the northeast of the Lemme valley, non-metamorphic rocks belonging to the oceanic Liguria–Piemonte Domain or to the Eocene to Pliocene synorogenic basins are prevalent.

These units represent the shallower part of the orogenic system, never involved in deep tectonic processes, and are a part of the Northern Apennines tectonic belt, formed since the late Oligocene in response to the overthrusting, toward the East and NE, of the Ligurian units onto the palaeo-Adriatic continental margin (Elter, 1973); Elter and Pertusati, 1973) and overlaying Cenozoic sediments of the Po plain subsurface (Biella et al., 1997); Cassano et al., 1986; Falletti et al., 1995; Pieri and Groppi, 1981; Roure, 1996; Roure et al., 1990).

(d) The hills of the Langhe, Alto Monferrato, Borbera- Grue, Monferrato and Torino areas consist of sedimentary units of the synorogenic basins, deformed and uplifted during the Cenozoic and Quaternary. The Padane alluvial basin (e.g. the Vercelli and Novara alluvial plains) and the Savigliano and Alessandria basins are filled by Quaternary successions whose deposition was controlled by recent tectonics (Delacou, 2004; Eva and Solarino, 1998; Morelli et al., 2011; Perrone et al., 2013).

For this reason, the Quaternary deposits are here considered as effective parts of the Alps–Apennines system.

In such a complex framework, tens of lithotectonic units were identified and represented on the Map. (Piana et al., 2017))

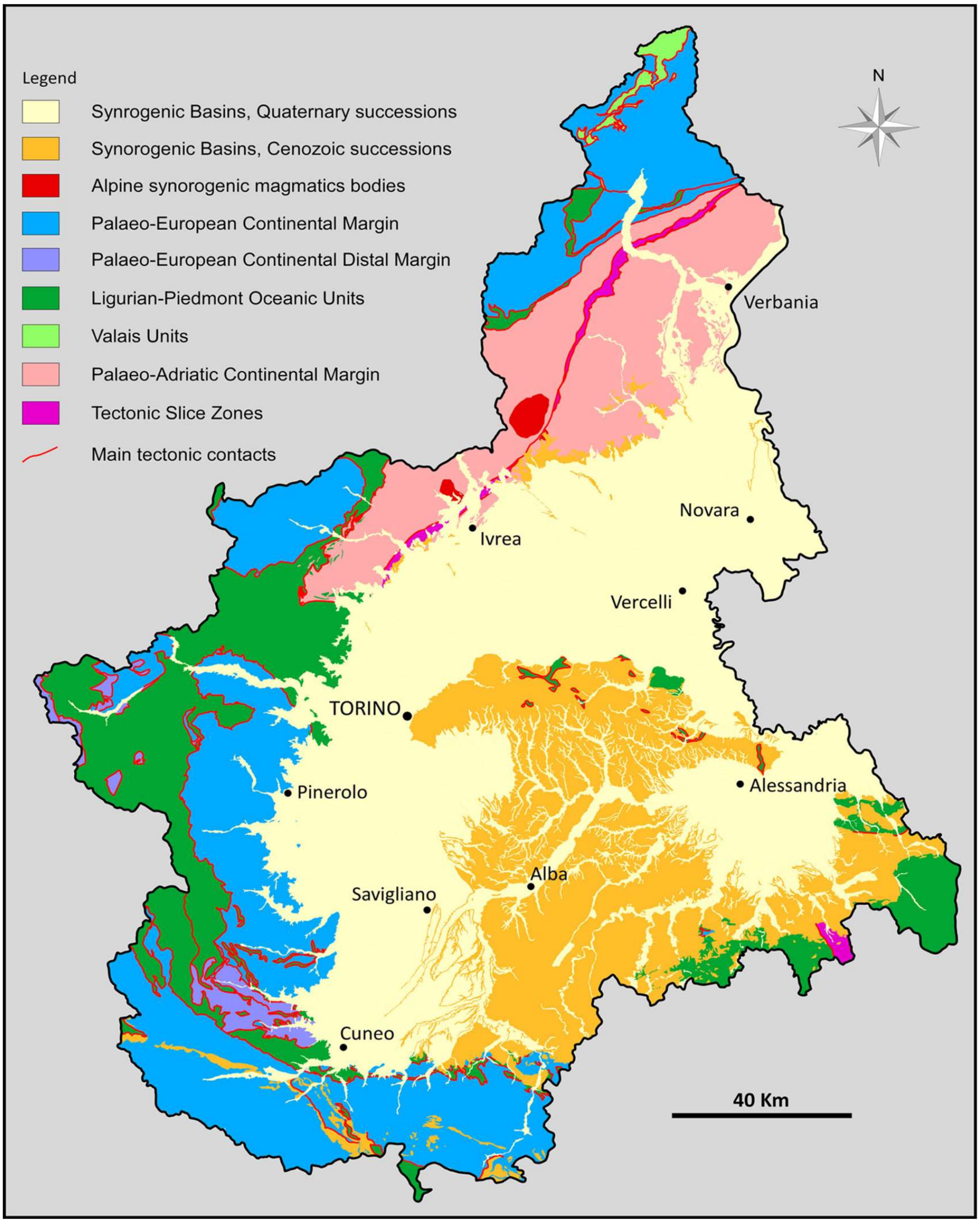


Figure 2-2 Scheme showing the present distribution of the paleogeographic and physiographic domains, as well as the geologic units belonging to the other main categories adopted to construct the Map Legend (modify from Piana et al., 2017).

2.3.1 Hydrography and Hydrology

2.3.1.1 Hydrography

Piemonte has a radial hydrographic network split into the two systems of the Po and Tanaro rivers. The predominant cause of the lack of flow of all the waters of Piemonte towards a single prominent collector is the presence of a wide hilly area which has forced the main waterways to considerable deviations.

The Po River, the most prominent Italian river (652 km), originates in Pian del Re at the foot of Monviso. Its mountain course of 35 Km up to Rovello has an average gradient of 48%.

After that, its slope decreases till the river's mouth.

A summary of its most essential tributaries in Piemonte is reported from upstream to downstream.

From the Western Alps comes the Pellice river (55 Km), enlarged by the Chisone river (57 Km) into which the Germanasca river flows.

Two other modest subalpine rivers join the Po river, the Chisola and Sangone rivers, then, after gathering the Bardonecchia and Cenischia torrents near Susa, the Dora Riparia river (125 km) also enter the Po river. Parallel to each other in their mountain course, the Sture di Viù river, the Sture di Ola river, and the Sture di Gravascallo river join the Lanzo river. After the Lanzo river, there is the Malone river who, before entering the Po river, joins the Orco river (80 Km). The Dora Baltea river (160 Km) is the largest left tributary of the Po river.

The Sesia river, fed by the glaciers of monte Rosa, has a length of 138 Km.

Worth mentioning are the streams in the Novara plain: the Agogna (140 Km), the Artogna and the Terdoppio rivers (83 Km), which has its source at the Passo di San Giacomo and has the right tributaries of the Diveria, Ovesca, Anza and Strona streams.

The Tanaro river (276 Km) is instead the most extensive right tributary of the Po river.

From a quantitative point of view, the volume of water that annually flows into the Po river section is estimated at 14.5 billion m^3 near Pieve del Cairo (just across the regional border), with a corresponding average annual flow of 460 m^3, the flow rate defined as semi-permanent (which represent the minimum value present for at least 182 days/year) is equal to 380 m^3/s.

The largest lake basin is Lago Maggiore, fed mainly in Switzerland by the Ticino river and in Piemonte by the Toce river; There are also numerous alpine lakes in the mountainous area and resurgences.

A small part of the Piemonte surface outflows is regulated by artificial reservoirs with a capacity of more than 1 million m^3 or a barrier height of more than 15 m, for a total of approximately 52,000 million m^3. Despite being located outside the regional territory, some reservoirs influence the hydrological regime of Piemonte's watercourses: 2 in Liguria, 11 in Valle d'Aosta and 1 in France.

In the Piemonte region's territory, 17 main hydrographic sub-basins flow directly into the river Po, divided into a further 34 hydrographic areas for a total area of 25,285 Km^2.

Furthermore, 683 elementary basins were identified, representing closed unitary territorial entities with hydrographic sections of particular interest, important for outflows and the presence of significant anthropic impacts.

2.3.1.2 Hydrology

The distribution of rainfalls in a mountainous area like Piemonte is strictly correlated to the morphology of the region other than the direction of propagation of perturbation and distance from the sea.

The blocking and raising effect of the humid currents towards the colder atmospheric layers caused by the mountain ranges are very relevant. As is known, the perturbations in Europe come from the Atlantic Ocean and, to a lesser extent, from the Mediterranean.

Only dry air currents arrive from the east and, in winter, are often icy, so much so that they constitute the leading cause of the abnormal periods of intense frosts that affect the Po Valley in specific years.

The humid currents from the West and the North tend to discharge on the outer side of the Alps (accordingly, in this specific case, on the French and Swiss sides), with contributions mostly limited to the Alpine watershed sectors. Therefore, the preponderance of the precipitations depends on the meridional currents.

Generally, the most intense ones originate in a minimum baric located in the Ligurian Sea or in the Gulf of Lion (usually the evolution of a perturbation of Atlantic origin moving eastward).

In these cases, the cloud fronts, in their anti-clockwise movement around the low-pressure nucleus, after being enriched with humidity in the Gulf of Genoa, are discharged in a considerable part on the Maritime Alps and the low reliefs of the Ligurian Apennines, causing modest rainfall in the hilly areas and the lowland areas and release the bulk of the inputs on the pre-Alpine belt.

The innermost sectors of the Alpine chain have scarce rainfall, often less than that of our southern regions, as well as the mid sectors of the plain and hilly areas (the Vercelli plain, the lower Monferrato, the Asti area).

Therefore, it is possible to identify two zones quite distinct from the others with high rainfall in Piemonte.

The southernmost one corresponds to the Liguria-Piemonte watershed and continues eastwards up to the Apuan Alps.

This band affects the regional territory only to a small extent, both because rainfall decreases as one moves away from the watershed and because, from an administrative point of view, these sectors mostly fall within the Liguria Region. However, it is understood that these contributions have a considerable influence on the regime of some important rivers in Piemonte, such as the Tanaro, the Bormida and the Scrivia.

The other band is the pre-Alpine one that can be distinguished starting from Val Pellice (but in this area, the increment compared to the surrounding areas is just around 50%), persisting along the mountain ranges overlooking the plain with averages around 1200 - 1400 mm up to the entrance to Aosta valley.

From here on, with the axis of the Alpine chain turning from North-South to East-West, rainfall becomes higher with values above 1700-1800 mm per year.

Departing from the mountains and reaching the plains, rainfall regularly decreases to stabilize at around 800 mm in the north of the Po.

South of the Po, in the Alessandrina plain, in the Asti area and in the Monferrato, the contributions drop to 650 mm/year (Asti and Alessandria stations).

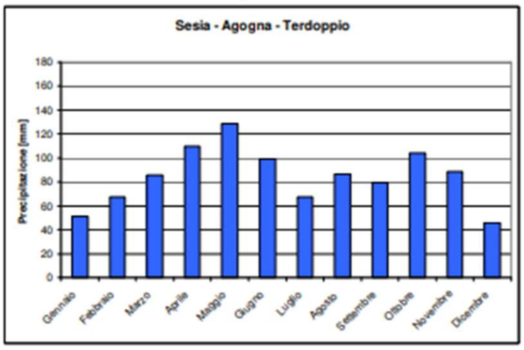
In the western Alpine arc at the heads of the valleys, the average values are between 800 and 900 mm/year. Exceptions are the innermost areas of the chain, i.e. the upper Susa valley (694 mm/year in Bardonecchia) and the Aosta Valley (495 mm/year in Aosta and even only 452 mm/year in Chatillon). In the north, the Val d'Ossola and the upper Val Sesia are around 1200 mm/year.

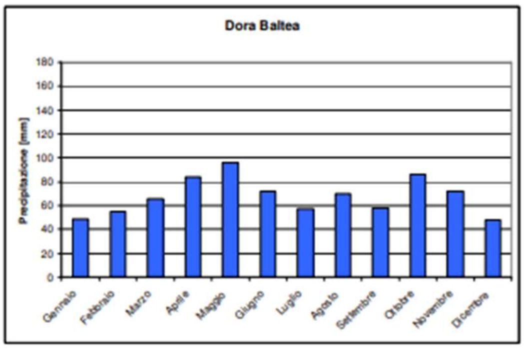
2.3.1.3 Precipitation trend

In general, in Piemonte, there are two wet seasons (spring and autumn) and two drier seasons (summer and winter).

As mentioned, the rainiest areas are north of the Po River, the northern parts of the provinces of Verbania, Biella and Vercelli. The less rainy ones are located in the lowland areas on the northern flank of the Apennine hills, and in particular between the Alessandria and Asti plains.

Taking the thirty years 1961-1990 as a reference for the analysis of the average monthly rainfall, by observing the trends of the average monthly rainfall on the macro-basins, the characteristics already highlighted above are confirmed, i.e. a rainfall regime in Piemonte characterized by a predominantly bimodal trend over the year (two seasonal highs and two lows).





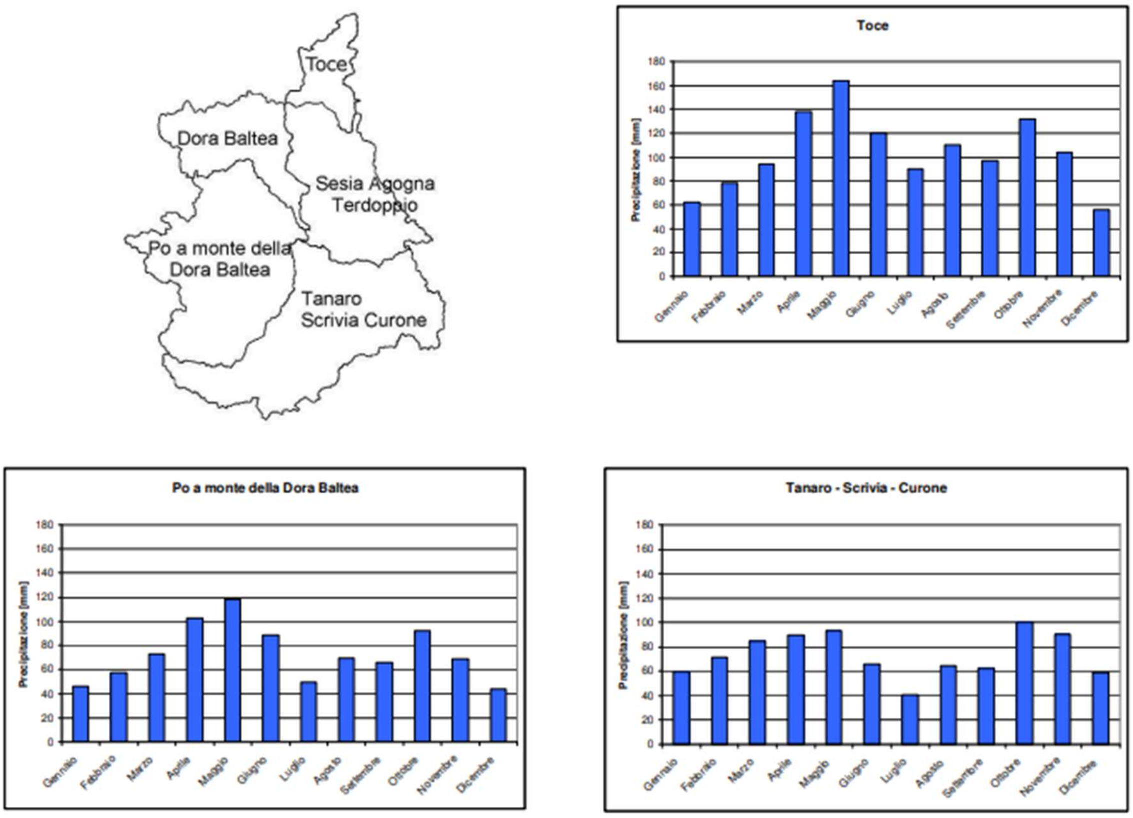


Figure 2-3 Trend over the year (from ARPA Piemonte)

April, May and October are the months characterized by the highest precipitation values throughout Piemonte. Instead, July and December are those with the lowest values.

The scarcity of rainfall between the winter and the beginning of spring is then compensated by spring rainfalls, which are the most important in most mountain areas.

The latter usually allows the storage of water resources even in reservoirs, supports the development of vegetation and overcomes any water crises that may occur in the summer months when the water requirement, mainly linked to agriculture, grows.

Considering the available data, the analysis of the annual average cumulative precipitation anomalies in Piemonte calculated from 1958 to 2016 does not outline a clear trend and even the weak signs of a trend (decrease over the entire period and increase in the last period) are not statistically significant.

It is evident instead that periods of several consecutive years are observed where the precipitation is below the reference norm, alternating with others in which the contribution of precipitation during the year is positive.

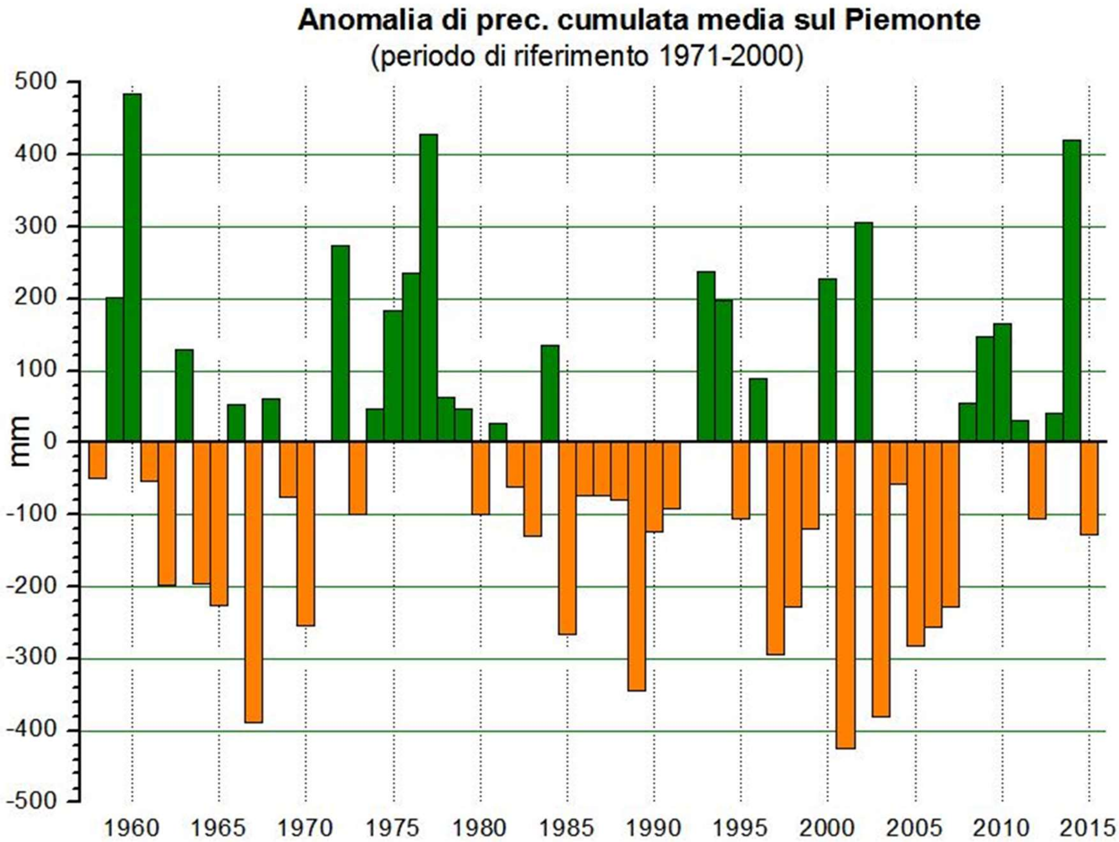


Figure 2-4 Anomaly of the average annual precipitation compared to the reference period 1971-2000. In orange the years with negative anomalies (less rainy years) in red the positive anomalies (years with more rain than in the reference period). (from ARPA Piemonte)

From a qualitative point of view, in the last twenty years, a greater frequency of years with a rainfall deficit can be observed compared to the average in the winter and spring seasons. In the autumn season, the number of years with a surplus of precipitation seems to increase.

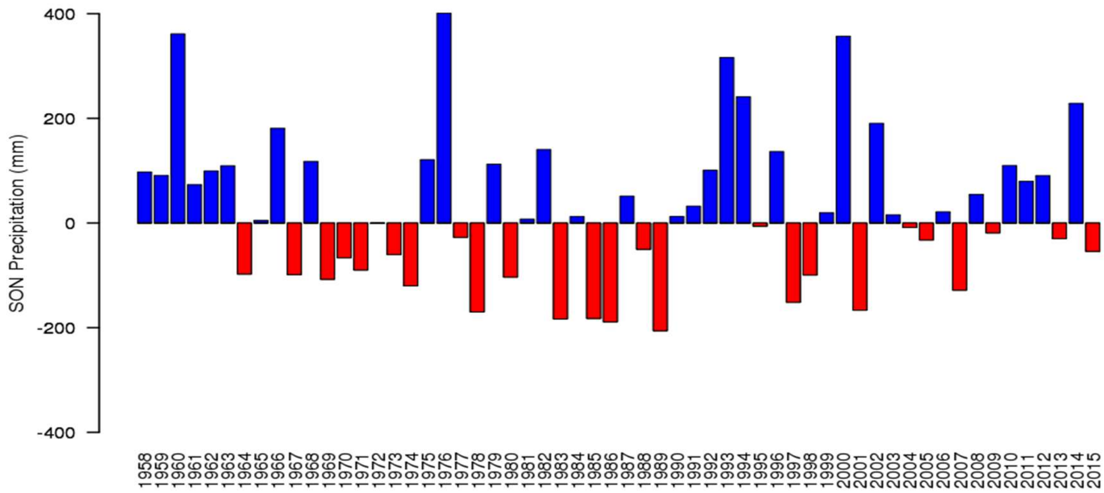


Figure 2-5 Anomaly of cumulative autumn rainfall in Piemonte compared to the average for the period 1971-2000 (in blue the years below the average, in red those above). (from ARPA Piemonte)

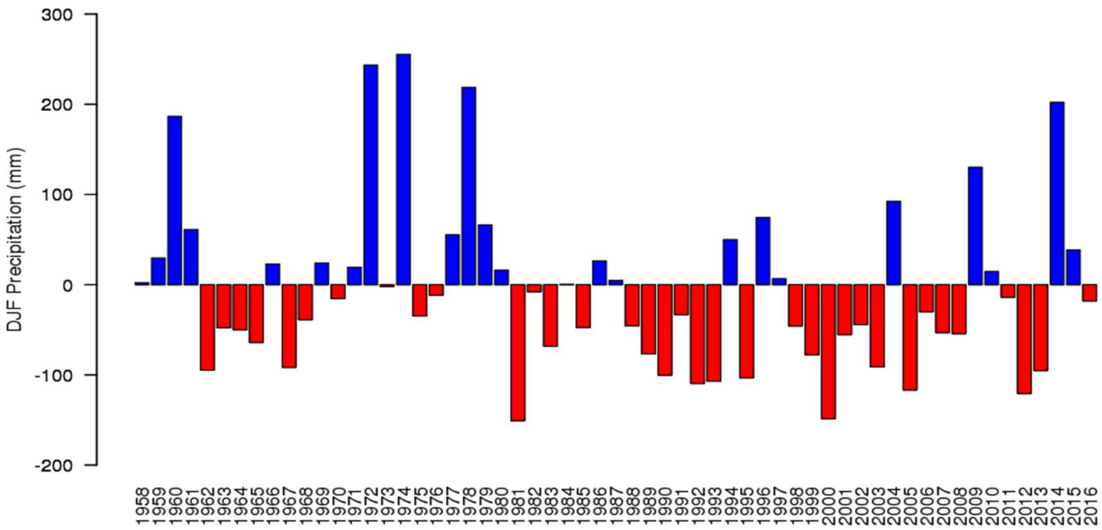


Figure 2-6 Anomaly of cumulative winter rainfall in Piemonte compared to the average for the period 1971-2000 (from ARPA Piemonte)

However, analyzing the last 15 years compared to the reference period 1971-2000, we observe a substantial decrease in the number of rainy days (precipitation greater than or equal to 1 mm) almost everywhere.

