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Digital Twin for flood prevention: digitalization of the Hydrogeological Plan for the town of Rosazza (BI)

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Abstract

Modern-day construction industry has to deal with unprecedented obstacles: the need for a radical digitalization and the inclusion of sustainability in an extremely polluting sector. These goals can be pursued simultaneously in a BIM environment when considering an already existent building or urban area through a "reverse engineering” procedure and the creation of a Digital Twin. This thesis aims to realize a Digital Twin of the town of Rosazza (Biella, Italy) to assess the risk of floods for existent buildings. Data about the city and flood events in the area were analysed and implemented in a BIM authoring platform to create an integrated environment that could offer a digital representation of the city through a Scan-to-BIM approach and an efficient data enrichment phase that exploited live-data coming from a combination of traditional weather station and an innovative monitoring system through sensors. The final result was the visualization of the Risk of Floods according to a formula that took into consideration the vulnerability of every building and weather parameters for the creation of a three-dimensional integrated PAI (Hydrogeological Plan). This could help local authorities determine better managing of evacuation, further implement sensor monitoring systems on a territorial level, or use the model as a ground basis for further data enrichment, detailing, and development. In conclusion, this thesis aims to analyse the correlation between historic elements and BIM, integrating these concepts in the larger spectrum of climate change and offering a practical application that could lead to a better implementation of technologies for heritage conservation.

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1. Introduction

Today's society is steadily striving towards an ever more complete and efficient digitalization in every economic field. On its part, the construction industry needs to take concrete action to facilitate its methodologies and offer a better management of projects, considering them holistically, with every phase of the design in mind in order to run in a smoother and more productive way, free of late deliveries and confusion because of non-digitalized documentation. At the same time, this has to be done bearing in mind the complexity of the background that it has to deal with, not only when looking at the practical aspect of vast and detailed designs, but most importantly when considering the location and context in which a project is to be carried out. The Sustainable Development Goals set by the United Nations in 2015 have made it clear how relevant climate change is becoming for everyday lives, starting from direct effects on people such as hunger and poverty and moving onto polluting industries such as the Architecture and Construction (AEC), which for instance accounts nowadays for about 40% of the total energy consumption in Europe. For this reason, the aim of architects and engineers worldwide should be the compromise of these two ideals, digitalisation and sustainability, in order to create buildings and infrastructures that could act as instruments of resilience against climate change. This encompasses both new constructions as well as already existent buildings, which could be modelled through a reverse engineering process, i.e., Scan-to-BIM, to represent reality through a digital twin of different scale possibilities and handle maintenance, refurbishment, or monitoring of that reality.

This thesis sets its goal in the application of digital twin technologies for the conservation of the cultural heritage in the context of climate change, more specifically in order to better monitor the historic town of Rosazza (Biella, Italy) against natural disasters such as floods. This case study was suggested by supervisor Professor Anna Osello, who advised to consider the Cervo Valley, area in which this town lies, on the one hand because it had already been studied through the PhD work of many in the drawingTOthefuture laboratory of Politecnico di Torino, second because the city itself is considered one of the most beautiful villages of Italy.

To carry out a coherent application of the model, it is necessary to define general and specific goals that the thesis will have to achieve. The main general goal of this study is the elaboration of a digital twin model of the town of Rosazza with the purpose of conservation of the architectural heritage against natural disasters such as floods. This was carried out thanks to two more detailed specific goals: the background research and the elaboration of the HBM model. To better understand both vast topics, they could be separated in their parts to better define the structure of the thesis.

As far as the background research is concerned, it was first of the utmost importance to define digital twin both on more general terms as well as in the specific case of the construction industry, explaining its applications and reporting some useful case studies for the creation of HBIM that would later be of help when defining the methodology and workflow of the project. Then, the Cervo Valley and Rosazza were detailed on a geographical, demographical, and historical level, so that the object of the thesis was clear to the reader. The last step of the background research was the chapter about floods: after a general definition, the harshening of this phenomenon due to climate change was detailed to highlight the importance of preventive actions to protect cities and people; international and Italian data regarding floods was provided and the functioning of Early Warning Systems worldwide and nationally was explored. A more recent and technologically advanced development of warning systems was detailed, discovering singular monitoring systems that could detect weather and hydrogeological parameters to give alert if certain metrics reached a level of risk for the surrounding areas, therefore exploring IoT applications. Flood events in the valley and more specifically in the city of Rosazza were also enlisted to have a ground base of knowledge for later developments.

After the background research, it was necessary to start the modelling phase and set more detailed steps for the second specific goal, the elaboration of the HBIM model and digital twin. First, the methodology for the project was set, using previous examples found in the literature to have a ground basis to start from. In the first steps, the data collection done in the preliminary phase was thoroughly explained to assess from whence every piece of information came from and how the retrieving of data worked out; then, the various stakeholders were detailed in order to define their involvement in the process, their power and interest in its output.

The model itself started outside of Revit®, the main software used for its development, because it was necessary to first set its structure through the selected Common Data Environment, Dropbox®, the naming convention for the files, and, last but not least, the designated Level of Development of HBIM elements, which was just a preliminary assessment that would later be enriched together with the parametric setting of the masses.

The Scan-to-BIM phase began by analysing the already existent data regarding the Cervo Valley and Rosazza, a set of point cloud and IFC files that was studied and elaborated to fit the purposes of the

thesis. The context of the model was set in Revit® through the implementation of these files together with the topography, that was elaborated through Open Street Map in InfraWorks®.
The actual modelling phase encompassed the shaping of the masses, that were modelled out of a combination of the previously elaborated IFC files and InfraWorks®' exports, and the definition of the necessary parameters to determine the risk of each mass. In this phase, the Level of Information Need of the masses was further detailed using UNI regulations.
In the data enrichment phase, each parameter was studied, explained, and defined through different ranges of risk to establish the overall risk of the specific building (and therefore mass) in relation to a hypothetical monitoring sensor located in a critical point of the torrent. At this point, it was necessary to relate to previous findings concerning historic flood data of the valley and the methodology through which national entities deal with floods and early warning systems in order to formulate a coherent and holistic approach to the matter. The parameters were linked to the formulation of Risk as a product of Vulnerability and Hazard. The first set of parameters, those dealing with vulnerability, was elaborated through a Dynamo® script that extracted distances between the masses and the sensor, while those regarding Hazard (weather and hydrological parameters) were treated as if they came directly from the monitoring work of the sensor and they were later implemented after the export of all the parameters in Google Sheets™. All the parameters were then elaborated through the Risk range values that had been previously introduced and the final Risk was imported in the masses. After this was done, the Risk values were associated with a colour grading from green to red according to a growing flood risk through another Dynamo® script, which resulted in a visualization of the risk for every mass/building in real-time according to the detected parameters.
Finally, various further developments were explored, considering this project as a methodology example for future applications and expansions in many fields, from hydrogeological studies and modelling to databases for private and public entities, from further enrichment of parameters to better detail the information of the masses as well as further detailing of the modelled entities themselves in order to use the model as a source for renovation or conservation in the case of damage because of a flooding event, to machine learning implementation that could predict the behaviour of the torrent and its affluents as well as weather forecasts in order to act before the flood presents itself. The most useful and direct application is the exploitation of the model by local authorities to better define an Early Warning System, aid the Hydrogeological Plan of the city, and better coordinate evacuation and protection measures for Rosazza.

2. Literature Review

2.1 Digital Twin and Historical Building Information Model: definition and use in modern AEC

2.1.1 History

Digital Twin is a concept that has been thoroughly analysed and used in many different fields in todays' time, but this doesn't mean that a common definition or knowledge on the matter has been established.

As the terms itself suggests, a digital twin can be referred to as an entity who has a close relation to another entity, and it is generally used to represent a physical entity in a digital way to extract and analyse its possibilities and properties without disrupting the original element. The concept of modelling a secondary entity to define the possible behaviour of the primary one was first developed during the configuration of computational models to study NASA Apollo programmes through flight simulations that could mirror manoeuvres in complete detail. The aerospace field was also the one that enabled this technology to become more refined, with the design of satellites and their study in the 80s and 90s; it was compulsory to create a digital duplicate of what was to happen in space because, in simple terms, no earth-based satellite existed and therefore it was impossible to study its behaviour in an experimental way (Boyes & Watson, 2022).

After a first approach, Michael Grieves proceeded to introduce the more specific concept of digital twin in his Product Lifecycle Management course at the University of Michigan. In the abstract of "Digital Twin: Mitigating Unpredictable, Undesirable Emergent behaviour in Complex System" (2016), he explains how this idea originates from the need to control unscheduled events in a system that is inherently complex and therefore could lead to unprecedented issues. Controlling its structure in a digital counterpart could lead to a more balanced and cautious dealing with the object, therefore avoiding normal accidents and incentivizing its development (Grieves & Vickers, 2017).

NASA continued to adopt digital twin in a more coherent and thorough way, as explained in "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles" (2012). The aim of the use of Digital Twin was a need for a 'fundamental paradigm shift' in the design of U.S. Air Force vehicles since they would have needed an ever-lighter mass subjected to higher loads. This shift was encouraged by the Digital Twin, which combined 'ultra-high-fidelity simulation with the vehicle's on-board integrated vehicle health management system, maintenance history and all available historical and fleet data to mirror the life of its flying twin and enable unprecedented levels of safety and reliability' (Glaessgen & Stargel, 2012).

The number of papers that dealt with digital twin technologies incremented rapidly, with a constant of around 100 paper per year between 2017 and 2019 and an outburst of 1934 in 2021 (Tao, Xiao, Qi, Cheng, & Ji, 2022a). As of now, Digital Twin Model and technologies are listed by Gartner (internationally relevant technological research and consulting firm based in the U.S. that researches in technology) as one of the top ten strategic technology trends of the present time from 2017 to 2019 (respectively as the fifth and the fourth in 2018 and 2019) (Panetta, 2016) (Panetta, 2017) (Panetta, 2018), then it has been mentioned as part of Hyperautomation in 2020 (Panetta, 2019), 2021 (Panetta, 2020) and 2022 (Gartner, 2022), since this concept is nothing but a result of the creation of a digital twin of a whole organisation, exploiting this process not only for objects but also for services and companies to deal with unprecedented events in our complex system reality.

2.1.2 Definition

In the context of increasing its relevance and attention, a lack of a common definition for Digital Twin arises. This is due to the fact that the fields in which this term can be applied are extremely different from one another, and a definition that lays its basis on functionality cannot be obtained in an unambiguous way. In their anthological study, Tao, Xiao, Qi, Cheng, & Ji (2022b) have identified a high number of application fields that could take advantage of digital twin technology, as demonstrated by the number of papers that deal with this matter out of a total of 331 studied: the main fields are manufacture, with 47.89% of papers analysed, then energy with 12.32% and aerospace with 7.39%.

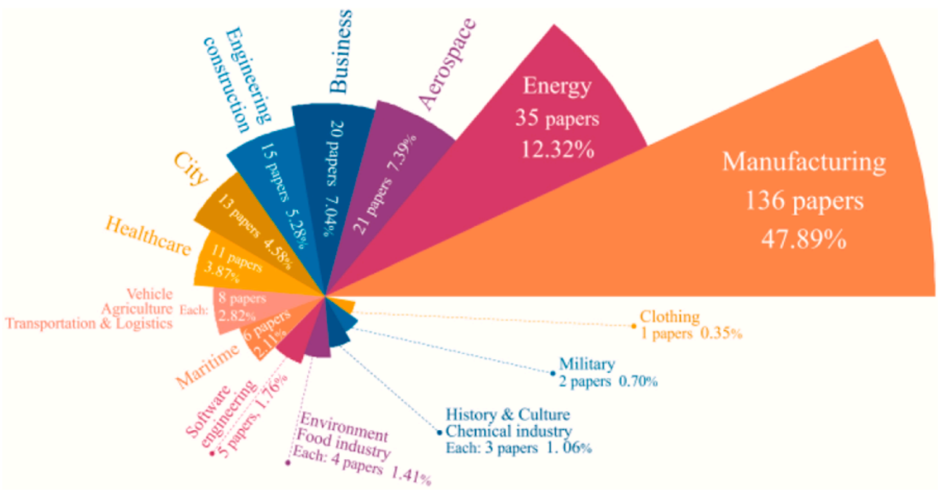

Figure 1 Application field distribution of digital twin models (Tao, Xiao, Qi, Chen & Ji, 2022b)

Of course, the application of digital twin models varies in relation to the field in which is it used. For example, the clothing industry uses digital twins mainly to reconstruct historical garments, but it could be expanded to virtual try-it-on applications through augmented reality in the future; the chemical field digitalises macroscopical environments as combustion furnaces, but it would be extremely avant-gardist to focus that on the microscopical level and develop digital models of molecular interactions.

More general definitions of a digital model have been gathered by Jia, Wang, & Zhang (2022) through their literature review, linking the definition with the parameters that were considered to elaborate the reference model. Grieves & Vickers (2017) had identified it as:

'A set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level'.

The parameters were the real dimension, the virtual space, and the third dimension of the link between the previous two as in data and information.

Tao & Zhang (2017) elaborated a more detailed definition that describes a digital twin as a combination of:

'The physical entity with high-fidelity virtual counterpart and the two parts company with each other during the lifecycle, it also integrates and converges data from multiple sources to generate more accurate and comprehensive information'.

In this case, the considered dimensions were five: physical entity, virtual entity, digital twin data, digital twin service system, and the connection.

According to Alam & El Saddik (2017), a digital twin is:

'An exact copy of a physical system that truly represents all of its functionalities, which can be used for monitoring, diagnostics and prognostics purposes'.

The interested dimensions were in this case related to a Cloud-based system and refer to physical thing, digital twin, hierarchy-based compositions of subsystems, relation network, and web services.

Furthermore, Zhuang et al. (2017), referred to a Digital Twin as:

'The process and method of describing and modelling the characteristics, behaviour, formation process and performance of physical entity objects using digital technology',

Rather than a simple object. They used a three-dimensional consideration: dynamic data acquisition in physical space, evolution of digital twins in virtual space, and feedback control based on monitoring and process optimization.

Boje, Guerriero, Kubicki, & Rezgui (2020a) elaborated literature-based research on the possibilities and actuations of Digital Twin (DT) Process in the AEC industry and generally defined DT as 'the ultimate, unachievable goal, as no model abstraction can mirror real world things with identical fidelity'. They then proceeded to use the term 'system of systems', previously introduced by other resources, as a relevant definition because it deals with the topics of scalability and sustainability of systems, both of which are linked to communicate data in an effective and efficient manner. Moreover, the considered three dimensions (and called in this case "components") are:

- The physical components
- The virtual models
- The data that connects the two.

This also is a relation with what Grieves (2014) reckoned, i.e., the connection from "Physical" to "Virtual" to be made of data that requires a level of processing, which demands the gathering of data then sent to be analysed and elaborated by the virtual in order to be implemented in the DT model. In return, the "Virtual" can provide new information that could help better manage and monitor the "Physical".

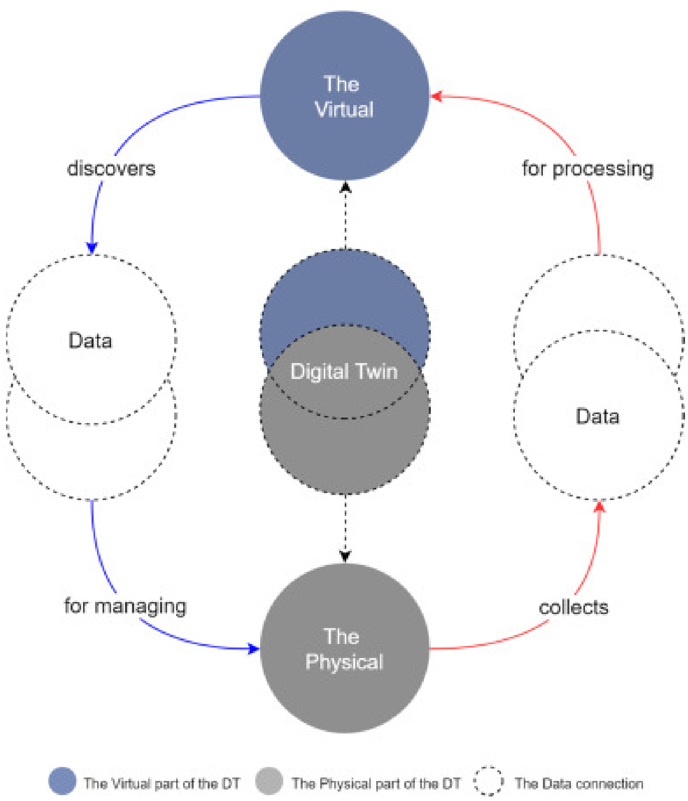

Figure 2 The Digital Twin paradigm (Boje, Guerriero, Kubicki & Rezgui, 2020)

2.1.3 Application in AEC industry

As reported by Opoku, Perera, Osei-Kyei, & Rashidi (2021), the construction industry contributes nowadays for about 8-10% to economies of different countries and promotes employment of different levels to the masses, as well as flows of services and goods in a transversal way through different sectors. As regarding the economic power of the AEC sector, it amounts to 10 trillion USD in 2017, the 8.1% of Australia's Gross Domestic Product, 6.5% of the UK's, and 5.7% of China's. Nevertheless, it appears to be stuck as one of the least digitalised sectors due to its radical traditionality and aversion to change, as well as the misconceptions derived by the use of digital instruments in a field where paper documentation is still majorly spread, which determines a proliferation of information that cannot be integrated, miscommunication, and a general stall of the workflow (Ghaffarianhoseini et al., 2017). This leads to the need for digitalization as well as a further development of technologies that could solve the main issues of the sector, such as low productivity and predictability, fragmentation, and lack of investment in innovation (Farmer, 2016).

Digital Twin technologies and processes have recently been introduced in the AEC field as a result of an expansion of the more known term, Building Information Modelling (BIM), that allows multiple professionals to work on the same project at the same time in a virtual environment. This environment relies on a 3D representation of a building and it has started to take into consideration a fourth dimension, time, that could determine a more comprehensive detailing of a building in relation to its adaptability on a longer period of time, not only in term of its degradation, but also of its future maintenance and restoration, as well as demolition and re-utilisation of its parts (Boje, Guerriero, Kubicki, & Rezgui, 2020b). It has also been highlighted how the fourth dimension has sometimes been overpassed by the fifth, cost, going on adding more layers and possible uses to reach up until a tenth dimension (industrialisation), amplifying its possibilities and applications (Sattineni & Macdonald, 2014). For this reason, the term "dimension" now refers to a broader functional concept, expanding the view of BIM fields to different contexts and utilities. In any case, it is of utter relevance to nowadays consider at least Time inside a new design or the renovation of an old building. This leads to the collateral aspects of health and environmental protection, site management and lean construction, which could be aided through a multiple dimension BIM procedure as the ones previously defined.

The issues that arise from this new view of a construction project is an explosion of new data, also known as "drowning in data". When a multi-dimensional BIM methodology is applied, all the stakeholders are working at the same time to ensure to reach their needs and requirements, therefore producing a high quantity of data both inside and outside the model (Boje et al., 2020). In this kind of environment all the dimensions are put together inside a single virtual reality and technologies such as Internet of Things or Augmented Reality are implemented to enrichen the experience and delivery of information. The integration of different information typologies on a main platform is the main issue creating a proliferation of data, issue that can be compensated through the introduction of IFC models instead of full-detailed models, but, as it has been thoroughly analysed in the field, this could lead to greater losses in terms of information and interoperability, therefore making this option unexploitable (Laakso & Kiviniemi, 2012).

Digital Twin, as explained in the previous chapter, could help integrate all the dimensions and technologies in the same environment. First and foremost, DT processes could include spatially larger elements inside the same model, whereas BIM normally focuses on a deeper level of detail for a single building element or group of buildings; a digital twin, on the other hand, could envelop a district or even a city, when defined through the appropriate technologies such as Scan-to-BIM (Boje et al., 2020). Moreover, inside a digital twin multiple additional and external elements could be inserted in order to better monitor or maintain an already existent element, such as sensors which will give back different kind of data if investigated, IoT technologies, which could directly monitor different parameters such as climate parameters for the Indoor Levels of Comfort, environmental and health parameters or, additionally, structurally related sensors that could help renovating and define the possibility for structural interventions that could avoid disastrous deteriorations. The diffusion of a sensor–based monitoring of buildings could therefore lead Artificial Intelligence to determine predictions based on the acquired Big Data and therefore the optimisation of any kind of future interventions on the district or building; once again, the reality of complex systems highlights the centrality of this kind of approach where the future can be studied and foreseen through technology (Díaz, Alarcón, Mourgues, & García, 2017).

Furthermore, BIM processes normally work with static data, whereas DT focuses on real-time flows of information; we could therefore say that, in a way, Digital twin technologies could include BIM as well as Data Analytics, machine learning and geomatics (Ghaffarianhoseini et al., 2017; Opoku et al., 2021).

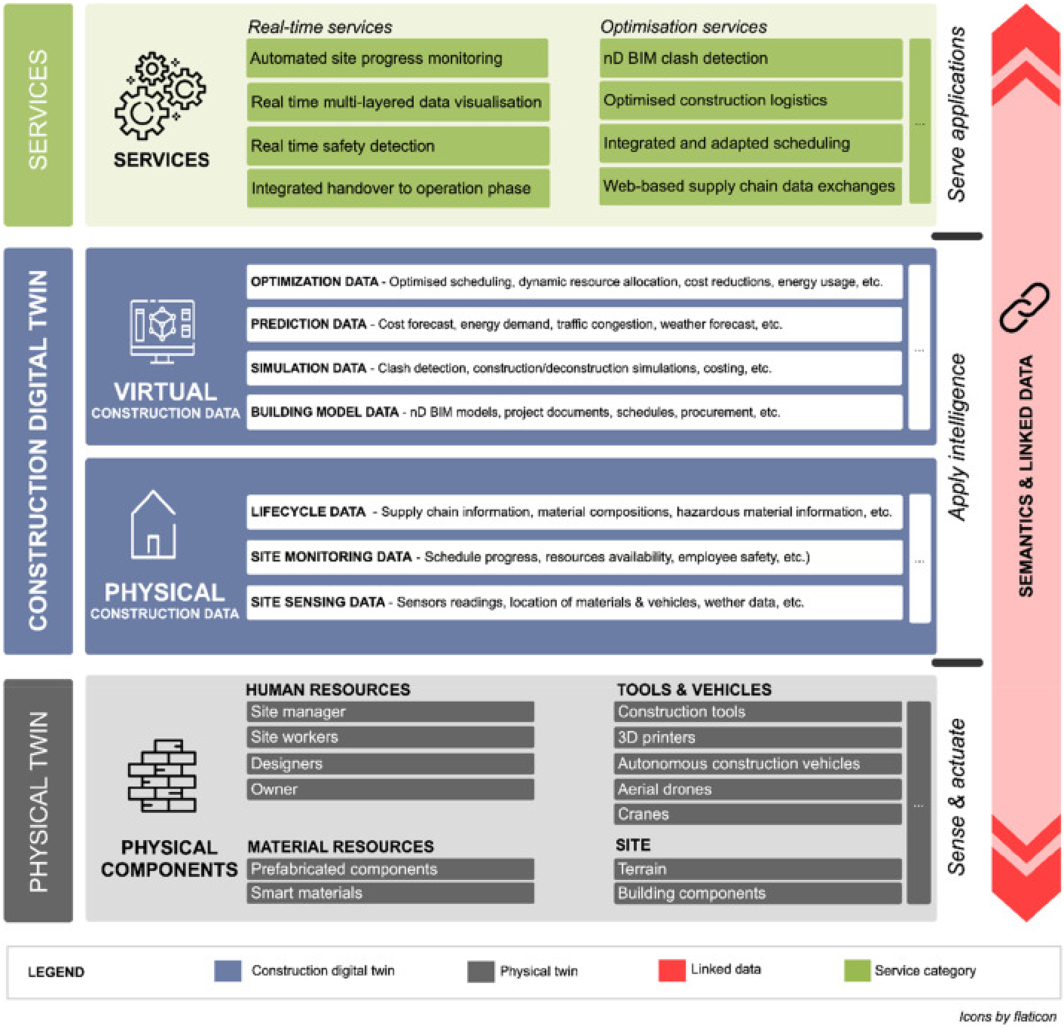

Figure 3 Construction Digital Twin data use for facilitating smart construction services (Boje et al., 2020)

2.1.4 Historical Building Information Model (HBIM) and Digital Twin

Before analysing the importance of introducing BIM in the context of digitalisation of a historic area or building, an introduction on the topic of cultural heritage in the AEC industry has to be addressed. The conservation of cultural heritage has been explored by the international community for centuries, but it has been given a more proper structure through the recommendations for UNESCO in 1962, that defined a cultural heritage as 'landscape, natural and anthropic environments, which are of cultural or aesthetic interest or constitute a harmonious natural whole' (Vecco, 2010). The knowledge regarding cultural heritage has originally been gathered in an analogical way, through dispersed and often inhomogeneous drawings or literary information, determining a high complexity of analysis. In this context, the importance of digitalization arises to suppress the difficulty in finding every single physical document that could help analyse or renovate an area or building, for instance in the case of different document locations, changes in the correct address of the area interested, that could cause issues in the research of a particular document through its address in archives. The first digitalization was two-dimensional, with projections and prospective images that are being replaced with interactive, 3D models from which to later obtain all the needed 2D tables. This concept, together with the idea of implementing a high number of different kinds of information, led to the use of BIM for the representation of cultural heritage and not only for new constructions, so that the fourth dimension of time and the possibility of renovation and maintenance plans could be introduced directly on the model (Moyano, Carreño, Nieto-Julián, Gil-Arizón, & Bruno, 2022).

When dealing with a portion of land such as a district or a municipality, BIM is not sufficient, as previously stated, and DT comes to the rescue (or District Information Model, DIT). This is a field in which not only is the state-of-the-art relevant for the representation, but also its predecessors and the layering of different renovations as well as the potential future development of the building and the district surrounding it. This allows the possibility of a historical digital representation in the final phases of the construction cycle, where the designer and maintenance officers are supposed to protect the works from different types of hazards and enhance the conservation of the cultural heritage (Opoku et al., 2021). The digitalization of the cultural heritage determines the necessity for integration of geographical information with other types of detail through the BIM implementation of Geographic Information System (GIS), which connects each object to its geo-spatial position (Pepe, Costantino, Alfio, Restuccia, & Papalino, 2021).

Such an approach is defined by (Dore & Murphy, 2012) as 'Historic Building Information Modelling', which is:

'A system for modelling historic structures from laser scan and photogrammetric data using Building Information Modelling (BIM) software)'.

Another definition was given by (Ewart & Zuecco, 2019) and describes HBIM as:

'A novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements (including detail behind the scan surface) are accurately mapped onto a point cloud or image-based survey'.

The acronym "HBIM" can actually signify more than one thing. It is not only referred to Historic Information Model, but also to the general process of Heritage Information Modelling (Rebec et al., 2022), which is also closer in meaning to the output and workflow of this thesis. This broader term could encompass the concept behind the model, favouring a holistic analysis of HBIM: it could include more levels of relevance for the model itself, not limiting it to a historic point of view, but also to a cultural, traditional, and social one, therefore determining its importance in the matter of heritage, which is the scope under which this thesis lies (Della Torre & Pili, 2019). The level of development of the geometries, for example, will not be taken to the highest possible level of geometrical development, because it is not necessary for this specific project; at the same time, the alphanumerical information will be much higher to satisfy all the requirements and generate an effective and comprehensive model that would be useful to shelter the cultural heritage against the hazard of floods.

The integration between a 3D-GIS system such as a point cloud or georeferenced laser-scanner data is therefore an inherent part of HBIM. This process leads to a "reverse engineering" approach, where the architectural or engineering components are designed thanks to techniques such as Terrestrial Laser Scanning (TLS) inside the 3D GIS environment, which offers the possibility of multiple connections between different databases (Pepe et al., 2021). Reverse engineering is also defined as 'the process of capturing massive data from LiDAR technology', which allows the designer to have an external representation of a shell of different elements and no information on the entity of those elements, but just an ensemble of a high quantity of points with geographical orientation (Moyano, León, Nieto-Julián, & Bruno, 2021).