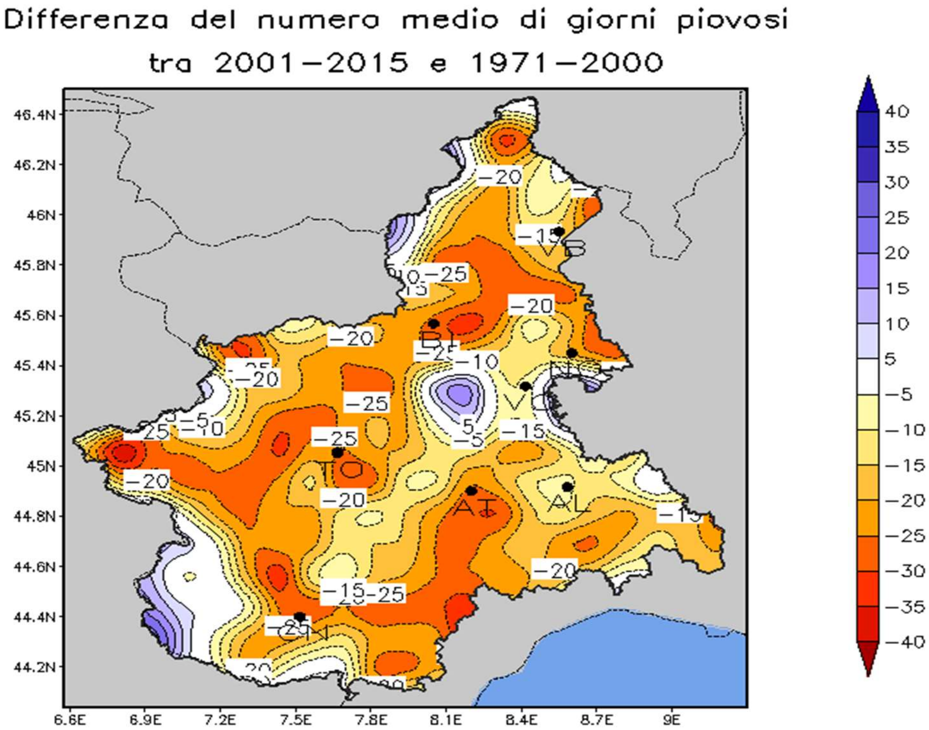


Figure 2-7 Average number of rainy days compared to the period 2001-2015 and 1971-2000 (from ARPA Piemonte)

The annual distributions of the daily precipitations (greater than or equal to 1mm) on all the grid points on which the objective analysis is performed were considered. There is a statistically significant positive trend of increasing daily extreme values (maximum of each year's distribution).

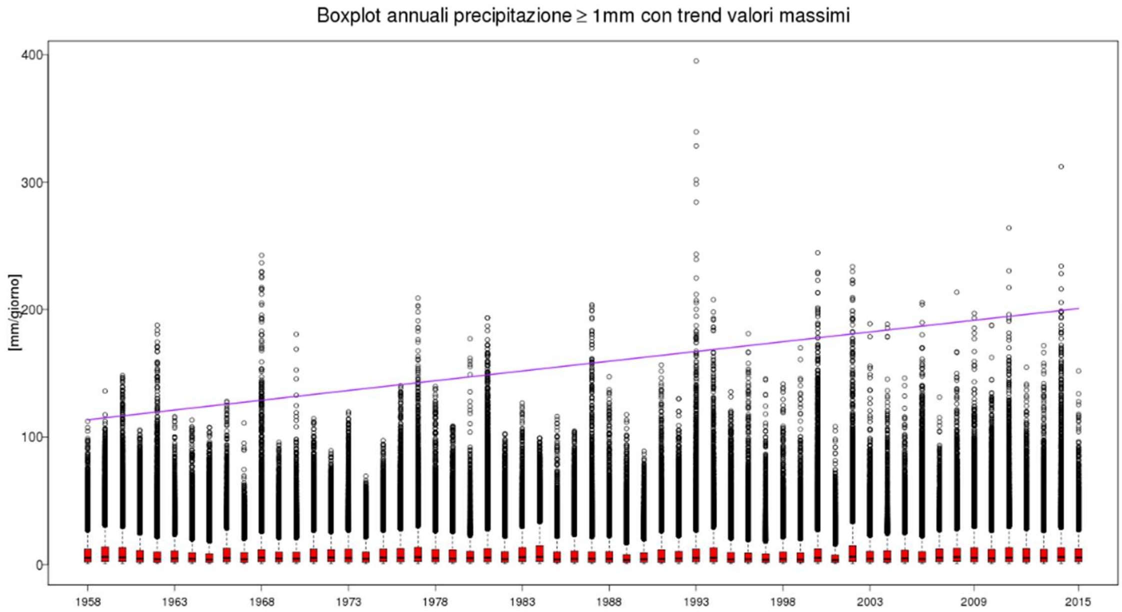


Figure 2-8 Boxplot of annual distributions of daily precipitation over Piemonte from 1958 to 2015, greater than or equal to 1 mm. In purple, the trend (statistically significant) of the highs. (from ARPA Piemonte)

2.3.2 Climate and wildfires

Climate change projections are particularly severe for the Alpine area during the 21st century. A careful assessment of the extent of this phenomenon was carried out with Multimodel techniques, which allow for correcting the grossest errors of the climate models (even for limited areas) and adapting them to the peculiarities of the Alpine area. The evaluation of the effects of climate change in the past and the future scenario on wildfires was carried out in the following figure.

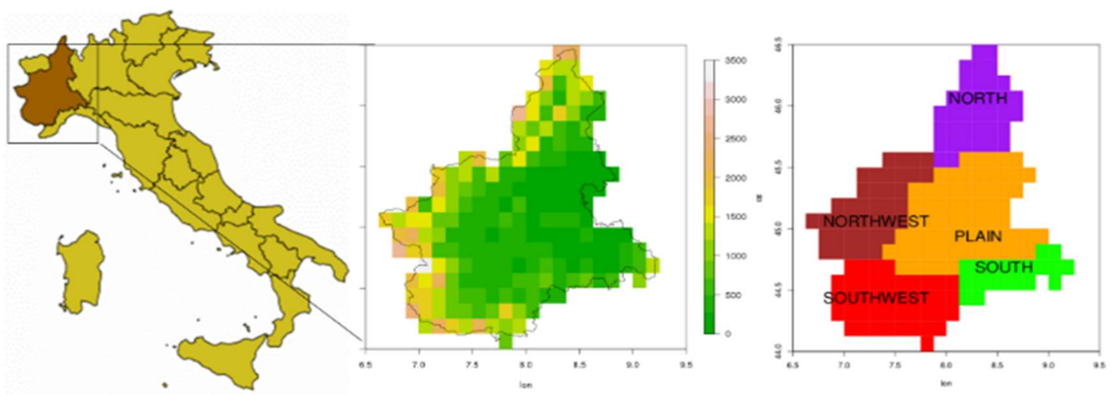
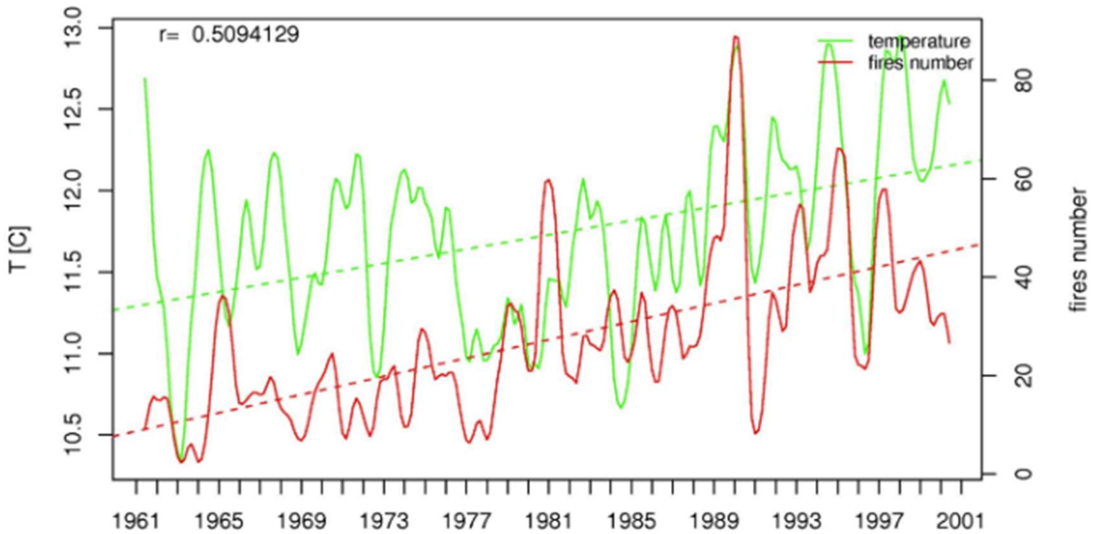


Figure 2-9 Study area with the average altitude of the grid points (on the left) and the five macro-areas of aggregation of the grid points. (from ARPA Piemonte)

The scenarios obtained with Multimodel SuperEnsemble, especially with high-resolution analyses, allow a better characterization of the temperature variations in the Alpine area, with the differences between the montane and lowland regions. The projection in the precipitation field shows less significant changes.

In 1961-2000, the number of wildfires was correlated with the temperature, and among the indices, it agrees better with the Fine Fuel Moisture Code (FFMC), i.e., the humidity index of fine fuels. This result is surprisingly good. 95% of the wildfires have an anthropic cause in Piemonte, and the wildfire statistics also depend on the land use changes in the considered period. The agreement of high FFMC occurrences and focus on the grid point scale (not shown) has also been observed.



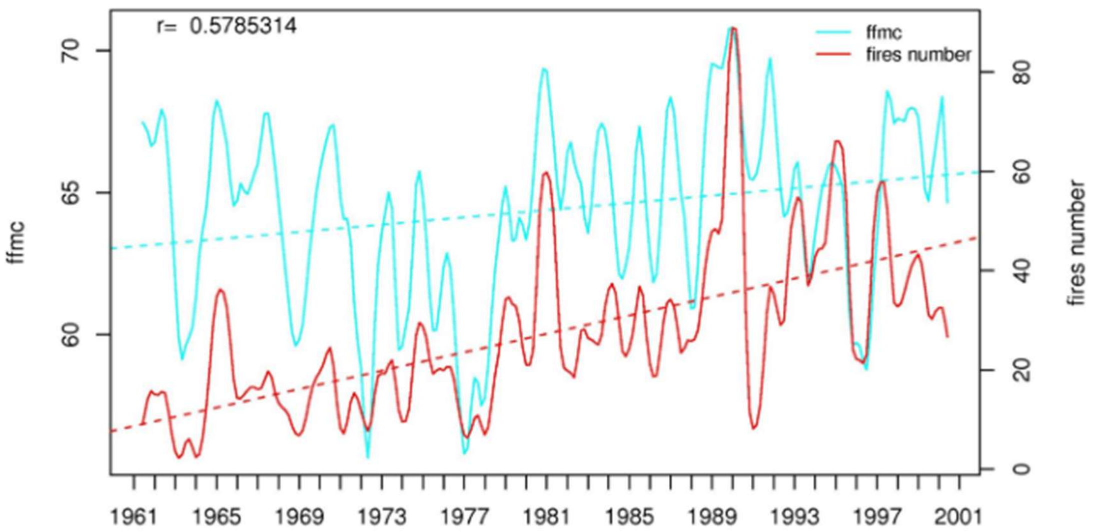


Figure 2-10 Comparison of the trends of the total number of wildfires observed with temperature (top) and FFMC (bottom) over Piemonte. (from ARPA Piemonte)

The procedure was repeated for the whole Piemonte and homogeneous climatic macro-regions on annual and seasonal data (DJF: winter; MAM: spring; JJA: summer; SON: autumn). The results are listed in Table.

Table 2-1 Change in frequency of the 50th and 90th percentile threshold of FFMC observed over the period 1981-2000 in the scenario, period 2031-2050. (from ARPA Piemonte)

	Annual		**DJF**		**MAM**		**JJA**		**SON**	
Area	50th	90th	50th	90th	50th	90th	50th	90th	50th	90th
Piedmont	+31%	+107%	+17%	+67%	+47%	+89%	+41%	+114%	+30%	+91%
North	+26%	+103%	+17%	+67%	+31%	+77%	+36%	+102%	+24%	+93%
NorthWest	+28%	+101%	+17%	+67%	+31%	+69%	+37%	+83%	+23%	+91%
SouthWest	+31%	+105%	+17%	+67%	+31%	+64%	+37%	+117%	+37%	+94%
South	+29%	+69%	+17%	+73%	+45%	+91%	+41%	+70%	+24%	+48%
Plain	+30%	+87%	+17%	+66%	+45%	+83%	+21%	+27%	+18%	+20%

All changes are positive, indicating increasing wildfire potential in the future scenario. The applied non-parametric statistics allow us to appreciate meaningful differences between the behaviour of the median of the distribution and its extremes: the "median wildfire potential condition" in the projection increases by 30% everywhere, but the "severe" conditions almost double in the scenario everywhere except in the south and on the plains.

The most significant increase is expected during the summer, indicating an extension of the wildfire season, which is currently mainly limited to the non-vegetative season (December - April).

Much of this information has been collected and processed from the ARPA Piemonte official website.

2.4 Gravitational phenomena - Shallow landslides

2.4.1 Landslides in Italy and Piemonte

In Italy, landslides represent one of the main natural hazards, as the Italian territory is characterized by a strong geological and geomorphological vulnerability, coupled with a dense population and extensive infrastructure networks.

Landslides in Italy are caused by a variety of factors, including intense precipitation, hydrogeological instability, seismic activity, and coastal erosion. In particular, landslides triggered by intense precipitation are the most common type of landslide in Italy, especially in steep areas with clayey and sandy soils.

In recent decades, Italy has recorded an increase in the number of landslides, their intensity, and frequency, partly due to climate change, which has led to an increase in extreme precipitation and temperatures. Furthermore, the lack of infrastructure maintenance and construction in high-risk areas increase the vulnerability of local communities to landslides.

To mitigate the effects of landslides in Italy, various strategies have been adopted, including risk assessment, territorial planning, implementation of civil protection measures and land management and maintenance, as well as the promotion of good practices for land management and emergency response.

In summary, landslides represent a significant challenge for Italy, but various strategies have been implemented to address them and reduce their negative impacts on the population and the economy.

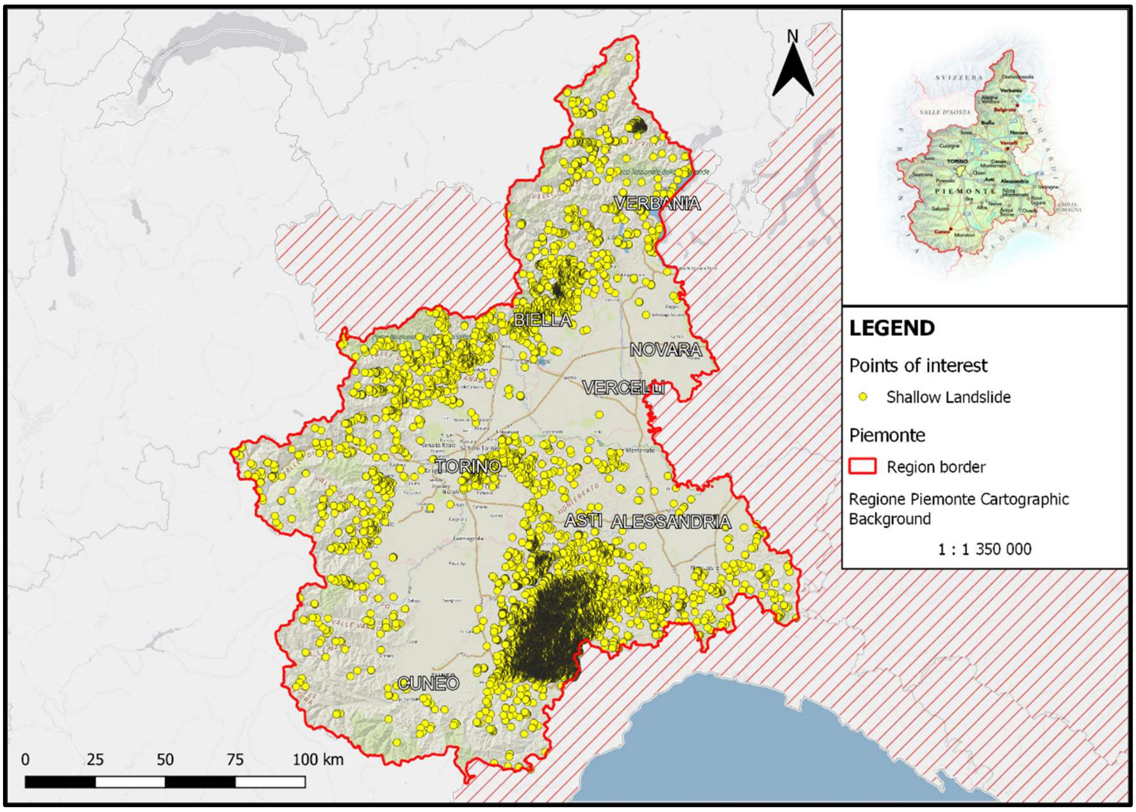


Figure 2-11 Overview of the points available from the shallow landslide databases in Piemonte

2.4.2 Type of landslides

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing. Figure 1 shows a graphic illustration of a landslide, with the commonly accepted terminology describing its features.

The various types of landslides can be differentiated by the kinds of material involved and the mode of movement. A classification system based on these parameters is shown. Other classification systems incorporate additional variables, such as the rate of movement and the water, air, or ice content of the landslide material.

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow
COMPLEX		Combination of two or more principal types of movement		

Figure 2-12 Types of landslides. Abbreviated version of Varnes' classification of slope movements (Varnes, 1978)

Although landslides are primarily associated with mountainous regions, they can also occur in areas of generally low relief. In low-relief areas, landslides occur as cut-and-fill failures (roadway and building excavations), river bluff failures, lateral spreading landslides, collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines.

Slides: Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides. Rotational slide: This is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide. Translational slide: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting. A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass.

Falls: Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs. Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

Topples: Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks.

Flows: There are five basic categories of flows that differ from one another in fundamental ways.

- Debris flow: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope. Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies. Wildfires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.

- Debris avalanche: This is a variety of very rapid to extremely rapid debris flow.

- Earthflow: Earthflows have a characteristic "hourglass" shape. The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

- Mudflow: A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles. In some instances, for example in many newspaper reports, mudflows and debris flows are commonly referred to as "mudslides."

- Creep: Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges.

Lateral Spreads: Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain. The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason. Combination of two or more of the above types is known as a complex landslide.

In conclusion, water plays a fundamental role in all types of landslides as is highlighted in many other articles including Tiranti et al. (2010, 2013, 2019, 2021).

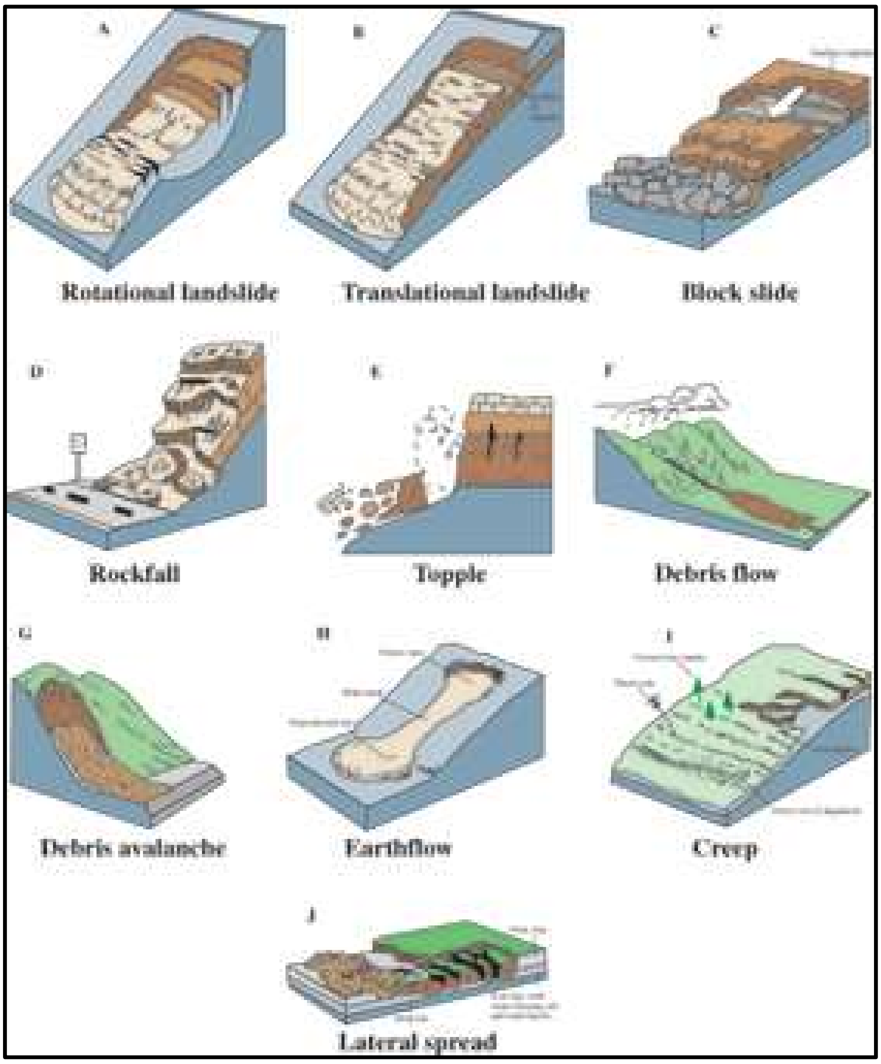


Figure 2-13 These schematics illustrate the major types of landslide movement that are described (from U.S. Department of the Interior, U.S. geological Survey)

U.S. Department of the Interior, U.S. geological Survey, July 2004 "Landslide Type and Processes", USGS.

2.4.3 Shallow landslides

Shallow landslides are a type of landslide that typically occur on slopes with a shallow soil layer, where the soil becomes saturated with water and loses its strength, causing it to move downslope. Shallow landslides can be triggered by a variety of factors, including heavy rainfall, snowmelt or changes in groundwater levels.

Shallow landslides are characterized by their relatively low velocity and the small amount of material involved. They can cause damage to infrastructure, such as roads, buildings, and utilities, and pose a risk to people living in or near landslide-prone areas.

To mitigate the risk of shallow landslides, various techniques can be employed, including slope stabilization measures, drainage systems to manage water, and vegetation management to improve soil stability. Understanding the factors that contribute to shallow landslides, such as soil type, slope angle, and rainfall patterns, is essential in developing effective mitigation strategies.

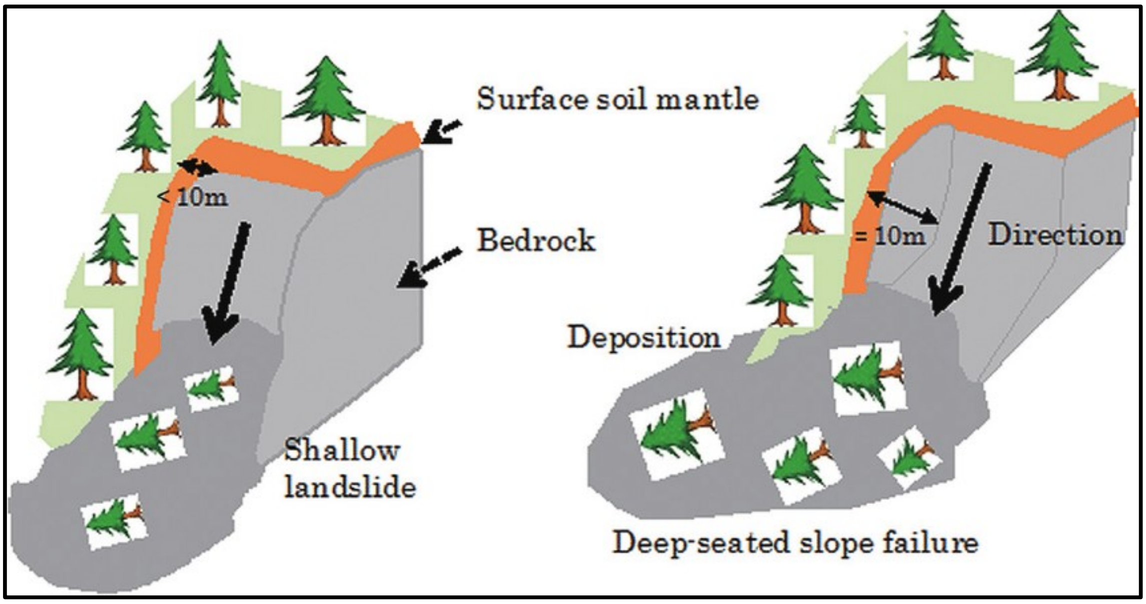


Figure 2-14 Sketch of shallow landslides (left) and deep-seated landslides (right) (modify from Shallow and Deep-Seated Landslide Differentiation Using Support Vector Machines: A Case Study of the Chuetsu Area, Japan)

3 Materials and methods

The work started with an internship (6 credits - 150 hours) at the ARPA Piemonte headquarters in Turin (Italy), where the work was conducted closely with the supervisor Dr. Davide Tiranti, at the Department of Natural and Environmental Risks.

During the first phase of the internship, bibliographic research has been conducted on articles related to the case study, followed by data analysis on databases made available by ARPA Piemonte and other sources. Then in the second phase, a new method was adopted to obtain helpful case studies, individually contacting professionals and administrations of Piemonte and making surveys.

3.1 Data

3.1.1 Step 1

The initial work focused on bibliographical research of the topics considered, including several articles such as:

News article on Emergency, 28 February 2020 "Forest fires, now fear is the hydrogeological risk: What to do in the areas that have been affected by the Civil Protection" - Consideration is given to changes in natural soil conditions caused by wildfires. In addition to the loss of fertile soil and vegetation, they can predispose phenomena of instability of the slopes, causing, in case of heavy or prolonged rainfall, the erosion of the soil and the possible initiation of landslides or sudden falling boulders.

Diandong and Lance (2020) underline some significant wildfires in 2017 in California, Montecito, which then favored the development of debris flow.

Phillips et al. (2021) say that rainfall-triggered shallow landslides is an important catchment process that affects the amount and size of sediment within river networks and creates a significant hazard, particularly when shallow landslides transform into rapidly moving debris flows.

Carabella et al. (2019) focuson the post-wildfire landslide hazard assessment, applied to the 2017 Montagna del Morrone fire. Wildfire increased the possibility of landslides triggering, as confirmed by the occurrence of a debris flow, triggered by an intense, short duration rainfall event in August 2018.

Tiranti et al. (2021) analyze the close correlation between wildfires and the occurrence of channelized debris flows that has been observed in the Western Italian Alps. Two debris flow events have been reported, after brief and localized rainfall of moderate intensity in Italy's Piemonte region (NW Italy) on 18 July 2005 in Verbania province (Pallanzeno municipality) and in June 2018 in Turin province (Bussoleno municipality). These phenomena occurred after a large portion of the catchments were affected by wide wildfires in the preceding months.

Subsequently, several databases with much information about wildfires and shallow landslides were examined to find case studies to explain the phenomena analyzed.

Information on wildfires has been obtained from the following sources:

1. MODIS (Moderate resolution imaging spectroradiometer) database cut out on the area of Piemonte, 89 firing ranges occurred from 2003 to 2022.

2. MODIS Thermal Anomalies/Fire products are primarily derived from MODIS 4- and 11-micrometer radiances. The fire detection strategy is based on absolute detection of a fire (when the fire strength is sufficient to detect), and on detection relative to its background (to account for variability of the surface temperature and reflection by sunlight). The product includes fire occurrence (day/night), fire location, the logical criteria used for the fire selection, detection confidence, Fire Radiative Power and numerous other layers describing fire pixel attributes. The product distinguishes between fire, no fire and no observation. Level 3 Daily fire products include 8 separate days of data detailing pixels according to their level of confidence as fires. This information will be used in monitoring the spatial and temporal distribution of fires in different ecosystems, detecting changes in fire distribution and identifying new fire frontiers, wildfires, and changes in the frequency of the fires or their relative strength.
3. Wildfire areas Regione Piemonte 2001-2007, polygonal shape file with 655 events all with date.
4. Wildfire areas Regione Piemonte 2008, polygonal shape file with 30 events all with date.
5. Wildfire areas Regione Piemonte 2010-2019, polygonal shape file with 1623 events all with date except 9.
6. Forest Fires – Burnt Areas and Ignition Points 1997-2021, shape file with 30 events with date (1388 areas and 6013 reported as points).
7. "Carta forestale e altre coperture del territorio (2000)" - Geoservice Web Map Service (WMS) that exposes the geographical data related to the Forest Charter and other land covers, made by Istituto Per Le Piante Da Legno e L'Ambiente

(IPLA) on the basis of data collected during the studies for the Territorial Forest Plans of the Regione Piemonte (conventionally updated to the year 2000). The geographical levels available are forest paper and other land covers, forest paper, other roofing, wooded area, linear formations.

Information on shallow landslides has been obtained from the following sources:

1. Database of unpublished shallow landslides points from ARPA Piemonte, 36127 coordinates point.
2. "Sistema Informativo Frane in Piemonte" (SIFraP) Geoportale Regione Piemonte, with related information sheets.
3. Database "Progetto Aree Vulnerabili Italiane da frane ed inondazioni" (AVI) hydrogeological disaster information system.

3.1.2 Step 2

In the second phase, the data obtained on the various case studies were acquired through direct contact with various professional experts.

In this second part of the work all the data relating to forest fires used in the first part have been reused and considered.

Many data have been collected by field surveys or by contacting several public institutions and professional companies.

All the data collected proved to be an excellent basis for future investigations into the conclusions reached through this thesis. In fact, several cases were not reported here as data and results as they would have required much more time for analysis and obtaining essential documents and information.

Basically, some of these cases required further research to gain a complete understanding of the study cases, more time to conduct on-site investigation that were not feasible due to unsuitable timing of the year and then much more analysis.

3.2 Tools

Data were processed mainly using Quantum QGis; Microsoft Excel was used for creating tables, explanatory charts and statistical analyses.

In QGis, in addition to the different links and WMS services, the tools of "Geoprocessing Tools" and "Data Management Tools" accessible from the "Vector" section have been used. These have allowed most of the graphic and spatial processing through the commands "Clip", "Buffer", "Intersection", “Merge” and more.

It was also helpful "Join attributes by spatial location" to get all the information regarding a certain point when the layers were multiple.

The Processing Toolbox also was used with the command "Raster analysis" and "Sample raster values" to get helpful information from raster files.

The "Field calculator" has been widely used to get more valuable information from the available data.

Finally, QGis was used to set up all the necessary frames and maps.

Excel has been primarily used, especially within the first step, for some selection and conditioning functions ("FILTER" and " XLOOKUP") to create simple algorithms that can automatically select the necessary data and to create explanatory summary tables.

3.3 Methods

3.3.1 Step 1

As already explained, the first part of the work was initially focused on bibliographic research and breaking down the databases, fundamental steps to understand the topics covered and the possible data available.

Therefore, the work's main objective was to search for a possible correlation between these phenomena, wildfires and shallow landslides through a careful analysis of the available data.

This argument is important to clarify an issue repeatedly reported as established in other geographical areas. There is currently no scientific evidence in Piemonte to demonstrate or contradict this relationship.

A very schematic approach was used to tackle the work. The available databases on both wildfires and landslides were analyzed on QGis. Regarding wildfires, numerous very reliable shapefiles were available, but they were structured differently from each other. Furthermore, during the analysis, it became clear that a data source often contained some unique information but many duplicates, which were also present in other shapefiles. A large part of the initial work was dedicated to the rearrangement of such data into a single compact file, and the search and elimination of duplicate wildfire areas reported more than once since there is no single database that really contains all the available data from 1997 to 2022, which is the period considered.

Due to the large amount of data, a similar but more complex procedure was used to analyze data on shallow landslides.

Actually regarding shallow landslides, the available databases were much larger and disorganized, coming from various and different sources. For this reason, it was necessary to subdivide them to proceed, even though this prolonged the time required for the analysis.

For the elaborations, QGis was used again, within which, referring to Istituto Nazionale di Statistica (ISTAT) data, the various elaborations were divided by Provinces. This method has been proper to divide the data to be processed and reduce the computing power required by the computer.

After a considerable effort in organizing the data, it was possible to perform an initial intersection between the landslide points data and all the previously considered wildfire areas in Piemonte. The initial analysis focused only on spatial overlap.

The last step was to verify the temporal correlation by searching for overlaps where the wildfire occurred before the landslide, resulting in only two valid correlations in the city of Loreglia, in the province of Verbano Cusio Ossola: the wildfire of February 2008 and the landslides of May and September 2008. Despite exploring the internet and contacting various municipal and technical administrations, unfortunately, no documentation on this matter could be found.

Other sources were considered for shallow landslides to enrich the database, like the Inventario dei Fenomeni Franosi in Italia "IFFI", "ISPRA", "SIFRAP", and "Progetto AVI", and similar analyses were conducted.

Nothing more has been achieved.

3.3.2 Step 2

Following the work carried out in the first phase several critical issues have been identified. It became clear that a change in approach was necessary due to insufficient and incomplete data.

However, the preliminary data analysis has allowed laying the basis for further analysis to obtain more accurate results.

A completely different approach was thus chosen: instead of starting with landslides and searching for the intersection with wildfire areas and thereafter verifying if there was a real correlation, the underlying logical process was reversed.

That was made possible by starting from a general overview of the situation of wildfires in Piemonte, a very reliable and available source of information regarding what has happened in the last 20 years.

It was noted that most events are located within the entire Alpine arc, an interesting area to study because of its typical steepness. Therefore, an effort was made to identify the areas with the highest concentration of wildfires, both in terms of occurrence and extension.

At this point, the idea arose of dividing the Alpine arc into well-defined and distinguishable macro-areas to facilitate subsequent research and categorization.

The following areas were thus selected:

Zone 1: Val Susa (TO), Val Chisone (TO), Giaveno (TO), Pinerolo (TO).

Zone 2: Canavese (TO), Gran Paradiso National Park (TO), Orco and Chiusella Torrent (TO), Ivrea (TO).

Zone 3: Ivrea (TO), Biella and the Alps of Biella (BI), Borgosesia (VC), Monte Barone (BI).

Zone 4: Lago Maggiore (VB), Verbano Cusio Ossola (VB).

After identifying the areas, the most time-consuming part of the entire work began, namely, contacting every single municipality in these areas, forest technicians, the barracks of the firefighters, the sections of the CAI and AIB, geological and engineering offices of each zone, and all the documentation available online.

This approach slowed down the research but also allowed for achieving results.

Ultimately, however, a screening was made of some of the most representative cases of the investigated phenomenon, which led to unexpected conclusions compared to the assumptions with which the work had started.

Subsequently, to provide a comprehensive analysis of the work performed, after identifying the case study areas, we examined how and to what extent the rainfall events influenced the considered events.

Regarding the rainfall analysis, reference rainfall data was extracted for each area considered. This was accomplished through the use of information and data provided by ARPA Piemonte and processed using QGis and Excel.

To obtain the data, the rain gauges distribution shapefiles and the meteorological database of ARPA Piemonte were used.

4 Results

4.1 Step 1

The results from the first part of the work were not exhaustive and statistically justifiable. However, they have allowed a better understanding of the current system, but some overviews of the work carried out are given as explanations, helpful in understanding the work done.

During the time dedicated to the initial phase, numerous analyses were performed, which were subsequently integrated with new data and information whenever a new database was found, or an error was discovered within those previously analyzed.

Regarding shallow landslides, in particular starting from the database provided confidentially by ARPA Piemonte, were analyzed initially 36’127 points corresponding to a shallow landslides.

As a result of the initial processing and organization, it was noticed that there were duplications in the database and cleaning it up resulted in 35’799 valid landslide points out of 36’127 initially identified. These steps are crucial in undertaking a robust and reliable statistical analysis. However, not all these points contained triggering dates, which is fundamental for conducting the research. Therefore, removing all the elements without dates resulted in 33’987 valid points.

However, to better understand the distribution of shallow landslide points in Piemonte, the analysis started from the 35’799 landslides, keeping even those without an occurrence date. The reason is explained later.

As a result of the first spatial intersection, all landslide points previous 1997 have not been considered since the wildfires data available start from 1997 onwards.

That significantly reduced the amount of data to work with, as about 17'000 shallow landslide points refer to the disastrous rainfall eventy of November 1994, which caused significant damage throughout the Piemonte, particularly in the Langhe area in the province of Cuneo (south Piemonte).

A large number of landslide points were added on the same day and in extremely close positions.

That event not only happened before 1997 and they were deemed unreliable but has affected an area not particularly subject to significant wildfires. Therefore, it is not important for the current research.

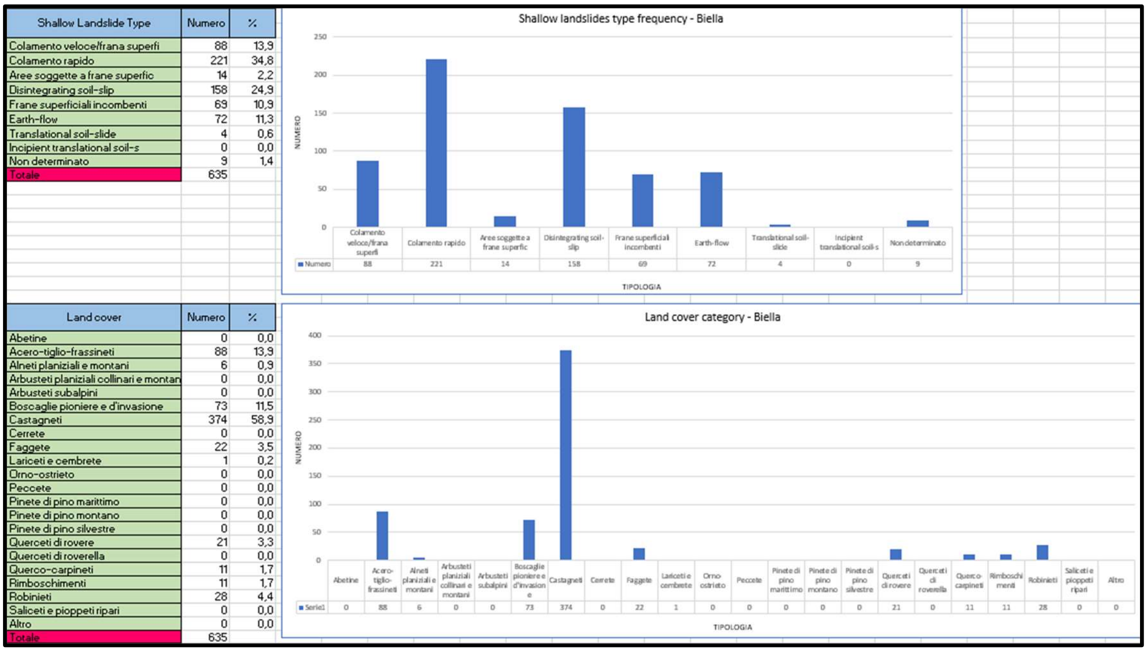
Of the remaining landslide points that overlapped with a wildfire area, only 182 points were obtained.

Among these 182 points just 27 have dates.

The reason why the intersections were held even if they did not have the dates of landslides occurrence is because, subsequently, an extensive online search was conducted on each of them, as it is known the location, in the hope of being able to find documentation that links the event to a date.

Correlation between Shallow Landslides and Wildfires						
	Shallow Landslide Area Km^2	Area burned at least 1 time m^2	N° Landslides	N° Landslides/Km^2	Spatial correlation	Temporal correlation
Alessandria	3563	10.390.463	531	0,149	1	0
Asti	1510	421.959	1.595	1,056	7	0
Biella	913	58.048.774	931	1,020	39	0
Cuneo	6899	42.113.509	30.662	4,445	292	0
Novara	1342	5.018.450	55	0,041	1	0
Torino	6828	180.995.899	1.334	0,195	38	0
Verbano Cusio Ossola	2264	37.649.561	889	0,393	12	2
Vercelli	2082	19.363.401	130	0,062	0	0
Total	25.401	354.002.016	36.127		390	2

Figure 4-1 Results of first attempt to analyse the correlation between Shallow Landslides and Wildfires before the database was fixed.



Shallow Landslide Type	Numero	%
Colamento veloce/frana superfi	88	13,9
Colamento rapido	221	34,8
Aree soggette a frane superfic	14	2,2
Disintegrating soil-slip	158	24,9
Frane superficiali incombenti	69	10,9
Earth-flow	72	11,3
Translational soil-slide	4	0,6
Incipient translational soil-s	0	0,0
Non determinato	9	1,4
Totale	635	

Land cover	Numero	%
Abetine	0	0,0
Acero-tiglio-frassineti	88	13,9
Alneti planiziali e montani	6	0,9
Arbusteti planiziali collinari e montan	0	0,0
Arbusteti subalpini	0	0,0
Boscaglie pioniere e d'invasione	73	11,5
Castagneti	374	58,9
Cerrete	0	0,0
Faggete	22	3,5
Lariceti e cembrete	1	0,2
Orno-ostrieto	0	0,0
Peccete	0	0,0
Pinete di pino marittimo	0	0,0
Pinete di pino montano	0	0,0
Pinete di pino silvestre	0	0,0
Querceti di rovere	21	3,3
Querceti di roverella	0	0,0
Querco-carpineti	11	1,7
Rimboschimenti	11	1,7
Robinieti	28	4,4
Saliceti e pioppeti ripari	0	0,0
Altro	0	0,0
Totale	635	

Figure 4-2 Data obtained for Biella on Shallow Landslides, along with Land Cover analysis.

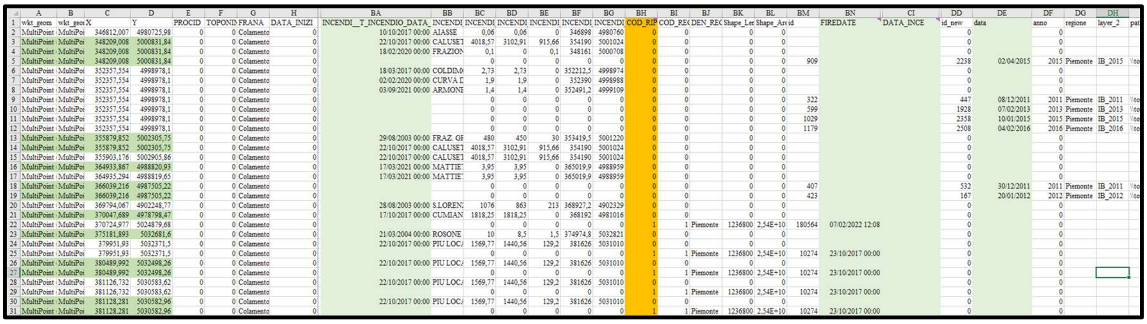


Figure 4-3 An example of the Excel processing of the 182 spatial overlapping points from multiple databases, which were cleaned of duplicate fire date entries

All these analyses have allowed us to identify the gaps and issues affecting the ARPA Piemonte’s landslide database, highlighting several areas in which database can be improved. As previously mentioned, all the work carried out within step 1 is undoubtedly useful as a starting point for further research.

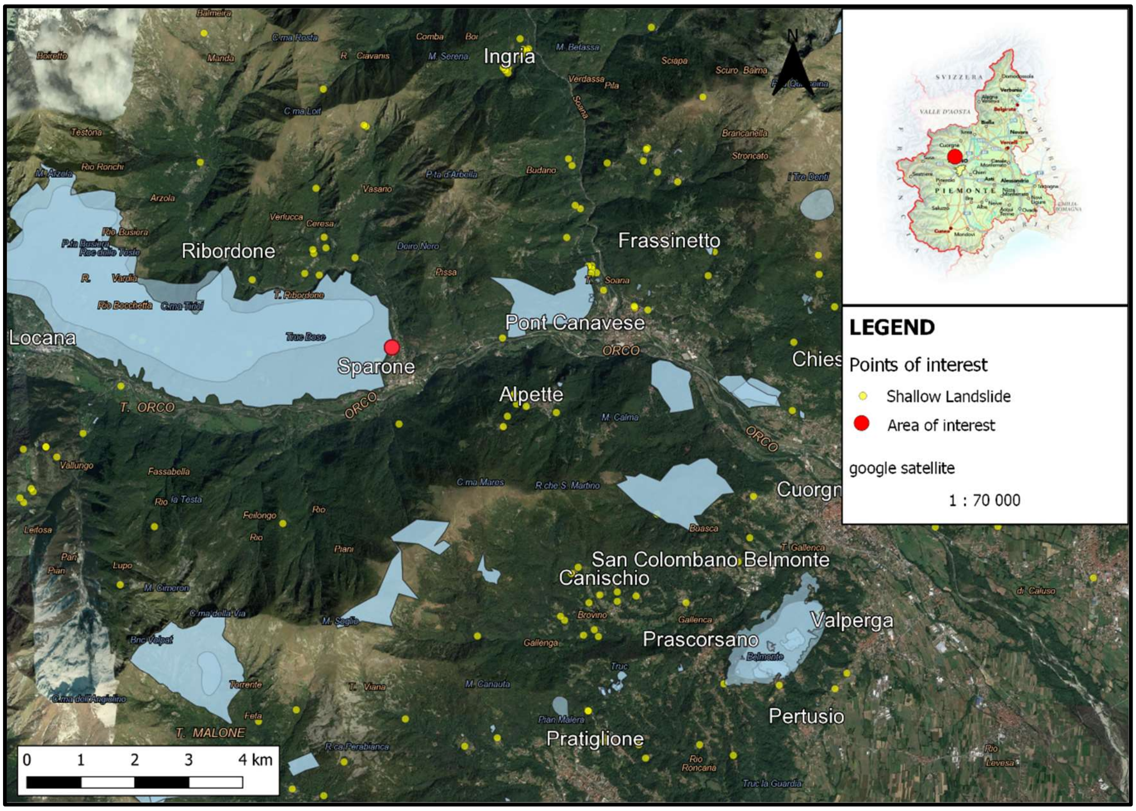


Figure 4-4 Example overview of the data processing, representing the points where there is spatial overlap between Shallow Landslides and Wildfire areas, without considering dates.

4.2 Step 2

The following are the most significant results obtained through the research conducted.

They are the result of professionals' considerations, and inspections carried out personally in the areas of interest.

As previously stated, these results are the product of intense and lengthy work over several weeks, highlighting the importance of maintenance that should be carried out on forested slopes following a wildfire.

That is because, for various reasons, the slope becomes weakened and more prone to triggering landslides.

4.2.1 Natural Park Monte Tre Denti - Freidour

4.2.1.1 Introduction

On January 17, 2023, an on-site survey was organized in collaboration with the Department of Parks and Protected Areas of the Metropolitan City of Turin. The full-day survey occurred inside the Natural Park Monte Tre Denti – Freidour, near the town of Cumiana (TO).

Several department technicians with different professional derivations have thus contributed describing the history of the park and the series of events that took place over the years.