The dispersion of said points leads to the issue of Level of Detail (LOD), a parameter that regulates, as suggested, the level of detail during the modelling of the objects. This can be interpreted in two consequent steps: the first one is the import of geospatial data such as point cloud, which could be extremely vast in term of number of points, whereas the second one is the geometrical definitions of the elements to be modelled in the modelling phase. In the first case, it is clear that the introduction of digital technologies to grant an environment in which to work is essential for a better and faster representation of the building or district (as previously stated, basing the modelling on the point cloud or photogrammetry previously gathered), but this leads to a difficult elaboration of the point cloud itself because of the indistinguishability of the points. A point cloud is a 3D scan of a volume through a finite number of projected points of an area and those points are inherently not classified into different topological elements or classes. To facilitate and fasten the work of a modeler, it is useful to group some points to define an element (such as a beam, for a building) and continue to mark similar elements in a similar way, therefore describing the point cloud in a logical and semantic way. This process of definition of different entities in a point cloud or a similar system is defined as "segmentation", more precisely "semantic segmentation" in this case, a *'way to process and organise the point cloud into meaningful subsets'"* (Moyano et al., 2021).

This could be executed in a manual or an automatic way; the first one is logically longer, as a historic façade could add up to hundred million points while the second one could be implemented thanks to different algorithm combinations that could group homogenous points due to function or shape and define different entities. Due to the need for automatic programmes that could elaborate point clouds, different kinds of software have been developed, such as The Point Cloud Library, an open platform that provide different algorithms with the purpose of filtering, reconstruct, segment, and model fit point clouds. Algorithms are further developed using Machine Learning (mathematical algorithms) or Deep Learning (based on biological networks) techniques, that make them grow in intelligence and intuition and let them detect and classify shapes in an easier and faster way (Moyano et al., 2021).

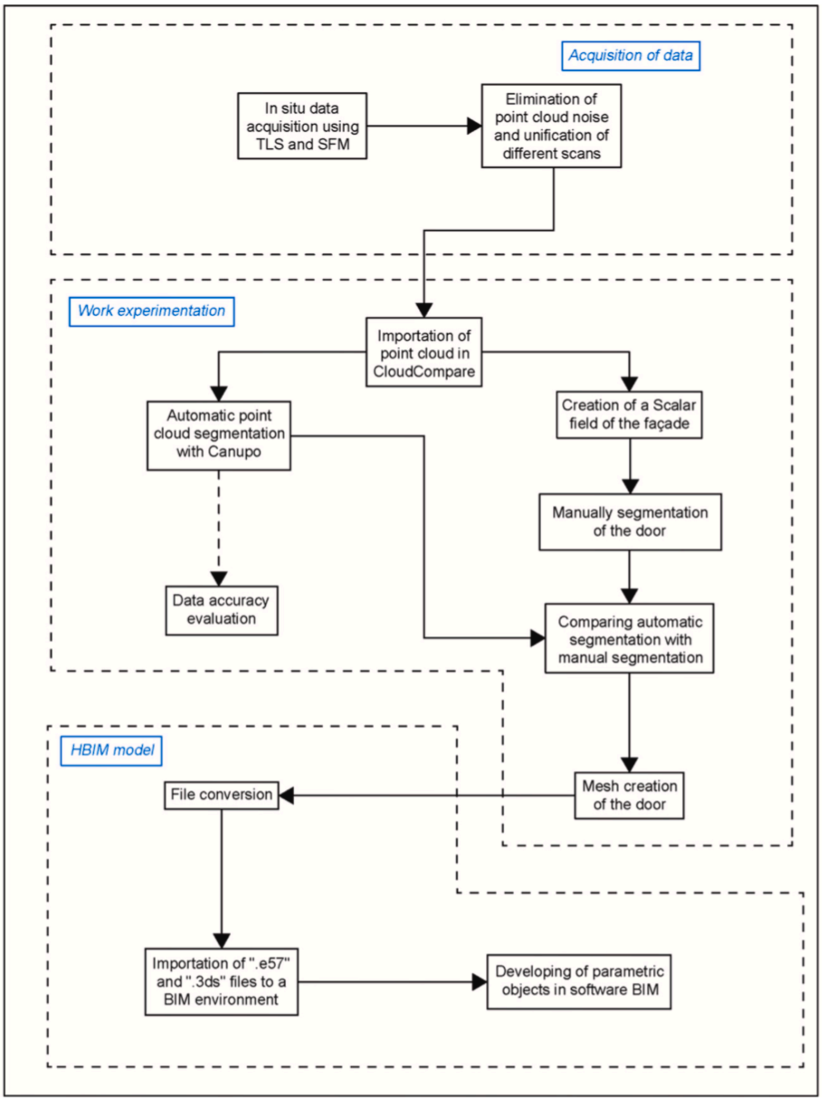

Figure 4 Possible workflow for point cloud elaboration (Moyano et al., 2021)

Stakeholders for the case of a conservation of the cultural heritage are also different in number and position in relation to a new construction: a simple example could be the participation of the designer, which is often not guaranteed because of the old age of the building itself; the occupants of the building can then be included together with the whole community, which should have an opinion on the intervention, as well as the government, but also historians, archaeologists, and researchers or cultural heritage organizations that could have a relevant saying in the actuations decided by the renovation or conservation company. This dynamicity determines the need for an unambiguous space where the partners could share their ideas as well as collaborate first on the realisation on the model and then on its exploitation by the public (Dore & Murphy, 2012).

Moreover, a difference between BIM and HBIM is the unavailability of pre-established libraries on a software like Revit® to model the buildings and its components. Since HBIM is applied to already existing buildings and digs into the historicity of the cultural heritage, it is almost impossible to find a system of elements that could represent with precision what the professional is trying to reproduce (Pepe et al., 2021). This deals with the previously mentioned issue of extreme detailing, as it is in this part of the modelling that the designer is set to determine how much to detail geometric information.

The application of BIM is normally done after the acquisition of the area information through different technologies, generally referred to as Scan to BIM, therefore the three essential steps of HBIM representation are:

- Data capture and survey, for example Scan to BIM
- Software implementations and interoperability
- Digital twin development and its enrichment (Moyano et al., 2022).

According to Pepe et al. (2021), these three phases should be completed with a preliminary phase of historic analysis to deal with cultural heritage. In any case, the gathering of GIS data, its exchange with a BIM platform and the elaboration of the digital twin are the main steps to create a HBIM model and the same that are going to be followed by this thesis.

2.1.5 Workflow examples

To define a methodology and the necessary workflow steps for an HBIM model, various papers were consulted to derive some inspiration and see how the academic environment perceives this concept.

Santagati et al. (2021) proposed a workflow that is basically a deepening of what has been previously explained concerning HBIM and Scan-to-BIM methodology. Their goal was the modelling of the St. John the Theologian cathedral in Nicosia, Cyprus, for the conservation of the building and its frescos. The phases it encompasses are the following:

1. Primary research: the first step when dealing with a historical building like in this case is to gather as much information as possible regarding its development and construction. This kind of material can be of different forms, from textbooks (literature) to drawings and digitalised sections, prospects, and plans of the building itself. In this phase, a physical survey of the building was conducted to define the state of conservation and identify the different building techniques that compose the cathedral.
2. 3D acquisition and modelling: the technology used to create the three-dimensional base to model upon is the combination of laser scanner and photogrammetry. A first terrestrial laser scanning (TLS) was performed with the TS surphased 25HSX both on the exterior (31 scans) and interior (42 scans); together, they produced a 2 billion points point cloud that was later processed using JRC Reconstruction and through a pre-processing phase to eliminate noise and detect edges. According to the Iterative Closest Point algorithm, the two groups of scans were aligned with an error of 2mm, and the point cloud was reduced to about 1 million points to make it more easily accessible. Since TLS point clouds do not have any colour, this point cloud was integrated through a photogrammetric survey using Structure from Motion (SfM) techniques and then processed through Agisoft Metashape. Once again, the images were separated in two groups, exterior and interior, and realigned. The final step was the application of the same reference system for both the point clouds in CloudCompare to identify homologous coordinates then further processed in Metashape for scaling and aligning.
3. Modelling (which was included in the previous phase that can in that case be referred to as "Scan-to-BIM"): first, the point cloud needs to be classified according to semantic segmentation to identify architectural components through FARO®, that was also used as a plug-in in Revit® to import the point cloud and automatically generate elements such as

walls. Later, these components need to be modelled and this opens two scenarios: those in which the libraries of the modelling software (in this case Revit®) can be exploited or those in which new libraries need to be established to define a group of objects of the same category. For walls, Santagati et al. (2021) generally used pre-made libraries because they are easily manipulated according to the necessary stratigraphies; for elements such as windows or doors, they created various similar elements on Rhinoceros and then imported them in Revit®. The deviation between model and point cloud was then examined through an as-built plug in.

4. Level of Development assessment: further data needed to be added to the different components in the form of images, text, tests, and conservation states. For this purpose, it was necessary to first establish the level of detail of the model, concerning both geometries and information for each part. Since regulations tend to be very strict when dealing with a historical building, that normally needs to reach a LOD F (as-it-is) and require invasive and non-invasive investigations, another parameter was included to define the combination between Level of Information and Level of Geometry.
5. Data enrichment and decay mapping: data was added to the single elements or components through parameter enrichment in Revit® and Dynamo®. Decay was then mapped according to the command “Region” and “Area” with some complications due to the difficulty in extracting quantities from the model directly, therefore Dynamo® was needed again.

A similar workflow was provided by Martinelli, Calcerano, & Gigliarelli (2022), who developed a HBIM of the Naples Archaeological Museum. When addressing an introduction to the topic, a general workflow for similar projects was detailed gathering the most relevant regulations on the topic at an international level. It can be summarised in Figure 5.

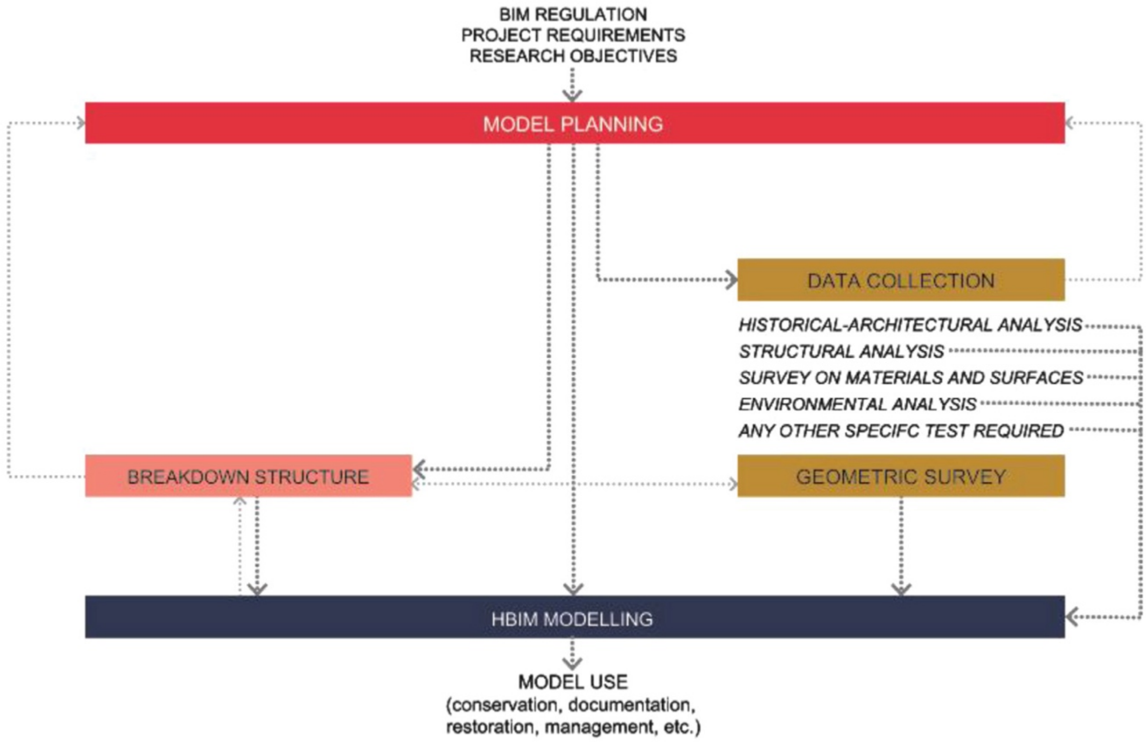

Fig. 1. Schematic representation of the proposed workflow.

Figure 5 Schematic representation of the proposed workflow (Martinelli, Calcerano, & Gigliarelli 2022)

The paper underlined how the procedure is not strictly linear, but it can include reiterations and flexibility in order to find the perfect combinations for a current modelling.

Once again, the workflow was similar to the previous one described. The different phases are differentiated as:

1. Model planning: according to the framework provided by Italian Legislation (UNI 19650), the different phases for the elaboration of an HBIM were examined to plan in the best way possible the future work. The most important part here was the mention of BIM Executive Plan (BEP), the model planning phase which states everything regarding how the information will be processed and handled in the following phases, relating them to all the actors involved.
2. Data collection: the data collected was of various types, here listed as historical and architectural, geometrical, structural, surveys on surfaces, and environmental. They were in forms of tests, analyses, and surveys. This helped gather enough practical knowledge on the components to determine the Level of Information that would be later applied to them, according to how much information was found on the object.

3. Design and implementation of geometric survey processes for HBIM: this dealt with Laser scanning and photogrammetry in a way that was extremely similar to the previously reported one.
4. Definition of the breakdown structure of the building into construction elements and identification of the Level of Information Need for each model object: this identification was more thorough but worked as previously.
5. HBIM modelling process: the complexity of a project of this kind was underlined, relating this level of difficulty to the detailing of a historical building, to its complicated history, and architectural peculiarity. The Scan-to-BIM process was similar to the previous one. In this case, well-structured parametric families and types were used for individual building components adapting the modelled object to the LOD required by Italian regulations instead of adapting the general indication to the specific component. Informational sheets, images and such were once again linked to the components through Dynamo® and parametrical information.

3 Rosazza and the Cervo Valley

3.1 The history of a Valley

Figure 6 Location of Cervo Valley in Piedmont (Ceragioli, 2012)

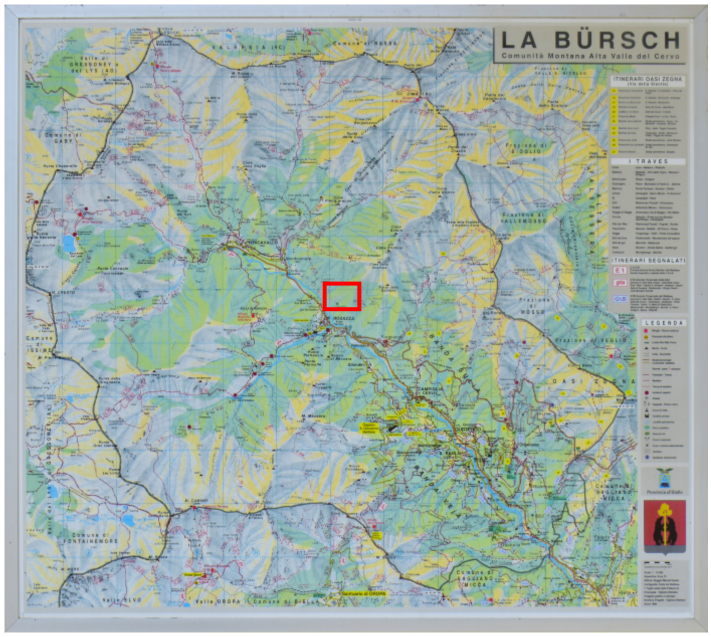

Figure 7 Detail of High Cervo Valley realised by Eventi & Progetti *nel 1999 thanks to the survey of Orazio Boggio Marzet (Centro Documentazione Alta Valle Cervo, La Bürsch, 2023)*

The Cervo Valley is situated in the northern part of Piedmont, Italy, and it is the deepest and longest valley of Biella province. It is also named "Andorno Valley" after its main municipality on an administrative and historical point of view, Andorno.

The valley is divided in two parts:

- the Low Cervo Valley, which extends itself for 10km in the north-western direction and includes the cities of Tollegno, Andorno Micca, Sagliano Micca, Miagliano, and Tavigliano. This is known to be more adequate for human settlements because of its morphological and geological formation, since it holds less rocks and mountains,
- the High Cervo Valley, that extends itself for 8km alongside torrent Cervo until its springs in Piedicavallo, and includes five municipalities, Piedicavallo, Rosazza, Campiglia, Quittengo, and San Paolo. This part of the valley is less inhabited due to the austerity of its mountains and the scarcity of land to exploit for agriculture (Deambrogio, 1976).

The focus of this part will be given to High Cervo Valley, since it includes the municipality of Rosazza, subject of this study.

3.2 Natural aspect

From a geological point of view, the Cervo Valley's mountains are mainly made of gneiss, which is the same type of metamorphic rock of the Alps in that area (Lanzo Valley, Aosta and Biella). Glaciers used to characterize the region, but they almost completely withdrew creating the main torrent of the area, Cervo, its affluents, and the different valleys that can now be encountered.

The valley is surrounded by not-too-high mountains in its higher part, and it is covered by different types of trees (mainly beech, ash, and birch trees). Regarding weather and temperatures, it is not very sunny during the winter, but it doesn't present too rigid temperatures. Rain periods are concentrated during Spring and Autumn, and they favour the development of the mountain vegetation. Most of the valley is made of woods, whereas meadows are only reduced to a fine portion of land next to the watercourses; grasslands can be found up on the mountains and proper fields are scarce. Vegetable gardens are either near the villages or along the mountain slopes crafted through drystone walls (Valz Blin, 1959). Terracing is indeed the most common way for a mountain area to be exploited for agriculture and the Cervo Valley behaved accordingly. They are obtained in the steep slopes of the mountains through excavation and the construction of drystone walls, as previously mentioned, following height contours and forming sort of "steps" on the slopes. This type of manipulation of the terrain is concentrated on the orographical left of Cervo Torrent and it does not only help with agriculture, but also with the prevention of landslides.

The past relevance of this area is due to the presence of important mountain passes through the Alps which represented the main and only connections among valleys. Some examples are the *Colle della Colma* which connected the Oropa Sanctuary with the one of San Giovanni d'Andorno or the *Bocchetta di Finestre* (2038m) between Rosazza and Oropa through the Gragliasca Valley, affluent of Cervo Torrent, which was used for the pastoral transhumance (Deambrogio, 1976).

3.3 Economy and demography

While determining the case study area of High Cervo Valley, Deambrogio (1976) highlights how the problems of mountain areas are the same throughout many different regions and can always date back to one main issue, the relationship between mountain and city: ever since the first municipality during the Middle Ages, the history of mountain villages is one of 'abandonment, emigration, and environmental degradation'.

This valley is defined as "territorial" for its greater influx on a regional level, and it is underlined how the presence of a developed urban agglomerate made it possible for the area to define a complex and well-organised structure of mountain "management" as well a great maintenance of the fragile mountain economy and its human and architectural environment.

As far as economy is concerned, it is important to highlight the relevance of water mills in the area ever since the Middle Ages, because they became not only a mean to fuel agriculture and the textile industry but also a connection among different classes of citizens and symbol for the economic and demographical recovery of the X century. The ownership of mills was generally attributed to different instances, such as the Church or private landowners in the beginning and they were then divided among the four municipalities that arose after the division of 1700; most of them were auctioned publicly and during the Napoleonic era they were mostly privatised. The relevance and activity of the mills deteriorated until the beginning of the XX century, where most of them were abandoned due to migratory movements.

Another historically relevant activity in the region was that of forges, which were used to produce working tools or animal shoeing. Forges were generally located in plane regions, they were first introduced in the XVII and XIX century and, since they were generally used for hydraulically engine mallets, they had to be served through a specialised canalisation and therefore be installed close to watercourses.

The activity of markets was also relevant since ancient times, since the geographical setting of this area made it essential for valleys to communicate through mountain passes to exchange goods such as food and manufacture products. The main market was in Andorno because of its easy access to the whole valley.

Probably the most important production in this valley was due to the presence of syenite mines and quarries in the XVIII century, that let this region and the Biella province in general be extremely influential for the construction industry, with a specialisation for the manufacturing of syenite stones. The exploitation of the quarries was private until the end of the XIX century, when the municipalities started to give them out through tendering. This production led the population to be invested in this industry and major workforces from these valleys started to be travelling around Piedmont and other regions for their extraordinary skills in the manufacturing of this kind of stone. The products were directly refined in the valleys due to the high costs of transportation and the heaviness of the material, which made many different workers in this field immigrate in this area to continue their work where it was the most prolific and appreciated, for example from Veneto, Murbe, and Verbeno. The railway that passed through the valley was one of the products of this industry and it connects these locations to Biella and the major networks of Andorno, Tollego, Sagliano, and Miagliano. The railway network was then dismantled and sequestrated by ATA in the 1950s. As of the end of the 1970s, seven syenite quarries were active and 10% of the male population was employed in this sector (Deambrogio, 1976).

Nevertheless, even though these productions were found to be relevant for the population and other provinces and regions, the generally low productivity of the valley and the aridity of the soil led many to emigrate in seek for different jobs since the XVI century. Many of the special workers who developed their abilities in direct contact with syenite and stone manufacture moved to other regions to exploit their skills where they could profit more, for example in Lombardy, where new constructions such as the Milan Dome or the Certosa of Pavia were in great need of workers. Duke Carlo Emanuele I of Savoy even favoured emigration in the surrounding areas in order to improve life conditions in the valleys and emitted a "collective foreign passport" for valley men in 1607. After an effective defence against the French during the first half of the XVIII century, the dukes appointed Cervo Valley workers with "motivated privilege for the tendering of the realm" for fifty years, making this region one of the most important for the fortification works against the French, attracting specialised workers such as bricklayers and stonemasons from all over Italy, Europe, Northern Africa, the Americas, and Asia. The following images show national and international examples of construction sites organised and carried out by Cervo Valley workers.

Figure 10 Railway bridge of Saati-Ghinda (Eritrea) - year 1902.

Figure 8 Metal bridge in Algeria - year 1890 (Valz Blin, 1959)

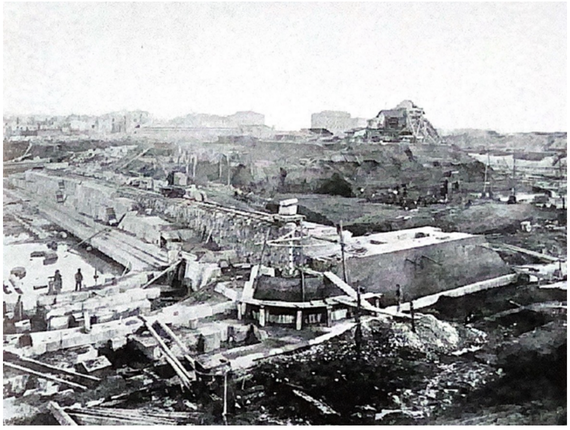

Figure 9 La Spezia Arsenal construction site - year 1862. (Valz Blin, 1959)

The relevance of valley workers and companies of this region continued to rise and for this very reason most of them moved to other countries. This led to the further depopulation of the area since 1850s, after the greater manufacture of refined stones determined an even further specialisation of workers and their consequent prestige in the work market. Data about the depopulation of the Cervo Valley have been gathered by Valz Blin (1959) and it estimates as follows:

- Piedicavallo registered emigration mainly directed to France, the United States of America and South America, with a total of 238 passports issued between 1928 and 1935. This must be noted taking into consideration the actual population of Piedicavallo so to have an order of magnitude, that was registered to be of 187 people in 2017.
- Rosazza, the focus of this research, favoured its emigrants in direction of Bolivia, Peru, and Argentina, as well as France and Belgian Congo. 47 people emigrated between 1930 and 1935, which is a huge number when considering a total population of 104 in 2017.

Valz Blin (2006) further details the emigration in Rosazza, which is deemed to be the municipality who contributed the most in terms of duration and magnitude. This phenomenon characterised the valley for a long time, but it got from being only seasonal to permanent relocations since XIX century. Mayor Federico Rosazza tried to counteract emigration through the creation of about a hundred new workplaces, but the beginning of the XX century showed other signs of impossibility for the valley to bring people back home due to lack of food and money. Most of the original population is now reported to be living abroad, especially in South America (Valz Blin, 1966). As of now, Rosazza holds a population of just 107 inhabitants, whereas of 985 inhabitants in 1911 (Istituto Centrale di Statistica, 1960).

The relevance of depopulation of mountain areas for this research is in showing how such demographic events can lead to deterioration and lack of care. It must be underlined how this is not only a trend for the Cervo Valley, but instead for every major mountain area in Italy, more localised in the Apennines but also in the Alps. The growth of cities and the mass movement of people towards the ever-expanding metropoles has led to disruptive economic, social, and environmental consequences in the abandoned mountain areas due to the general negligence it has therefore suffered from. Lands that were previously privately owned and therefore treated well by their owners, whether they were farmers or else, are now left on their own, which causes a series of environmental issues that can then lead to natural disasters in the event of difficult weather manifestations such as heavy rains, fires, hydrogeological instabilities such as landslides, and general neglect of the landscape when the public sphere doesn't offer as much financial support as needed. On a social point of view, this phenomenon can induce a higher cost of life for the remaining inhabitants, difficulty in achieving basic services for the people (schools or hospitals) and a general concentration of people in the cities which can lead to a lessening of quality of life and distribution on the land. It is indeed of the utmost importance to underline how national actions against this phenomenon have not produced many changes, as mountain areas keep getting even scarcer in terms of population, and it should be analysed how these areas could be incentivised through the high quality of their products, air and natural resources, obtained in better environment and healthier climate in relation to the polluted plains. Sadly, the attention of Italian institutions tends to be more focused on bigger cities, as they are demographically more relevant, which only leads to further neglect (Pascale, 2016). There have nevertheless been some initiatives from the national government and regional councils to encourage moving to mountain areas, such as the call for bids of the Piedmont Region for a grant of 10,000€ to 40,000€ open to anyone who wants to make a home of a mountain municipality which counts for maximum 5,000 inhabitants. Anyone born after 1955 can apply and if someone was born later than 1980, they receive more points to participate in the bid, as well as in situations in which the gross annual income is less than 20,000€, having at least one child or finding a job in the mountain area itself, or smart working to support their permanence. In order to apply, it is necessary to initiate the procedure to own a house in the appointed municipalities (Rosazza is for example enlisted) and make it their city of residence (Gennaro, 2021).

3.4 Rosazza: from the division of the municipalities to the modern day

The history of the Valley is closely linked to that of its municipalities and Rosazza is no exception. The rise and fall of the splendour of Cervo Valley can also be grasped in documentation related to Rosazza, but it seems to be of relevance to report more precise events about the focus of this Thesis. Rosazza is the smallest municipality of Cervo Valley, with an area of 9.02km^2 (“Rosazza”, 2022), and it is located 882 m a.s.l., which offers a fascinating landscape as well as a stretching nature that makes it seems as if it is climbing onto the surrounding mountains. It is also known to be “Italy’s most mysterious town” because of the numerous esoteric symbols that are decorating its architecture and its links with the Freemasonry, of which Federico Rosazza was said to be a member, a name that will be explored later in this chapter (AltoPiemonte, 2023).

Despite its size, Rosazza held the title of the most populated village in the area up until the last decades of 1800s and it was a centre for the entire valley, thanks to its school for building constructors which favoured the entrepreneurship of its citizens. Indeed, Rosazza had been the centre of many constructions throughout the XIX century, for example that of the main church in early 1800s, which also granted the municipality of autonomy on a religious point of view. The next step was the achievement of the administrative independence, which triggered a more difficult topic because of the national legislation of the time, which didn’t allow a municipality to be made out of less than 4000 inhabitants; moreover, the close towns of Montesinaro and Capoluogo, which constituted the municipality of Campiglia Cervo together with Rosazza, were strongly against the independence (Valz Blin, 2006).

At this point, Francesco Rosazza Pistolet intervened. He was born in Rosazza in 1813 and he was a Law graduate whose family worked on many working sites in Northern Italy, as did many families from Cervo Valley. He got closer to politics thanks to the ideals of Italy united, which were spreading in the first half of 1800s thanks to many important voices like Giuseppe Mazzini, close friend of Pistolet, who also joined its revolutionary association *Giovine Italia*, aspiring for the pensinsula to be unified under a republican democracy (AltoPiemonte, 2023). After the tragic death of his wife and daughter, he came back to his hometown and he put economical means and his intellect into further developing the town on a construction point of view, creating jobs that fuelled economic growth and splendour for the city. Products of this time were for example the monumental cemetery and the road that led to the Sanctuary of Oropa, as well as aqueducts, fountains, and mule tracks on the surrounding mountains.

On an urbanistic point of view, the town is interesting because of the height of its buildings, that easily reach the fifth floor, and their disposition, which climbs up the contour lines of the mountains enabling the fight for the scarce hours of sunlight of this portion of the valley.

The strong commitment of Federico Rosazza Pistolet to his community granted him the honour of becoming Senator of the Republic in 1892 under declaration of King Umberto I. His efforts did not see the light of Rosazza as a municipality, because he died in 1899, seven years before the declaration of administrative independence. In his will, he gave the famous *Palazzina* to the future municipality with the promise of detaching from Piedicavallo. The *Palazzina* was (literally) a small palace finished in 1880 and it counted future accommodations for the local doctor, the municipal secretary, the post office, cooperation societies as well as wide rooms to be dedicated to municipal affairs. As any other building sponsored by Federico Rosazza, the *Palazzina* was mainly built out of materials from the area, as well as the manpower, which was made of people from the valley.

The early years of XX century were full of failed attempts at gaining independence, until two senators from Biella, Rondano and Rigola, proposed a special law that could make Rosazza eligible to become a municipality of its own in 1903. After three years of quarrels with Montesinaro and the Italian government, King Vittorio Emanuele III declared Rosazza to be administratively independent on 11 August 1906. One year later, the first city council was instituted and in 1909 the *Palazzina* was given back to Federico Rosazza's heirs, who rented it out to the municipality. These years saw also the creation of the principal educational institutions of the town, primary schools as well as technical professional schools and a kindergarten.

Rosazza is deemed to be the municipality that contributed the most to emigration outside of the Cervo Valley during XX century, especially after the death of Federico Rosazza, who sponsored most of the works that could be found in the town (Valz Blin, 2006). The history of the town interlaces itself with that of the valley, determining a progressive emptying of its inhabitants due to emigration and age. At the same time, its tradition and history are passed on thanks to local associations of heartfelt citizens such as *Casa Museo dell'Alta Valle Cervo*, founded in 1987 and gathering relevant anthropological and photographical documents about the valley as well as exhibits about the history of its population in a historical building in the centre of the town (AltoPiemonte, 2023).

As of nowadays, the town offers different ways to relax surrounded by nature. The Municipal Park lets the youngest use swings and slides while having a wonderful view on the village perched on mountain slopes. As for museums, the *Casa Museo* is a valuable gathering of documentation about the valley, Rosazza and its people, as well as the building in which it is hosted is itself heritage. During the summertime, many events are organised in order to entertain its inhabitants and visitors, such as the "Lunch for the elders", instituted to celebrate those who have lived in the municipality the longest, as well as many food and wine events organised by *Pro Loco Rosazza*, the local association the organises touristic routes and events, such as the "*Risottata*", a competition to determine the local chef who can make the best *risotto*. Other events are related to sport and hiking, as this portion of the Alps is full of wonderful paths that generally end in one of the good restaurants of the town, where hikers can have *polenta concia*, one of the most famous dishes in northern Italy and typical for mountain area, which consists in corn flour cooked on low heat and then enriched with butter and different cheeses.

Below, a photographical journey in the town of Rosazza will be shown, based on pictures taken by the author in July 2022.

Figure 11 Different building examples of Rosazza. The architecture is differentiated based on the social status of its owners, but a general theme can be found: stone and wood, as well as relatively high buildings, and stone decorations. (Personal photographs).

Balconies.

Figure 12 Examples of balconies in the town. It is evident how the typical stone of the valley, syenite, was used in every construction detail. (Personal photographs)

Roofs.

Figure 13 Examples of roofs in buildings of Rosazza. It is possible to see how generally the roof typology is a wooden structure with stone panels on top. (Personal photographs).

Doors and windows.

Figure 14 Examples of windows and doors. Once again, the elaboration of the stone is impressive even in details concerning the entrance of the buildings (Personal photographs)

Castle of Rosazza.

Figure 15 Ruin of the Castle of Rosazza. It was built in 1883 under request of Federico Rosazza and it was designed by Giuseppe Maffei through the aesthetic of the ruin, creating chipped walls and roofs on purpose, reminiscing of ancient building in ruin like the temples in Paestum, Sicily (Personal photographs)

City hall, *la Palazzina.*

Figure 16 City Hall of Rosazza, also known as La Palazzina*. Richly decorated building designed by Maffei in perfect Eclectic style, shows the refined stone decorations that determine the whole town's aesthetic (Personal photographs).*

Other.

Figure 17 More details gathered around the town of Rosazza. Examples of elaboration of the stone in different scenarios: gates of buildings, ramps, bridges, towers, fountains, and seatings alongside the road (Personal photographs).

Figure 18 Cemetery of Rosazza (Personal photographs)

3.5 Regulations and protection

3.5.1 *Borgo più bello d'Italia*

Rosazza can be found among the so-called "*Borghi più belli d'Italia*" ("Most beautiful Villages in Italy"), whose list is gathered by the homonym *Associazione de I Borghi più belli d'Italia* (Association of the Most Beautiful Villages in Italy), under the suggestion of *Consulta del Turismo dell'Associazione Nazionale dei Comuni Italiani* (Tourism Council of the National Association of Italian Municipalities). The purpose of this list is the incentivisation of tourism of smaller scale in comparison to the main Italian attractions and the counteraction of depopulation in smaller but nonetheless incredibly beautiful and historically relevant villages scattered around the country (I Borghi più belli d'Italia, 2022a)

There are several steps that lead to the recognition of *Borgo più Bello d'Italia*. Among the requirements to apply, we can find:

- A population of under 15,000
- At least 70% of the buildings built before 1939.

These are eliminatory, which means that are compulsory for every village that applies to the list. Then, in terms of quality parameters, we can find:

- Urban quality, meaning a cohesion of the constructed heritage, easy accessibility of the village and a connection between village and surroundings,
- Architectural quality, in terms of internal and external harmony among the buildings and the surroundings, as well as of decorative elements and the relevance of some of them in a characteristic way.

Action of the conservation and valorisation of the cultural heritage must be taken upon by the municipalities if they want to be considered, such as:

- Valorisation, meaning the management of possible traffic and parking spots outside of the village, aesthetic mitigation of external elements such as overhead power lines, care for the public green spaces, a palette of colour for the facades,
- Development, meaning a correct management of tourism i.e., hotel options, restaurants, ludic activities, commercial activities, and cultural institutions,
- Promotion, meaning information points or guided visits, brochure or general guides on the village and appropriate touristic signalling information,
- Animation, such as spaces with the purpose of events and parties and temporary or permanent exhibits.

All the data regarding these quantitative and qualitative parameters must be submitted to the association through previous approval and signatures of the mayor and the city council, as well as the payment of Valuation Expenses (750€ for villages with a population under 5,000 inhabitants and 1,000€ if the population exceeds said number). Then, an expertise on the village is carried out by the Association's Scientific Committee which is followed by the examination of the report by the Committee, that then furthers it to the Directive Council so that it can approve the admission of the village in the Association.

After the approval, the municipality is to use the Association's trademark in different occasions:

- At the entry of the municipality in the sign of the name of the municipality

Figure 19 Example of the use of the Borghi più Belli d'Italia *trademark at the entry of the municipality (I Borghi più Belli d'Italia, 2022b)*

- On every communicative and promotional document issued by the administration

Figure 20 Example of the Borghi più Belli d'Italia *trademark to be applied on official documentation (I Borghi più Belli d'Italia, 2022b).*

- Commercial activities and reception services such as restaurants and hotels can use the following logos (I Borghi più Belli d'Italia, 2022b).

Figure 21 Commercial and hospitality activities's trademarks for Borghi più Belli d'Italia*. In order, they can be used for commercial activities, hospitality, restaurants and various. (I Borghi più Belli d'Italia, 2022b).*

The utilisation of the trademark is allowed only until the municipality respects the conditions through which it was enlisted. For this reason, since Rosazza is still in the list, it means that it encompasses every point of the Quality Check and provides specific attention to the touristic aspect of the village, as well as precaution and attention regarding its cultural heritage.

3.5.2 *Piano d'Assetto Idrogeologico*

Another document to take into account when dealing with buildings and flood interaction is the *Piano per l'Assetto Idrogeologico* (PAI), translated into Hydrogeological Plan, which is defined as 'the juridical instrument for the hydrogeological defence of the territory against landslides and floods' (Regione Piemonte, 2023). The main goal of this plan is to reduce the hydrogeological risk of an area (municipality or region) after a hydrogeological study of the terrain so that to reduce at a minimum level the risk to things and people. The focus for flood prevention measure is of course applied to riverbeds and their study, which is then showed in a map through different colours or hatches to differentiate areas at risk or portions of the torrent itself. Regarding the riverbed, PAI involves these kinds of information:

- A scheme of structural and non-structural, intensive, and extensive intervention on the banks of the torrent,
- The so-called *Piano Stralcio delle Fasce Fluviali* (PSFF), Fluvial Strips Plan, which delimitates different fluvial strips on the principal watercourses,
- The individuation and parameterisation of the areas at hydrogeological risk for hilly and mountain areas (Regione Piemonte, 2023).

The PSFF is probably the most useful measure for this research because it shows hydrogeological considerations in a graphical and intuitive way. It includes different information and the cartographical delimitations of fluvial strips of the main watercourses in Piedmont Region as well as possible flooding areas and their risk. The main aims of this document are to:

- Define the boundaries of the flood bed and floodable areas and therefore protect the built heritage,
- Balancing among flood containment for the safety of population and buildings as well as flood lamination,
- Safeguard natural flooding areas,
- Favour the morphological evolution of the riverbed during flooding periods and minimise anthropic interference,
- Favour the recovery and maintenance of natural conditions (Dotti, 2016).

PAI for the city of Rosazza has been granted by the Technical Office of the municipality and can be found in the following images.

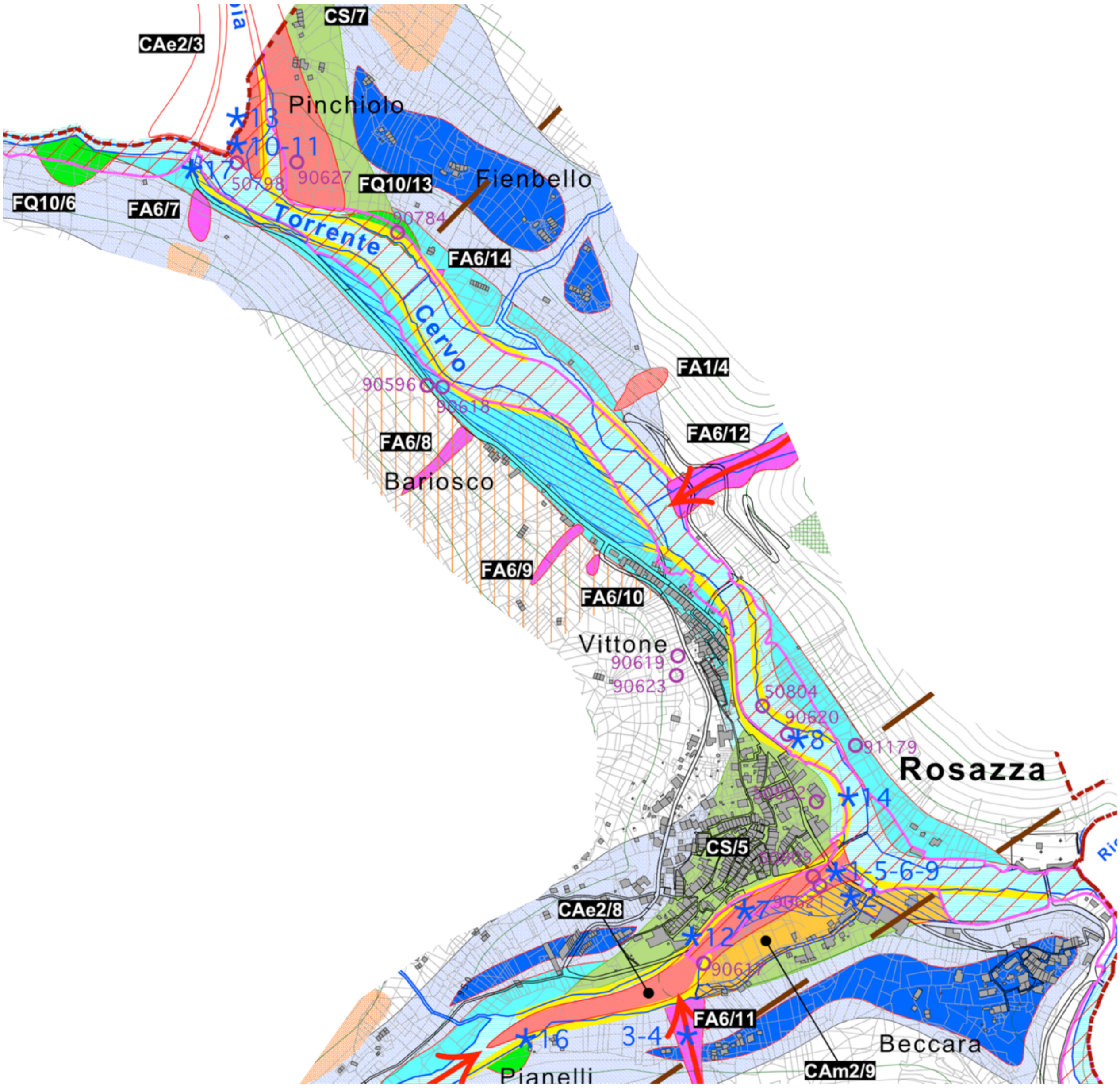

Figure 23 PAI for the municipality of Rosazza, valley area (Comune di Rosazza, 2004)

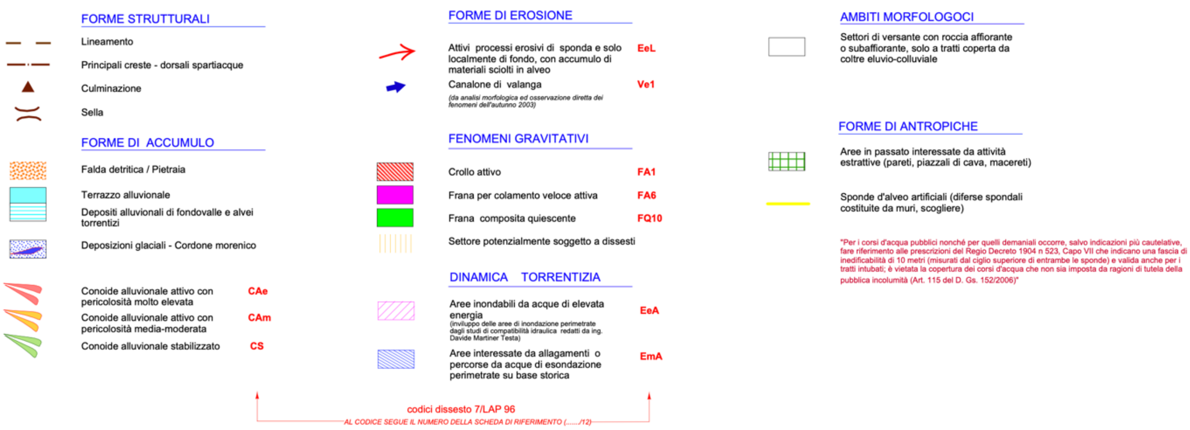

Figure 22 Legend for the figure above (Comune di Rosazza, 2004)

From these cartographies it is noticeable how most of the buildings in the city of Rosazza lay under the definition of "alluvial fan", defined as:

'Accumulation of sediments that fans outwards from a concentrated source of sediments, such as a narrow canyon emerging from an escarpment) and normally determine a path or the river to follow during the event of a flood' ("Alluvial fan", 2023).

Most of the torrential dynamics of the main torrent (Cervo) are also very close to the building area, which means that the buildings that are the closest to the watercourse are also extremely vulnerable to floods.

4 Floods

4.1 Definition and relation to climate change

As defined by the World Health Organization (WHO), floods are:

'*The most frequent type of natural disaster and occur when an overflow of water submerges land that is usually dry. Floods are often caused by heavy rainfall, rapid snowmelt or a storm surge from a tropical cyclone or tsunami in coastal areas'* (WHO, 2023).

Generally, floods tend to happen over a long period of time (hours or even days) and therefore the population has time to prepare and prevent possible damage. The issue arises when floods develop too quickly and abruptly because of the intensity of its effects.

There are two main types of floods:

- Riverine floods: a river or a stream overflows its bank, generally caused by heavy rainfalls (defined as "flash flood"), broken dams or levees or rapid ice melts that overwhelm a river, spreading in the nearby land, the "flood plain" ("river floods").
- Coastal floods: rushing of the sea inlands due to large storms or tsunamis (National Geographic, 2023).

The purpose of this thesis is analysing a methodology to better manage the risk of riverine floods due to heavy rainfalls that determine unforeseeable events. The urgency of taking action against this kind of events has become evident in recent times because of the harshening of extreme natural disasters that seem to have a strong correlation to climate change. Secretary General of World Meteorological Organisation, Petteri Taalas, has stated that 'the number of weather, climate and water extremes is increasing and will become more frequent and severe in many parts of the world as a result of climate change, which means more heatwaves, drought and forest fires such as those we have observed recently in Europe and North America' (Pavlinovic, 2021). For instance, in Europe, 1.672 natural disasters have been reported between 1970 and 2019, with 159.438 lives lost and $5 billions of economic damage; 38% of the disasters were floods, 32% storms and 93% of deaths were taken by heatwaves. This is caused by the increase of water vapour in the atmosphere due to higher temperatures and therefore evaporation of water sources, which eventually leads to precipitations: warmer oceans have caused an increase in tropical storms, elongated and harsher periods of drought, more extreme sea level events and therefore extreme flooding events, negatively influencing low-lying cities, deltas, coasts, and islands (Pavlinovic, 2021).

According to what has been gathered by Shao (2022), the relationship between climate change and floods is more subtle than it seems. An increase in temperature and vapour concentration in the atmosphere has not directly increased the frequency of said events, but it has heightened their intensity and consequent hazard to nearby communities. It is the number of moderate floods that has been registered to have decreased because of drier soils which are unable to hold in moisture due to heavier precipitations and therefore cause rivers to overflow harshly with damage to persons and objects. The natural cycle of water cannot be executed in the same way as before if the soil is not ready to do its part in the process, which leads to shortened and more abrupt cycles as observed by satellites and reported by the World Economic Forum (Rosane, 2022). The image below shows a prevision done by EPA in 2009 (USGCRP, 2009) about the alteration of water cycles due to climate change and an overall increase of temperature and moist in the air, which has been proven to quite comply to what has previously been said.

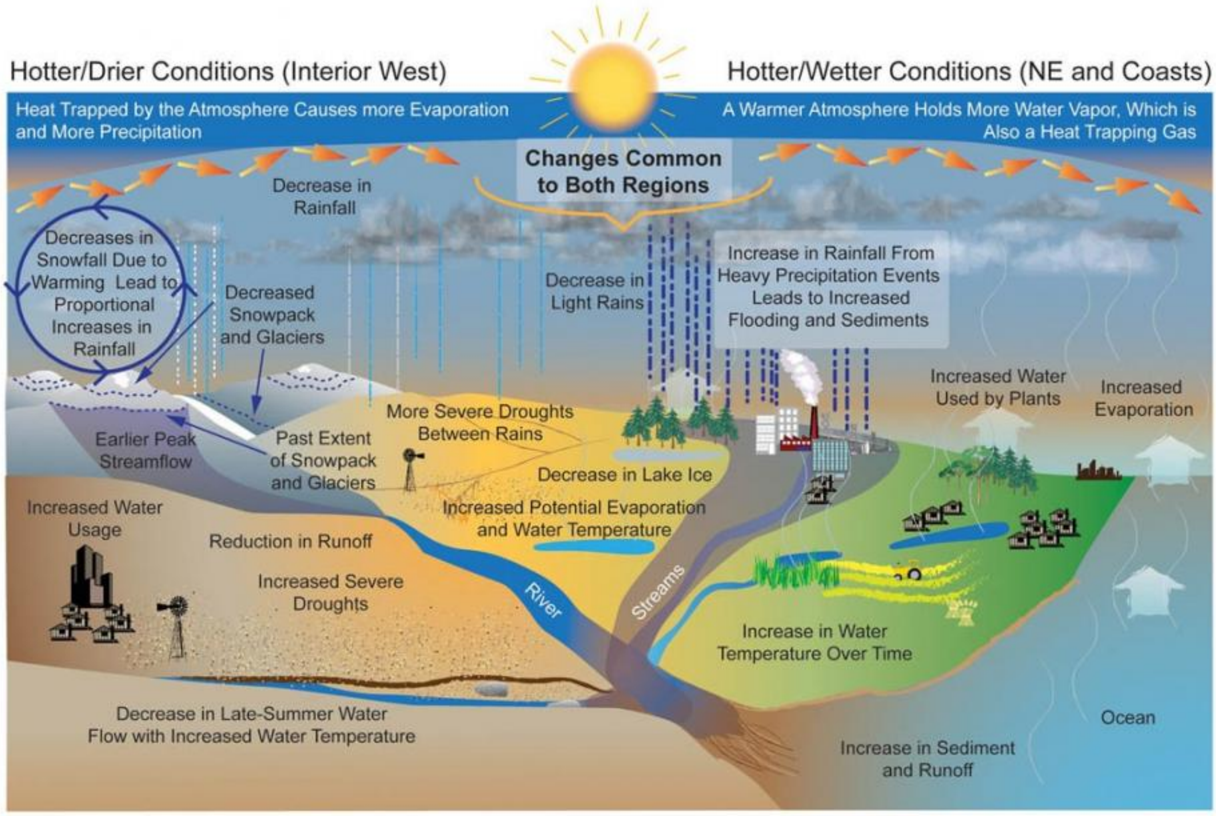

Figure 24 Prevision of altered water cycle in North America in drier and wetter conditions. (USGCRP, 2009)

4.2 Floods in Italy

Its annual 2021 report, The Italian Superior Institute for Environmental Protection and Research, ISPRA, has registered an increase in the national surface area potentially subject to landslides (4%) and floods (19%). What is alarming is the percentage of Italian municipalities at risk of hydrogeological instabilities, which is 94%. This adds up to worrying numbers:

- 540,000 families and 1,300,000 inhabitants at risk of landslides,
- 3 million families and 7 million inhabitants at risk of floods,
- 3.9% of buildings located in high and very high landslide hazard area,
- 10.7% buildings located in areas of medium flood hazard,
- 220,000 employees of industries and services are exposed to landslide risk because of the location of their workplaces,
- 12,000 out of a total of 213,000 architectural, monumental, and archaeological assets could potentially be subject to landslides (38,000 if considering lower hazard areas),
- Culturally relevant assets can add up to 34,000 in medium hazard scenarios and 50,000 in lower scenarios, which has nevertheless to be taken into account in this case because the potential damage is way higher than in any normal scenario, since it could be completely irreversible (ISPRA 2022).

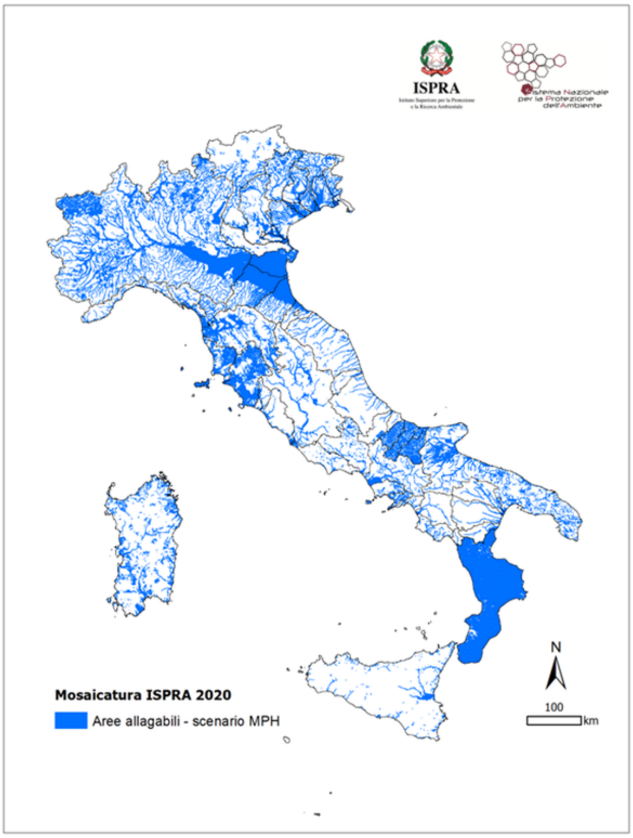

Figure 25 Medium hydraulic hazard areas (ISPRA, 2021)

Figure 25 shows the possible exposure to floods in Italy with the colour blue. Being an extremely water-rich country, not only since it is a peninsula but especially for the vast presence of rivers, it is easily subject to these processes, which, as previously explained, are getting harsher and more damaging each year due to the catastrophising of climate. The percentage of buildings or monuments associated with cultural heritage in Italy and exposed to possible damage is extremely high: a total of 23.5% is considered at flood risk, which adds up to 65% in regions like Emilia Romagna and the highest percentage of high risk is found in Veneto, Liguria, and Calabria. The foundation Openpolis, aimed at the gathering and provision of high-quality data, created a map of Italy that shows the level of hydrogeological risk in different provinces (Openpolis, 2023).

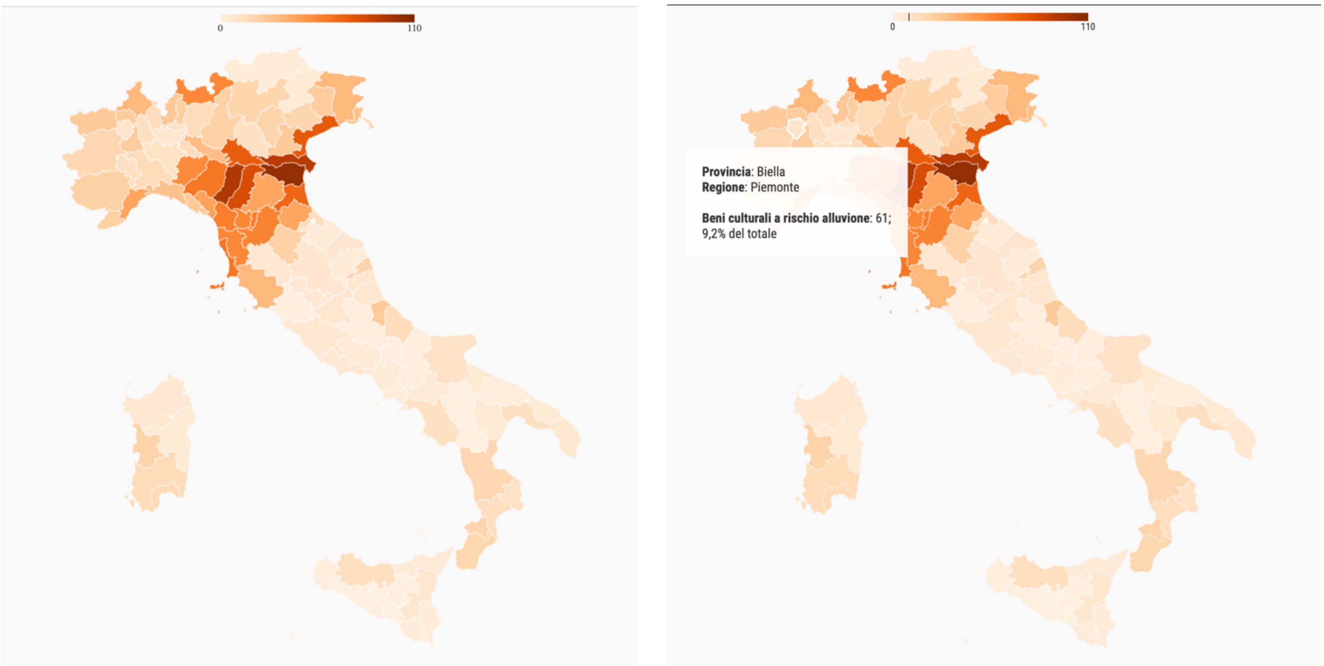

Figure 26 Cultural heritage at risk of floods. Specification of Biella province, where Rosazza lies (Openpolis, 2023)

For instance, Ferrara province has 100% of its cultural heritage at risk of floods, whereas Venice holds the highest objective number, with 4,500 sites at risk and 57.3% at high risk. For instance, the Venice flood of 2019 determined a 187 cm rise in the level of water and devastating damage to the cultural heritage and the buildings of the city: water broke glasses and invaded the crypt of Saint Mark Cathedral, reaching a level of one meter inside the church, destroying the fire-alerting and electrical system, libraries were heavily damaged by water entering their storage rooms and boats sunk while moorings were completely destroyed (Il Post, 2019).