That made it possible to gather a great deal of information, personally examine the places affected by wildfires and landslides, carry out a rich photographic documentation then integrated with the databases of the Protected Areas.

The system of Protected Natural Areas of the Metropolitan City of Turin consists of six Natural Parks and two Nature Reserves that, protecting and safeguarding an extensive portion of the province, allow one to enjoy natural beauty and landscapes of high environmental value: the Colle del Lys, Conca Cialancia, Lake Candia, Mount S.Giorgio, Mount Tre Denti - Freidour, the Rocca di Cavour, Pelati Mountains and the Pond of Oulx.

4.2.1.2 Territorial framework

The shape of the Tre Denti di Cumiana can be recognized even from a great distance and strongly characterizes the landscape of the Provincial Park, which embraces part of the head of the Chisola torrent basin and a small part of the Sangone basin.

The vegetation is noteworthy because, in addition to the tree species typical of the transitional environment between hills and mountains, such as beech, birch, linden, maple, laburnum, mountain ash and rowan, chestnut, oak, black alder and hazel, there are some specimens of Mediterranean species such as Quercus crenata and Quercus ilex (holm oak). Among the floristic species is the presence of the lily of San Giovanni, the martagon lily and the endemic Campanula elatines.

Figure 4-5 Natural Park Monte Tre Denti – Freidour (from https://it.wikipedia.org/wiki/Monte_Tre_Denti 19/02/2023).

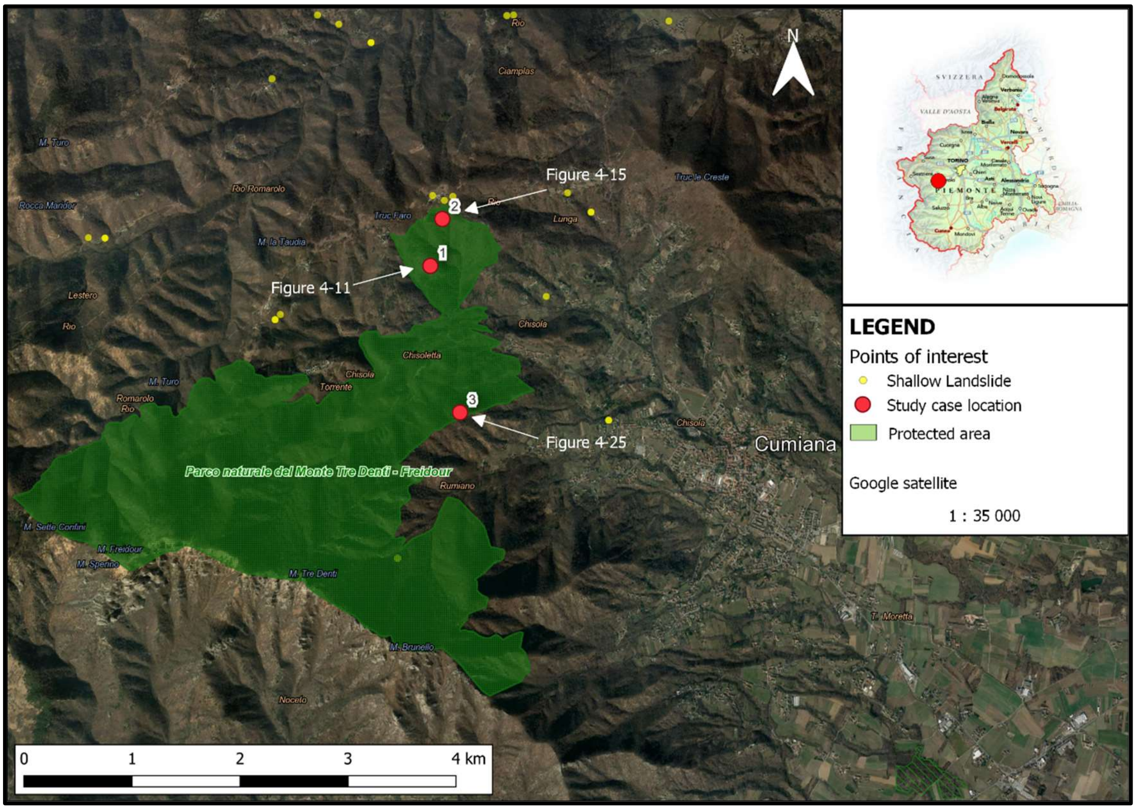


Figure 4-6 Overview of the area of interest - Natural Park Monte Tre Denti – Freidour.

The case study, red point number 3 (Figure 4-6), is positioned to show which area was investigated, in fact near the point there are hundreds of small detachment surfaces, in order to indicate a range of all these would be necessary to carry out other more thorough surveys.

4.2.1.3 Wildfire of 2015 – Shallow Landslide February 1st, 2017.

The first part of the investigation took place in an area above a forest barracks, red point number 1 (Figure 4-6). A major wildfire occurred here on April 1, 2015, and this part of the park is typically the least affected by wildfires. It should be noted that the shallow landslide was not reported in any of the analyzed databases, and that the area affected by the wildfire is much smaller than the actual extent of the phenomenon.

The area does not have a rich undergrowth and mainly consists of giant chestnut trees. Fortunately, the wildfire did not reach the canopy but only burned the lower part of the trees, saving most of them, which, however, suffered significant damage still visible today. Additionally, the soil was heavily affected, but it has returned to nearly its pre-event conditions over the years.

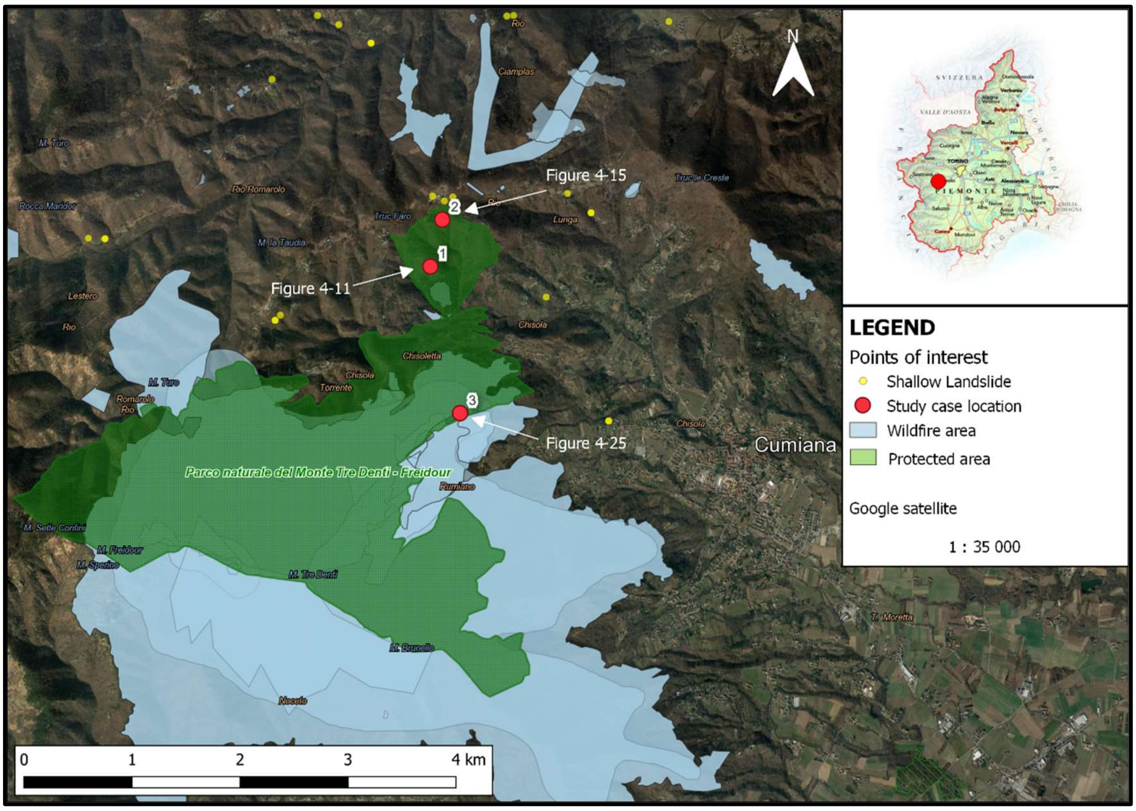


Figure 4-7 Overview area of interest - Natural Park Monte Tre Denti – Freidour

It is important to note that although wildfire data are generally better catalogued than landslides, at least for the research in question, these also report several errors.

In fact, it is evident that there is a wildfire area, a blue area, near the area of detachment of the landslide, red point number 1 (Figure 4-7), but that it does not include the landslide itself.

From the survey on field instead it is clear just the opposite, the wildfire area is much more extensive and the perimeter drawn is not correct.

The data representing the wildfires comes from the data of the Regione Piemonte from 2010 to 2019.

The shallow landslide occurred around February 1st, 2017, and the main causes can be attributed to a large group of chestnut trees that were particularly affected by the wildfire and died over time.

A determining factor was also the wind and the light rain of the area, which certainly favored the loading of the slope following non-exceptional rainfall.

Figure 4-8 Post-wildfire operations in 2015 (from Aree protette Città Metropolitana di Torino)

Figure 4-9 Survey 17 January 2023 - Evident signs of the passage of the wildfire in 2015

Part of the detachment crown and the landslide body are clearly visible both in the reference photos and in the ones taken during the inspection in 2023 (Figure 4-11).

Figure 4-10 February 2, 2017 (from Aree protette Città Metropolitana di Torino)

Figure 4-11 Current situation of the landslide detachment zone – View from above – Survey January 17, 2023

Figure 4-12 Current situation of the landslide detachment zone - valley view – Survey January 17, 2023

Furthermore, part of the logs piled up after the event can be seen. This landslide affected an infrequently visited area, damaging and causing the path below and access to the barracks to become unusable.

Figure 4-13 Some logs cut and stacked 2017 (from Aree protette Città Metropolitana di Torino)

Figure 4-14 Current situation near the detachment area – Survey January 17, 2023

Many dying plants even on the edges of the paths that should be identified and removed.

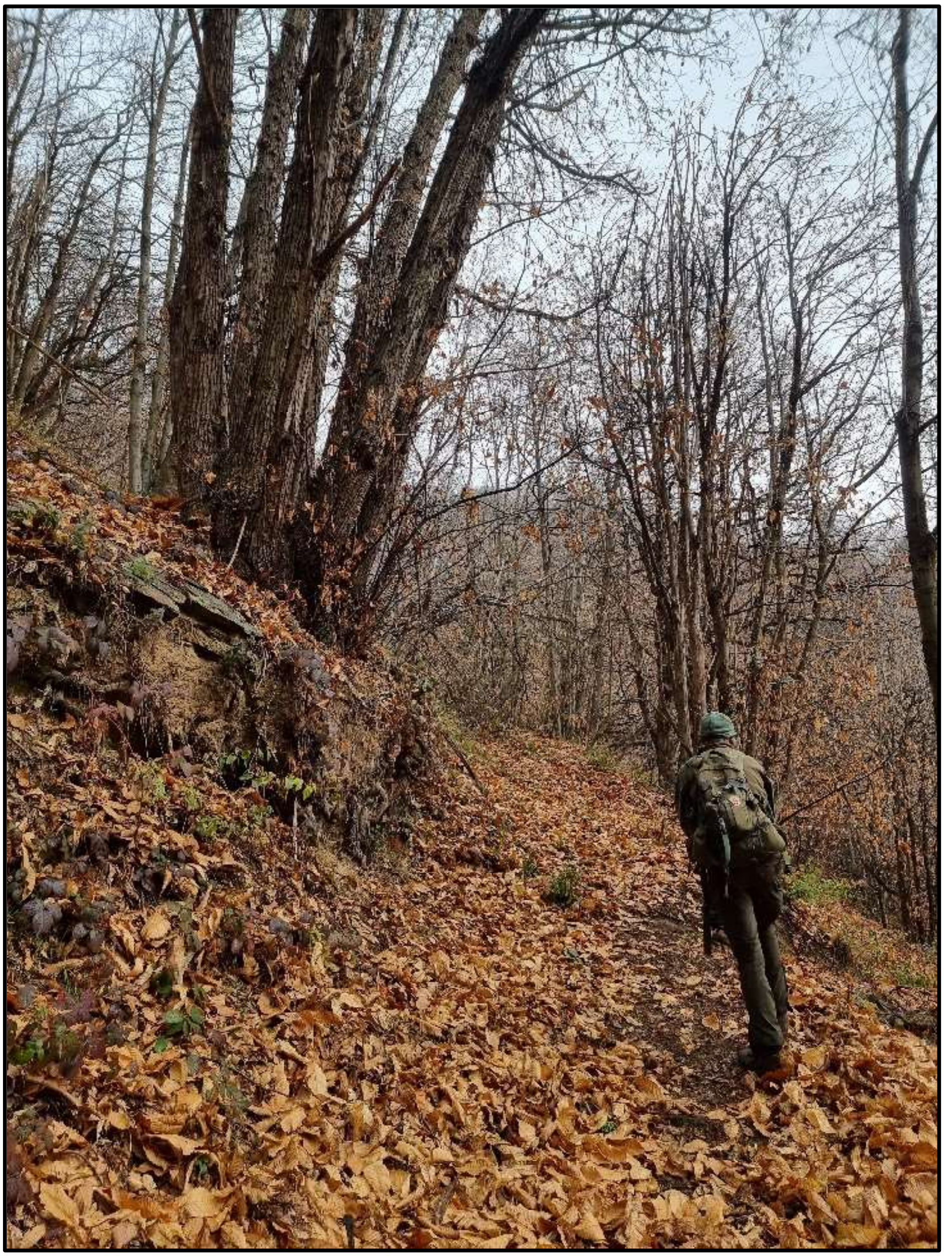


Figure 4-15 Very large chestnut completely dry – Survey January 17, 2023

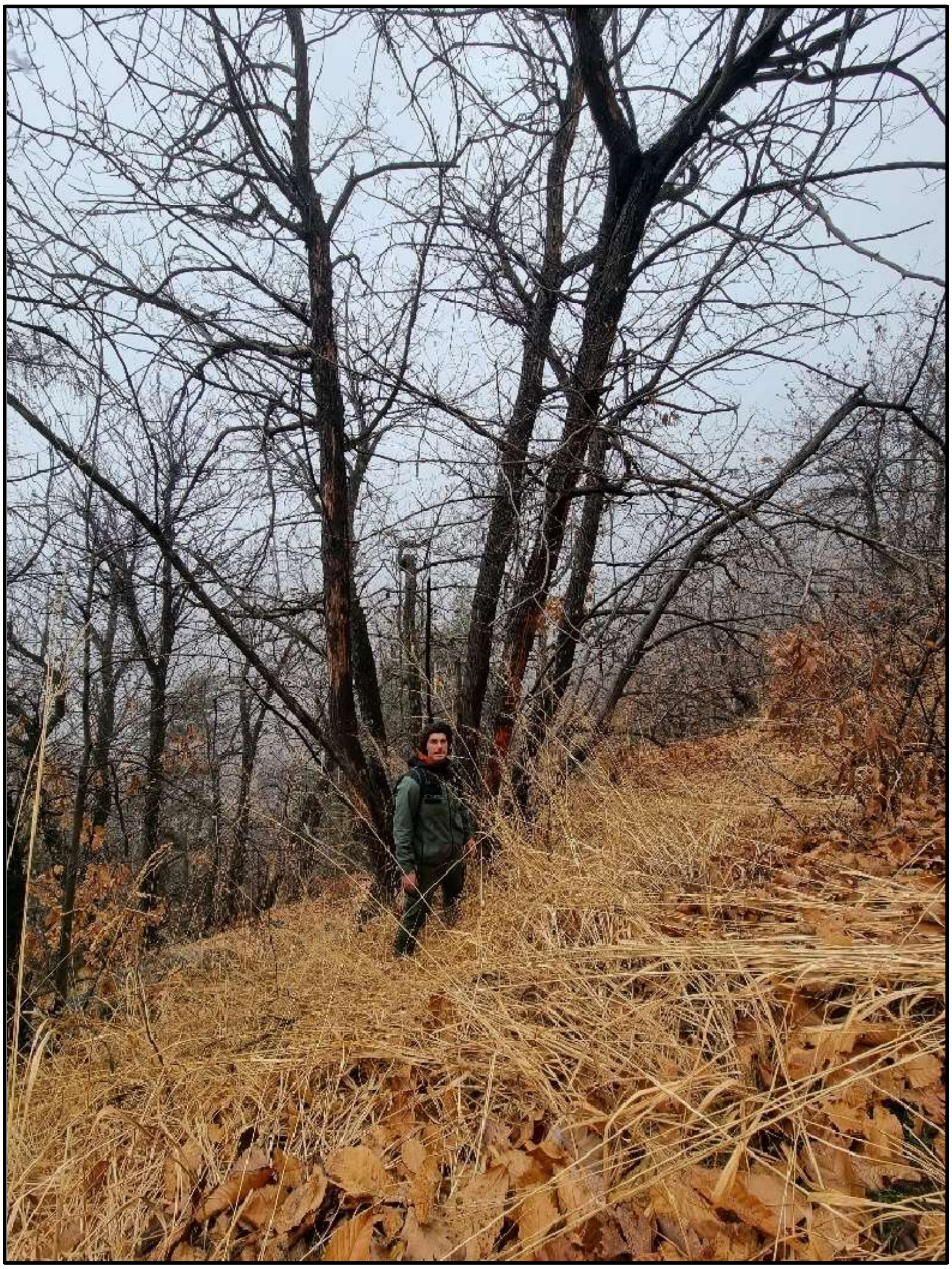


Figure 4-16 Matthew Mcdowell, 1.93 m tall compared to a dying chestnut January 17, 2023

As already mentioned, a very important factor is the phenomenon of puddle that is created when these large trees die and fall.

These large chasms create in a short time preferential routes of infiltration that can lead to the triggering of shallow landslides.

Figure 4-17 Puddle phenomenon due to recent eradication. Survey January 17, 2023.

Figure 4-18 Wildfire Monte Tre Denti Cumiana 2015 (modify from L'Eco del Chisone 19/02/2023 https://www.ecodelchisone.it/news/2015-01-04/cumiana-monte-tre-denti-incendio-cima-colle-sperina-19453)

4.2.1.4 Wildfire of 2017 - West part of Cumiana

In this other area of the park, the wildfire occurred at the end of October 2017 and lasted several days, spreading throughout the park and beyond, encompassing a very large area. Although mostly surface wildfires and creeping wildfire (a slow-moving ground wildfire that burns vegetation at the surface level), it caused significant damage.

Figure 4-19 Wildfire of October 2017 Monte Tre Denti – Cumiana (modify from TorinoToday 19/02/2023 https://www.torinotoday.it/foto/cronaca/incendi-boschivi-in-provincia-23-e-24-ottobre-2017/#incendio-cumiana-cantalupa-171024.html)

Figure 4-20 Wildfire of October 2017 Monte Tre Denti – Cumiana (modify from L'Eco del Chisone 19/02/2023 https://www.ecodelchisone.it/news/2017-10-24/emergenza-incendi-presidi-notturni-cumiana-cantalupa-27917)

Strong winds allowed the flames to repeatedly flare up in the woods around Mount Tre Denti above Cumiana. The flames approached the hamlets of Ciom and Ravera, but were contained thanks to the intervention of firefighting teams. An Erickson firefighting helicopter also responded to the scene.

Figure 4-21 Survey of November 15, 2017 (from Aree protette Città Metropolitana di Torino)

The photographs clearly show the signs of wood cancer and the presence of fungi in the damaged trees. The dark base of the trees visible in the photographs is due to the signs of the passage of the wildfire.

Figure 4-22 Current situation in the wildfire area – Survey January 17, 2023

Figure 4-23 Current situation in the wildfire area - Survey January 17, 2023

Figure 4-24 Matthew Mcdowell, 1.93 m tall compared to a flipped and detached chestnut January 17, 2023

Inside the wildfire area there are many sick and collapsed trees, only some of the representative photos of the situation have been reported.

4.2.1.5 Rainfalls

In the following the results obtained for the area in question regarding the rainfalls information are presented.

Furthermore, data concerning the most severe rainfall events from the date of the wildfire to the shallow landslide events occurrence was analyzed, as well as the trend of the rainfall by referring to the near rain gauges.

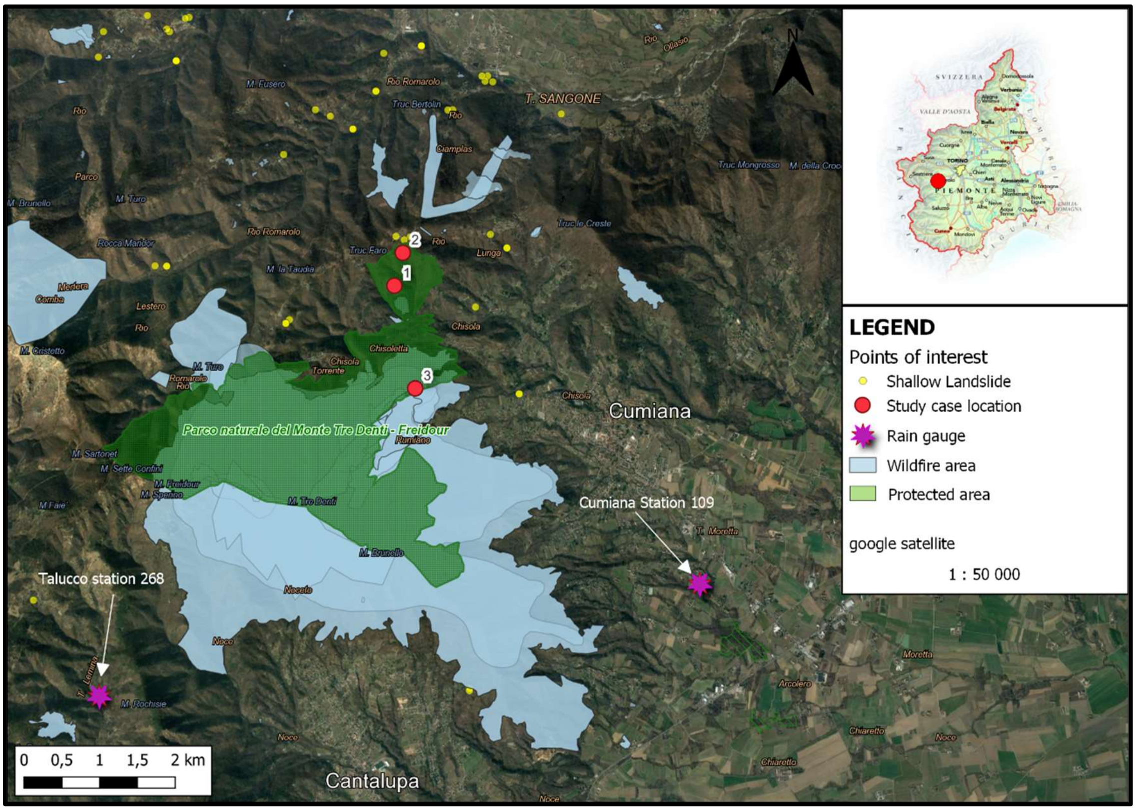


Figure 4-25 Overview of the area – Rain gauge stations

Below are the graphs representing the rainfall data of the period concerned and the most severe rainfall events that occurred between the wildfire of 1 April 2015 and the shallow landslides occurred around February 1st, 2017, the survey took place the day after.

The results obtained from the research conducted on data recorded by rain gauges sited in the natural park area are reported below. Indeed, the official website of ARPA Piemonte provides free access to both rain gauges and snow gauges data.

Often, the spatial positions of rain gauges and snow gauges do not coincide, for this reason it is necessary to formulate hypotheses regarding what might have actually occurred in the region of interest on the event dates.

Data from more than one rain gauge station has been reported to support the analyzed data and reduce uncertainty regarding the recorded rainfall values, as there could be errors due to malfunctions of weather stations.