Figure 27 St. Mark Basilica's interiors flooded in 2019 (Il Post, 2019)

4.3 “When the levee breaks: Spatial and temporal dynamics of flood risk”

Lecture by Professor Brandimarte, KTH

“When the levee breaks: Spatial and temporal dynamics of flood risk” was a lecture held by Luigia Brandimarte (2022), Professor of the School of Architecture and the Built Environment (ABE) of Kungliga Tekniska högskolan (Stockholm) specialised in Hydraulic Engineer. The theme of the lecture was the analysis of the relationship between society and nature and how their mutual interaction affects the management of floods in communities. First, Professor Brandimarte presented the timeline of a flood prevention model and its effects on the administration response, which can be summarised as:

- Flood risk: possibility of a flood happening,
- Vulnerability of its surroundings: determination of possible damage in the context of the river,
- Risk assessment: research of the effect of the flood on its surrounding, prevention models
- Administration: effective actions to mitigate the effects and better control the behaviour of the river.

The action taken by the administrations is normally relative to possible physical restraints to the river such as a levee, an embankment that runs parallelly to the river and is supposed to block the flood as it is happening to prevent it from damaging surrounding structures or persons. Brandimarte also mentioned Gilbert White’s work, the Professor of Geography at University of Colorado and appointed “father of floodplain management” who first introduced the “Levee Effect” or “Levee Paradox” in his 1945 paper “Human Adjustment to Floods”. According to his theory, the risk for damage is proportional to the multiplication of probability of hazard to occur and consequences of the hazard itself, which determines an expansion of risk in the occurrence of one of the two parameters. A practical explanation of this is the situation in which one or more levees are built next to an area at-risk; this leads more buildings to be constructed nearby because the administration and private owners feel safer in living there, but in the case of a flood happening and the river overlapping the levee, the risk of damage is higher than before the creation of the levee itself, since less buildings would be affected by the damage in that case.

An example is the case of Brahmaputra in Bangladesh, an extremely dynamic river that changes in shape over the course of time due to flooding phenomena. These frequent events determine the creation of small temporary islands that appear and disappear over short amounts of time and are the temporary homes of many who then must move to another one due to floods. In order to cope with migration and floods, the government decided to install an embankment on the most affected side of the river, and the results were in accordance with the Levee Paradox, since floods determined more damage in this area rather than the free one.

Professor Brandimarte also mentioned an Italian example, the river Po, which was studied on an urbanization point of view. It was noted how the ever-growing urbanization of the area determined the creation of levees, but at the same time how this kind of measures are extremely dependent on the society's perception of risk. While keeping the coping capacity constant:

- Under a certain threshold, the risk perception doesn't rise, which determines no action by the administration,
- Above that threshold, private citizens tend to check if the coping capacity is respected and, if not, they install private measure of preventions such as protective barriers in front of their houses in an autonomous way. This can reduce the risk perception by 50%,
- If the risk perception is too high, the administration takes action. Even in this case, it depends on how many people are complaining about it:
    - If below the 20%, the levee would probably be less high than its optimal dimension,
    - If it is very high, the levee will be higher than its optimal dimension.

Moreover, the correlation between society and flood consequences is noted through the examination of new people moving to stay in the area. Their initial risk perception is close to zero, because they never experienced a flood, but it can rise in time and therefore trigger reaction by the administration to install new embankments.

Risk assessment plans and their development seems then to be way more linked to qualitative elements such as public perception than it should. Professor Brandimarte highlighted the importance of understanding mutual dynamics between society and hazards, as well as of the collaboration between disciplines such as construction industry, civil engineering, hydraulic engineering, economy, management, and social sciences (Brandimarte, 2022). A scheme created during the workshop Warnings and emergency Response to Hazardous Weather Events (Stav, 2022) shows the close interaction between natural disasters and human society and it is reported in Figure 28.

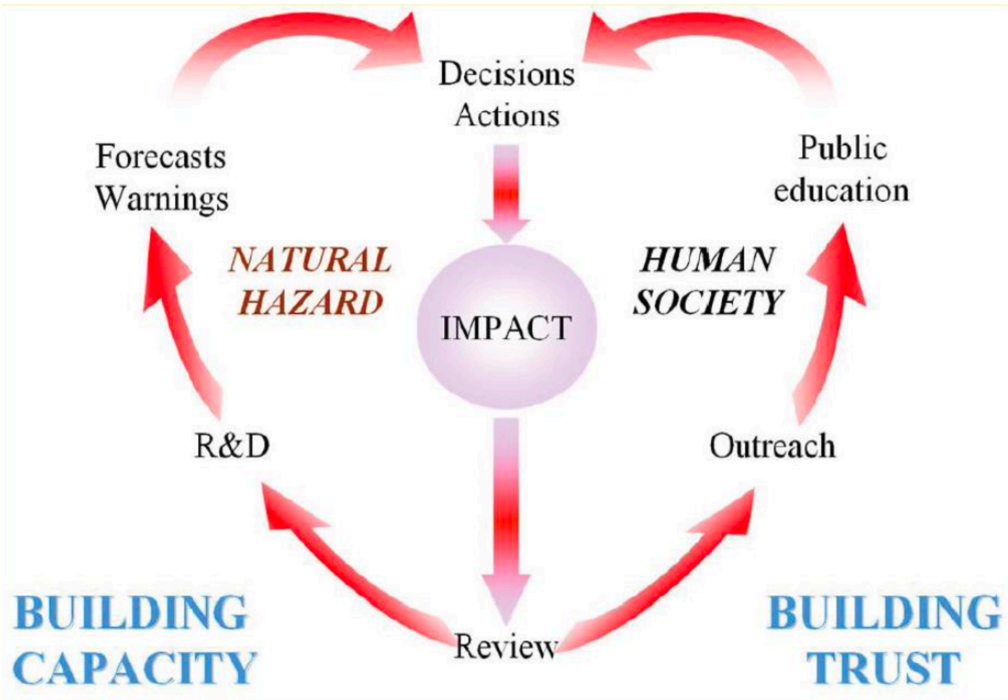

Figure 28 Interaction between natural disasters and human aspects (Stav, 2022)

4.4 Early Warning Systems (EWS)

The most efficient measure against floods is the introduction of an Early Warning System (EWS), which are used in half of World Meteorological Organization's 193 member countries according to their websites. On World Meteorological Day on 23rd March 2022, UN unveiled the goal of reaching full coverage by these systems in the next five years so that the fast-growing population could be protected against ever-rising extreme weather events and climate change. An early warning system can be used for multiple types of extreme natural events (floods, droughts, heatwaves, or storms) and it is defined as:

'An integrated system which allows people to know that hazardous weather is on its way, and informs how governments, communities and individuals can act to minimize the impending impacts' (WMO, 2022).

Another definition given by the United Nations (2023) is that of:

'An adaptive measure for climate change, using integrated communication systems to help communities prepare for hazardous climate-related events. A successful EWS saves lives and jobs, land and infrastructures and supports long-term sustainability. Early warning systems will assist public officials and administrators in their planning, saving money in the long run and protecting economies' (UN, 2023).

The purpose of these systems is the monitoring of real-time atmospheric conditions to effectively predict future events using mathematical models, which leads to assess risk and possibility of disasters and therefore implement measures that could minimize damage to persons and things. Of course, the type of governmental response depends upon the location of the early warning system, which will work differently according of the environment it is set into (coast, rural area, city, mountain etc.). Recent reports highlight the efficiency of these kinds of monitoring systems by saying that a 24 hours warning of a coming storm or heatwave, for example, could help save 30% of damage, while investing $800 million in EWS could lead to of $3-16 billions saved in the long run (WMO, 2022).

The urgency of implementing EWS is also evident in the involvement of the United Nations in their introduction in vulnerable countries and climates, for examples through the UN Development Programme "Strengthening Climate Information and Early Warning Systems for Climate Resilient Development and adaptation to climate change", which operates in Africa, Asia, and the Pacific with the aim of ensuring preparedness and response to natural disasters, 'using a model that integrates the components of risk knowledge, monitoring and predicting, dissemination of information and response to warnings' (UN, 2023). This programme ensured for example the re-establishment of weather stations in Uganda after the civil war which led their maintenance to get neglected, or the re-activation of the Automatic Weather and Agrometeorological Stations and Automatic Hydrological Stations across Colombia after the terrible increase in floods and damage that went from 1.7 million people affected in 2013 to 2.5 million in 2016 (UN, 2023).

4.4.1 EWS in Italy

Early Warning Systems are implemented in Italy mainly through *Protezione Civile*, Civil Protection, a governmental department placed directly under the Presidency of the Council of Ministers of Italy. The Civil Protection was founded in 1982 after the terrible Irpinia earthquake, which resulted in 2734 deaths and whose initial lack of coordination was so astounding that the government realised the relevance of having an organisational body which could not only rescue, but prevent, prepare, overcome, and coordinate action against emergency throughout the country. The Civil Protection coordinates the National Service of Civil Protection which involves public and private initiatives. The way it functions is complex, and it is not related to a single task, since it handles emergencies on different levels, from local to national, caused by natural events or human provoked, and it all leads to ensuring the best management of relief operations and better decision-making processes. The regular workflow of Civil Protection is:

- Forecasting
- Prevention and preparedness
- Emergency management
- Overcoming emergency ("Protezione civile", 2022).

Early Warning Systems in Italy are regulated by D.P.C.M. 27/02/2004 and they are managed by the Civil Protection and Regions, which control 21 regional centres for forecasting and surveillance, that have the responsibility of weather and hydrological alerts in the territory, 1 statal centre, and 30 Knowledge Centres like Universities and Agencies, all coordinated by the National Department of Civil Protection.

The warning system encompasses two main phases:

- Prediction, which consists in the evaluation and numerical modelling of the weather situation of the considered area; this phase activates the risk prevention phase,
- Monitoring and surveillance, which activates the emergency management and is divided in:
    - Qualitative and quantitative, direct observation of the meteorological and hydrological event,
    - Short-term prediction of the consequences of said event through models.

Hydraulic and hydrogeological risk assessment is managed through real-time (time of action is measurable in months and deals with prediction and fight against unexpected phenomena) or not-real-time activities (counteractions are over a period of time of years and deals with reconstruction works and better permanent conditions), which are respectively handled by Regions and the Ministry of the Environment.

The Ministry of the Environment handles the so-called Alert Zones, the delimitation of geographical areas with a specific risk of natural disasters, dividing Italy into low risk, medium risk, high risk, and very high-risk Alert zones depending on the level of possible damage if a disaster happens. This delimitation must be done through a combination of the study of the climate of the area through time and history and numerical models. The Civil Protection Department and the Regions, on the other hand, handle National EWS and Centres for forecasting and surveillance (Indirizzi operativi per la gestione organizzativa e funzionale del Sistema di allertamento nazionale, statale e regionale per il rischio idrogeologico ed idraulico ai fini di protezione civile, 2004).

Italian Regulations label “risk assessment” as:

‘The activity, performed in terms of months and years, to identify, in a given territory, the potential hazards, the related causes, mechanisms and their consequences’. (Corina, 2022).

Whereas “real time risk assessment” is defined as:

‘The activity, performed in term of hours, to predict the evolution in space and time of the hazard event and its effects, taking into account the estimated distribution of exposed subjects and their vulnerability (risk scenario)’ (Corina, 2022).

An Early Warning System is defined by the Civil protection as:

'EWS system comprises tools, methods, and procedures to develop and acquire, in real-time, knowledge, information and assessments relating to the advance warning in terms of probability, and the real-time monitoring and surveillance of events and the consequent evolution of risk scenarios in order to timely and effectively activate civil defence actions at various territorial levels' (Corina, 2022).

As previously stated, the national EWS for hydrogeological and hydraulic risk is managed by the Civil Protection Department and Italian Regions. EWS are introduced in the moment in which certain threshold values are exceeded or even when this is simply foreseen. The tasks performed by EWS cover both the time before the manifestation of the event as well as during and after the event until the emergency is resolved (Indirizzi operativi per la gestione organizzativa e funzionale del Sistema di allertamento nazionale, statale e regionale per il rischio idrogeologico ed idraulico ai fini di protezione civile, 2004). The tasks performed by EWS are the following:

- Declaration, monitoring, and surveillance of risk scenario in real time,
- Announcement of expected severity levels, which can be graded from ordinary, to moderate, to high creating a map of risk in each region,
- Activate warnings and the consequent operative responses in real-time (Corina, 2022).

Forecasts are handled by different technical bodies throughout Italy, for example *Agenzia Regionale per la Protezione Ambientale* (ARPA) Piedmont, whose database has been used in the next chapter for analysing historical data regarding floods in the area of study. Simpler weather forecasts are used together with different kinds of data like rain gauges, soil moisture, river gauges, and landslides to model a real-time framework that could integrate them into creating a singular warning for a specific natural event like a flood. This is usually used for larger rivers like Po or Tevere and not for smaller watercourses. The scheme of Figure 29 is provided by the pdf of the class "The Italian Flood Early Warning system", held by the member of Civil protection Angela Corina and Regional Adviser for Italy at WMO whose work has been thoroughly analysed for better describing this chapter (Corina, 2022).

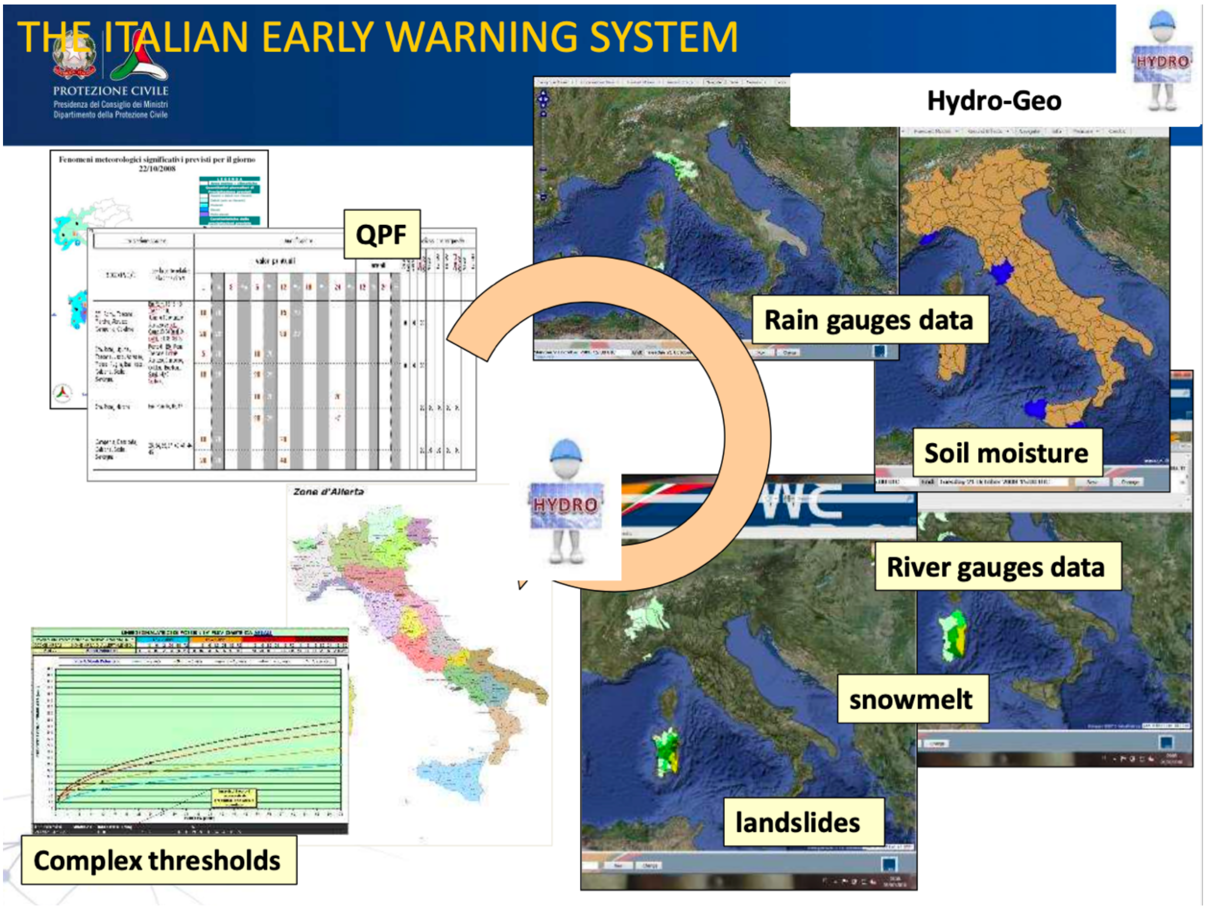

Figure 29 Example of framework for EWS in Italy (Corina, 2022)

Figure 30 shows changes in the map according to weather forecast and other type of data extraction that could possibly lead to the verification of a flood.

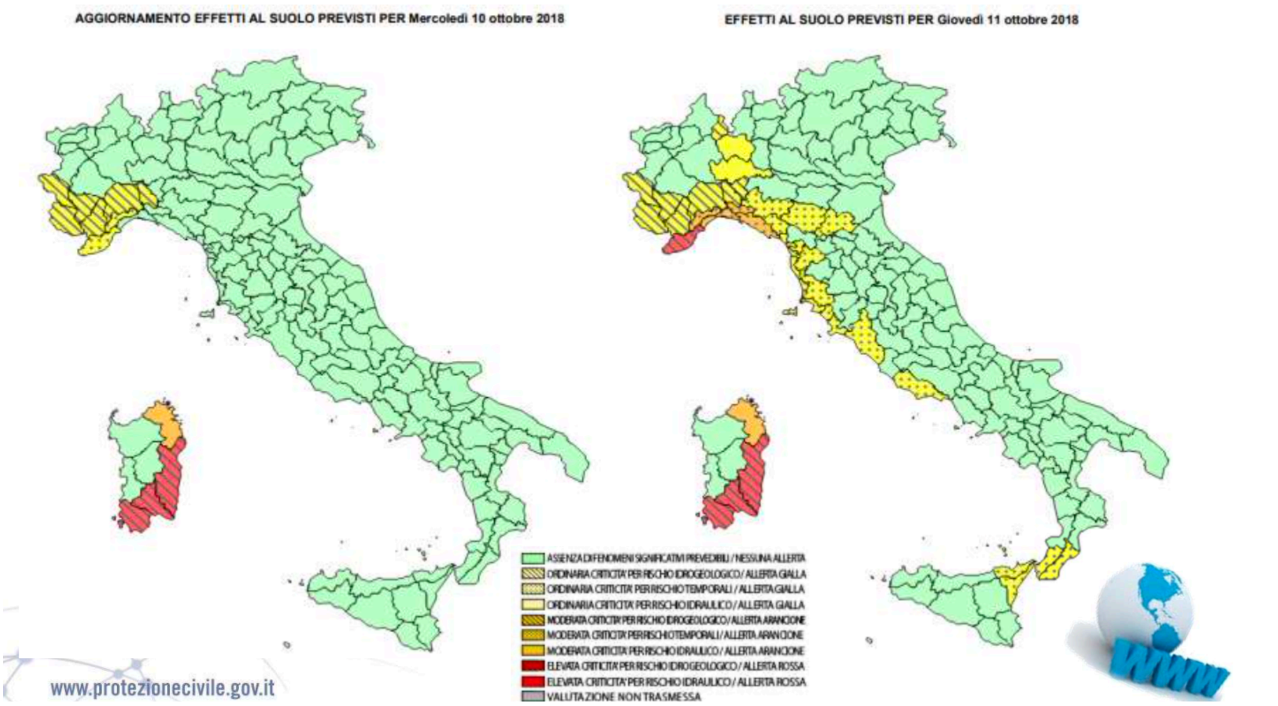

Figure 30 Example of identification of risky situation. The redder the area, the riskier the situation according to EWS (Corina, 2022)

Figure 31 summarizes the process of an Early Warning System, better describing roles and actions taken by different bodies involved in prediction, monitoring, and active phases. Italy is provided with about 5200 weather stations which account for hydraulic information like rain gauges, river gauges and other monitoring systems that control temperatures, humidity, snow and similar parameters. These metrics are studied by Knowledge Centres, which then alert regions and the Civil protection in order for them to determine different levels of alert (Yellow, orange or red according to the hazardousness of the event), which then lead to the alert of municipalities which implement protective measures for the citizens (Corina, 2022).

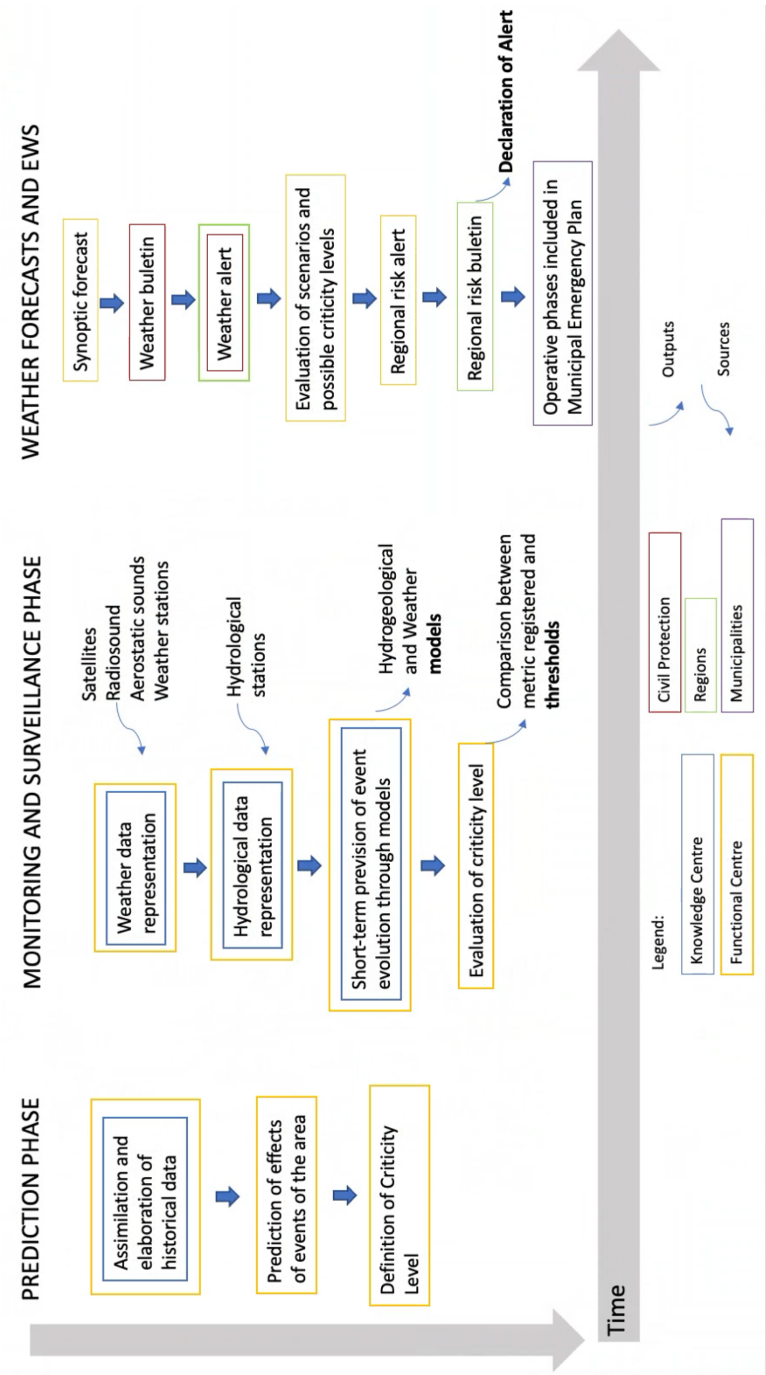

Figure 31 Principal actors and actions during the EWS process in Italy (Re-elaboration of Corina, 2022)

4.4.2 Impact-based risk assessment elaboration

This process is defined as "impact-based", which means that it stems from weather data or similar and leads to an assessment of possibility of a consequence (for example a flood) and therefore provides with an according warning. The warning given to the population normally includes the specific impact scenario, actions taken to mitigate the risk, and instruction for safety (Corina, 2022). Risk is then assessed through a formula that includes exposure, information about risk and hazard, determining:

$$R = E * V * H$$ (Corina, 2022)

Where:

R = risk

E = exposure

V = vulnerability

H = hazard.

This formula is easily found on multiple sources related to this topic. Brandimarte (2022) spoke about it during her lecture, Buta et al. (2020) described risk as a multiplication of flood hazard and vulnerability, defining these parameters as:

'Vulnerability is the extent to which a system can be affected by impact with a hazard and includes all physical, social, economic and environmental conditions that increase the susceptibility of that system',

'Flood hazard is defined by the probability of exceeding the maximum rainfall'.

The International Water Resources Association has also published a paper entitled like the formula itself, defining risk as made of the multiplication of its three components, hazard, values at risk and vulnerability, that are defined as follows:

'*The hazard: the threatening natural event including its probability of occurrence',*

'The values or values at risk: the buildings, items, humans that are present at the location involved',

'The vulnerability: the lack of resistance to damaging/destructive forces' (Kron, 2005).

Risk assessment has always been evaluated based on these parameters, hazard, vulnerability and exposure, and this formula doesn't only belong to flood analysis but to the broader concept of natural disasters.

4.5 IoT for flood monitoring: metrics and BIM integration

Considering the previously gathered data, it is of utmost importance to detect a system through which public administrations could not only deal with the aftermath of natural disasters such as floods, but also prevent them from damaging the cultural heritage and putting the lives of many at risk. Naturally, Regions and local municipalities have already detailed plans that could protect cities and the environment from such phenomena, but what seems to be lacking is a digitalization of said systems and most importantly a connection of said digitalization with a digital twin of the investigated area. For example, analysing ARPA's instruments against natural disasters of hydrogeological nature, the website doesn't mention specific methods against floods but generally focuses on landslides, which are treated through an indicator called "Number of studied hydrogeological instabilities", which refers to the monitoring of the evolution in time of landslides number in order to design and manage monitoring networks and further detail alert plans in advance (ARPA, 2022). ISPRA (2016) detailed a suggested monitoring approach for hydrogeological instabilities in its publication in 2016 and among the future tendencies it underlines the importance of a morphological monitoring of past and present situations in order to follow the evolutive tendencies of the considered area and river and later detail a prediction of the morphological evolution of that very river to examine its dangerousness and behaviour. This kind of monitoring takes into consideration morphological parameters, i.e., parameters connected to the shape and change in shape of the river to determine its evolution in time. Among the considered parameters it is possible to find:

- Planimetric parameters, which are linked to the shape of the rivers,
- Longitudinal profile,
- Transversal section,
- Riverbed's sediments,
- Woody material,
- Vegetation in the perifluvial zone,
- Morphological units,
- Hydrogeological parameters:
    - Liquid flow rate: continuous registration of flow rates at selected hydrometrical stations deemed representative for the considered watercourse, two different parameters are obtained:

- Average annual flow rate (q_{med}) [m^3/s]: obtained based on the daily flow rate registered over a year
- Maximum annual peak flow rate (Q_c) [m^3/s]: necessary for updating the historical data and allow the computation of the biannual flow rate and register the occurrence of events of floods of high intensity (return time greater than ten years) (ISPRQA, 2016).

In the context of possible conceptual models that could lead to the description of previsions for the future of floods, digitalization is not included. The conceptual models are defined as simple and intuitive and designed to predict qualitative measures such as the direction of evolution of the hydrogeological system and they are deemed to be potentially followed by more complex models that could lead to detailed information. The types of models presented, though, do not refer to digital twins of BIM models, whereas to statistical or analytical models, physical models relative to the impact of interventions and verifications, and numerical models. This kind of monitoring systems are of course extremely useful, but it is also relevant to underline how introducing these parameters and indicators inside of a virtual environment could expand this analysis to the real-time evaluation of said parameters for the purpose of alerting the municipalities and the people and preventing damage to cultural heritage and persons.

There are many ways to assess hydrogeological and hydraulic risk through a monitoring system. An advanced way of handling this kind of phenomena is to define a series of parameters and indicators encompassing some of them that could be useful for determining the risk of floods, as previously stated. The European Space Agency (2022a) underlines for example the importance of satellite pictures for determining the impact on floods on the surrounding area and see, through time, if the area affected by the flood is larger or smaller than the previous occasion, so to determine eventual increases in dry portions of land which cannot hold water anymore.

The European Flood Awareness System (EFAS) is the first operational European system monitoring and forecasting floods across the continent, and it provides various types of information to national and regional entities. It also defines a Map viewing of Europe based on real time forecasts made through their technologies (probabilities, medium range flood forecast, flash flood indicators, impact forecasts), but this is only available to EFAS Partners (EFAS, 2023a). Through its predictions, accurate weather forecast of 5 days lead-time for flash floods can be reached as well as outlooks over a period of 6 or 8 weeks with the purpose of predicting changes of high and low flows (hydrological extremes) (EFAS, 2023b). In 2021 EFAS introduced GloFAS, Global Flood Monitoring

(GFM), the real time global flood monitoring system that maps out in real time all flood events in the world through the gatherings of Sentinel-1, RSA powered constellation of two polar-orbiting satellites. This system uses a highly technological layering of different types of information regarding water bodies, the identification of flooded areas, and historical data to determine the most adequate predictions. The results of GFM are divided into 11 different products, as stated by EFAS, referring for example to the extent of the flood, the classification of the water body into open and calm water, areas of uncertainty, flooded land areas etc. (Copernicus EU, 2023).

The novelty of this thesis is to show the possibility of introducing this type of indicators in a BIM environment through their application on a digital twin and therefore obtain a real-time analysis. This analysis would be carried out through the positioning of sensors in specific locations (the thesis will analyse the location of one and suggest for further development) to detect the needed parameters and quantify the possibility of flooding through its risk level, then give this information to the administrations that would have an idea of how the flood will attack different building areas of Rosazza and how to intervene in the event of a flood. These kinds of indicators should be pertinent to parameters related to short-term interventions for protection rather than long-term research for prevention of floods; the two aims could then be integrated, as will be suggested in the section dedicated to Further applications.

Various sensor systems can be implemented. A market study regarding offers for this kind of monitoring has been conducted and led to discover various brands, such as CAE, the 'biggest Italian company which designs, installs and manages monitoring and multi-risk alert systems useful for decision making processes during emergencies' (Fiera365, 2022). The company's solutions deal with extreme weather phenomena and mitigation of their impact in different occasions such as hydraulic and hydrogeological risk, geological risk, extreme weather events (precipitations, heat waves, swells, avalanches etc.), risk of wood fires, and pollution of hydric resources. Regarding hydraulic and hydrogeological risk, CAE introduces systems that could mitigate the effects of these phenomena. In order to foresee and control floods, for example, their solutions determine the gathering of information relative to the river conditions and precipitation, i.e., the events that can lead to these natural disasters in a way that is not connected to the frequency of the event itself, so that the measuring can happen nevertheless thanks to the redundancy of the system and its accuracy. The evolutions of these sensors led then to a process of machine learning that makes them identify possible risk scenarios and manage alert systems and the lamination of the flood itself in a more efficient way.

The parameters in these sensors are:

- Intensity and rainfall accumulation
- Hydrometric level
- Rainfall flow rate
- Superficial velocity of the hydric body (CAE, 2022).

Another brand who provides this kind of systems is Envira, a Spanish company founded in 2015 out of *Ingenieros Asesores S.A.* to 'implement integrated systems for monitoring environmental quality and pollutant emissions' as well as 'design devices for IoT networks and software platforms that make accurate measurements and analyse multiple parameters in Industry 4.0 environments, smart cities, and precision agriculture' (Envira IoT, 2022a). Among its solutions, there is a Flood Monitoring and Warning System that receives information about real risks with the aim of preserving vulnerable areas through optimal protection strategies implemented by Public Administrations thanks to the statistical analysis of the gathered data. The flood warning system offered by Envira is made of two parts:

- Wireless sensor network: hardware, actual sensors with the goal of capturing relevant parameters about river flows and the stream level,
- Smart computer system: software, system of elaboration of hydrogeological and weather data used to signal alerts in the case of situation that could trigger a flood risk situation.

The hardware is highly customisable in terms of what to analyse and how to analyse it. Among the possible parameters to capture:

- Level of watercourse
- Humidity
- Turbidity
- Water speed
- Capacity
- River flow.

Each station can then be defined through a series of determinants so that an alert can be sent to the control centre. The range in terms of location is between 10 and 70 m from the sensor.

The software part is called "Envira DS platform" and it is provided by Envira. It deals with the elaboration of data collected by sensors: as soon as it gets a warning, it connects directly to verify the situation and later can contact the emergency centre to act against the risk (automatically if set according to specific limits not to overpass).

Similar sensors could be implemented in the region of Torrent Cervo and its affluents as well as on relevant buildings of the city of Rosazza in order to use the gathered data to determine short-term and long-term predictions for future floods. Machine Learning and Artificial Intelligence techniques could elaborate the data and determine more accurate predictions, as well as interpolate this data with weather forecasts from local weather stations to make them real-time and precise. The analysis of the development of the flood could also be integrated with satellite data to study the size and propagation of the flood for further modelling and elaboration of future flood events. All these measures lie in the spectrum of Digital Twin of the Earth, an idea proposed by the European Space Agency with the purpose of better understanding the planet and its behaviour for further analyses and knowledge in the era of climate change (ESA 2021).

4.6 History of floods in the Cervo Valley

The history of floods in the Cervo Valley has been detailed through the integration of two different sources:

- Database A: A list of the more relevant flood and landslide events that date back to the 1600s, provided by PhD student Davide Aschieri (Aschieri, 2023),
- Database B: A similar list from 1827 to the recent day, provided by the municipality of Rosazza (Francini, 2004).

These two databases are integrated in Table 1 and can offer a detailed idea of the hydrogeological risk of the valley in the past two centuries. The colour blue is referred to data deriving from Database A, while colour yellow refers to database B; colour green is attributed to data that was included in both reports. The second column, Damage Cervo Valley, includes the information originating by database A, while the third column, Damage Rosazza, to database B.

Data found in Database A

Data found in Database B

Data shared by Databased A and B

Date	Damage Cervo Valley	Damage Rosazza
26th September 1666	Cervo destroyed twenty houses and removed land and things. No victims.	
27th September 1827	Only the upper part of the basin was hit, causing victims and damaging some houses in Piedicavallo and Rosazza.	In Rosazza specifically, there was heavy damage on the roads and the bridge over Pragnetta watercourse collapsed.
1839		Pragnetta carried away part of the road starting a short distance from the last houses of the hamlet of Pistoletto Borgata Rosazza, as far as at a short distance from the first staircase that leads to the Vittone houses, also threatening the cemetery.
June 1840	Rio Piaro caused the flooding of the town of Campiglia and damaged the torrent embankment and a bridge	
1841		In spring, a flood caused the landslide of brook Grametto, carrying away farmsteads. In autumn, another flood destroyed the Rialmosso bridge.
29th August 1885		On 29 August from 8 a.m. to 9 p.m., after a rainstorm, extraordinary flood burrowed under the foundation of the dam at the bottom of the Grametto brook causing devastation of gardens and meadows

13th October 1910	Roads and hydraulic works in the upper side of the Cervo Valley have been flooded.	The Pragnetta removes the parapet and part of the Rosazza bridge.
5th May 1914		A portion of Rosazza's ring road and and the Pragnetta bridge were destroyed
5th April 1916		After a very wet winter and large avalanches descending along Pragnetta, snow and erosion loam had 'built' numerous shapeless dams in the riverbed. At 5.35 p.m. on 5th May, a landslide breaking away on the right bank of Pragnetta impacted the water. The consequent flood wave poured downstream and destroyed everything in its path, invading the church square and the public park, leaving mud and snow even on the cemetery bridge.
1921		Rosazza's newly built crossing near the market square collapses
29/30th May 1923	Cervo stream eroded the foundations of some houses, caused the partial collapse of the Piedicavallo's bridge, and partly removed the provincial road.	In Rosazza, part of the provincial road and the square were highly damaged with consequential danger for adjacent houses
14th-17th May 1927	Cumulated rainfall heights of 845mm in just 4 days were recorded in the Biella station, the highest value ever	
28th October 1928	Relevant rainfall event with 250mm/24h	

29th November 1930	Relevant rainfall event with 290mm/24h	
1931		Flood at Pinchiolo stream
1948		Flood on the right of Pinchiolo
November 1951	Significant rainfall, but lack of information regarding damages to structures	
12-24th June 1957		Pragnetta stream causes damage to the road that runs alongside it
22-24th August 1965		Chiobbia stream destroys hydraulic defence works
2nd November 1968	In the basins of Valle Strona, Valle Mosso and Val Sessera, the most catastrophic event of the twentieth century took place. Cervo Valley have been badly affected too. Damage to the regulation works on the Cervo at Rosazza	Damage to embankments
October 1977	Flooding of houses in Piedicavallo, Montesinaro, Rosazza. Landslides damaged the provincial road to San Paolo Cervo	Flooding of houses in Rosazza
October 1979	The flood arrived till Biella, where industrial sites were flooded, and part of torrent embankments were destroyed.	Pragnetta erodes the right bank in the region of Pianelli
21st – 26th September 1981	The upper basin of the Cervo Torrent and the Chiobbia stream were mainly affected. Piedicavallo station recorded a precipitation height of 250 mm in 16 hours	Abundant precipitations caused enlargements of Chiobba, Valdescola and Pragnetta streams.. The force of the water severely damaged the provincial road between Rosazza and Piedicavallo, destroyed a building in Pinchiolo and caused bank erosion.

November 1994	Relevant rainfall event	Considered to be the most relevant meteorological event of the valley, but didn't cause much damage
4th – 6th June 2002	Damages all along the valley. Some bridges were destroyed, and the main valley road was flooded and covered by landslides in multiple points. Different houses and industrial areas were flooded. Watercourse embankments were seriously damaged all along the torrent	Rainfall on 5th June 2002 was registered to account to 300/400 mm in 24 hours, with intensity peaks between 15 and 17 (100mm/h), which is labelled as being "very high levels" and was registered at the station of Alpe Camparient (Trivero), while Piedicavallo and Oropa stations registered intensities higher than 60mm/h. The precipitations caused many landslides in the High Cervo Valley, which caused a lot of rock material to slide down to the torrent and determine flooding of adjacent areas.
2nd - 3rd October 2020	Damages in all the valley: torrent embankments, bridges, roads, houses were hit. San Giovanni D'Andorno monastery was hit by a landslide.	More information about this specific event has been detailed below.

Table 1 Integrated database of flood events in Cervo Valley and Rosazza (Elaboration of Aschieri, 2023, and Francini, 2004)

As far as the flood of October 2020 is concerned, more data has been analysed thanks to the contribution of the owners of the most damaged building on that occasions, Family Valz Blin. Architect Anna Valz Blin could enrich the research with photographical material regarding the situation before and after the flood and, most importantly, with the expertise report regarding the condition of their building after the flood, document they had to present to the Piedmont Region for damage compensation (Valz Blin, 2022).

As explained in the text of the upper part of the following image and in the report by Valz Blin (2022), in addition to its natural bed, Cervo Torrent overflowed in the area north to the *Ponte delle cave*, a structure built in 1778 and enlarged in 1856, which collapsed between 3 and 4 a.m. on 3rd October 2020. The collapse of the bridge determined the creation of an alternative path for the water, which could no longer flow under the bridge, and a violent waterflow through gardens and stone masonry of buildings carrying down material together with high velocity water. The properties downstream of the bridge (which are numbered as 91, 98, 99, 299, 101 and 104 in the picture below) were damaged on their north/south and north/east side by the course of the water. The building highlighted in yellow is property of Family Valz Blin and shows the exported portion of land. The blue arrow is the alternative route taken by Torrent Cervo when it encountered the collapsed bridge and could not follow through its natural path.

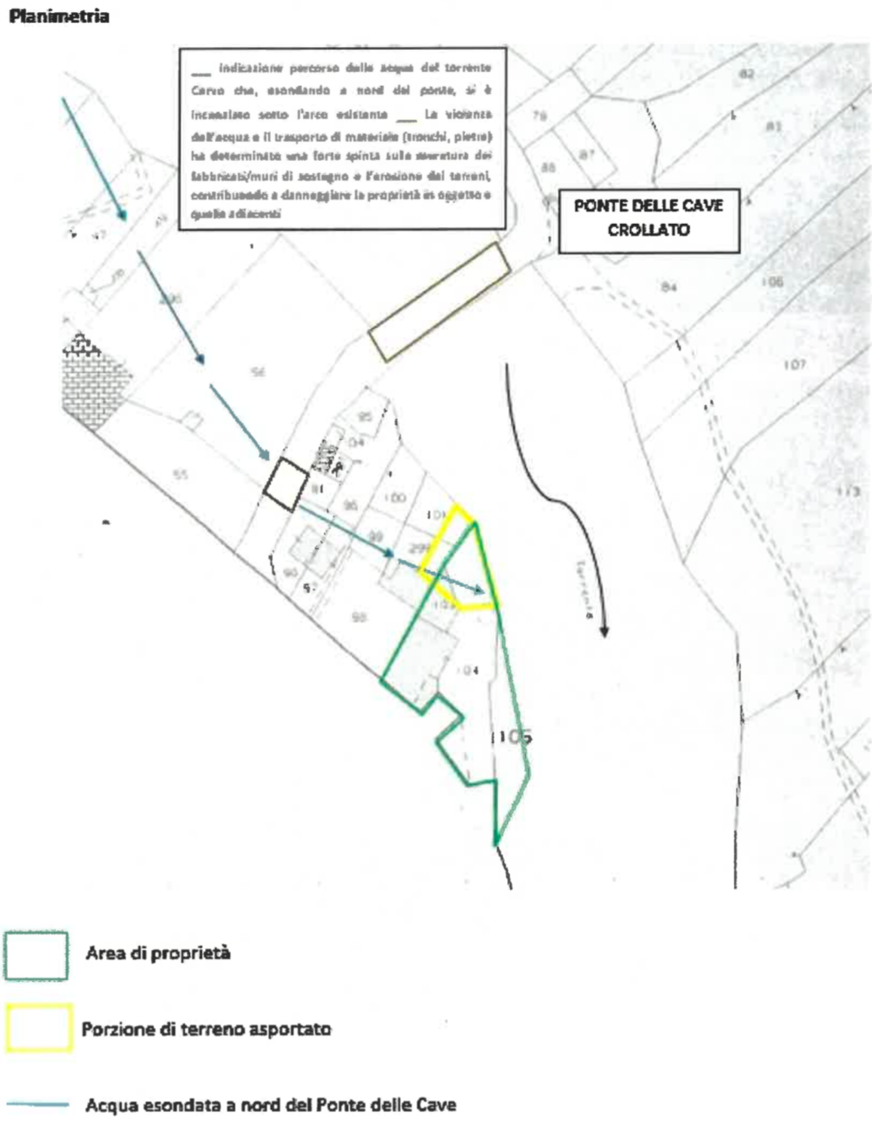

Figure 32 Graphical representation of the path followed by Torrent Cervo during the flood (Valz Blin, 2022)

Figure 33 Picture of Valz Blin's building in early XX century (Valz Blin, 2022)

Figure 34 Valz Blin's building after 2020 flood. It is visible how the house was hit by the flood and possibly by the fall of Ponte delle Cave*. (Valz Blin, 2022)*

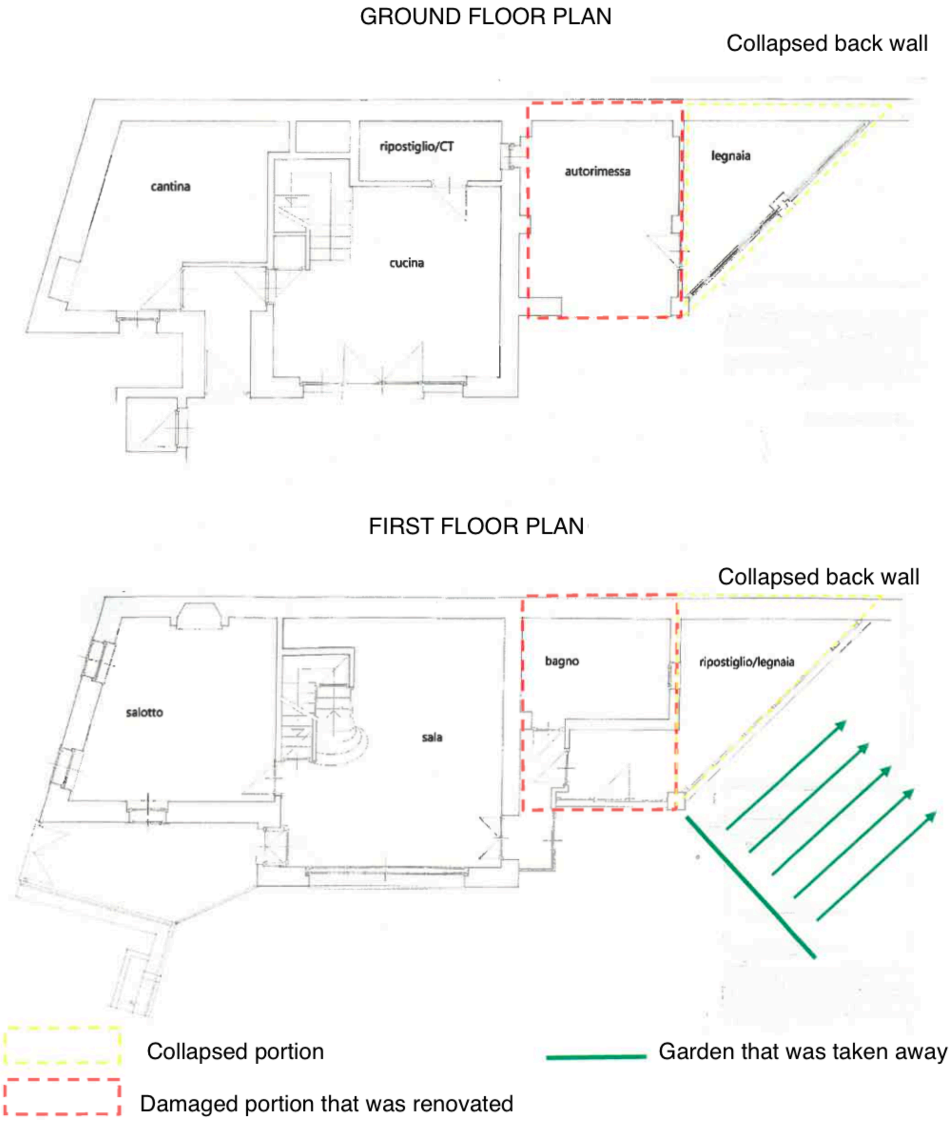

Figure 36 Damage to Valz Blin's property seen from Torrent Cervo (north). The blue arrow represents the flow of the water (Valz Blin, 2022)

Figure 35 Damage to Valz Blin's building. (Valz Blin, 2022)

5 Methodology

The workflow of the modelling and parametric implementation of this thesis will have many points in common with the two that were previously presented in Chapter 2.1.5. This is due mainly to the fact that most of the works on this topic were developed according to this structure, since it is not only the most logical one for its progressive detailing nature, but it has also become somewhat of a standard in literature concerning digital twins and HBIM projects.

It is composed of mainly eight phases, that will here be explained briefly before going through each step in a more thorough way in the corresponding paragraphs. The phases are the following:

1. Data collection and Survey: historical, bibliographical, literature, and archive research on Cervo Valley and Rosazza,
2. Stakeholder analysis: gathering of information and requirements from various stakeholders in order to better design the conservation solutions, consultation with local authorities,
3. Planning: Common Data Environment selection, Naming codification, preliminary LOD definition,
4. Scan-to-BIM: Point cloud and topography elaboration, GIS import in a BIM environment, interoperability check,
5. HBIM development: modelling phase, preliminary setting of parameters, Level of Information Need definition,
6. Data enrichment: parametrical enrichment of the model, Dynamo® and Google Drive™ integration, prediction and monitoring phases development, risk assessment,
7. Results: application of the model for heritage conservation purposes, different risk scenarios visualisation, comparison between the final risk model and the Hydrogeological Plan,
8. Further development: additions to already established results, further scopes and applications.

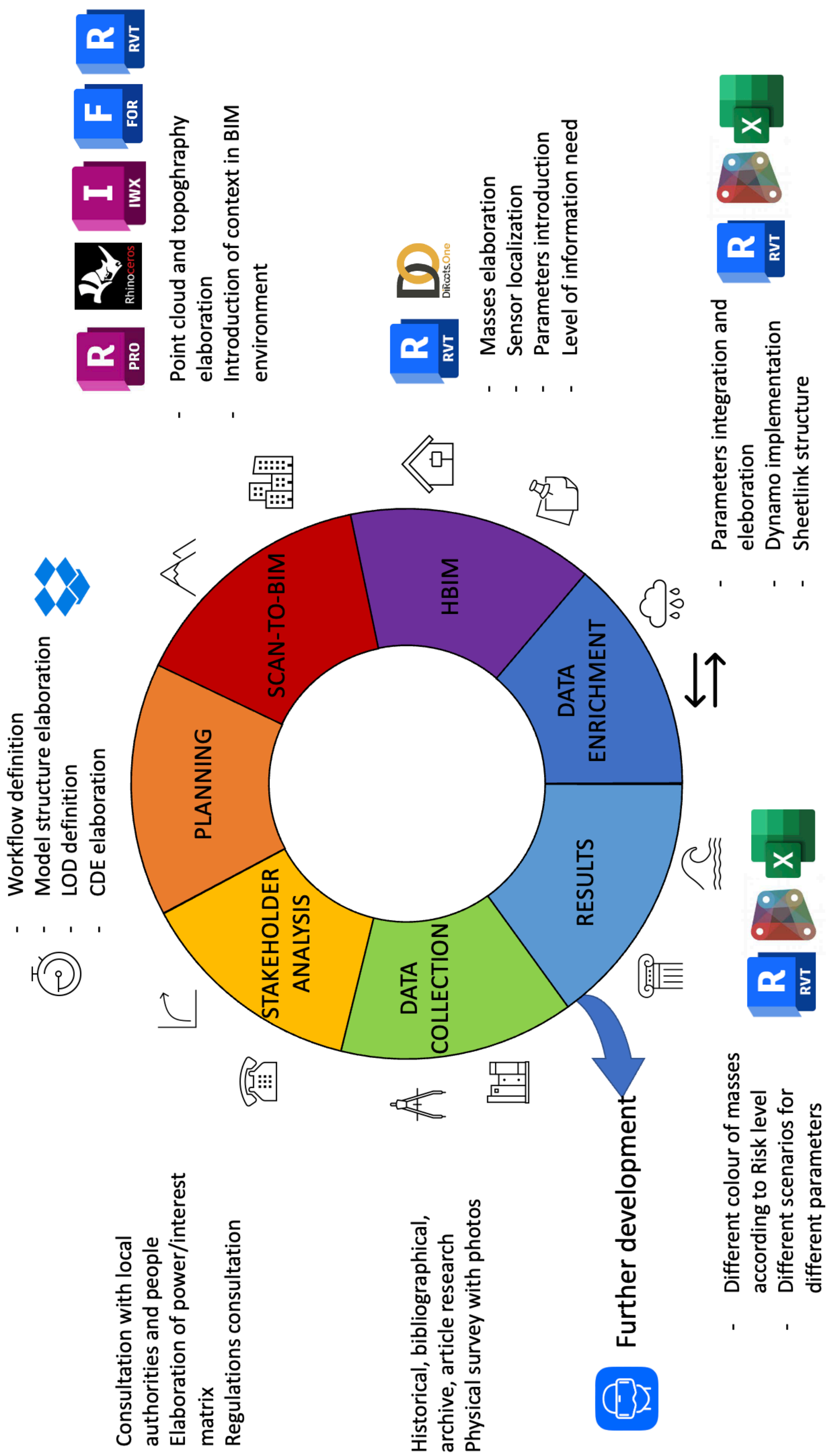

Figure 37 Methodology scheme (Personal Elaboration)

6 Data collection and survey

The first step towards any kind of an architectural entity representation is data collection. The types of data that needed to be gathered for the purpose of this thesis were mainly four:

- Historical: books, guides or anything related to Rosazza's and Cervo Valley's history,
- Digital: articles, papers, digital theses, and everything related to the topic of discussion, HBIM, Digital twin, floods, and Cervo Valley,
- Three dimensional: laser scanning and photogrammetry to gather GIS data of the area,
- Metrics: different types of data related to precipitations and floods that have affected Rosazza and the Valley in recent years to set a basis for a risk assessment for the conservation of this historical village.

As far as the historical data is concerned, the first issue was trying to figure out which kind of books or theses dealt with Cervo Valley and, more specifically, the village of Rosazza. Rosazza is technically known to be a prestigious village belonging the most beautiful ones in Italy, but the actual material regarding the municipality is scarce, since it is so small. Therefore, local authorities of the area were contacted in order for them to be of guidance through the existent material. The associations and administrative bodies that were reached out to were *Centro Documentazione Alta Valle Cervo* - La Bürsch, a Group of Interest founded in 2018 under the *Fondazione O.P.L. di San Giovanni d'Andorno* and in collaboration with *Casa Museo dell'Alta Valle del Cervo* and *Associazione Amici di San Giovanni ONLUS* (Centro Documentazione Alta Valle Cervo – La Bürsch, 2022), to assess the knowledge of some volumes that were mentioned on their websites. Second came the visit to Biella Municipal Library to search for said volumes; here, Director Anna Bosazza was extremely useful because she has the matters of the Valley at heart. After a private encounter, even more material was assembled, such as books about the history of the city and the Valley, a Master's Thesis that studied the Valley on a demographical and management point of view, and various original drawing such as maps and building typology details.

Digital documentation was mainly found through Science Direct, one of the most popular web databases of scientific and medical publications ("Science Direct", 2022). Some of the digital material gathered was also suggested by the supervisor and the assistant supervisors, Anna Osello, Kjartan Gudmundsson, and Arianna Fonsati. The collected papers mostly focused on Digital Twin, HBIM, Scan-to-BIM procedures, conservation of the historical heritage through digital means, and digitalisation of the AEC sector.

The three-dimensional material useful for a realistic surrounding representation and an efficient Scan-to-BIM procedure was obtained thanks to Davide Aschieri, PhD student who is researching on the region on a civil engineering point of view and could provide me with the point cloud, laser scanning, photogrammetry, and procedural report previously obtained for his work, as well as another student whose Bachelor's Thesis focused on a digital representation of Rosazza and therefore already had its own elaborated point cloud divided into four different parts.