In this case, reference is made to the Cumiana rain gauge (Figure 4-26, Figure 4-27).

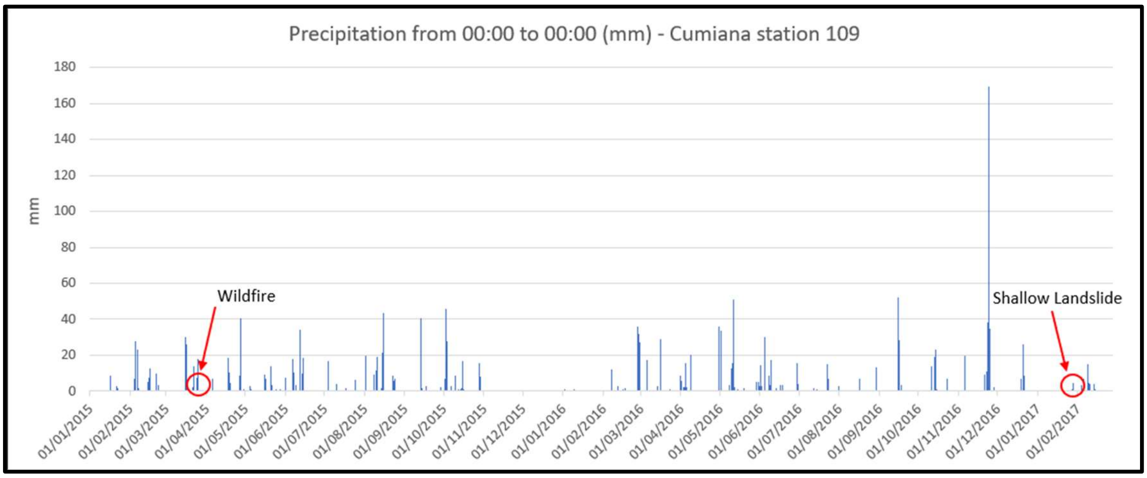


Figure 4-26 Precipitation overview from January 2015 to February 2017 – Cumiana – ARPA Piemonte data

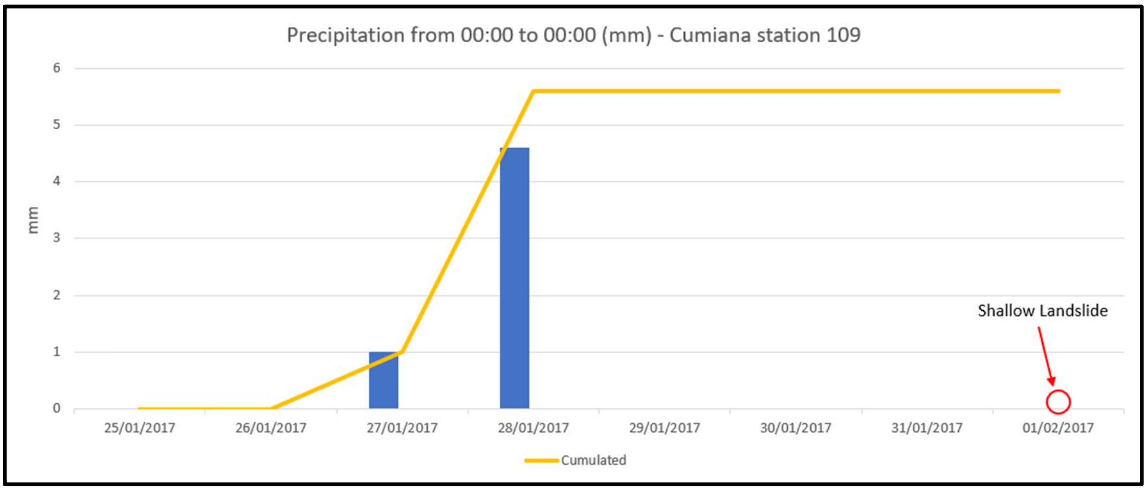
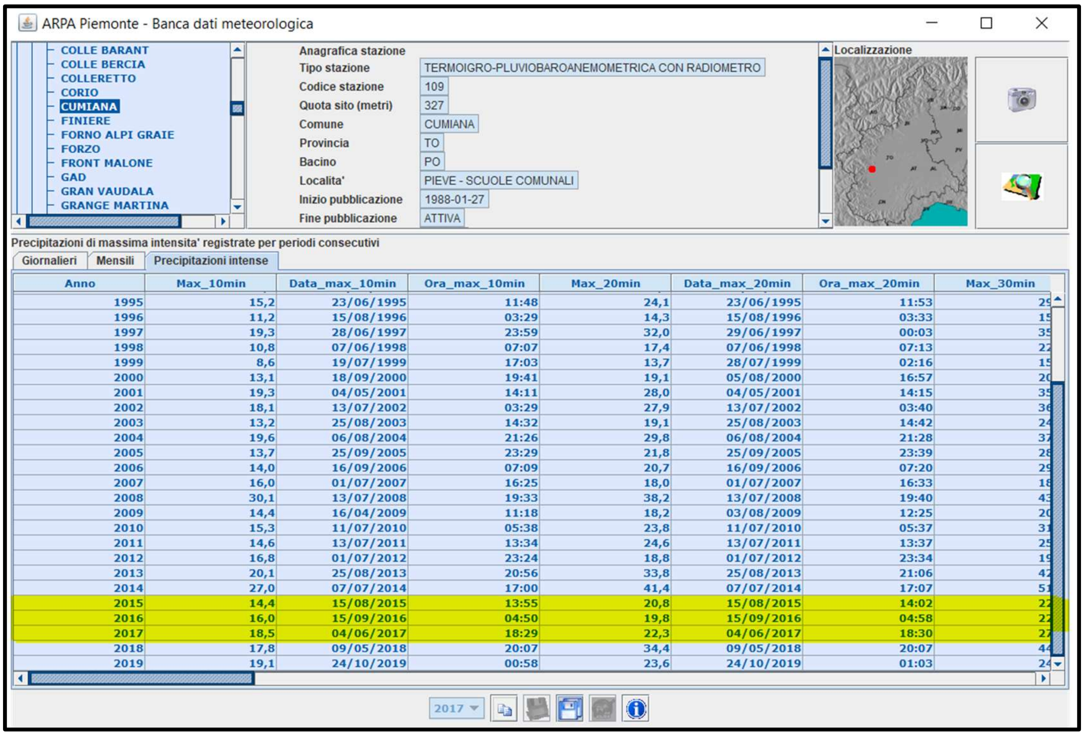


Figure 4-27 Overview of few days before the Shallow Landslide - Cumiana – ARPA Piemonte data

In addition, event reports of heavy rainfall were analyzed for each case between the wildfire period and the shallow landslide (Figure 4-28).



Anno	Max_10min	Data_max_10min	Ora_max_10min	Max_20min	Data_max_20min	Ora_max_20min	Max_30min
1995	15,2	23/06/1995	11:48	24,1	23/06/1995	11:53	29
1996	11,2	15/08/1996	03:29	14,3	15/08/1996	03:33	15
1997	19,3	28/06/1997	23:59	32,0	29/06/1997	00:03	35
1998	10,8	07/06/1998	07:07	17,4	07/06/1998	07:13	22
1999	8,6	19/07/1999	17:03	13,7	28/07/1999	02:16	15
2000	13,1	18/09/2000	19:41	19,1	05/08/2000	16:57	20
2001	19,3	04/05/2001	14:11	28,0	04/05/2001	14:15	35
2002	18,1	13/07/2002	03:29	27,9	13/07/2002	03:40	36
2003	13,2	25/08/2003	14:32	19,1	25/08/2003	14:42	24
2004	19,6	06/08/2004	21:26	29,8	06/08/2004	21:28	37
2005	13,7	25/09/2005	23:29	21,8	25/09/2005	23:39	28
2006	14,0	16/09/2006	07:09	20,7	16/09/2006	07:20	29
2007	16,0	01/07/2007	16:25	18,0	01/07/2007	16:33	18
2008	30,1	13/07/2008	19:33	38,2	13/07/2008	19:40	43
2009	14,4	16/04/2009	11:18	18,2	03/08/2009	12:25	20
2010	15,3	11/07/2010	05:38	23,8	11/07/2010	05:37	31
2011	14,6	13/07/2011	13:34	24,6	13/07/2011	13:37	25
2012	16,8	01/07/2012	23:24	18,8	01/07/2012	23:34	19
2013	20,1	25/08/2013	20:56	33,8	25/08/2013	21:06	42
2014	27,0	07/07/2014	17:00	41,4	07/07/2014	17:07	51
2015	14,4	15/08/2015	13:55	20,8	15/08/2015	14:02	22
2016	16,0	15/09/2016	04:50	19,8	15/09/2016	04:58	22
2017	18,5	04/06/2017	18:29	22,3	04/06/2017	18:30	27
2018	17,8	09/05/2018	20:07	34,4	09/05/2018	20:07	44
2019	19,1	24/10/2019	00:58	23,6	24/10/2019	01:03	24

Figure 4-28 Heavy rainfall between Wildfire and Shallow landslide

For completeness is also reported another rain gauge nearby, the Talucco rain gauge (Figure 4-29, Figure 4-30).

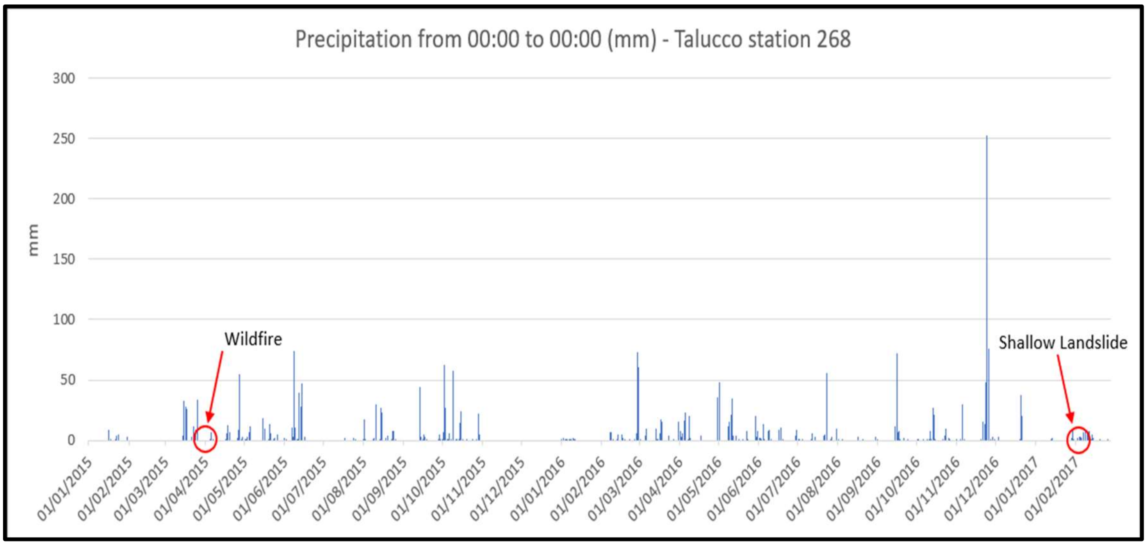


Figure 4-29 Precipitation overview from January 2015 to February 2017 – Talucco – ARPA Piemonte data

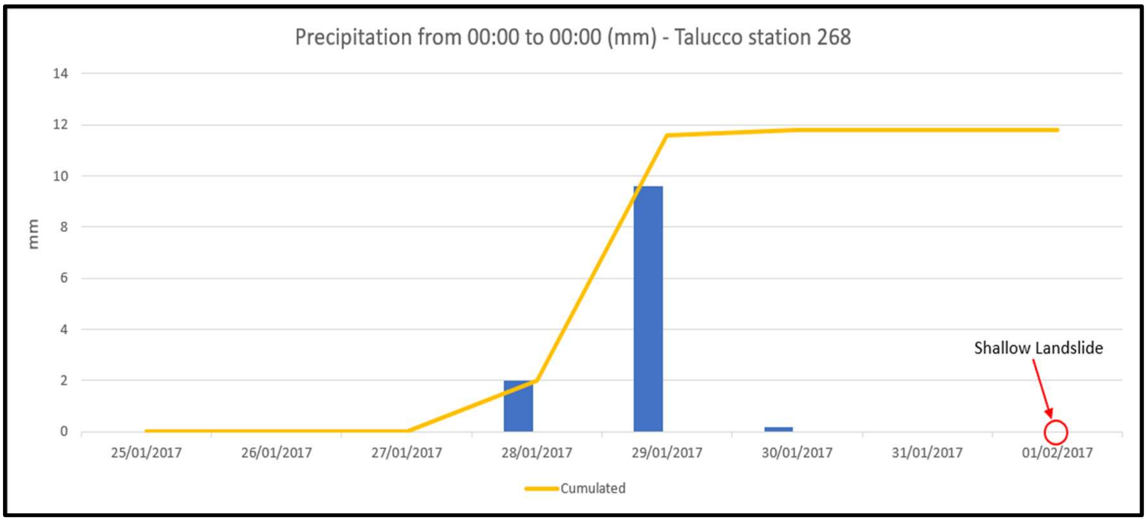
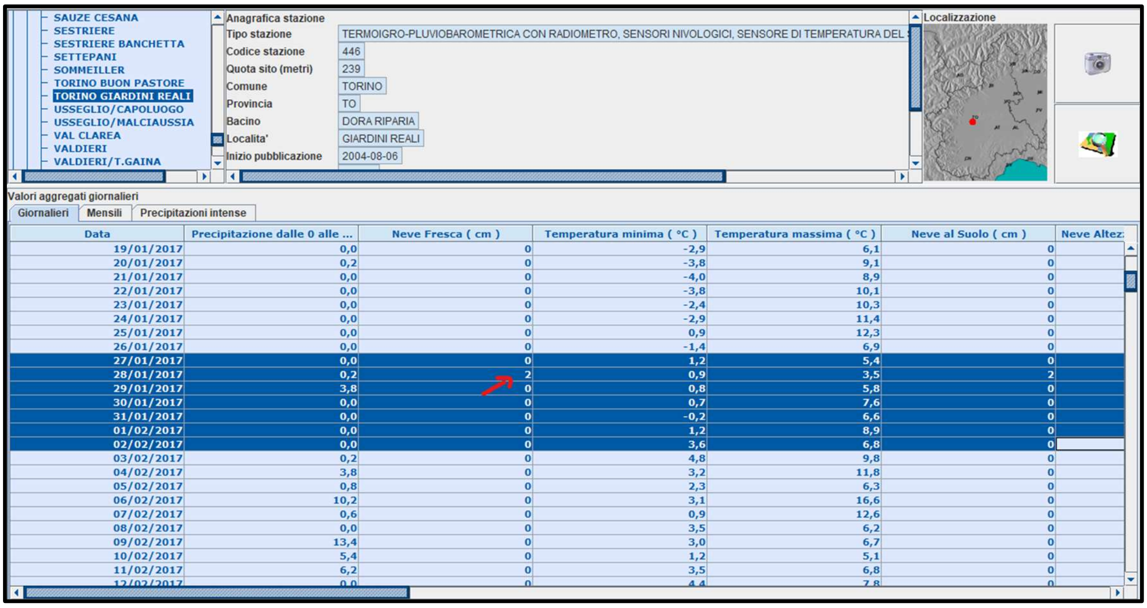


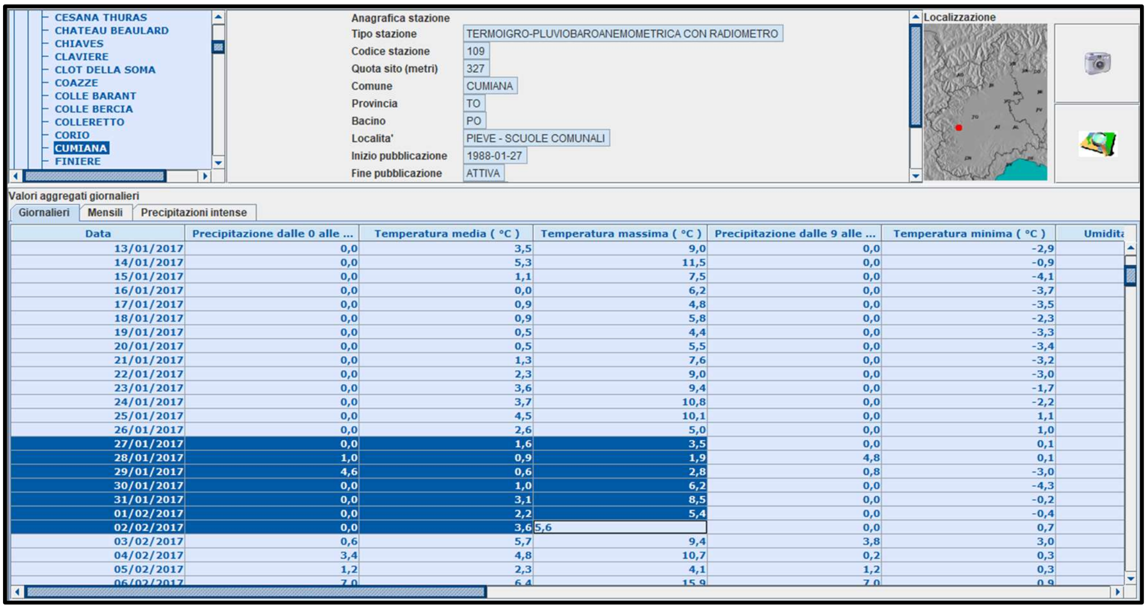
Figure 4-30 Overview of few days before the Shallow Landslide - Cumiana – ARPA Piemonte data

Below is shown an image of the snow level sensor located in Turin, along with the corresponding temperatures.



Data	Precipitazione dalle 0 alle ...	Neve Fresca (cm)	Temperatura minima (°C)	Temperatura massima (°C)	Neve al Suolo (cm)	Neve Altez
19/01/2017	0,0	0	-2,9	6,1	0	
20/01/2017	0,2	0	-3,8	9,1	0	
21/01/2017	0,0	0	-4,0	8,9	0	
22/01/2017	0,0	0	-3,8	10,1	0	
23/01/2017	0,0	0	-2,4	10,3	0	
24/01/2017	0,0	0	-2,9	11,4	0	
25/01/2017	0,0	0	0,9	12,3	0	
26/01/2017	0,0	0	-1,4	6,9	0	
27/01/2017	0,0	0	1,2	5,4	0	
28/01/2017	0,2	2	0,9	3,5	2	
29/01/2017	3,8	0	0,8	5,8	0	
30/01/2017	0,0	0	0,7	7,6	0	
31/01/2017	0,0	0	-0,2	6,6	0	
01/02/2017	0,0	0	1,2	8,9	0	
02/02/2017	0,0	0	3,6	6,8	0	
03/02/2017	0,2	0	4,8	9,8	0	
04/02/2017	3,8	0	3,2	11,8	0	
05/02/2017	0,8	0	2,3	6,3	0	
06/02/2017	10,2	0	3,1	16,6	0	
07/02/2017	0,6	0	0,9	12,6	0	
08/02/2017	0,0	0	3,5	6,2	0	
09/02/2017	13,4	0	3,0	6,7	0	
10/02/2017	5,4	0	1,2	5,1	0	
11/02/2017	6,2	0	3,5	6,8	0	

Figure 4-31 Overview of the snow levels and temperature the days on which the shallow Landslide occurred – Torino Giardini Reali – ARPA Piemonte data



Data	Precipitazione dalle 0 alle ...	Temperatura media (°C)	Temperatura massima (°C)	Precipitazione dalle 9 alle ...	Temperatura minima (°C)	Umidità
13/01/2017	0,0	3,5	9,0	0,0	-2,9	
14/01/2017	0,0	5,3	11,5	0,0	-0,9	
15/01/2017	0,0	1,1	7,5	0,0	-4,1	
16/01/2017	0,0	0,0	6,2	0,0	-3,7	
17/01/2017	0,0	0,9	4,8	0,0	-3,5	
18/01/2017	0,0	0,9	5,8	0,0	-2,3	
19/01/2017	0,0	0,5	4,4	0,0	-3,3	
20/01/2017	0,0	0,5	5,5	0,0	-3,4	
21/01/2017	0,0	1,3	7,6	0,0	-3,2	
22/01/2017	0,0	2,3	9,0	0,0	-3,0	
23/01/2017	0,0	3,6	9,4	0,0	-1,7	
24/01/2017	0,0	3,7	10,8	0,0	-2,2	
25/01/2017	0,0	4,5	10,1	0,0	1,1	
26/01/2017	0,0	2,6	5,0	0,0	1,0	
27/01/2017	0,0	1,6	3,5	0,0	0,1	
28/01/2017	1,0	0,9	1,9	4,8	0,1	
29/01/2017	4,6	0,6	2,8	0,8	-3,0	
30/01/2017	0,0	1,0	6,2	0,0	-4,3	
31/01/2017	0,0	3,1	8,5	0,0	-0,2	
01/02/2017	0,0	2,2	5,4	0,0	-0,4	
02/02/2017	0,0	3,6	5,6	0,0	0,7	
03/02/2017	0,6	5,7	9,4	3,8	3,0	
04/02/2017	3,4	4,8	10,7	0,2	0,3	
05/02/2017	1,2	2,3	4,1	1,2	0,3	
06/02/2017	7,0	6,4	15,9	7,0	0,9	

Figure 4-32 Overview of rainfalls and temperature the days on which the shallow Landslide occurred – Cumiana – ARPA Piemonte data

Rainfall analyses for the natural park area affected by the 2017 wildfire are not reported due to the lack of a specific reference date for the numerous shallow landslides that occurred within the area following the wildfire.

4.2.2 Sacro Monte di Belmonte - Canavese

Overlooking the vast panorama of the Turin plain and the Alpine views of the Canavese, the Sacro Monte di Belmonte (Figure 4-33) is the most recent of the Sacri Monti del Piemonte included in the UNESCO site, created to integrate the religious offering of an ancient sanctuary dedicated to the Madonna, which dates at the beginning of the XI century.

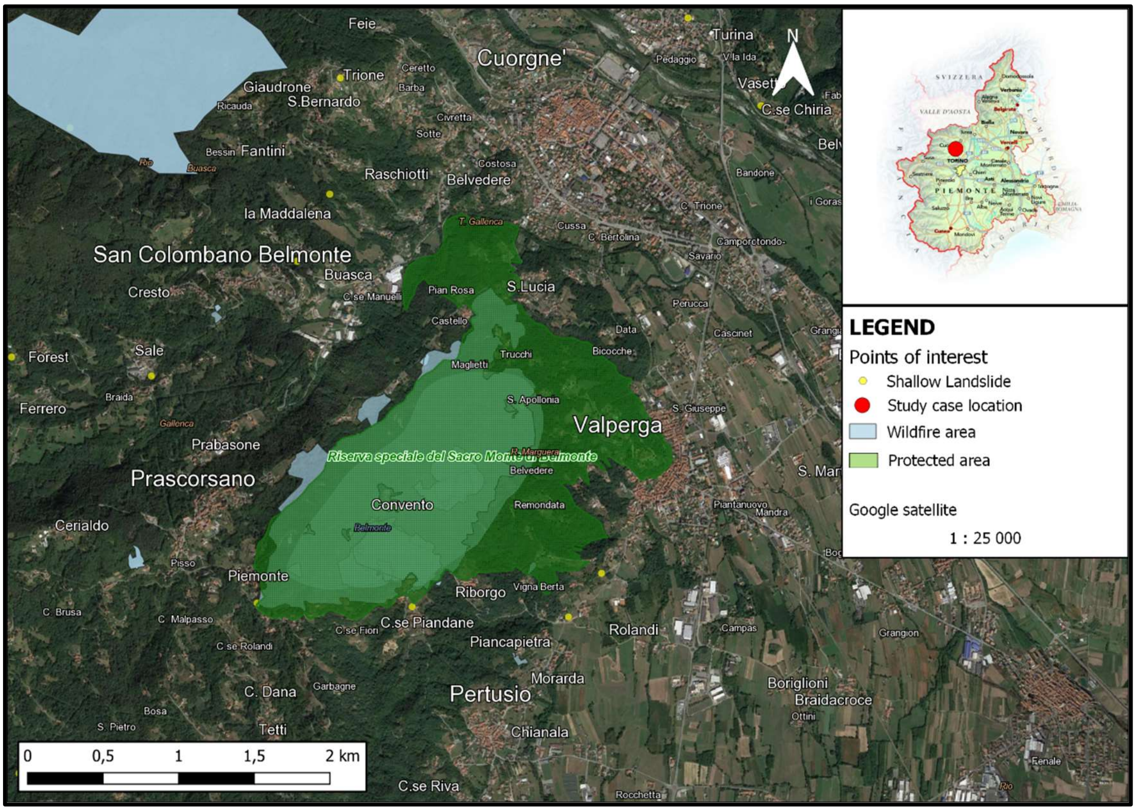


Figure 4-33 Overview area of interest – Sacro Monte di Belmonte

The redevelopment project is part of a tender issued in 2019.