As far as metrics are concerned, the first step was defining which kind of data were relevant for my study and most importantly its application on a practical level, to find out which kind of parameters were to be introduced in the Digital Twin to make it useful for our stakeholders, mainly the Municipality of Rosazza and the Italian Civil protection. For this purpose, several authorities were contacted, such as *Pro Loco Rosazza*, a voluntary association of citizens with the aim of touristic promotion of the territory (Pro Loco Rosazza, 2022). *Pro Loco Rosazza* then suggested to get in touch with Rosazza's mayor, that could better provide with needed information. The main metrics that were asked for were the following:

- Any relevant material about history of floods and natural disasters in the area and how they have affected the municipality of Rosazza. This was provided by the Technical Office of Rosazza and by Davide Aschieri,
- Regulation or preventive measures that are already being taken for preventing natural disasters and damage to the architecture of the city (for example, PAI and related documents),
- Any parameter that is already considered by the municipality as an organizational body or the Civil protection in relation to heritage conservation.

The obtained material has already been assessed and discussed in Chapter 4, when dealing with floods and the Italian regulations concerning these natural phenomena. It is nevertheless necessary to underline how difficult to find specific material about Rosazza was, since, once again, it is a very small municipality. Data deriving from ARPA databases will be thoroughly analysed in Chapter 11.

7 Stakeholder analysis

One of the most important steps into examining the broadness of action of a designer is the stakeholder analysis, defined as ‘a project management tool used to identify the project’s stakeholders, issues they care about and how they will be impacted by the project’ (Hoory & Bottorff, 2022). During this phase, the main people, administrations, or companies involved in the project are investigated so that their role in the development of the project can be detailed, which will lead to the definition of the level of communication the engineer should have with said entities, how often they should speak to them, regarding what and, most importantly, which are the power and the interest of said people in the project and how they will be impacted by it (Hoory & Bottorff, 2022).

The first step is, of course, the identification of the stakeholders involved. This could be represented by different users, in the case of an intervention on the built heritage they could be public administration, profit or non-profit organisations and associations involved with public heritage, the people who live in the area or nearby, protective bodies that could be national or international and, on a broader spectrum, if necessary, professional figures such as historians, architects, and archaeologists that could have relevance into the decision making process.

The second step is determining how relevant the identified stakeholders are and, therefore, which one has to be more thoroughly analysed and involved in the project in order for every delivery to go smoothly and little to no changes to be made. If the desires of the stakeholders are correctly gathered and the parties involved are constantly updated according to the scheme developed after the stakeholder analysis, the whole process could be a lot smoother because the design team knows how and who they are working for.

The third step is creating a matrix with two axes referring to power (ordinate) and interest (abscissa), which could determine the stakeholder’s priority in the decision-making involvement. This will create four different areas in which the stakeholder could lay:

- High power/high interest: most important ones, they must be constantly updated and the design team has to gather as much information as possible regarding their requirements and interest because their decision will greatly influence the development of the project,
- High power/low interest: they hold decision-making power but at the same time they are not as interested in the project as others, they must be satisfied but be put as top priority,

- Low power/low interest: normally these are the stakeholders who care about the project on a personal level, therefore their opinion should be of great influence in the decision-making process for identifying the real needs of the area, but since their power is low, their needs are not as absolute as those of the higher powers in terms of efficiency of the results,
- Low power/low interest: the least important stakeholder, it has to be involved for avoiding trouble but should only be marginal to decision making processes, their priority is low.

In the case of this research, the stakeholders are mainly four: the Italian *Protezione Civile*, the administration of the municipality of Rosazza, the Pro Loco Rosazza (and more generally local associations and organisations), and last, but not least, the people of Rosazza itself.

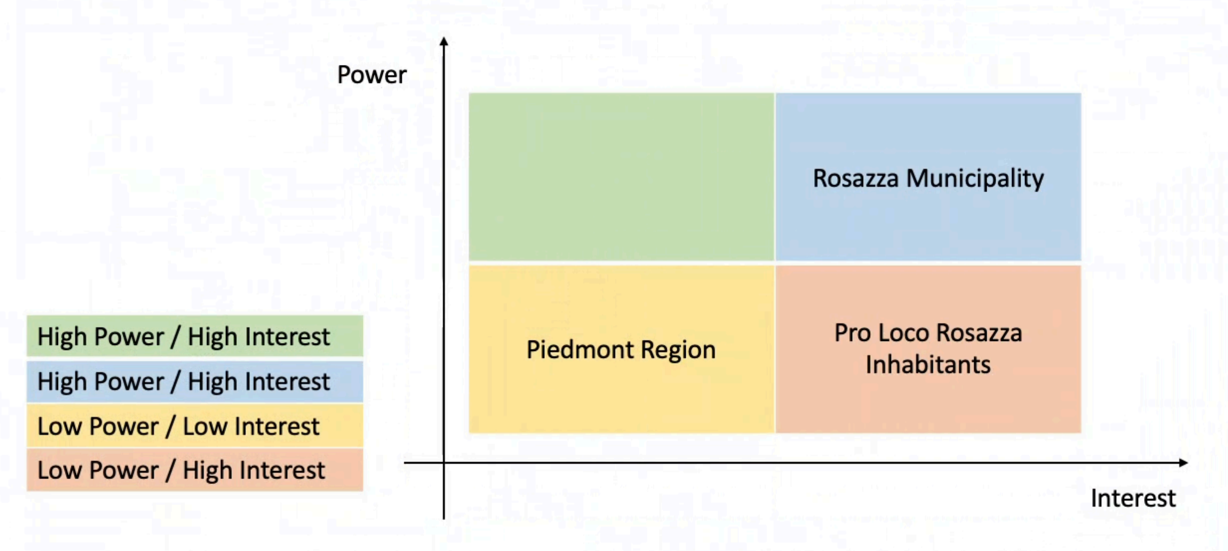

Figure 38 Stakeholder Analysis (Personal elaboration)

8.1 *Protezione civile*

Protezione Civile ("Civil Protection", literally, which could also be translated as "Civil Defense") is the body of the Italian government dedicated to the coordination of actions relative to the national service of the civil defence, i.e., public rescue activities in situations of natural disasters and/or accidents ("Protezione civile", 2022). As written on the Biella Province website (Provincia di Biella, 2022), the goal of Civil Protection in Italy is that of 'safeguarding life, goods, and environment from damage caused by natural disasters, catastrophes, and other calamity events', for example the prevention and prediction of various risk situations, the organisation of relief for the population interested by disasters and, more generally, every rapid action aimed at overcoming emergencies connected to calamities of natural or human causes. The bodies responsible for this kind of actions in Italy on different scales and levels are the State Administration, the regions, the provinces, and the municipalities, as well as scientific research institutes and groups, private, public or voluntary organisation or professional orders relative to this field.

As described in the matrix, the Civil Protection has a very high decisional power, because it holds most of the money related to intervention in the event of a flood, but at the same time, since it has to deal with larger portions of land (its main co-operators are the Regions), their interest in pursuing specific measures is not very high, especially in a very small village like Rosazza (Protezione civile, 2021).

8.2 Local administration

The second main stakeholder is the public administration of Rosazza, i.e., the mayor and more specifically the technical office of the municipality which deals with the architectural and engineering issues the city might be facing. Local administrations have the duty of dealing with alert systems and monitoring systems and then deal with the measures provided by the Region in order to better handle the aftermath of a damaging flood. Local authorities also have the duty of operatively organise the actions taken previously and after a flood, determine a prevention system and handle the connection to the Regions and the Civil Protection to repristinate what has been lost after a flood (Protezione civile, 2021).

For these reasons, local authorities such as the municipality and the Technical Offices are considered the highest both in power and interest, because not only can they take important decision against floods (both in prevention and protection phases), but they also are extremely interested in dealing with the topic in the better way possible to preserve their heritage and the safety of their people.

8.3 Local organisations and people

Rosazza and the surrounding villages have many different local associations and organisations to look up to when dealing with the built heritage, such as *Pro Loco Rosazza*, *Borghi più belli d'Italia* and *Casa Museo dell'Alta Valle Cervo*. Those organisations all deal with the preservation of the history and tradition of the valley as well as pass it on to their people or to tourists visiting the area. As far as the locals are concerned, some issues were directly investigated with people working at the technical office as well as local owners of the property that has been damaged in the last flood of 2020. It was immediately perceivable how valuable their territory is to them both on an architectural point of view as well as emotional and natural.

This puts the local organisations and people at the highest level in terms of interest because they care for their territory more than anyone, but also in the lowest power, because they have no practical power over administrative decisions without consulting the necessary authorities first.

8.4 Data to be analysed

According to the previously detailed stakeholder analysis, it resulted evident which kind of data should be gathered through this process and preliminary investigation to figure out what to implement in the applicative part of the model. Divided by the stakeholder who provided them, the kind of documentation gathered was:

- Civil Protection: almost nothing directly but mostly data obtained by local authorities that then submit their results to the Civil protection, for example ARPA (regional) as far as floods, weather, and hydrological parameters are concerned,
- Local authorities: PAI, local and historical data regarding floods in the Cervo Valley, PRGC,
- Local organisations and people: books and theses regarding the Cervo Valley, architectural plans, and prospects of the most damaged building during 2020 flood.

8 Planning

The lack of productivity of the construction sector is also due to poor management skills. Wang et al. (2021) point out that the construction sector is based on excessive specificity, which makes any change in the project a problem to be dealt with, with consequent slowdowns and delays leading to stakeholder dissatisfaction, then a systematisation of the construction process as that of the factory would be helpful (e.g., through modularisation and standardisation of building components). The low profit margin in the construction sector is caused by the essentially complex and dynamic nature of the changes that can be made in a construction project. Extensive project management leads to delays that, in the long run, reduce the efficiency of an *ad hoc* schedule, creating a domino effect that reduces the efficiency of the whole cycle (Weiqi et al., 2021). These are just few of the reasons why the planning phase is to be considered the most relevant: as Benjamin Franklin once said, 'if you fail to plan, you're planning to fail'. This step encompasses each of the following ones and manages to give a comprehensive view of the project so that each decision toward the realisation of the model, its enrichment, and further applications could be taken bearing in mind its goals and structure, in a smooth process that can lead to few to none management issues, better time-management, and generally less wastes in terms of time and energy.

The first issue to figure out was how to define the workflow. For this purpose, various papers regarding the main topics of HBIM, Digital Twin, and Scan-to-BIM were analysed to figure out a general operational structure that could be exploited for the purpose of this Thesis. Since specificity leads to delays, it is important to try to find a structural common ground in terms of methodology that could be used by different project to reach similar goals, in this case, a digital district representation for heritage conservation purposes – as specified in Chapters 2.1.5 and 5. Then, it is necessary to establish a regulation framework into which to insert the project, as well as determine preliminary settings and requirements which will be studied in the following paragraphs.

8.1 Italian regulations: UNI

UNI 19650 deals with the recommended concepts and principles for company processes dealing with the management and production of information during a building's life cycle using Building Information modelling (BIM) (UNI-19650-1, 2019). The regulation is aimed to those who handle the information of the process in exchange with the stakeholders involved, as in the clients of the project. It can be applied to all kinds of building relating to their complexity and dimension. In this case, data is used, elaborated, and edited only by the author of the thesis, therefore this kind of flow was not necessary. On the other hand, it was crucial to define a system of archiving of the files on Dropbox®, the chosen cloud operating system, which is later explained. Other Italian adaption of international and European regulations on the matters of archiving, Common Data Environment, and Level of Detail are explained in this chapter.

8.1.1 LOD

The regulations on Level of Detail of the different objects in a digital project in Italy are defined by UNI 11337, more specifically Part 4 (UNI 11337-4, 2017). First, the more general Level of Detail (LOD) is defined as:

'*Level of depth and stability of data and information of digital objects that compose the model'.*

The so-called Level of Development (LOD-Development) is internationally defined as a combination of the levels of development of graphical and non-graphical attributes in the model.

LOD is itself formed by Level of Geometry (LOG) and Level of Information (LOI), as previously explained. LOG is defined as:

'*Level of depth and stability of geometrical attributes of digital objects that compose the model'.*

Whereas LOI is referred to as:

'Level of depth and stability of informational attributes of digital objects that compose the model'.

As previously explained, LOD is measured based on the nature, quantity, quality, and stability of data and information constituting the object in question (LOG) as well as the stable and structured connection of its geometrical and non-geometrical attributes, i.e., technological, juridical, and economical for example (LOI).

The information can be expressed in different forms:

- Graphically, through the 3-dimensional virtualisation of the objects and eventual 2-dimensional representations,
- In a written way or through multimedia devices, for example regarding information referring to management of cost, time, and sustainability or maintenance, using specific product and process sheets.

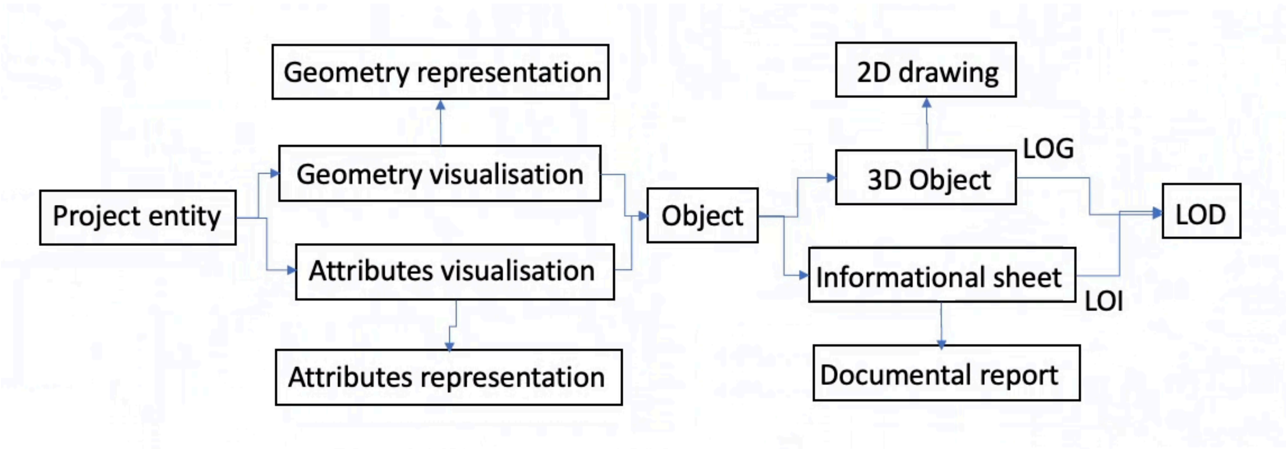

Figure 39 Flow of LOD representation and object detailing (Re-elaboration of UNI 11337-4, 2017)

It is compulsory by Italian regulations to introduce LOD definition for each object in a digital project at different levels corresponding with the type of project considered, i.e., new construction, restoration, territorial interventions, or infrastructures. Further levels of detail are characterised by capital letters from A to G, where:

- LOD A: symbolic object
- LOD B: generic object
- LOD C: defined object
- LOD D: detailed object
- LOD E: specific object
- LOD F: executed object
- LOD G: updated object.

Further details about single object typologies in the model can be found in the Annex of UNI EN ISO 11337-4 (2017).

For this research, the type of detailing that will be necessary belongs to the geometrical and informational definition of the modelled masses of Rosazza and implementation through data enrichment of the parameters conserving into the risk assessment value.

The considered LOD is therefore LOD C, for which '*the entities are graphically virtualised through a 3-dimensional defined geometrical system*' and '*the quantitative and qualitative characteristics are defined (performance, dimension, geometry, location, cost, etc.)'.*

It has to be noted that this only refers to a preliminary consideration of LOD and it therefore will be further detailed in Chapter 10 when dealing with its deeper and more considerate version, Level of Information Need, since the model will hold items of lower geometrical definition but higher information and parametrical description.

8.2 Common Data Environment

As the main phases were identified, it was necessary to give the project a structural component in terms of data organisation and hierarchy. For this reason, a Common Data Environment (CDE) was selected, Dropbox® in this case, because Politecnico di Torino provides its student with a licence for free use of the platform. CDE is defined by ISO 19650 as:

'An agreed source of information for any given project or asset for collecting, managing and disseminating each information container through a managed process' (Kirby, 2022).

Of course, this kind of environment must be digital, and it usually consists of a cloud-based software such as Dropbox® that can easily hold and share information. In order to be properly set for the steps to come, it had to be installed on the C drive. The advantages of this kind of solution and flow of information are mainly a reduction of time spent on the project, since the organisation of the information makes use and consultation much easier, and an audit trail of every piece of information which allows to track and characterise data and reach the original source in a few simple and intuitive steps (UNI EN ISO 19650-1, 2019). Every piece of information regarding this thesis was collected and archived in Dropbox® according to a system of folders that follow a naming convention, so that every file could have its own unique, logical, and unmistakable name and therefore not be mistaken with other ones.

8.3 Naming convention

As specified by UNI EN ISO 19650-2 (2019), the naming convention should be decided in accordance with the stakeholders' requirements. In this regulation, indicative naming conventions are also explained as involving different aspects of the information collected:

- The unicity of the identifier used for that specific piece of information, which should be based on a pre-defined naming convention which includes two types of information:
  - A revision code, which defines the chronological level of information i.e., when that was last revised,
  - A status code, which determines the possible uses of that piece of information,
- The iterative process through which information is elaborated, analysed, and checked before submitting it to a stakeholder / continuing to model or develop new information,
- The definition of who can access data (UNI EN ISO 19650-1, 2019).

The reason behind these needs is that of a constant access and interaction among different parties to these files. In the case of this thesis, though, the necessary data is organised only through an archive system and not a constant exchange of information, therefore the update status and the iterative process of checking is not necessary. What is due is the presence of a specific naming convention that could identify in an unambiguous way every single piece of information to be archived properly and logically to create an easily accessible database for who is using the data for the project to retrieve files in a fast and easy way.

The methodology through which every file is identified follows a further detailing process that creates a code that will be explained through the following list. Each part of the code is separated by an underscore, "_", and the further detailing holds names and acronyms as follows.

1. Name of the project:
   a. DTR, which stands for Digital Twin Rosazza. It has been given as a first identification for each file in Dropbox®.
2. The typology of data to be considered (XX):
   a. 00: general data about Rosazza or Cervo Valley, screen captures, pictures, and textual data,
   b. 01: data related to the point cloud and its elaboration,
   c. 02: data related to the Revit® model, the masses, the topography, and Dynamo®.

3. The nature of the data to be dealing with (YYY):
    a. ARC: architectural information such as plans, prospects, planimetries etc.
    b. CPT: screen capture
    c. DYN: Dynamo® script
    d. EXC: Excel™ file or Google Sheet™
    e. HGP: Hydrogeological Plan
    f. MAP: geographical information such as maps or cartographies
    g. MAS: previously elaborated mass files
    h. MOD: model
    i. MOV: video
    j. PCL: point cloud
    k. PHT: photograph
    l. TPG: file related to the topography
    m. TXT: text document, such as books, theses, guides etc.
4. To what location this data is related in terms of object in the model (WWW):
    a. CVL: Cervo valley
    b. RSZ: Rosazza.
5. The file format of the data (if necessary) (ZZZ):
    a. DXF: .dxf file exported from FormIt®
    b. FBX: .fbx file developed in Infraworks®
    c. IFC: .ifc file developed either in Revit® of ArchiCad®
    d. OBJ: .obj file developed in InfraWorks®
    e. RCP: .rcp file developed in ReCap Pro®
    f. RVT: .rvt file developed or modified on Revit®.
6. Number of the data if more than one items of this type is available (NN).

For example,

- DTR00_TXT_CVL: textual document about Cervo valley
- DTR00_TXT_RSZ: textual document about Rosazza
- DTR01_PCL_CVL: point cloud of the Cervo valley
- DTR02_MOD_RSZ_RVT: Revit® model of the digital twin
- DTR02_MAS_RSZ_RVT: Revit® file of the previously elaborated masses.
- DTR02_DYN_RSZ_01: first Dynamo® script for the Revit® model.

DTRXX_YYY_WWW_ZZZ								
DTR	**X**		**YYY**		**WWW**		**ZZZ**	
Name of the project	**Typology**		**Nature of data**		**Location**		**File format (optional)**	
DTR	00	General information	ARC	Architectural graphical information	CVL	Cervo Valley	DXF	.dxf file exported from FormIt®
DTR	01	Point Cloud	CPT	Screen capture	RSZ	Rosazza	FBX	.fbx file developed on InfraWorks®
DTR	02	Rosazza model	DYN	Dynamo® file			IFC	.ifc file
			EXC	Excel™ or Google Sheet™			OBJ	Developed on InfraWorks®
			HGP	Hydrogeological Plan			RCP	Developed on Recap Pro® 2020
			MAP	Cartography			RVT	Developed or modified on Revit® 2020
			MAS	Previously elaborated masses file				
			MOD	Model				
			MOV	Video				
			PCL	Point cloud				
			PHT	Photograph				
			TPG	Topography				
			TXT	Textual information				

Table 2 Naming convention scheme (Personal elaboration)

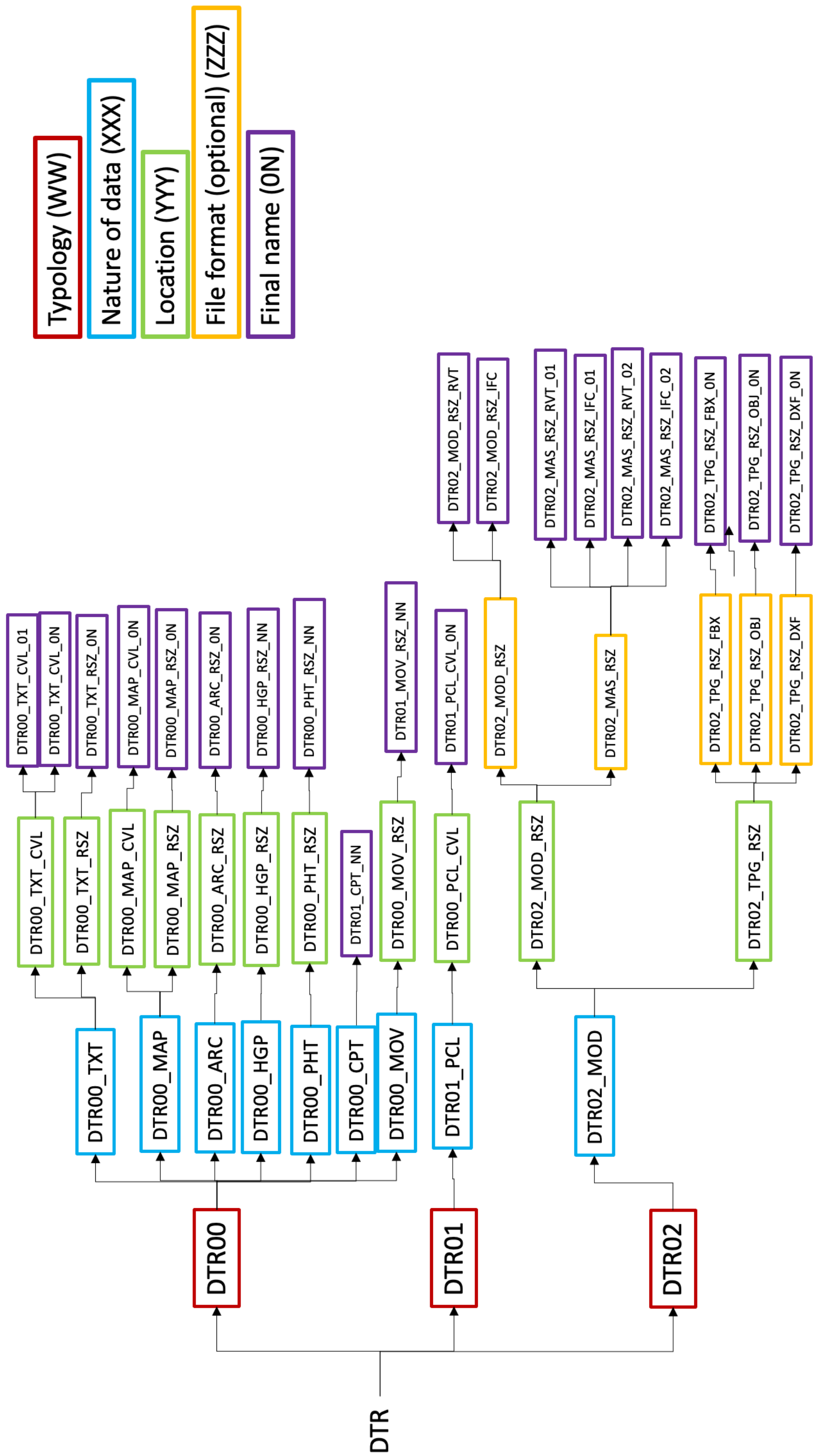

Figure 40 Naming convention detailing process (Personal elaboration)

9 Scan-to-BIM

The first step of the modelling phase was Scan-to-BIM, which, as previously explained, encompasses the phase of transferring scanned data such as point clouds in a BIM environment for furthering the reverse engineering process of elaborating the HBIM model.
The sources of data concerning the context of Cervo Valley and Rosazza were multiple, elaborated by different people and through different methods:

- Point cloud of the entire valley scanned by Politecnico di Torino drawingTothefuture Lab and elaborated by PhD Student Davide Aschieri,
- Masses of the buildings of the municipality of Rosazza with a topographical context elaborated by Bachelor's student Emilio Brunazzi with Archicad® for his Bachelor's Thesis,
- Open Street Map provided by InfraWorks®.

9.1 Point cloud

The Point Cloud of the entire Cervo valley had been realized through by Politecnico di Torino for research purposes and it is currently used by drawingTOthefuture lab for PhD projects regarding the valley. PhD student Davide Aschieri was in particular involved in this thesis because he was contacted to gather more digital or conceptual information regarding different flood data. The Point Cloud itself was provided by Emilio Brunazzi, student of Politecnico di Torino who had already worked on Rosazza for his Bachelor's thesis and therefore had already elaborated and segmented the Point Cloud so that could directly be used in ReCap Pro 2020® (and not Revit®, since the format of the scans could not allow a direct import in and needed a preliminary conversion).
The point cloud was originally divided into four different scans that were imported altogether in ReCap Pro® 2020 so that they could be visualised in the same space. After syncing the scans and launching the project, one of the most important steps was updating the origin to reduce the total extension of the point cloud in terms of coordinates. It was noted that importing the converted file (.rcp) in Revit® caused issues because of the vastity of the point cloud, so updating the origin (meaning choosing another point and then clicking update as shown in Figure 41) determined better chances of importing correctly.