The photographic documentation provided for the landslides refers to a very large period, are reported both events of 2004 and much more recent occurred in 2021.

The wildfires of greater impact and documented instead refer to different events in the years 2011, 2013, 2016, and 25 of March 2019 where almost 200 hectares were burned.

According to local experts there is no doubt that the wildfires have predisposed these phenomena and that several criticalities have accumulated over the years.

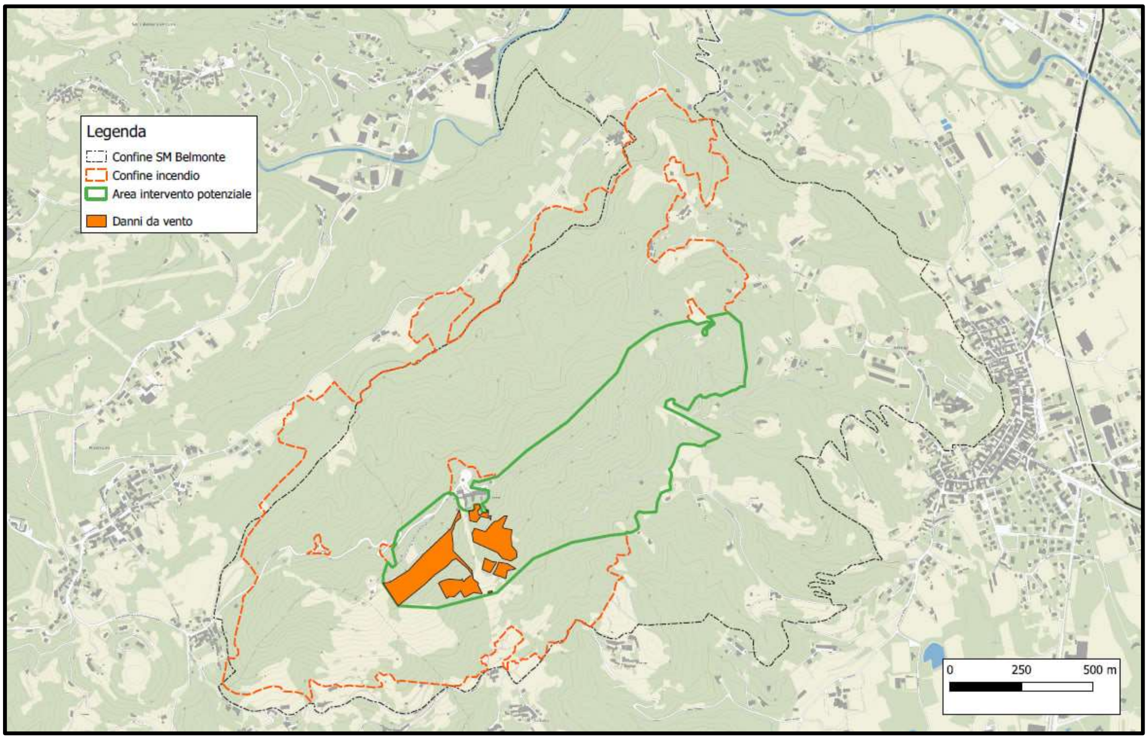


Figure 4-34 Cartography within the technical report for the redevelopment of the park – (from Sacri Monti PDF report)

Also in this case most of the landslides occurred and some wildfires were not reported. After contacting all the neighboring municipalities of the park, the direct number for the person responsible for managing the park's work and maintenance was obtained.

They provided a considerable amount of documentation (Figure 4-34), requalification projects, and photographic documentation. Over the years, several wildfires of varying extents have occurred within the park, not all of which have been documented, as well as several landslides of various types, including shallow landslides.

The technical report also concluded that, following on-the-spot surveys, that in high-severity areas the percentage of dead trees is such that it is necessary to cut all the stand in order to avoid the collapse of the stand on the road.

Figure 4-35 Photo within the technical report for the redevelopment of the park (from Sacri Monti PDF report)

Once again, it is evident how the presence of dead plants following wildfires plays a fundamental role in slope stability. When these plants fall, they can trigger shallow landslides, which can then evolve into debris flows under certain conditions (convergence of shallow landslides from the slopes towards channels or impluvia).

Figure 4-36 Photo within the technical report for the redevelopment of the park (from Sacri Monti PDF report)

Figure 4-37 Photo within the technical report for the redevelopment of the park (from Sacri Monti PDF report)

Figure 4-38 Photo within the technical report for the redevelopment of the park (from Sacri Monti PDF report)

Figure 4-39 Photo within the technical report for the redevelopment of the park 13/05/2021 (from Sacri Monti PDF report)

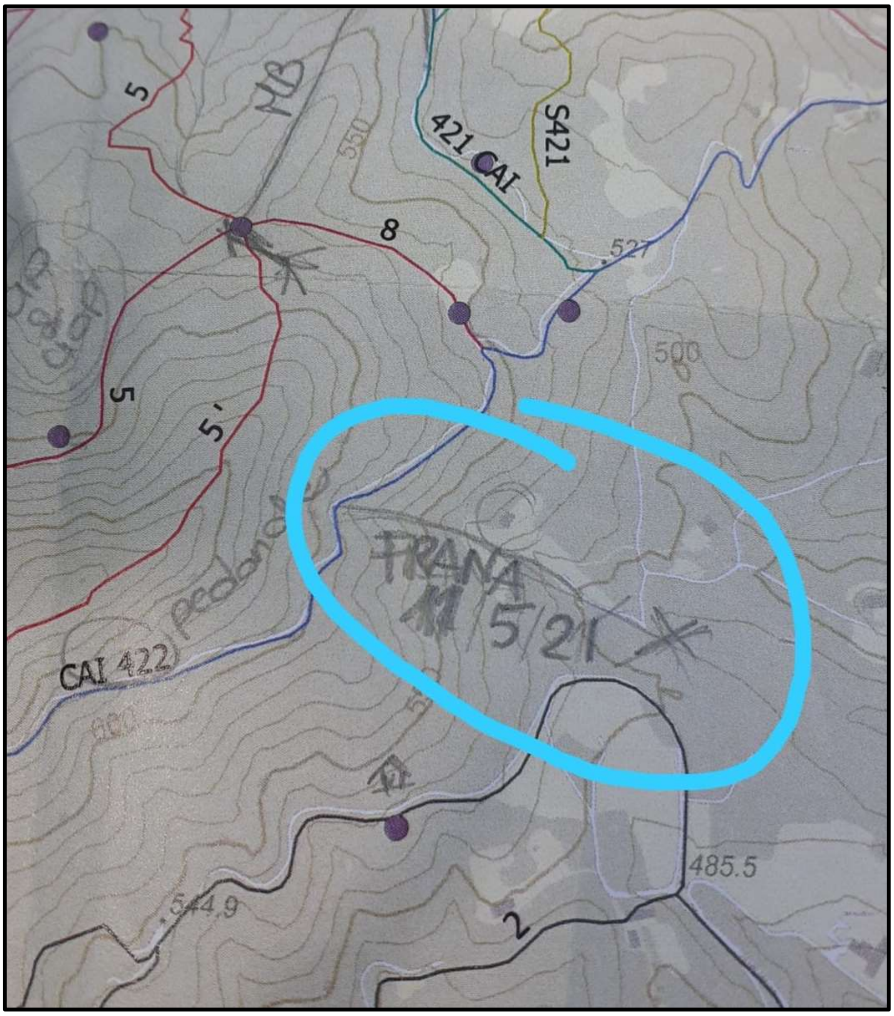


Figure 4-40 Note from the Dott. Andrea Maccioni from Sacri Monti. Reported landslide outlined by light blue contour

4.2.2.1 Rainfalls

In the following are the results obtained for the investigated area regarding the rainfall information.

Furthermore, data concerning the most severe rainfall events from the date of the fire to the dates of the shallow landslide events was analyzed, as well as the trend of the rainfall by referring to the reference rain gauge stations.

All the considerations already made in the previous section "4.2.1.5 Rainfalls" regarding the data reported here also apply to the case reported here.

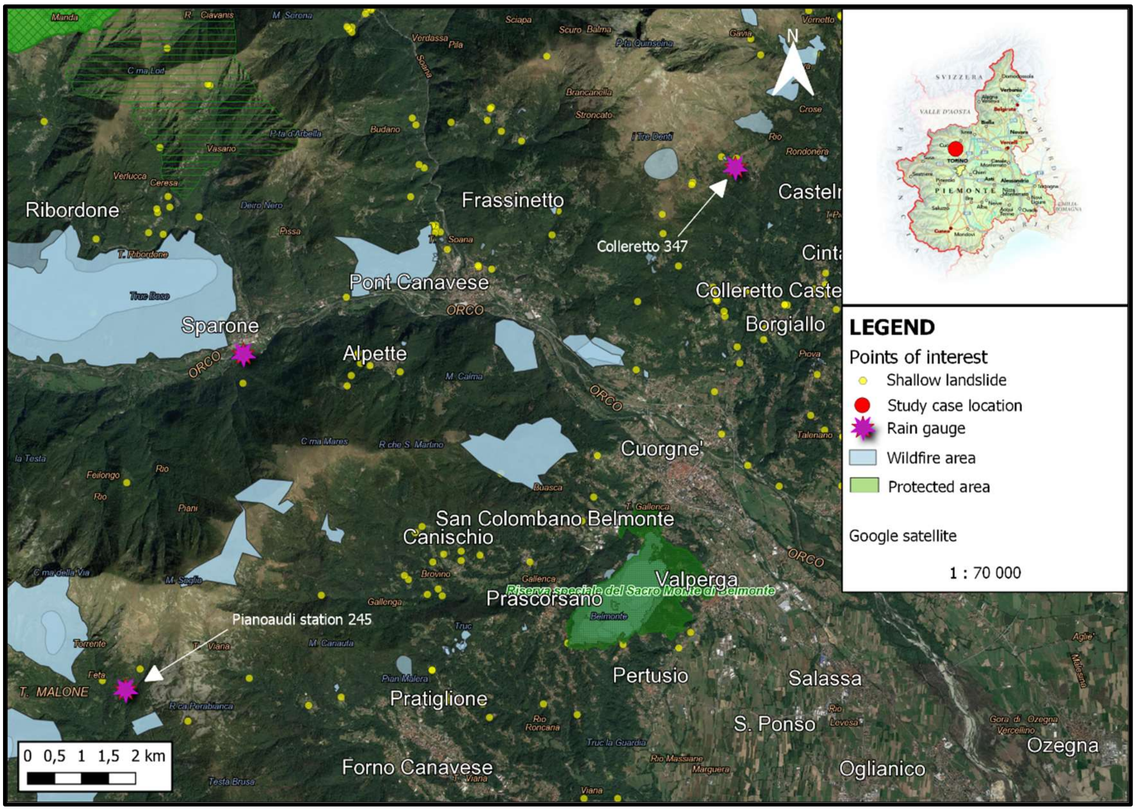


Figure 4-41 Overview of the area – Rain gauge

Below are the reference rain gauges in the area (Figure 4-42, Figure 4-44), Colleretto and Piano Audi. Only the case of May 15th, 2021 is reported because it is the only one for which official documentation was found declaring its connections with the 2019 wildfire and the precise date of the inspection.

However, as previously stated, many more landslides occurred in the area than those officially declared and catalogued. Without precise information on the dates of these events, it would be misleading to conduct a rainfall analysis.

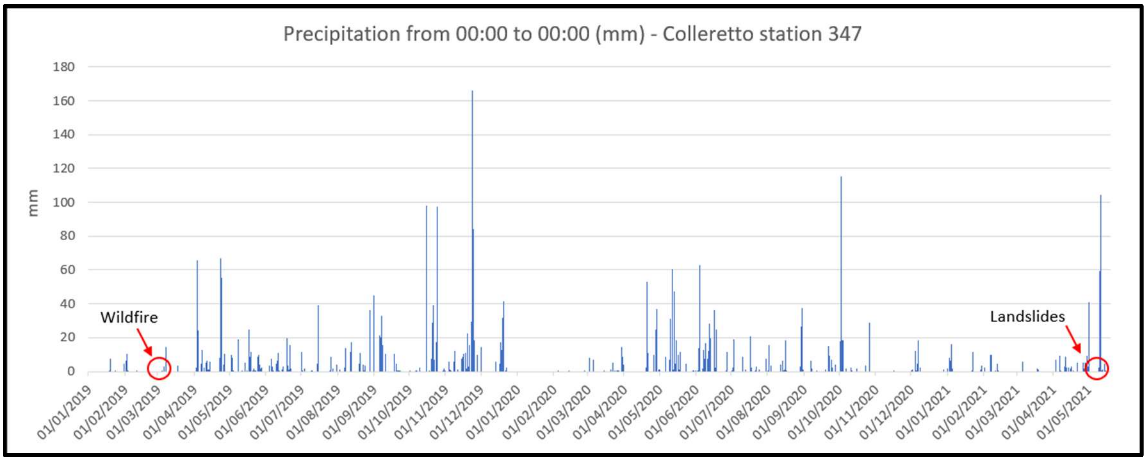


Figure 4-42 Precipitation overview from January 2019 to May 2021 – Colleretto – ARPA Piemonte data

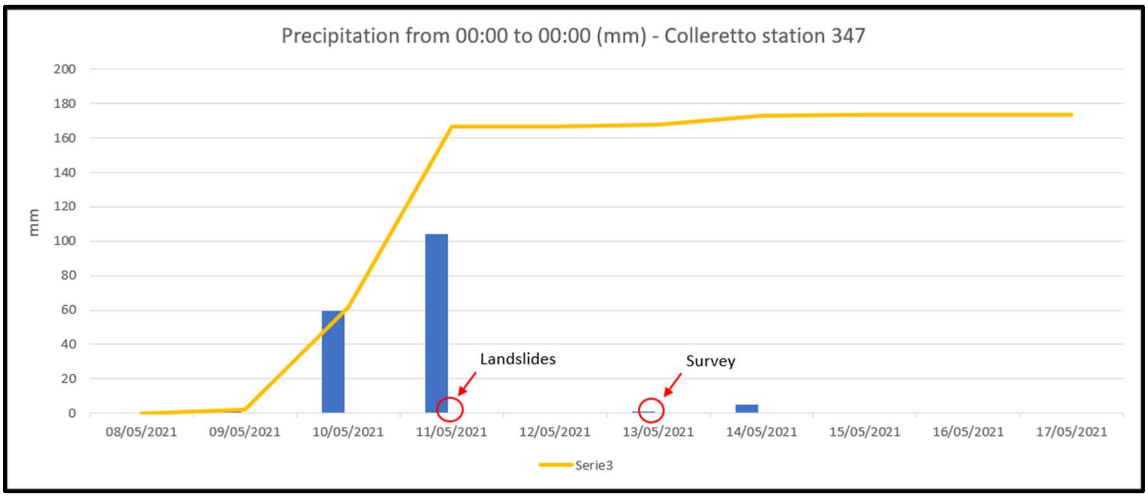


Figure 4-43 Overview of few days before the Landslides - Colleretto – ARPA Piemonte data

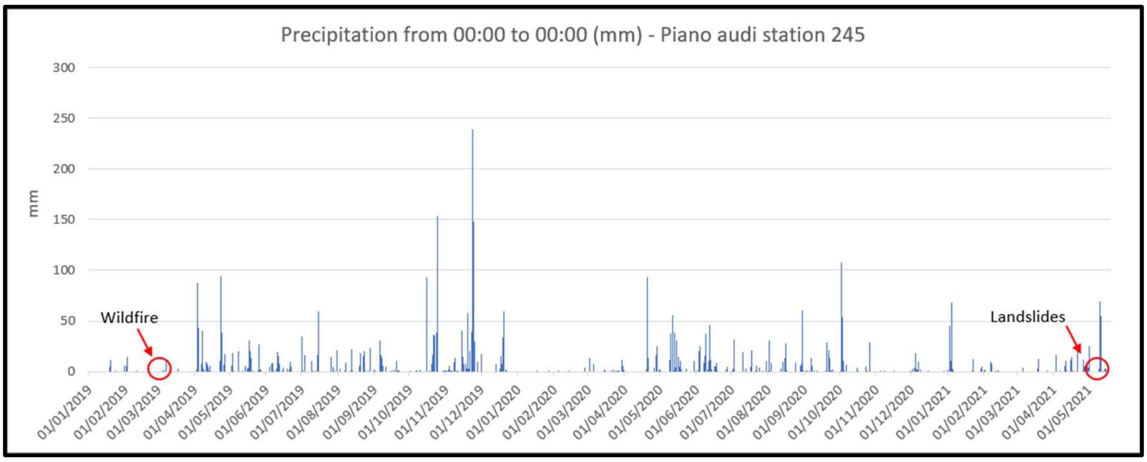


Figure 4-44 Precipitation overview from January 2019 to May 2021 – Piano audi – ARPA Piemonte data

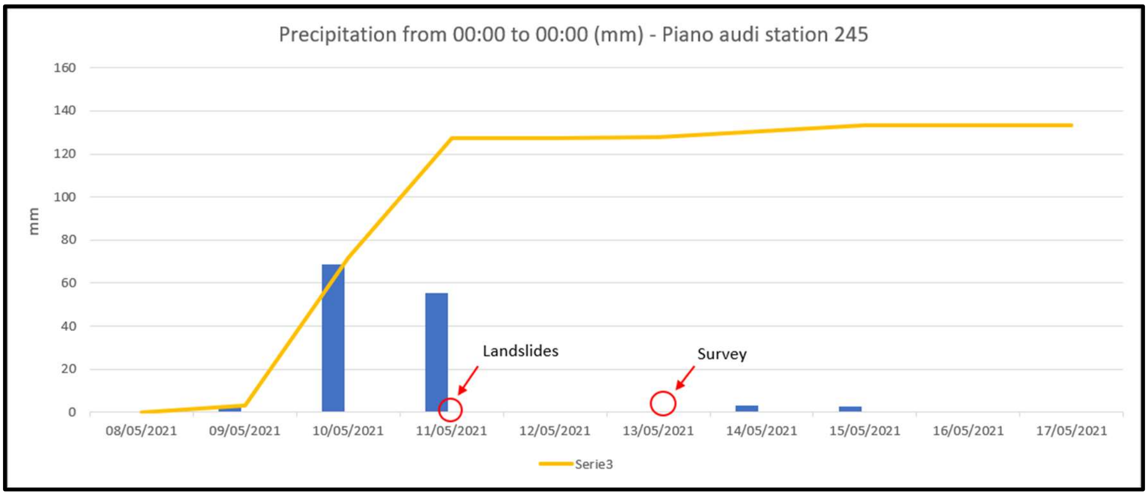


Figure 4-45 Overview of few days before the Landslides – Piano audi – ARPA Piemonte data

4.2.3 Municipality of Sparone

By contacting the various municipalities in the area, the contact information for a private geological company was obtained, whose head is Dr. PGeol Chiuminatto. He has been tasked in recent months with conducting site inspections due to some detachment surfaces and landslides in the municipality of Sparone (TO).

Wildfire occurred on 22 October 2017 in an area where the vegetation is almost exclusively composed of chestnut trees and almost 1600 hectares were burned (Figure 4-46).

The extraordinary rainfall events that occurred on November 23-24, 2019 made it necessary to declare a state of emergency with the opening of the Centro Operativo Comunale C.O.C. n. reg. ord. 15 on November 23, 2019.

As a result of this rainfall event, the municipality of Sparone suffered damage to public infrastructure there was a significant shallow landslide with the sliding of large boulders upstream of Via Olivetti.

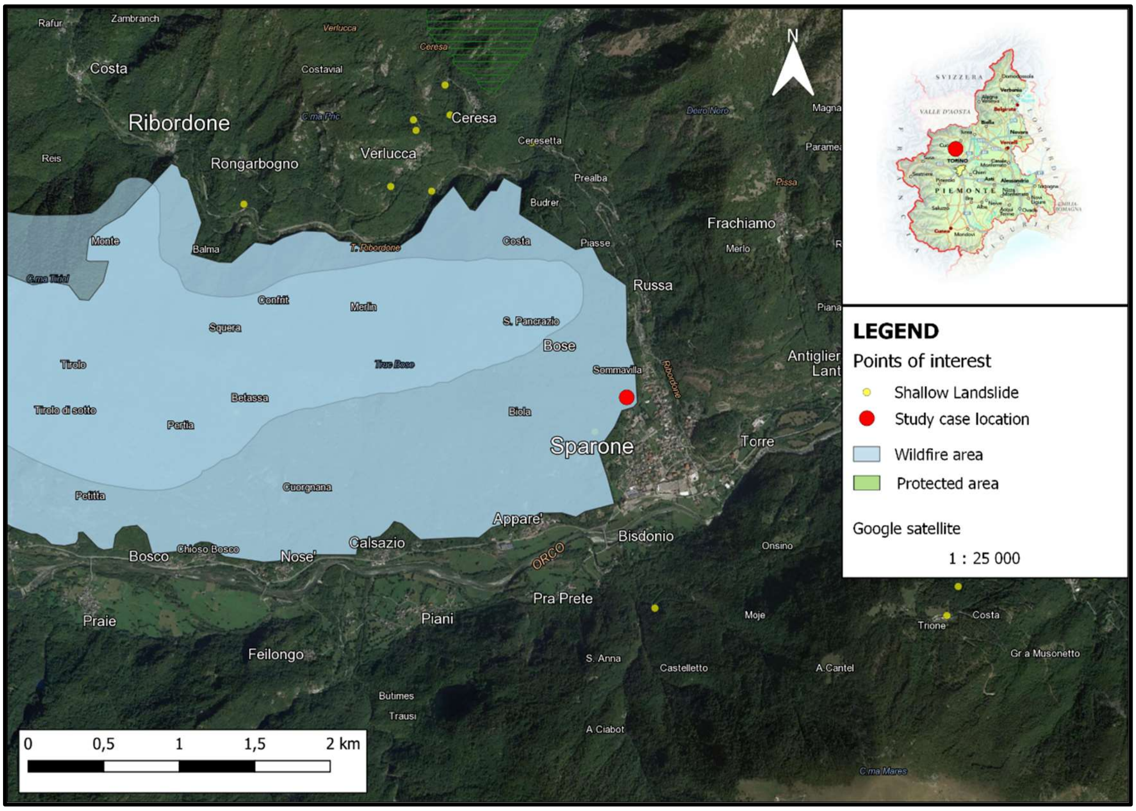


Figure 4-46 Overview area of interest – Municipality of Sparone

Thanks to the help of the mayor of the municipality of Sparone, it was possible to easily access official documentation on the shallow landslides occurred.

In particular, the event involved a well-defined area where multiple localized landslide events occurred, causing damage and disruption of the road network.

In fact, urgent works were subsequently commissioned through a resolution of the municipal council to restore the road network and ensure safety.

Most likely, most of the vegetation was weakened because of the wildfire, the consequences of which have also led to create new preferential infiltration pathways. Although there did not seem to be any clear signs of widespread wood cancer.

In the following years, the wind caused the standing dead trees to crash down, releasing large boulders and their root systems (Figure 4-49).

Figure 4-47 A large boulder that detached as a result of the collapse of some chestnut trees (from Dr. Geol. Chiuminatto)

The boulder depicted in the photo (Figure 4-47) is precariously balanced, and the surface runoff is freeing it.

In recent years, some boulders have rolled down to the foot of the slope where the municipal road passes.

Certainly, felling the dying trees would prevent the current problems. In general, in the municipality of Sparone, there has been a release of rock blocks due to the overturning of tree stumps since 2017.

Figure 4-48 Site inspection following a series of detachments (from Dr. PGeol Chiuminatto)

Figure 4-49 A large dead chestnut tree that fell from the slope with its entire root system (from Dr. PGeol Chiuminatto)

Figure 4-50 Site inspection following a series of detachments (from Dr. PGeol Chiuminatto)

4.2.3.1 Rainfalls

In the following are the results obtained for the area in question regarding the rainfall information.

Furthermore, data concerning the most severe rainfall events from the date of the fire to the dates of the shallow landslide events were analyzed, as well as the trend of the rainfall by referring to near rain gauges.

All the considerations already made in the previous section "4.2.1.5 Rainfalls" regarding the data reported here also apply to the case reported below.

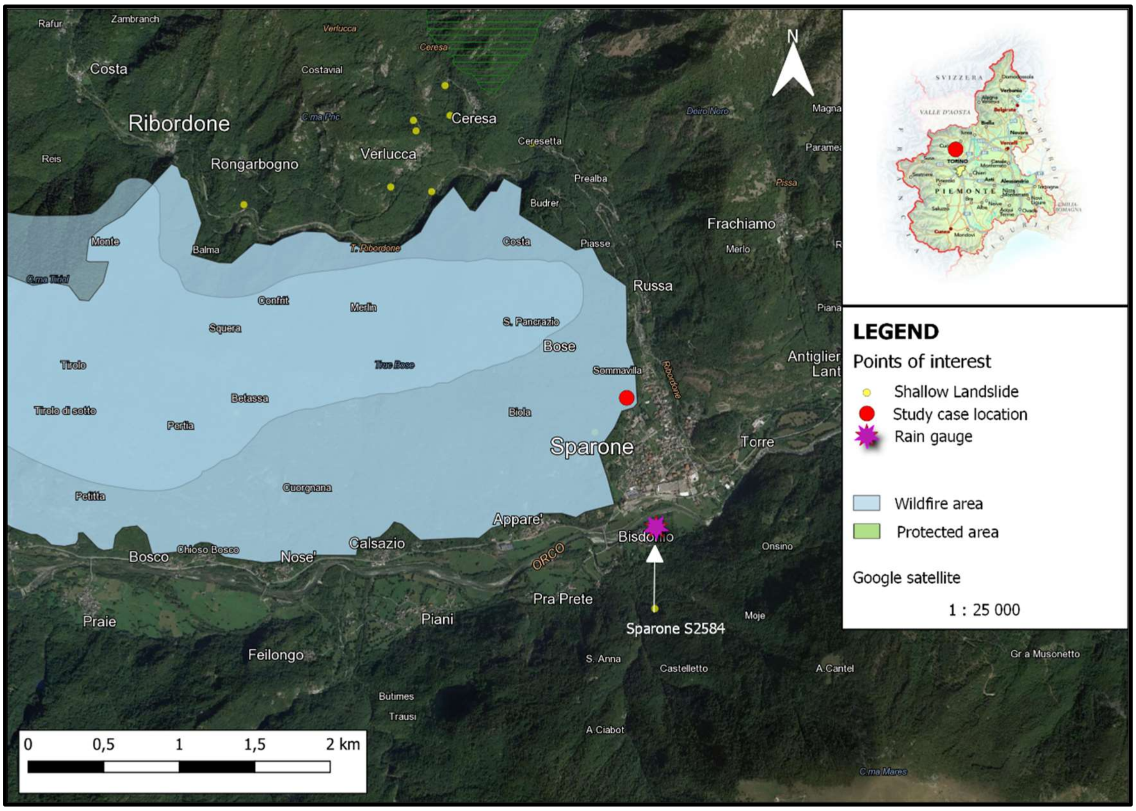


Figure 4-51 Overview of the area – Thissen Polygons

In this case, reference is made only to the rain gauge Sparone (Figure 4-52, Figure 4-53), as it fully confirms the data of the various event reports analyzed. The graphs relating to the rainfall on the days when most of the shallow landslides occurred are reported below. It can certainly be noted that the values in mm are rather high and it is not surprising that there were consequences.

However, as reported by several sources, the events were not limited to that period alone, but continued to occur even afterwards in the presence of less intense rainfalls.

In addition, other heavy rainfall events had already occurred between the period of the wildfire and the analyzed event but did not trigger such consequences. This observation supports the thesis that the vegetation gradually weakened over time due to the wildfire, and as they died, they increased the susceptibility of the slope to shallow landslides.

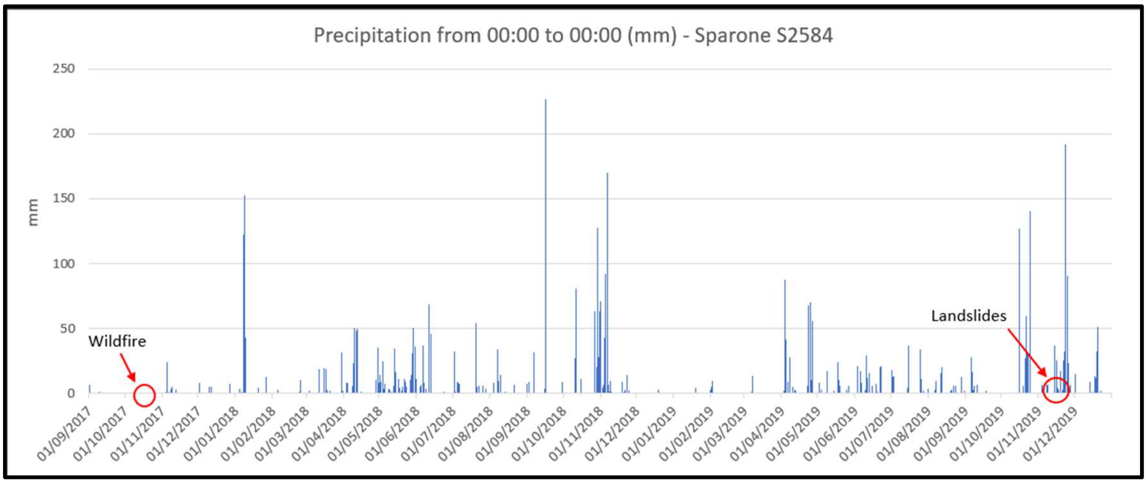


Figure 4-52 Precipitation overview from September 2017 to December 2019 – Sparone – ARPA Piemonte data

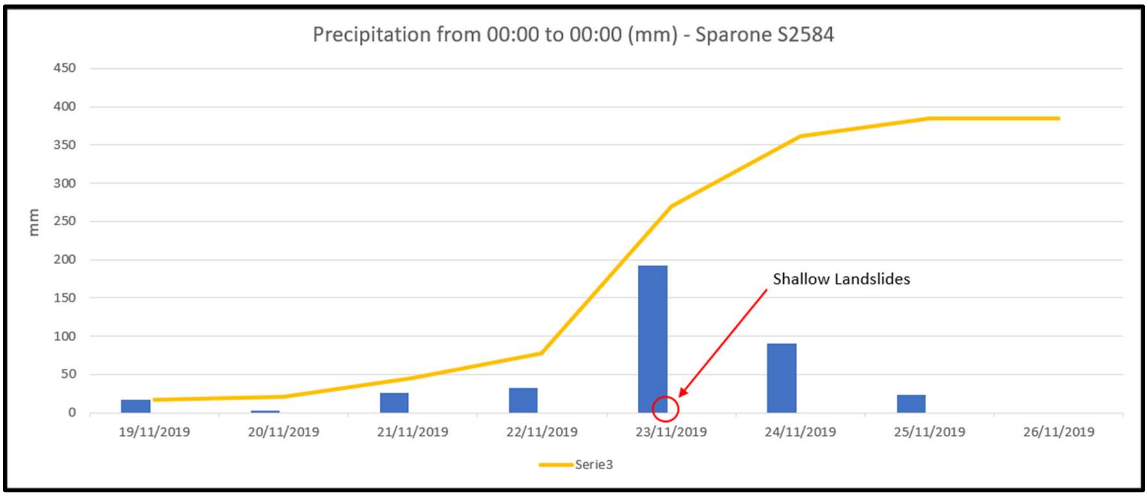


Figure 4-53 Overview of few days before the Landslides – Sparone – ARPA Piemonte data

As can be appreciated from the graphs presented, in the case being analyzed, on November 23, 2019, the rainfall height reached nearly 200 mm.

5 Discussion

Many considerations can be drawn from the results obtained.

Following wildfire, the slopes undergo substantial changes both in terms of hydrological characteristics and vegetation distribution. These changes are important because they affect the behaviour of the slope in response to external conditions that may occur. Indeed, the consequences resulting from atmospheric agents, such as heavy rainfall, can vary considerably depending on the state of the slope. Additionally, it should be noted that all these modifications typically contribute to making the slope more vulnerable and predisposed to gravitational phenomena. There is never a single predisposing or triggering factor, but rather a combination of several elements that can lead to the development of a given phenomenon, more or less intense.

Regarding the changes in hydrological characteristics, many studies have been conducted on this topic, which present important considerations including the entire process that occurs within the soil during and after the passage of the fire. For the work carried out, it was essential to have a clear understanding of these mechanisms that can be triggered by the passage of the fire.

Regarding landslides, it is not always easy to make an exact distinction between the various types of landslides within the same event. It can happen that, as reported in some of the case studies presented, rainfall events affecting areas previously hit by wildfires can cause debris flows in the first months after the wildfire due to the temporary changes in the hydrological characteristics of the slopes (Tiranti et al., 2021), but then, over longer time intervals (years) they can be responsible for the occurrence of widespread shallow landslide events linked to the damage to the vegetation (fall of trees with the formation of puddle areas in the eradication zone) which persist and worsen over time, if forestry interventions are not implemented quickly.

In Tiranti et al. (2021), much attention is focused on the phases that lead to the triggering of debris flows of high magnitude. The article analyzes two cases that occurred in Piemonte in 2005 and 2018.

These phenomena occurred after a large portion of the catchments were affected by wide wildfires in the preceding months. Debris flow deposits showed an unusually large number of fine-grained particles, forming dark-brown mud-rich deposits associated with burnt wood deposits. Rainfall analysis related to the period between the wildfires' occurrence and the debris flow events, using both rain gauge and weather radar data, pointed out that the debris flows triggered in July 2005 and June 2018 were characterized by greater magnitude but associated with less precipitation intensity rates as compared with previous mud flows occurring just after wildfires.

These behaviors can be explained by the presence of burned organic material and fine-grained sediment, generated from the soil's thermal reworking, which formed a thick layer, centimeters deep, covering a large percentage of catchments and slopes. Most of this layer, generated by wildfires' action were winnowed by rainfall events that had occurred in the months before the debris flow events of significant magnitude, exhuming a discontinuous hydrophobic soil surface that changed the slopes' permeability characteristics. In such conditions, runoff increased, time of concentration shortened, and, consequently, discharge along the two catchments' channels-network increased as well. Consequently, the rainfall effects associated with rainfall events in July 2005 and June

2018 were more effective in mobilizing coarse sediments in channel beds than was typical for those catchments.

It was essential for the work carried out to have a clear understanding of the mechanisms that can be triggered by the passage of wildfires.

This was useful in order to better understand the case studies considered and to have the awareness and ability to analyze the various situations that arose.

In the case studies analyzed in this thesis, the mechanisms described in the cited article did indeed occur as a result of the wildfires.

However, the focus of this work was on the unexpected results that were obtained, namely that the triggering factors for shallow landslides were the fall of dead vegetation due to wildfires, even years later.

However, it is also true that with regard to shallow landslides, the reduction in permeability of slopes (formation of hydrophobic soil surfaces) tends to inhibit the initiation of such landslides, which would require water infiltration into the soil to reach the triggering conditions.

Therefore, this phenomenon initially acts as an inhibitor of shallow landslides, but as previously mentioned, it is specifically the dead vegetation that predisposes the conditions for local increases in infiltration through ponding.

In fact, following the fall of dead vegetation, especially in the case of plants with large root systems (such as chestnuts), areas of standing water are created, as documented in photos taken during a site surveys (Figure 4-24 and Figure 4-17). These areas of standing water act as preferential infiltration pathways.

These preferential infiltration pathways, through the stagnation of even low-intensity rainfall or snow melting, completely transform the hydrological conditions of the area, even for a long time-period, significantly increasing the run-in and drastically decreasing the run-off. This behavior implies a greater and faster weighting of the slope, which can then lead to the development of shallow landslides, as seen in the reported cases.

Another important result of the research conducted is the diseases that damaged plants can incur because of wildfires. This aspect, which may initially seem completely unrelated, is substantial in that it can lead to the death of vegetation even many years after the wildfire. In addition to making more vegetation material available for transport, it can trigger unexpected and unforeseen landslide phenomena.

A very particular case is that of chestnut trees.

Another problem found was that for many years after the wildfires parks are no longer receiving adequate maintenance, unfortunately certain phenomena and interventions require much foresight by the decision maker, there are many dying plants even on the edges of the paths that should be identified and removed.

As can be seen in the photos (Figure 4-15), there are many risky situations along the trails where the collapse of a tree of that size can be both a danger in itself and triggering landslides.

Concerning step 1, the processing and comprehension of the data took a significant amount of time. There were numerous instances of shallow landslides and wildfires, which were disjointed and originated from various sources. Unfortunately, the initial approach of directly correlating the shallow landslide events with wildfires through spatial overlap and subsequently temporal data proved to be unsuccessful due to incomplete or inaccurate data. The original idea was also to easily correlate such phenomena with periods of intense rainfall. The aim was to demonstrate that because of a wildfire, the triggering thresholds of shallow landslides (Tiranti and Rabuffetti, 2010; Tiranti et al., 2019) decreased compared to pre-wildfire event conditions and other similar areas that had not experienced wildfires.

This highly intricate objective has not been pursued for two key reasons. Firstly, there was an insufficient number of suitable cases to analyze, which rendered any statistical reasoning invalid. Secondly, it was observed that, for shallow landslides in Piemonte, one of the primary triggers is the fall of dead vegetation due to fires.

As a result, a correlation between precipitation and shallow landslides cannot be ruled out; however, with the currently available and analyzed data, it is not possible to provide a definitive answer.

Having arrived at this conclusion, a change in approach was necessary.

This, in fact, has led to good results on which to reason.

It has shown that with a longer period for research and analysis, there is plenty of material available to investigate and process.

The challenge with this material is that it can be time-consuming to obtain, as it is often not centralized but dispersed across the archives of small municipalities, engineering and geological companies. This factor is crucial because, as it happened during this thesis, a significant amount of time must be spent searching for contacts to obtain data and case studies to work with.

Nevertheless, only the most pertinent cases and comprehensive information were included in the results of this study. These findings allowed for a highly consistent correction of a specific situation, namely, that most shallow landslides occur due to the overturning and detachment of plants that died because of wildfires.

It is essential to note that these plants, which can be very large (e.g., chestnuts with diameters greater than 2 meters Figure 4-16), can die even many years after the fire.

The fire, especially during grazing, damages the bark and root system of the plant, making it highly susceptible to fungi and pests. An illustrative example is chestnut, which is prone to contracting cancer if damaged (Figure 4-23). However, it is critical to understand that this wood cancer can spread to other healthy chestnuts in the vicinity, putting the entire area at risk.

The critical result, reported through several case studies, is that plants affected by wildfire, not entirely burned, as often happens with chestnuts, remain in place for several years after the wildfire.

In the months or years following wildfires, these plants significantly weaken.

Particularly windy days or heavy rain, which weigh down the no longer healthy root system, can trigger shallow landslides.

Falling these plants can move even large quantities of surface material and prepare preferential infiltration routes through the phenomenon of the puddle that is created where before there was the root system that has detached, triggering chain-drop reactions of other healthy plants and nearby boulders.

Over time, these plants are subject to deterioration and are more susceptible to diseases due to damaged bark or root system, such as chestnut blight.

The pathogenic agent of chestnut blight, Cryphonectria parasitica, is an ascomycete fungus.

Its spores are dispersed through rainwater, insects, snails, and birds. When the spores land on a chestnut with fresh wounds (from pruning or grafting, growth, branch breaks, or burning), they can germinate.

The affected bark initially takes on a reddish color and a depressed appearance, then longitudinal cracks form. The tree reacts by attempting to heal the destroyed tissue, which gives rise to the classic cortical necrosis commonly called cankers.

When the fungus has colonized the entire circumference of a trunk or branch, the distal portion of the affected part dries up. The leaves wither but remain attached to the affected branches. The presence of branches with dry leaves during the growing season or in winter is a typical sign of an attack of chestnut blight.

In regions still free from the disease, any first outbreaks of chestnut blight must be eradicated as quickly as possible, by eliminating infected tree parts or entire trees. The resulting wood must be burned on-site, and regular pruning to remove virulent cankers helps reduce infestation in the chestnut grove. After interventions on infected trees, removal pruning, as well as grafting operations, regular disinfection of the tools used is recommended.

This disease has a high speed of decay. In fact, if not properly treated or neglected, it can lead to the death of the plant itself within a few months (Rigling, et al., 2016).

5.1 Rainfalls

Following the results obtained, a thorough analysis was conducted on the factor of rainfall in the locations considered as case studies. Several rain gauges were considered, each referring to the area of the respective case study. Rainfall triggering thresholds for shallow landslides deriving from the Landslide Early Warning System of Piemonte (Tiranti et al., 2019) were compared with the rainfall values associated with the shallow landslide events investigated in the four case studies.

An interesting result has been obtained in the Natural Park Monte Tre Denti case study, whereby analyzing the historical series made available by ARPA Piemonte, it has been observed that shallow landslides are not directly correlated to significant rainfall events (Figure 4-27). From the graphs presented in the results chapter, it is evident that prior to the 2017 shallow landslide, there was not enough rainfall to justify the triggering. Consequently, this supports the hypotheses and conclusions that the shallow landslide was mainly caused by the collapse and overturning of large chestnut trees that destabilized the entire slope, resulting in a chain reaction.

In this case study, snow data from the reference period were also analyzed (Figure 4-31). Although there is no adjacent snow station to refer to, some considerations can be made by analyzing the data from the closest ones. Given the reference period, which is the end of January and the beginning of February, and, considering that the location of the event is approximately 700 m a.s.l. it is reasonable to evaluate the hypothesis that it snowed instead of rained. This aspect could be crucial, especially when looking at the temperature data reported during those days.

As shown in the graphs, the temperatures during precipitation were quite low (Figure 4-32), close to 0 Celsius degrees, but these temperatures were recorded in rain gauges at about 200 m a.s.l., so about 500 meters lower down.

This leads to the idea that it may have actually snowed in the study area. In the following days, however, higher temperatures were recorded, which could have caused the snow melt. This mechanism favors infiltration into the slope, weighing it down and leading to all the consequences that have already been extensively discussed. This could explain the delay in the occurrence of the shallow landslide.

In the other case study in the Park, a specific date for a single event could not be identified. However, it is clear from the declarations that the number of reports increased significantly in the period following the 2017 wildfire. Further investigations are needed, particularly to find information on the dates of individual landslide events. What is certain is that the peeling of the chestnut root systems promotes run-in.

The Belmonte case study presents a particularly complex situation to analyze, because of the numerous wildfires that occurred within a few years and the rapid recovery of vegetation. Therefore, it was decided to analyze only the period from 2019 onwards, following a significant wildfire, as some of the most significant and documented photos date back to the months following this wildfire.

In contrast to the previously described event, in this case, many landslides occurred in conjunction with heavy rainfall, over 100 mm of cumulative rainfall, or within a few days (values under the shallow landslides triggering threshold characteristic of this area). However, there had been previous heavy rainfall events, as shown in the accompanying graph. This further supports the theory of preferential infiltration pathways generated by the collapse of dead vegetation and the combination of different types of landslides in the same event. Figure 4-39 clearly shows landslide behavior, induced by the mechanisms described above.

Regarding the case of shallow landslides in the municipality of Sparone, Analyzing the data from the rain gauge in the proximity of the investigation area, it can be inferred that in this case, heavy rainfall were crucial in triggering several shallow landslides that occurred.

It is important to note, however, that other significant rainfalls occurred between the date of the wildfire and this main event (Figure 4-52).

Probably, during this period, other minor detachments of rocks and dead vegetation occurred, creating preferential infiltration pathways, but only years later did these factors lead to the development of such a relevant event.

Even this case indicates that they are mostly caused by the detachment of dead vegetation, partly due to strong winds and the heavy rainfalls. The photographic documentation clearly shows how large boulders and the large root systems of trees have been displaced. The subsequent rainfall events certainly facilitated the occurrence of further detachments.

5.2 Regione Piemonte special plan of action for wildfires 2017

An important document that gave rise to all the work done is the one approved on 18 April by the Regional Council, or the Extraordinary Plan of interventions to restore the territory following the wildfires of autumn 2017.

The Plan is valid from its approval until 31 August 2029 as reported by the official website of the Regione Piemonte.

Reference is also made to the national framework law on wildfires (L. 353/2000, Art. 10), which lays down a series of prohibitions concerning the forest and pasture areas covered by them for periods ranging from 15 to 5 years.

These documents are of fundamental importance because they outline what are guidelines to restore areas compromised by wildfires, also show that in recent years there are critical

issues that need to be addressed and not neglected as according to the trend will be increasingly frequent.
A very thorough analysis is made on the fundamental role that the forest assumes in different phases, is also highlighted as it serves foresight in dealing with these situations that affect without discriminating. Increased awareness of the issues addressed by administrations would ensure a better understanding of the risks involved.

The year 2017 was characterized by abnormal climatic conditions: high temperatures and a persistent absence of rainfall have been a predisposing element for wildfires and have amplified the effects. During the autumn - in a few days - the wildfire has covered over 9,700 hectares of land area (of which 7,200 hectares covered by forests). The annual average for the last 20 years is 2,280 hectares.

Regione Piemonte has therefore considered it necessary to equip itself with tools able to assess the damage, orient the allocation of financial resources and efforts where more useful, without neglecting the regulatory implications. In fact, the national framework law on wildfires (L. 353/2000 art. 10) lays down a series of prohibitions concerning forests and pastures covered by wildfire; these include the prohibition, for five years, of using public financial resources to carry out "afforestation and environmental engineering activities".

This prohibition, however, is not absolute but the possibility is provided for the granting of specific permits "for documented situations of hydrogeological instability and in situations where urgent action is needed to protect particular environmental and landscape values.

The Plan consists of the following documents:

- Extraordinary plan of interventions of restoration of the territory crossed by the wildfires of autumn 2017;
- Report for the Impact Assessment;
- Cartography surfaces covered by wildfire.

5.2.1 Guidelines

It is important to understand how fundamental forest cover is within a basin and how important it is to restore it when it is missing or damaged.

Proper maintenance leads to effective prevention against various phenomena, even not treated directly within this thesis.

If it is abandoned or compromised by human activity, the same plants that offered protection can result in an aggravating factor, leading to even more serious consequences.

The action in forest terminology is defined as "general or indirect protection" if it is carried out through the contrast to erosion, diffused or channeled, also through the better regimation of meteoric waters, and as "direct protection" when the forest protects buildings and settlements exposed to natural hazards (avalanches, falls of boulders, surface slipping and torrential washes), preventing the occurrence of the disaster or mitigating the harmful effects.

The forest also has more complex functions; for example, the function of drainage of soils is typical, especially cohesive ones, reducing the time of their saturation and therefore the predisposition to the formation of landslide movements; also form a physical obstacle to the surface flow of water.