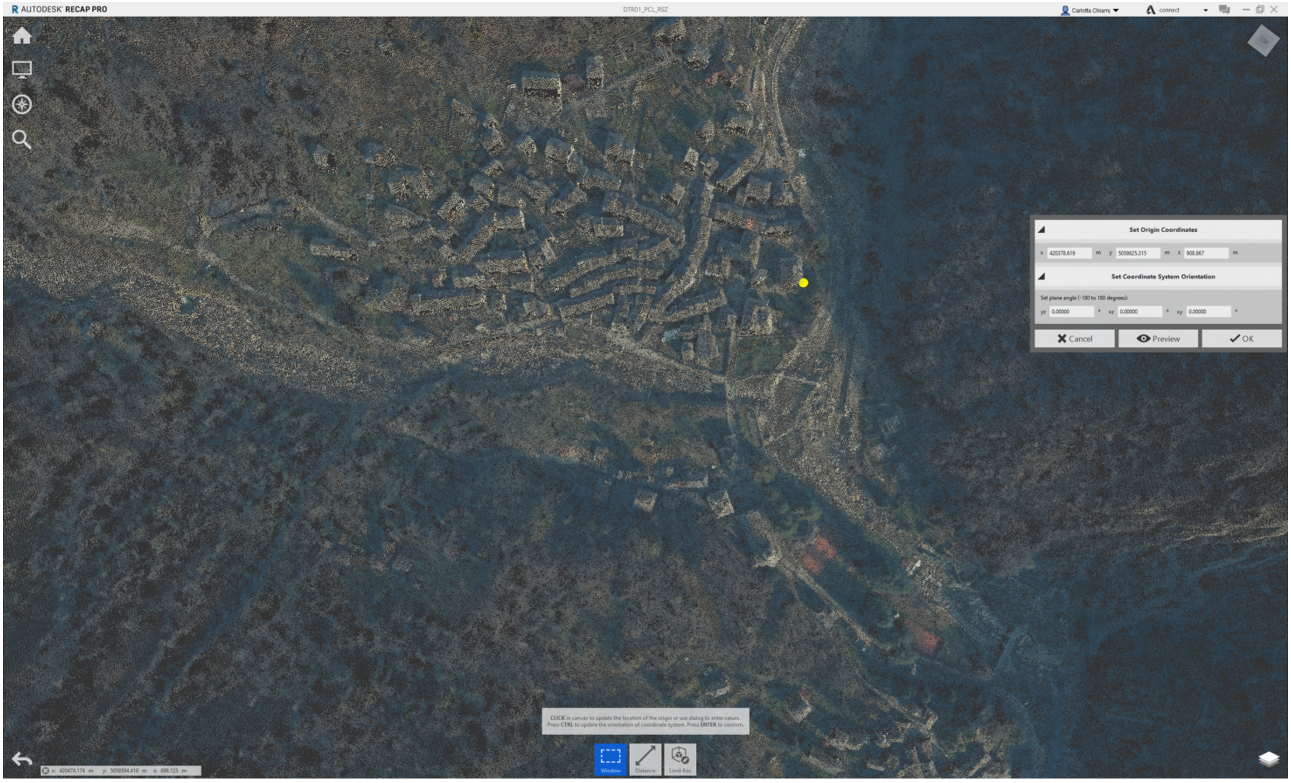

Figure 41 Origin update on ReCap Pro 2020® (Personal elaboration)

The point cloud was then divided into 7 Regions in ReCap Pro®, with the purpose of differentiating the views when imported in Revit®. Even though the plug-in DiRoots One was implemented, which is supposed to help the management of point clouds in Revit®, it wasn't possible to hide a single region while others stayed visible, so the purpose of the regions was lost.

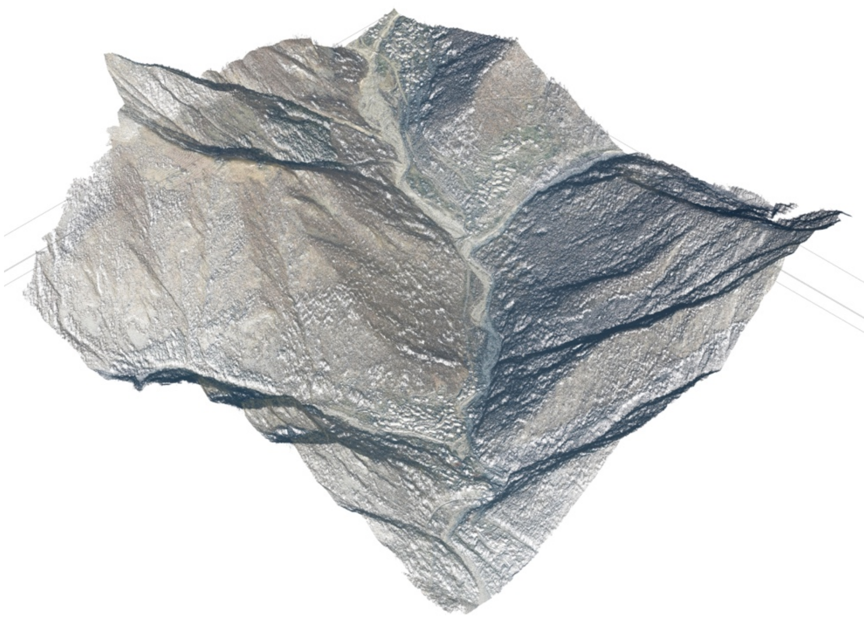

Figure 42 Point cloud on Revit® (Personal elaboration)

9.2 Digital Terrain Model

From the point cloud, another type of model data could have been obtained: the topography useful for modelling in a Revit® environment. For this purpose, the point cloud was imported in Rhinoceros to try to create a mesh out of it. The issue that arose in this phase was that, as soon as the mesh creation button was clicked upon (Mesh through points), the program stopped working. Probably, the reason behind this resides in the fact that the point cloud had too many points and the elaboration was too hard for the computer. Some plug-ins were also downloaded to make this transition easier, but they needed a premium version to implement point cloud tools and therefore this path was also discarded.

Considering the lack of detailing of the topography provided by the existent masses file and the impossibility of creating one out of the point cloud, InfraWorks® was introduced to create a correct shape of the area.

First, the area had to be detected through the Open Street Map feature of InfraWorks®. Model builder was selected and then the meaningful area of the city of Rosazza was enclosed in a rectangular shape that would then create a mesh of that portion of land (Figure 42). After the processing, two files were exported (figure 43):

- One containing every information, including the buildings.
- One only containing the topography.

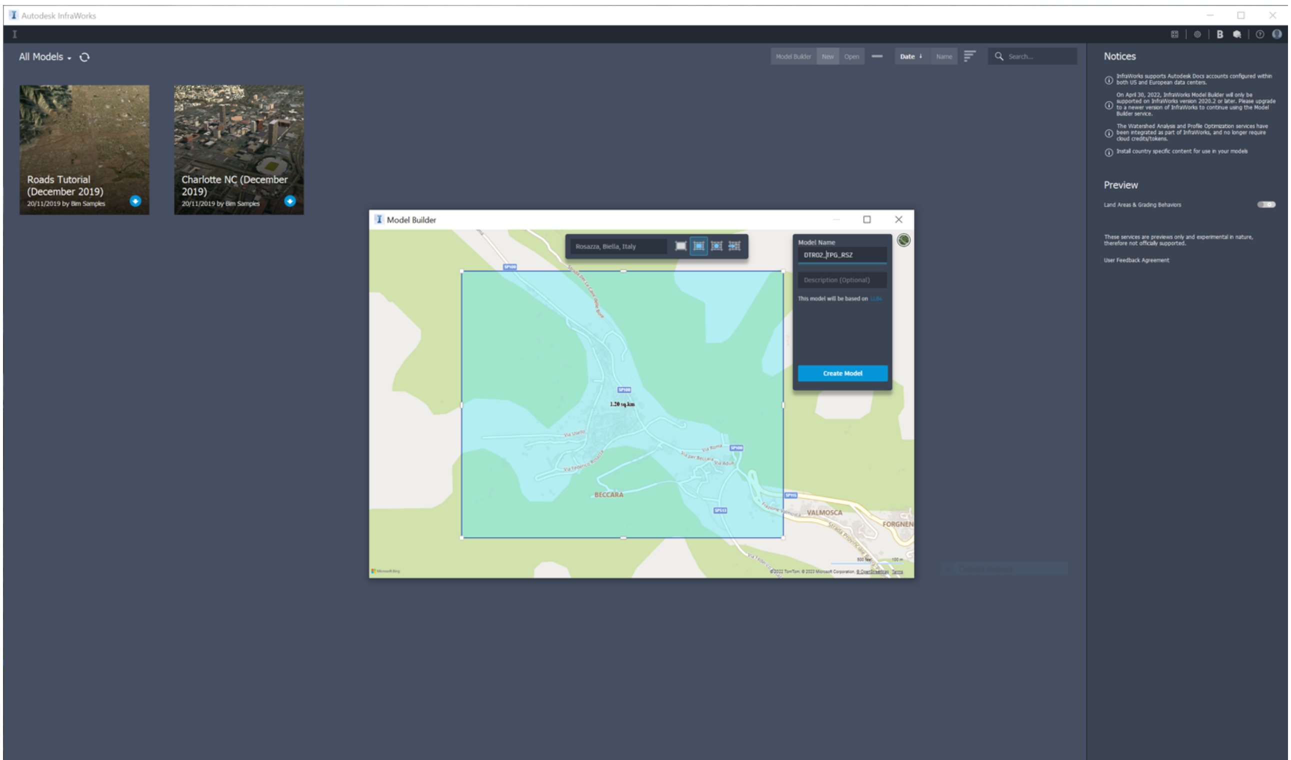

Figure 43 Creation of the InfraWorks® model through the selection of a portion of the Open Street Map over Rosazza (Personal elaboration)

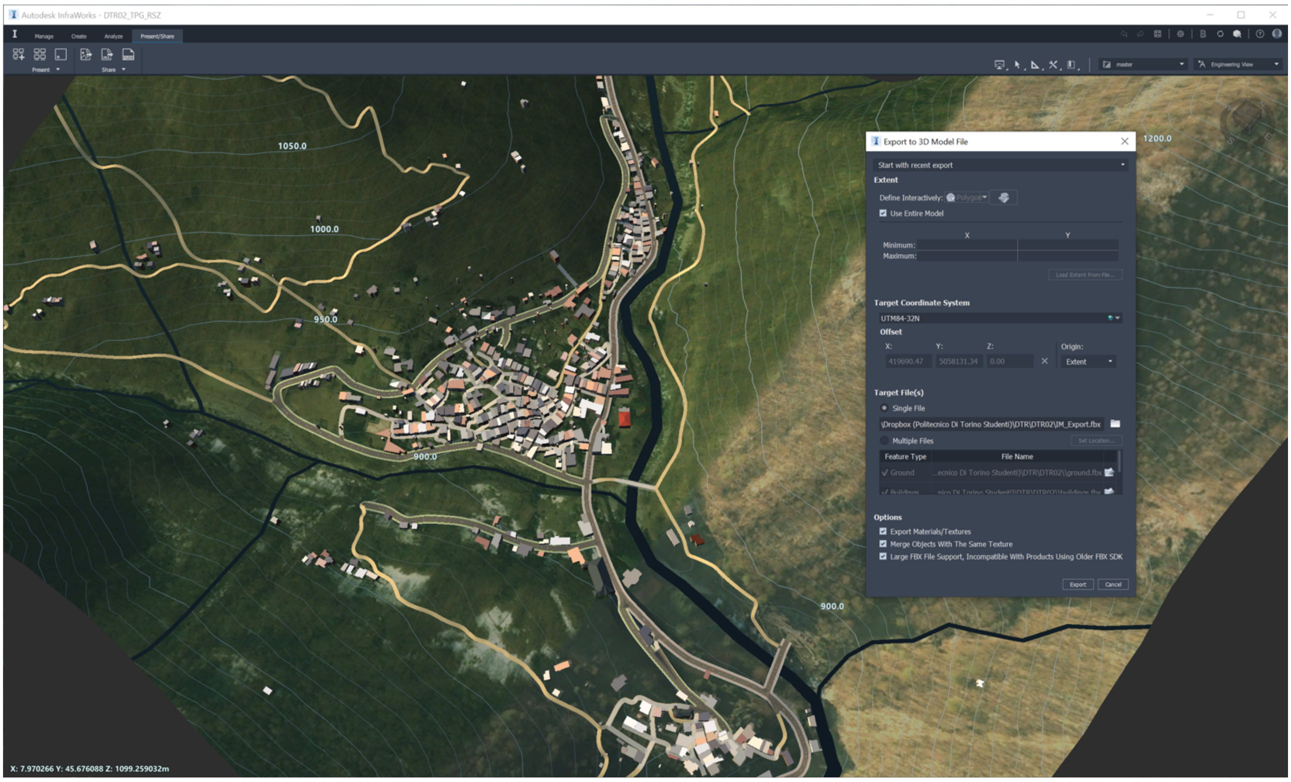

Figure 44 Export selection from InfraWorks®. It is visible how to customise the export through the selection of a portion of the model or the entire model (designated option), the final location of the file, and the possibility to select between the export of only the Ground or Buildings, which will hold both. (Personal elaboration)

Both of the files were exported in .fbx format, so that the transition to Revit® would have been less problematic. The .fbx were then imported to FormIt®, which would make it possible to further export them in .dxf, a format readable by Revit® through a simple Import of a CAD file. This operation was done with particular attention to the different units of measure present in the different software, because otherwise it led to difficulties in scale and rotation of the mesh in Revit®.

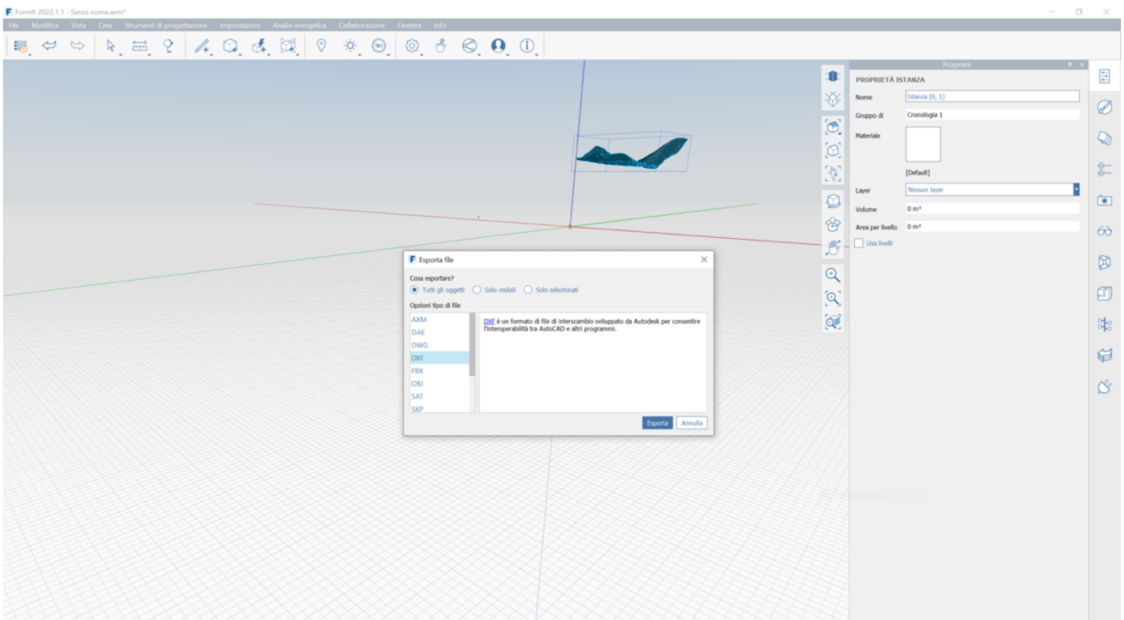

Figure 45 FormIt® export (Personal elaboration)

Once imported in Revit® and correctly positioned on the point cloud and the masses, the mesh was transformed into topography through the appropriate command: Massing and site -> topography -> import from link -> topography. The mesh was then deleted.

To better define the location of Cervo Torrent in the topography, a Subregion was created and designed out of the Hydrogeological Plan of Rosazza, which was linked to the model Importing its PDF and scaling it according to the Building + Ground InfraWorks® file.

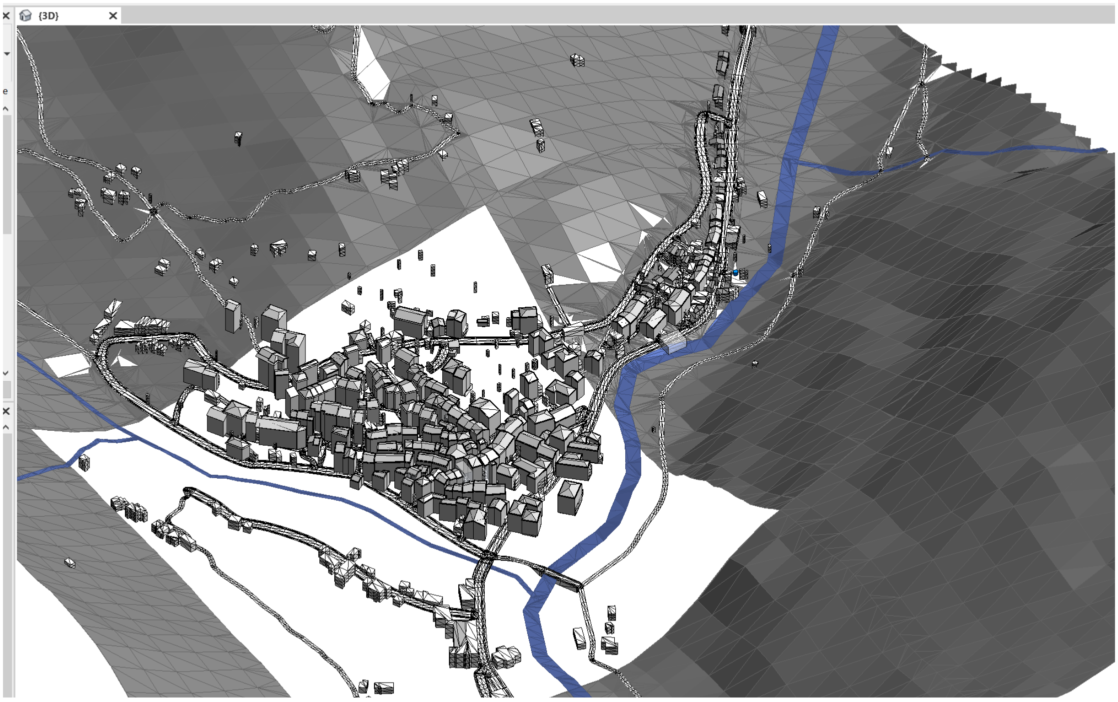

Figure 48 Revit® import of InfraWorks® .dxf file with Ground and Buildings (Personal elaboration)

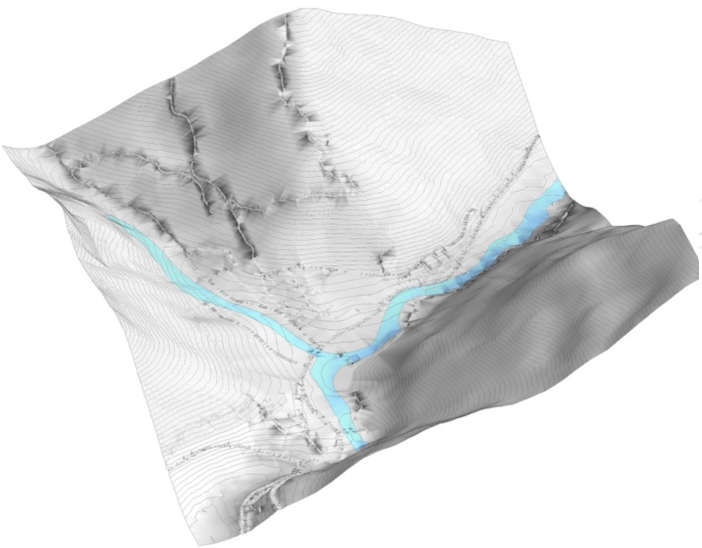

Figure 47 Final topography after elaboration, identification, and torrent shape addition through subregion (Personal elaboration)

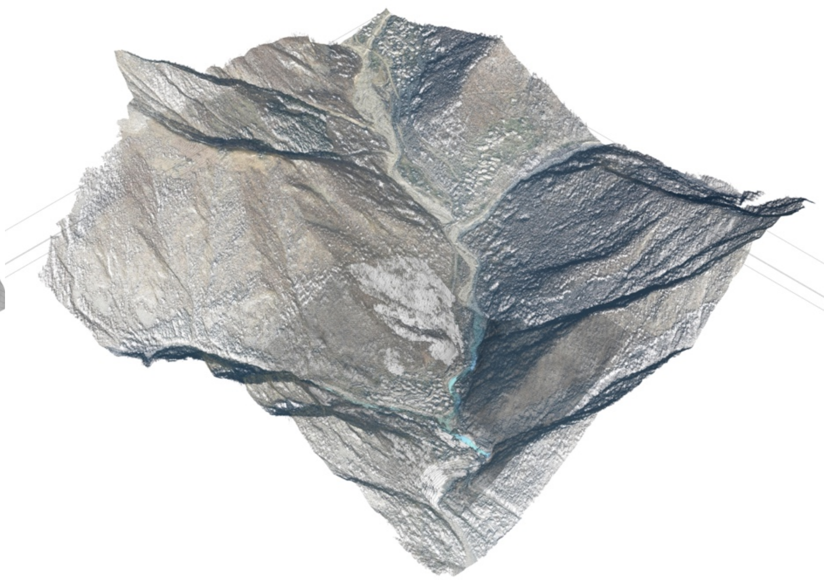

Figure 46 Visualisation of the topography together with the Point Cloud (Personal elaboration)

9.3 Masses

The reference for the masses was provided by a graduated Bachelor's student that developed them using ArchiCad® and the exported an .ifc. not having access to the original files caused some issues. The IFC making process as well as the export/import from ArchiCad® to Revit® caused interoperability issues that resulted in some walls sticking out of the roofs, different textures for the roofs' surfaces (as it is visible in the picture below), as well as difficulties in handling the different layers, because the different entities were modelled using different objects and not just masses.

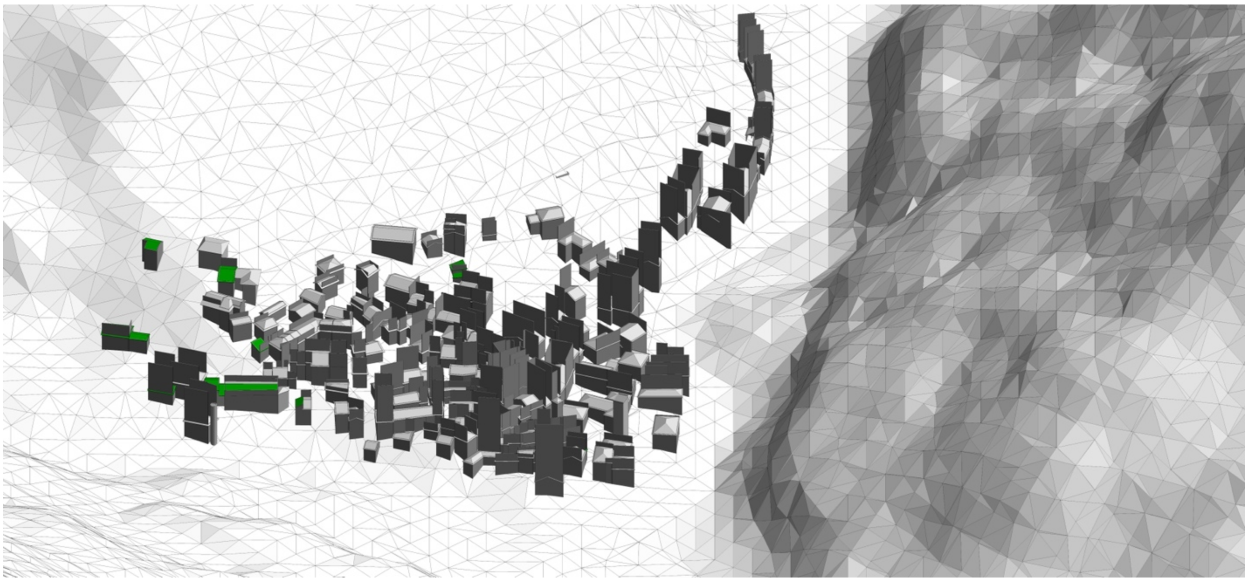

Figure 49 Masses errors. It is possible to see the walls that resulted too high as well as different textures of the roofs (Personal elaboration)

For this reason, the incorrect .ifc file was only used as reference, while developing a new file that could be used for its roofs, since their modifications were easier. The complete .ifc file was only opened in Revit®, so that it could be modified and then linked to the main model through its .rvt version. The modifications were mainly three:

- First, the topography was removed, because the level of detail was not high enough,
- Since the walls of the masses were partially unusable, it was decided to delete them completely and model them from scratch. Therefore, all the walls were removed,
- Lastly, the incoherent roofs were modified through their properties to change their material and aspect in the model, so that all the roofs were homogenous. The roofs were kept as a guideline for the later modelling of the masses.

At the end of this process, the two .ifc files opened in Revit® generated two .rvt files, which were:

- DTR02_MAS_RVT_01: holding everything, even if wrong, to be used as reference for the new masses' shape,
- DTR02_MAS_RVT_02: just with the roofs, to be exploited directly in the model.

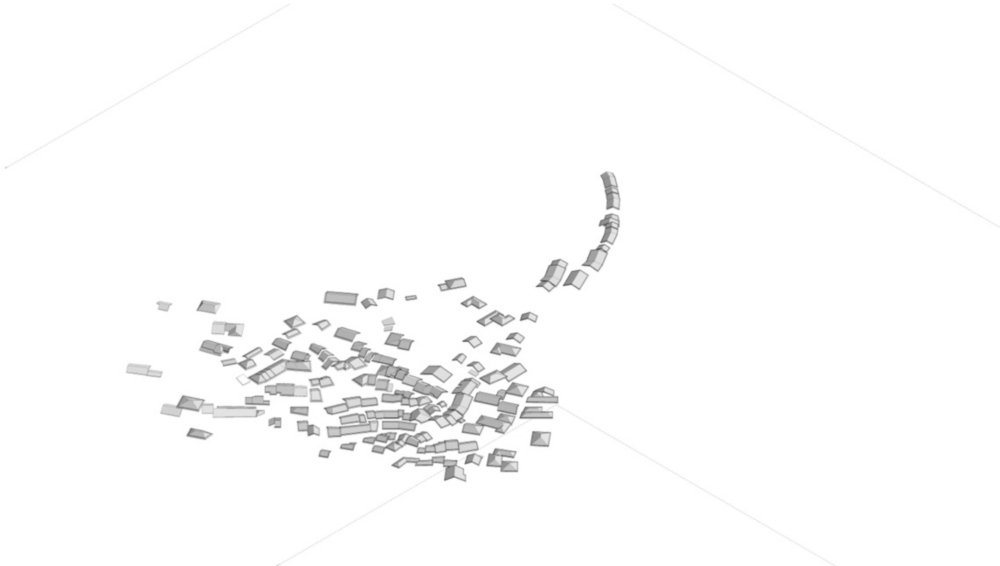

Figure 50 Perfected file that was used as reference for the height of the masses and offered the possibility to keep these roofs for most of them (Personal elaboration)

10 HBIM development

In order to facilitate the further development of the model and the introduction of parametrical data, it is necessary to develop a model structure that could be coherent with its application purposes and the information that will be later introduced. As it has been previously explained, the model holds in this phase various links, which will now be listed:

- The point cloud, DTR01_PCL_CVL,
- The topography without buildings, already converted in a topographical surface, DTR02_TPG_RSZ_01,
- The topography with buildings, which has been imported as a DXF file, DTR02_TPG_RSZ_02,
- The already elaborated masses file with its errors, DTR02_MAS_RSZ_IFC, to be used as a base source for the modelling of the new masses,
- The modified masses file, which is more accurate than the original and only holds the correct roofs, DTR02_MAS_RSZ_RVT.
- Rosazza's Hydrogeological Plan, whose .pdf was linked to the masses and used for checking correct locations and shaping the torrent.