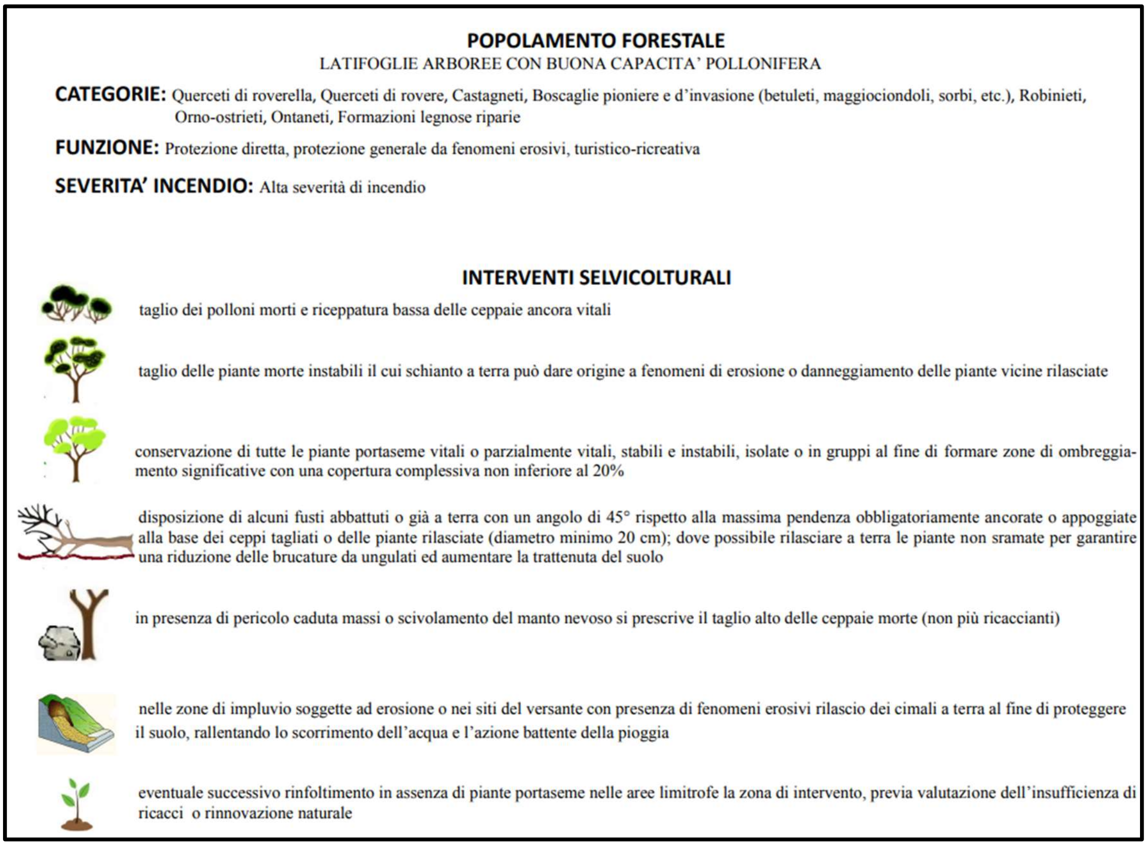
The tree cover, if poorly managed, can also determine phenomena of instability, either through the liberation of rocky blocks immersed in the debris, or, in case of falls of individuals, through the creation of discontinuity in the ground, possible fluidifications or other landslide movements.

The protection of forests should not be assessed solely on the basis of the trees' role in preventing disruption, but also on the presence of exposed and vulnerable elements protected by them.

All the functions described above are compromised if the wildfire involves the complete removal or part of the forest cover.

Guidelines are, therefore, very useful.

Below are some very representative summary images extracted from the guidance document. They are only a tiny part of this very exhaustive work and are particularly interesting for the case of Caselette, which is presented later.



POPOLAMENTO FORESTALE

LATIFOGLIE ARBOREE CON BUONA CAPACITA' POLLONIFERA

CATEGORIE: Querceti di roverella, Querceti di rovere, Castagneti, Boscaglie pioniere e d'invasione (betuleti, maggiociondoli, sorbi, etc.), Robinieti, Orno-ostrieti, Ontaneti, Formazioni legnose riparie

FUNZIONE: Protezione diretta, protezione generale da fenomeni erosivi, turistico-ricreativa

SEVERITA' INCENDIO: Alta severità di incendio

INTERVENTI SELVICOLTURALI

taglio dei polloni morti e riceppatura bassa delle ceppaie ancora vitali

taglio delle piante morte instabili il cui schianto a terra può dare origine a fenomeni di erosione o danneggiamento delle piante vicine rilasciate

conservazione di tutte le piante portaseme vitali o parzialmente vitali, stabili e instabili, isolate o in gruppi al fine di formare zone di ombreggiamento significative con una copertura complessiva non inferiore al 20%

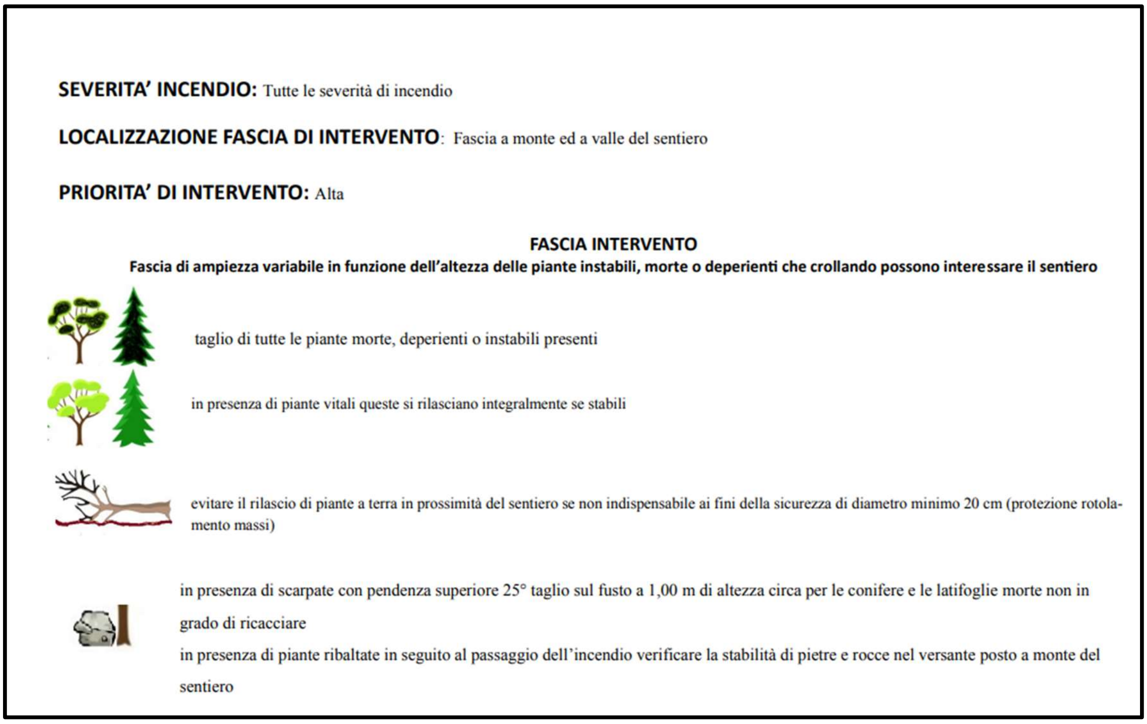
disposizione di alcuni fusti abbattuti o già a terra con un angolo di 45° rispetto alla massima pendenza obbligatoriamente ancorate o appoggiate alla base dei ceppi tagliati o delle piante rilasciate (diametro minimo 20 cm); dove possibile rilasciare a terra le piante non sramate per garantire una riduzione delle brucature da ungulati ed aumentare la trattenuta del suolo

in presenza di pericolo caduta massi o scivolamento del manto nevoso si prescrive il taglio alto delle ceppaie morte (non più ricaccianti)

nelle zone di impluvio soggette ad erosione o nei siti del versante con presenza di fenomeni erosivi rilascio dei cimali a terra al fine di proteggere il suolo, rallentando lo scorrimento dell'acqua e l'azione battente della pioggia

eventuale successivo rinfoltimento in assenza di piante portaseme nelle aree limitrofe la zona di intervento, previa valutazione dell'insufficienza di ricacci o rinnovazione naturale

Figure 5-1 Intervention form for wooded areas predominantly of broad leaves, Extraordinary Plan of the Regione Piemonte (modify from Piano straordinario di interventi di ripristino del territorio percorso dagli incendi boschivi dell'autunno 2017 pdf)



SEVERITA' INCENDIO: Tutte le severità di incendio

LOCALIZZAZIONE FASCIA DI INTERVENTO: Fascia a monte ed a valle del sentiero

PRIORITA' DI INTERVENTO: Alta

FASCIA INTERVENTO

Fascia di ampiezza variabile in funzione dell'altezza delle piante instabili, morte o deperienti che crollando possono interessare il sentiero

taglio di tutte le piante morte, deperienti o instabili presenti

in presenza di piante vitali queste si rilasciano integralmente se stabili

evitare il rilascio di piante a terra in prossimità del sentiero se non indispensabile ai fini della sicurezza di diametro minimo 20 cm (protezione rotolamento massi)

in presenza di scarpate con pendenza superiore 25° taglio sul fusto a 1,00 m di altezza circa per le conifere e le latifoglie morte non in grado di ricacciare

in presenza di piante ribaltate in seguito al passaggio dell'incendio verificare la stabilità di pietre e rocce nel versante posto a monte del sentiero

Figure 5-2 Interventions along the path, Extraordinary Plan of the Regione Piemonte "restoration of the safety of the path" (modify from Piano straordinario di interventi di ripristino del territorio percorso dagli incendi boschivi dell'autunno 2017 pdf)

5.3 Example of slope stabilization and removal of dead vegetation after an event – Caselette (TO)

5.3.1 Overview

Below is the example case of the Municipality of Caselette, where a recovery and redevelopment plan for the slope has been implemented in recent years, and which was affected by a wildfire in March 2021. With foresight and following the new directives promoted by the Regione Piemonte, the municipality, in collaboration with "company name", is currently planning a series of interventions partly reported in the technical reports made available to me, which are part of the "Interventions for the recovery of areas affected by the wildfire in March 2021 and support for the fight against wildfires on Mount Musinè in the municipality of Caselette".

As reported in these documents, these increasingly frequent and intense wildfires are also the result of particular climatic conditions, including hot and dry winds (foehn) and scarce precipitation. This does not concern the triggers, but rather the greater predisposition of the territory to favor the spread and intensity of the wildfire.

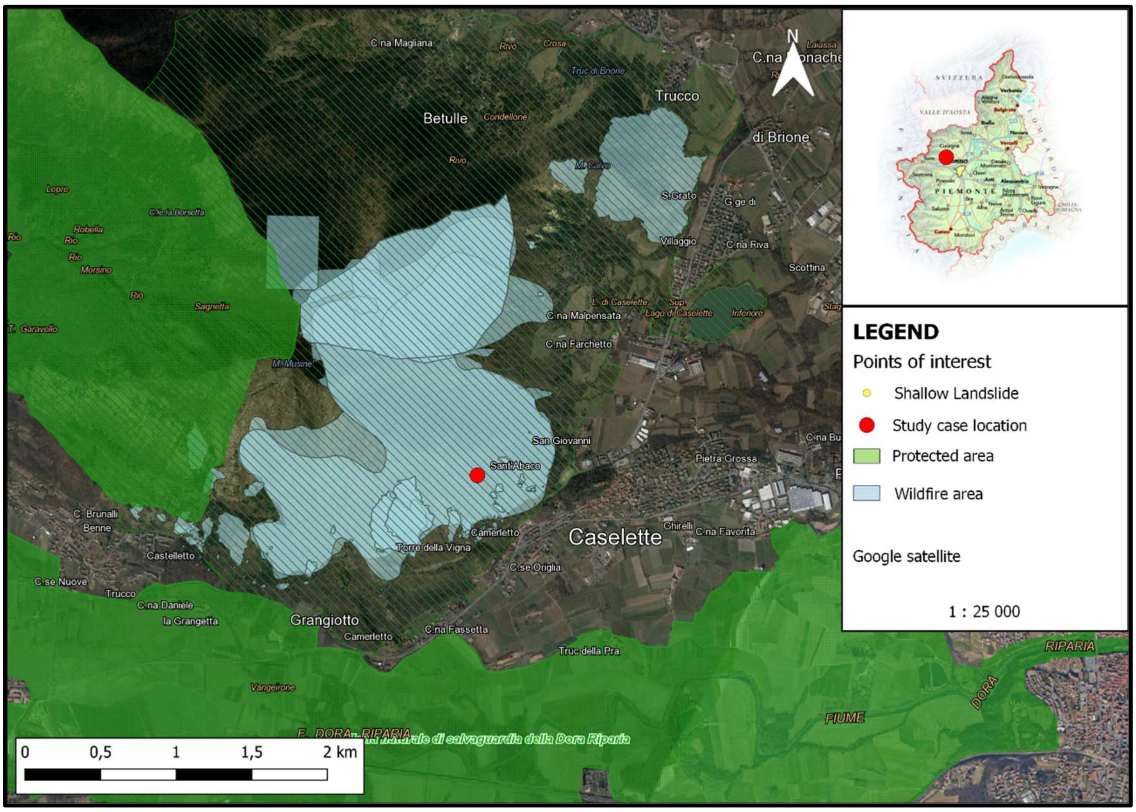


Figure 5-3 Overview area of interest - Caselette

The wildfire in question is quite extensive, with a total surface area of approximately 250 hectares, or 2.5 km^2. Immediately after the event, the first surveys were carried out, during which it was noted that it was necessary to carry out detailed surveys to verify the actual extent of the damage caused by the wildfire to the forest component. A map of the severity of the wildfire was then drawn up, and priority areas for intervention were subsequently identified.

One of the most commonly utilized techniques in these fields, particularly for sufficiently large regions, involves analyzing spectral changes in vegetation cover following a wildfire using satellite imagery.

In this case, remote sensing data provided by Sentinel-2A and Sentinel-2B were employed, readily accessible for download from the Copernicus Open Access Hub portal (https//scihub.copernicus.eu). The images utilized for comparing pre-wildfire conditions date back to July 2020, while post-wildfire images date from May 19th, 2021.

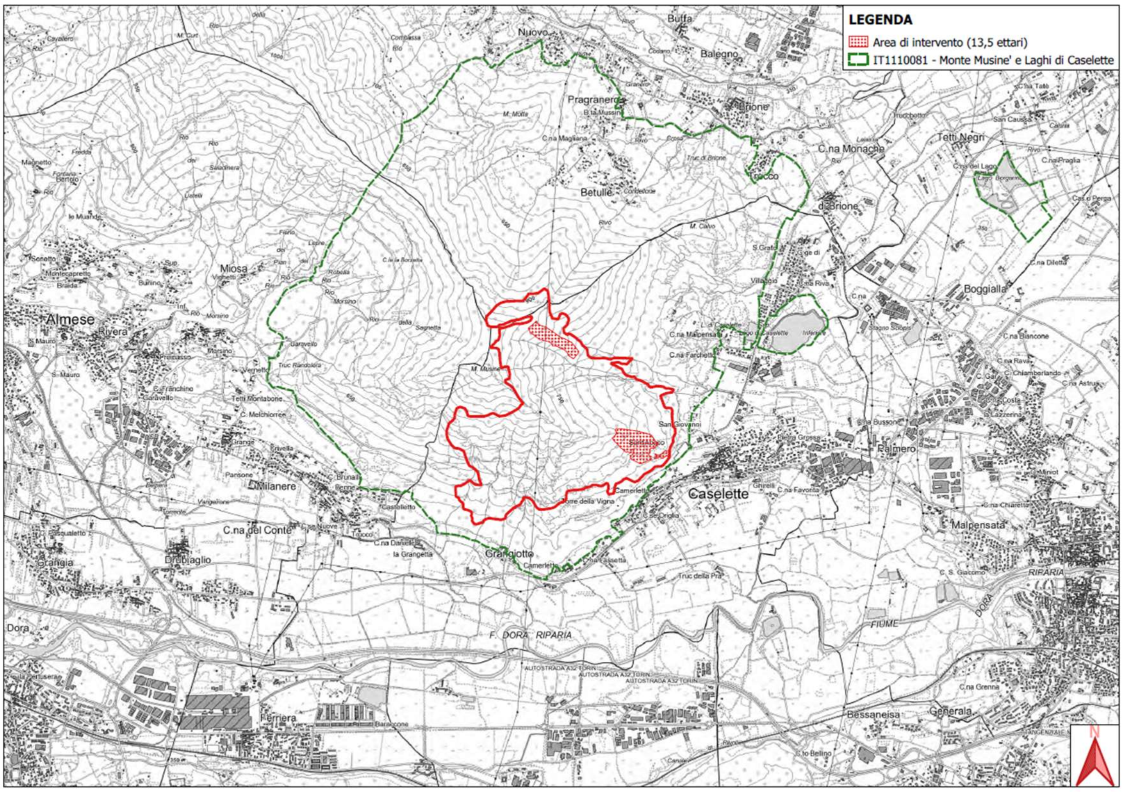


Figure 5-4 General overview on BDTRE - Areas of intervention and redevelopment (modify from Interventi di recupero delle aree percorse dal fuoco nel marzo del 2021 sul Monte Musinè in Comune di Caselette)

By utilizing this data, the NDVI index can be estimated, which helps assess vegetation vigor via spectral signatures. Darker areas correspond to lower NDVI values, including roads, population centers, and specifically, burned areas, while lighter areas correspond to higher NDVI values, indicating greater vegetative vigor in wooded areas.

Although this approach is extremely valid and provides a brief overview of the situation, for example it allows to avoid going and checking areas where even before the wildfire there was little vegetation, it is always necessary to validate the results and assumptions with specific inspections.
The area subject to interventions is occupied mainly by oak woods in Potentilla alba with the exception of areas near the Sanctuary of Sant'Abaco, characterized by reforestation of conifers such as black pine.
Interventions of a purely forestry nature were defined within the executive project, aimed at restoring the stability of the slopes and the forest populations most affected by the wildfire. These interventions are in accordance with the guidelines of the "Extraordinary Plan of Interventions for Wildfires of 2017", for the reconstruction and restoration of slope stability. Their purpose is to restore the hydrogeological and naturalistic equilibrium conditions present before the passage of the wildfire. Concurrently with forestry interventions, the planting of native tree species is planned in the areas most damaged by the wildfire near Sant'Abaco.

These interventions are necessary considering the greater predisposition to instability of the areas affected by the wildfire, which cannot be overlooked in relation to the widespread and sometimes significant anthropic pressure that characterizes the valley floor areas. In addition, the increase in accessibility and water points significantly reduces the response time of the A.I.B. teams to the areas in question, facilitating both maintenance and prevention operations and active firefighting.

5.3.2 Type and characteristics of projects

The following case study is reported precisely because it is interesting to analyze how the interventions are mainly silvicultural.

The main aims of the interventions are to contrast the erosive phenomena taking place on the side affected by the wildfires and to predispose the recovery dynamics of the oak oaks hit by wildfire and seriously damaged.

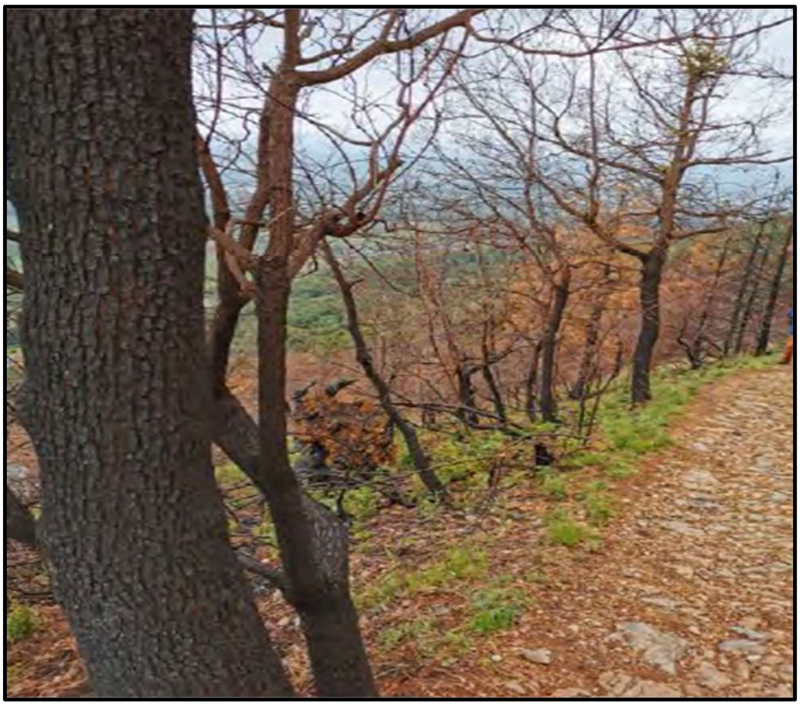


Figure 5-5 Areas covered by high severity wildfire along the mule track to the Sanctuary of Sant'Abaco (modify from Interventi di recupero delle aree percorse dal fuoco nel marzo del 2021 sul Monte Musinè in Comune di Caselette)

Figure 5-6 Dead vegetation along the road to the Sanctuary of Sant'Abaco (modify from Interventi di recupero delle aree percorse dal fuoco nel marzo del 2021 sul Monte Musinè in Comune di Caselette)

Two types of work are planned: forestry restoration in the forest and along the trails.

The restoration intervention involves about 13.5 hectares of forest, providing three types of processing. It is stressed that a part of the felled wood must be used to construct anti-erosion barriers.

Everything always follows the guidelines of the extraordinary plan, adapted to the case in question, especially for the choice of native plants to be replanted:

- Planting of native forest species: at the end of the forestry measures, it is planned to plant about 2000 species of native deciduous trees. The planting of the seedlings must take place in the autumn.

- Wood hauling: the extraction will be carried out either by aircraft (helicopter) for coniferous trunks larger than 45 cm in diameter or by land means (tractors) whose use is limited by territories' conformation and access routes.

- Cutting the dead vegetation and "riceppatura": most dead plants will be divided into smaller and manageable pieces, placed in safe and easily accessible areas. The "riceppatura" consists of practicing strains energetic cuts lowering the tree to stimulate the growth of new "polloni".

These types of intervention are very important to ensure safety, unfortunately very often these accommodations are not undertaken by the municipalities.

6 Conclusion

The work carried out has resulted in obtaining results that are very different from the initial assumptions and what is usually analyzed in these types of analyses. The initial approach of exploiting available databases to investigate whether there were any correlations or statistics between shallow landslides, wildfires, and heavy rain at regional scale did not yield the expected results. However, the first part allowed for a better understanding of the analyzed subject and the issues related to the type of information necessary to obtain valid and interesting case studies.

The evidence of the obtained correlation between dead vegetation, even many years following wildfires, and shallow landslides was unexpected and certainly poorly documented, as was the development of this type of landslide in the absence of significant rainfall. While rainfall events and soil conditioning certainly play an important role and cannot be excluded from a thorough analysis of these phenomena, the presented case studies and considerations highlight how multiple consequences result from the passage of a wildfire and how even years later, a slope can remain highly vulnerable and predisposed to shallow landslides.

Therefore, considering the fall of dead vegetation among the predisposing causes of shallow landslides and the consequences that fall vegetation have over time, such as the creation of stagnant areas and preferential infiltration pathways, is of fundamental importance. This is not only to have a better awareness of the hazard associated with such phenomena but also to acquire a better understanding of how to intervene in the perspective of prevention and restoration of safety.

Thus, this is presented as the main mechanism for predisposition to the triggering of shallow landslides following a wildfire, namely the dead vegetation that leaves these portions of the slope uncovered and unprotected, which become preferential pathways for infiltration and pooling at various scales, from large root systems to smaller and more diffuse ones.

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To all the ones I've ever loved

To all the path I crossed that led me to this place