Type of file	Name	Provider	Elaboration software	Level of Reliability		Use
Point cloud	DTR01_PCL_CVL_RCP	Politecnico's laboratory	ReCap Pro® + Revit® + DiRoots One	Medium	✓ entire valley modelled. ✓ low density of the PC in the villages ✓ doesn't allow high LOD	Background to model masses
Masses IFC **Roof Masses IFC**	DTR02_MAS_RSZ_RVT_01	Bachelor's student's thesis	Archicad® + IFC on Revit®	Medium - High	✓ buildings already detailed, ✓ export errors, issues with some walls	BUILDINGS: Reference to model masses from
	DTR02_MAS_RSZ_RVT_02	Bachelor's student's thesis	Archicad® + IFC on Revit®	Medium - High	✓ Reliable roof ✓ Usable only for a number of masses	ROOFS: Reference for height for the masses, mass detailing
Open Street Map	DTR02_TPG_RSZ_DXF_01	InfraWorks®	InfraWorks® + FormIt® + Revit®	Medium - High	✓ details in the terrain ✓ Precise	Topography surface
	DTR02_TPG_RSZ_DXF_02	InfraWorks®	InfraWorks® + FormIt® + Revit®	Medium - High	✓ Details for the masses location ✓ Precise ✓ Incoherence with already DTR02_MAS_RVT_01	References for missing masses.
Hydrogeological Plan	DTR00_HGP_RSZ	Rosazza's Technical Office	Pdf	High	✓ Details for masses location ✓ Extremely accurate ✓ Official	Checking masses location, shaping the torrent as a topography subregion

Table 3 Detailing of the linked files, their providers, software in which they were elaborated, reliability and use (Personal elaboration)

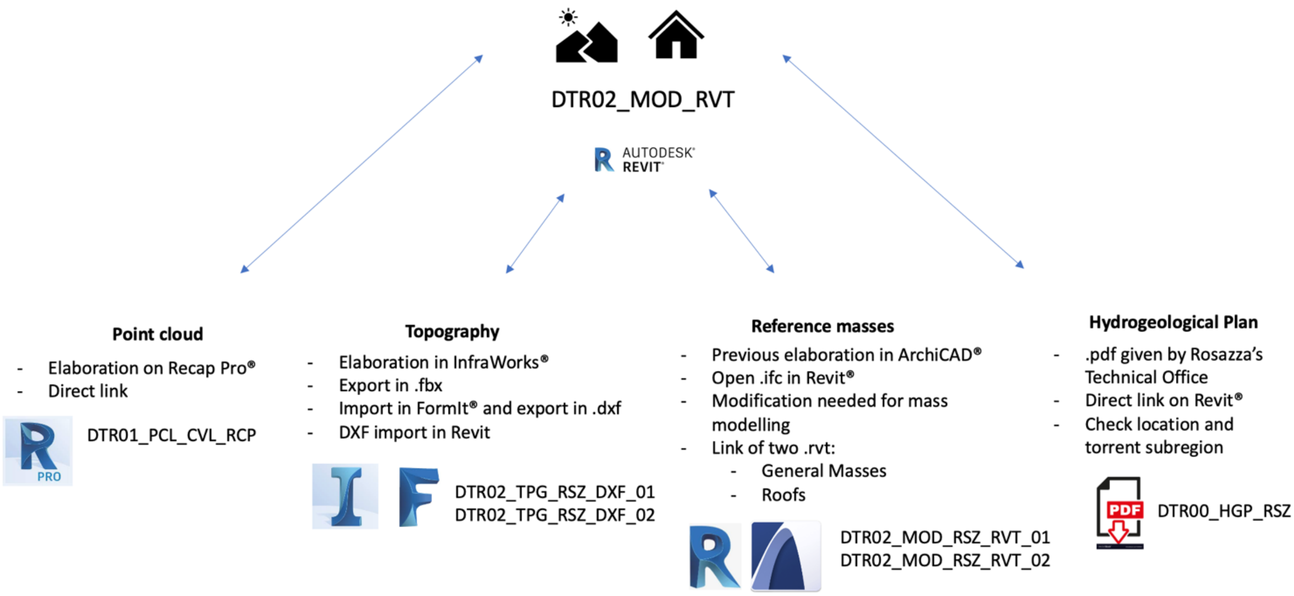

Figure 51 Link structure in Revit® (Personal elaboration)

Before the modelling phase started out, the project was georeferenced through its coordinates, selecting Rosazza as the origin of the model in "Set project coordinates".

To initiate the modelling phase, only the topography and the roof file were kept visible, so that the masses could be modelled thoroughly. Through a split view, the Site plan was kept on the left while the 3D view was on the right. Massing and Site was selected, then In-Plane mass to define the first mass. It was decided to create a single family for every single mass of the project, so that they could be singularly defined in terms of geometry and parameters implementation in the future steps through Mass Schedule. Each mass was given a Family coding name structured as:

- BLD_NN

Where NN is a progressive number from 01 to 218, the total number of designed masses.

In the Site plan view, the ground outline was defined using the roof outline of the linked file ad a reference, then the extrusion was created in the 3D view up until the lower level of the roof.

At this point, it was evident that the paralepidid shape of the mass was not coherent with the already linked roofs, because there was a pyramid gap between mass and roof. For this reason, each mass that was modelled using the roofs as reference was further detailed in terms of geometry through the addition of an edge. First, the mass was selected, then modified in-place; the addition of an edge allowed to modify the shape of a face and create "house" form that better adhered to the roofs. The material of the masses was also modified so that their visualisation was the same in a Shaded view to a customize "General Mass" material with a grey colour.

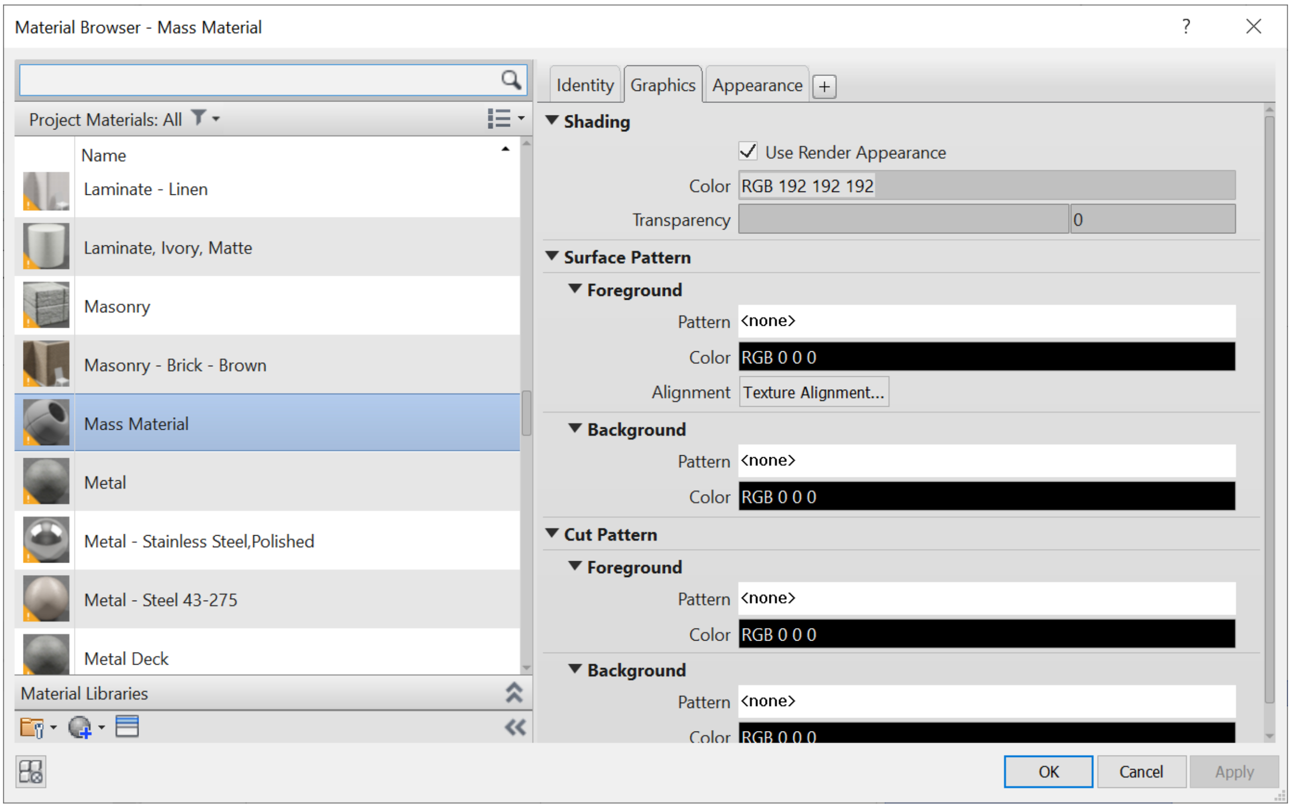

Figure 52 Mass material definition (Personal elaboration)

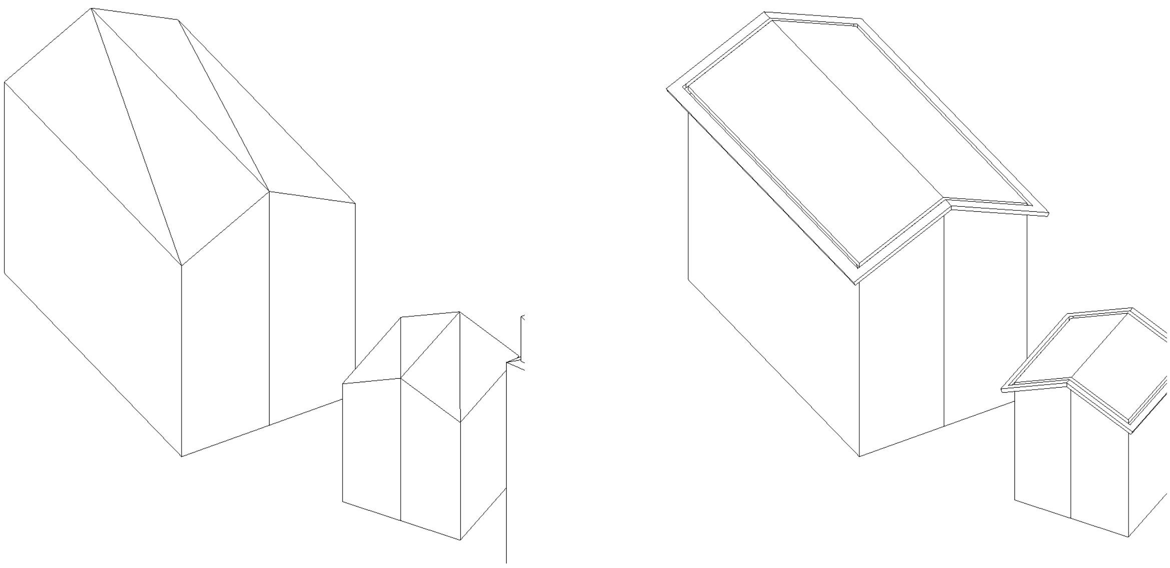

Figure 53 First mass typology (Personal elaboration)

When all the masses present in the IFC-RVT file were modelled, a comparison between these buildings, the Hydrogeological Plan of the town of Rosazza, and Google Maps was done to understand the reliability of the masses that had been designed previously. At this point, it became evident that some buildings of the northern part of Rosazza had not been previously modelled. Therefore, the InfraWorks® file that held ground and buildings together came at hand again, because its representation from Open Street Map was more reliable, after comparing it with Google Maps. This file was made visible again and the last masses were modelled using it as reference.

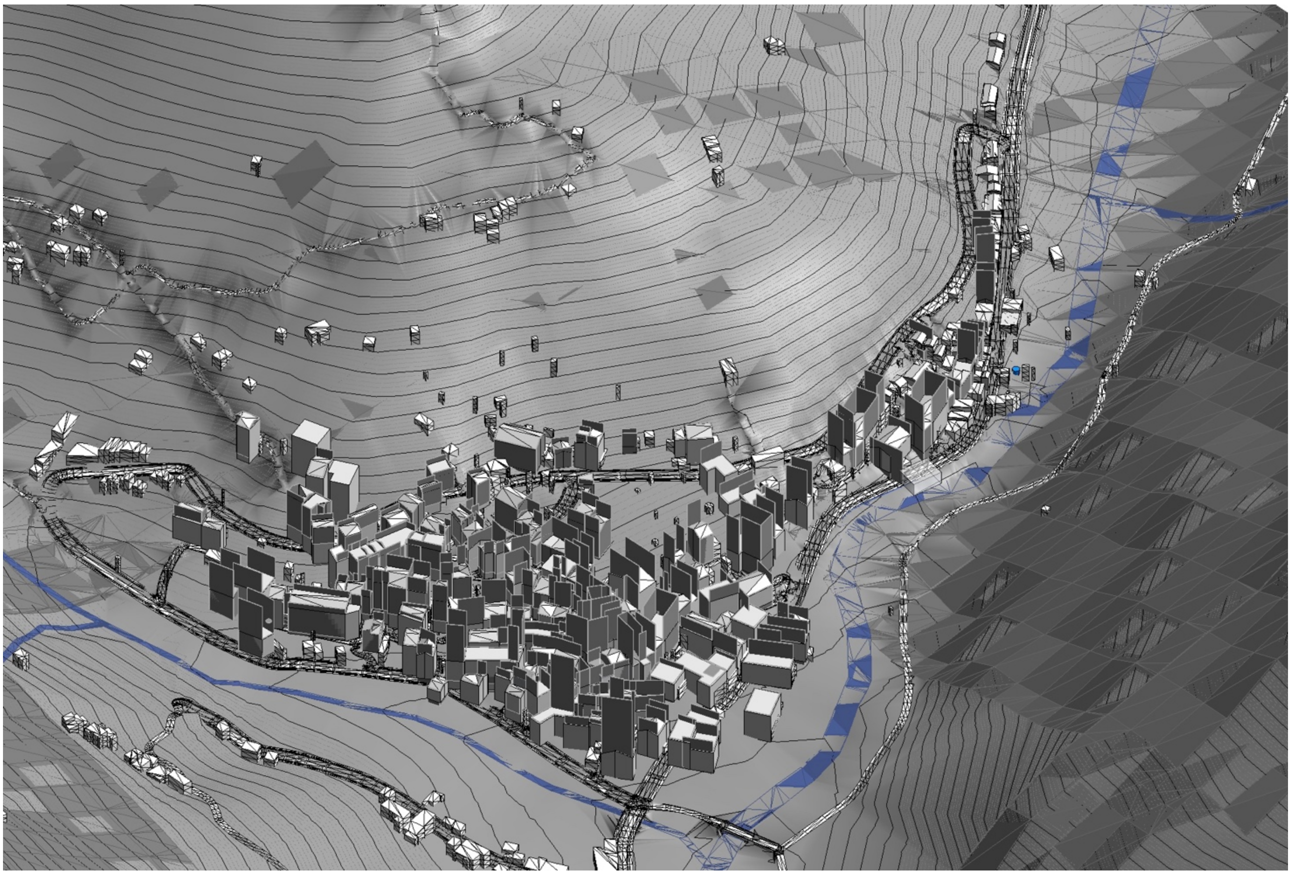

Figure 54 Comparison between InfraWorks® ground + buildings file and imported IFC-RVT masses. Especially in the upper-right side of this screen capture it is possible to see how the InfraWorks® masses (more wireframed) are more than the ones that had previously been modelled (with incorrect roofs and more solid colours. (Personal elaboration)

The roofs, in this case, were modelled differently: another shape was added, per mass, creating a pyramid-like shape on top of the parallelepiped; then, the roof was added on top selecting Massing and Site and create Roof and the top faces of the finished mass.

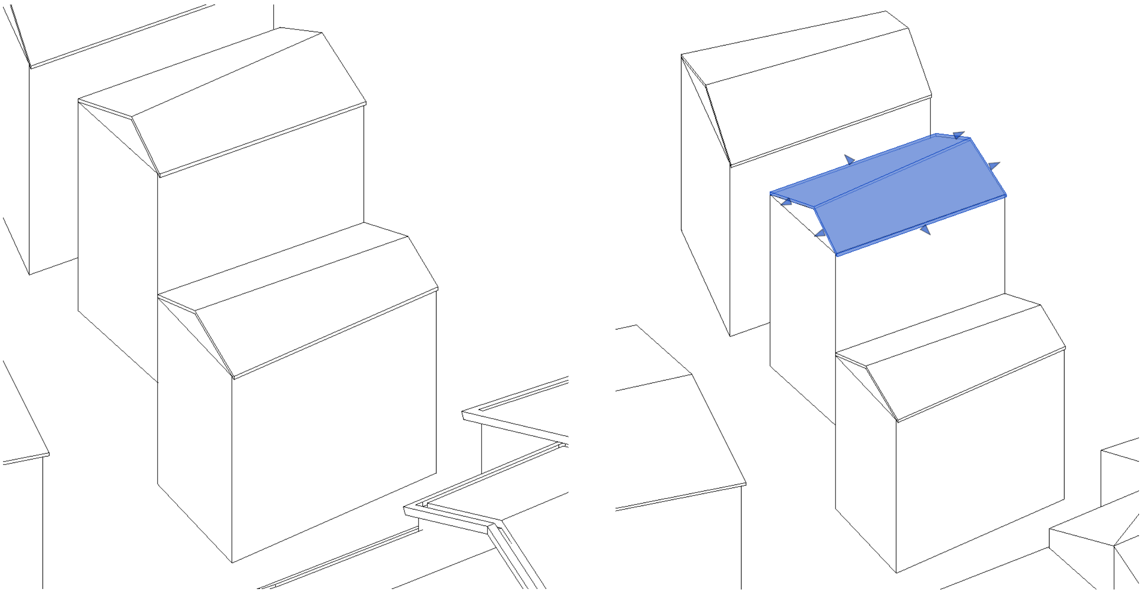

Figure 55 Second mass typology. It is possible to see how the roof is here made from the mass directly (Personal elaboration)

At this point, it was necessary to set everything ready for the Data Enrichment phase. Six different parameters were created according to what had to be used in terms of data to create the integrated Digital Twin. Clicking over Manage, Shared Parameters was selected to create a set of parameters that could potentially be implemented in every project. In this phase, six number parameters:

- DTR_Height
- DTR_Distance
- DTR_Rainfall_Accumulation
- DTR_River_Flow
- DTR_Hydrometric_Level
- DTR_Risk.

The information these parameters will hold is further detailed in the following chapter. In order to apply them to the masses, Project Parameters was selected; in this way, the previously created Shared parameters could be imported in the current project and applied to the category of choice, in this case the Masses, in order for every mass to hold a now empty parameters with that name and characteristics, located under "Other".

The video DTR00_MOV_RSZ_01 available at the link connecting to the Google Drive™ folder DTR00_MOV_RSZ, and it allows to explore the model 3-dimensionally in Revit®, https://drive.google.com/drive/folders/1CoCb9w47BFYUepauALQ9XowY797kmQ09?usp=share_link.

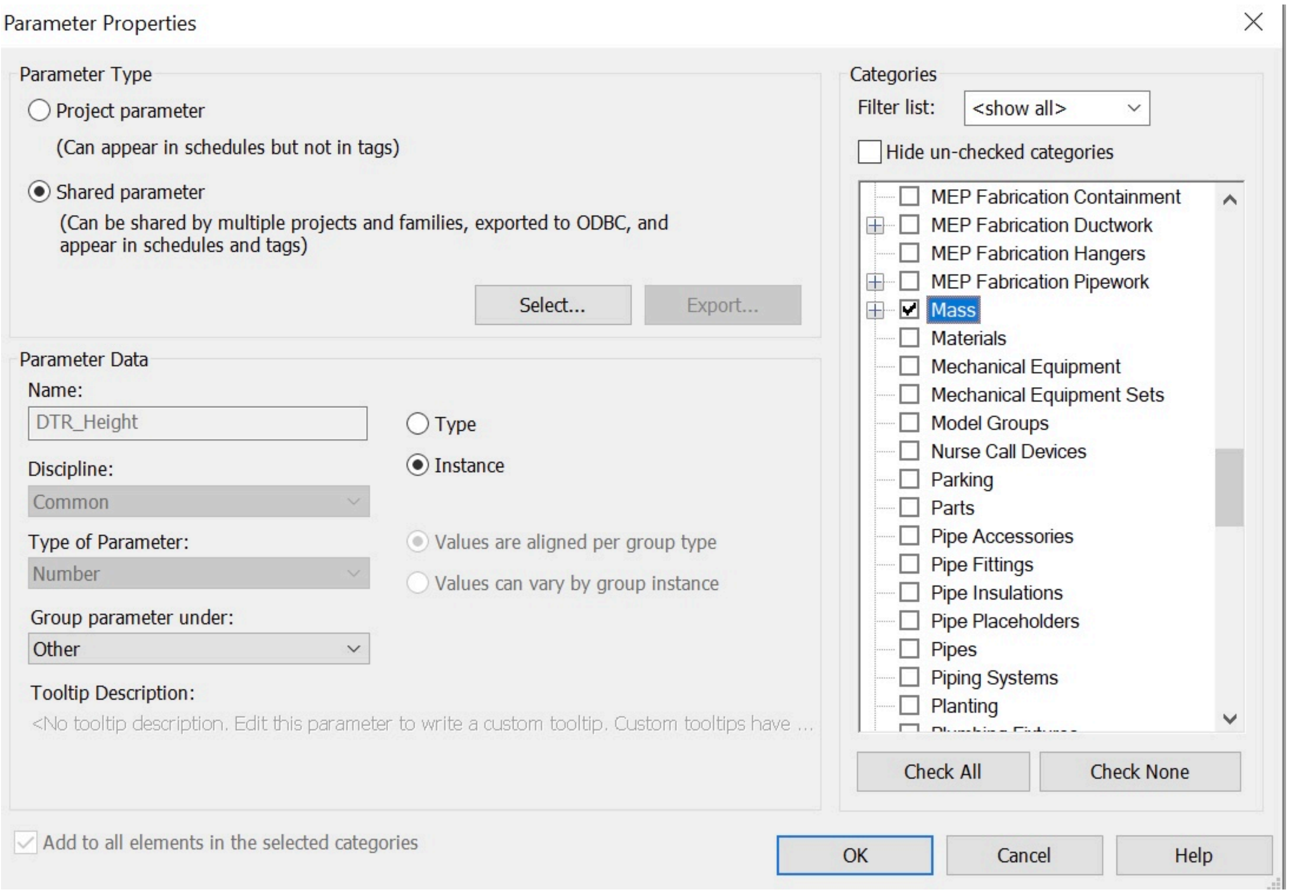

Figure 57 Example of Project Parameter definition (Personal elaboration)

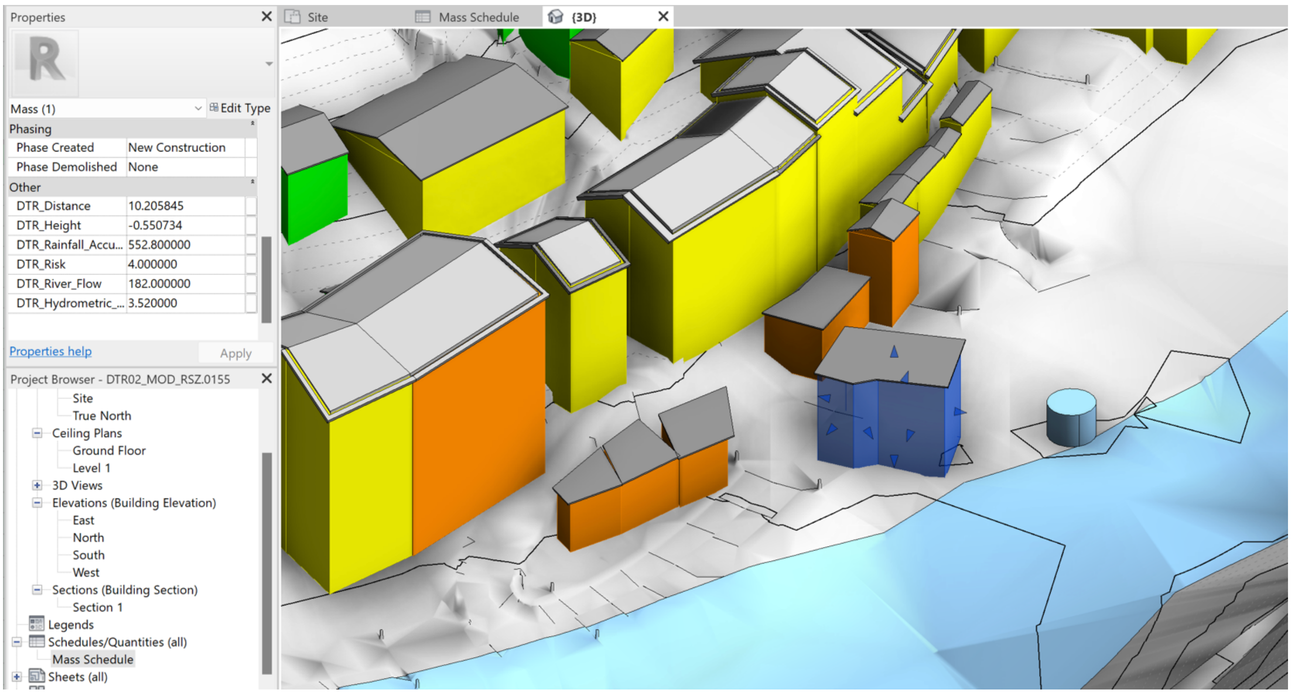

Figure 56 Example of a mass after the complete data enrichment. It is possible to see, on its left, how all the parameters are filled in with their values (Personal elaboration)

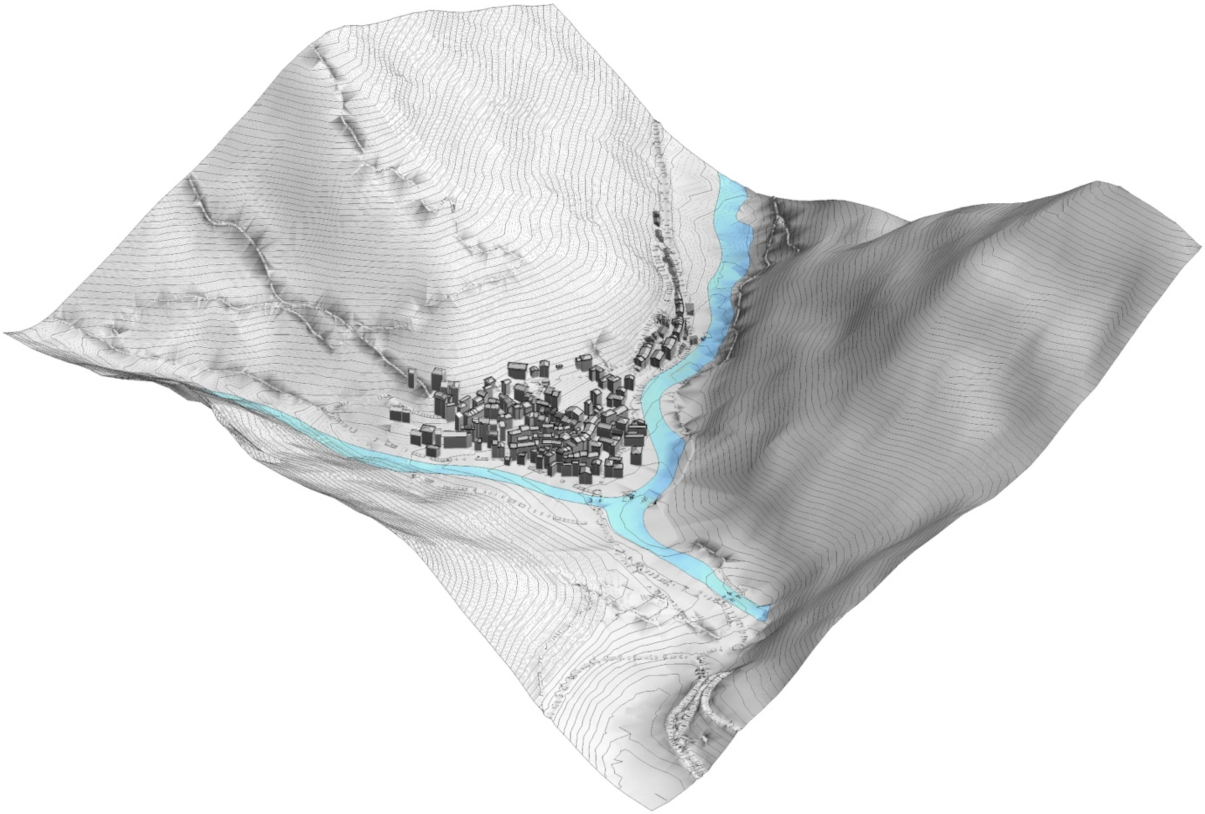

Figure 59 Final masses modelled. Here visible with topography (Personal elaboration)

Figure 58 Masses with their roofs, topograhy and point cloud (Personal elaboration)

10.1 Level of Information Need

At this point, the definition of LOD for the masses changed. It has already been mentioned in Chapter 8.1.1 how the Level of Development on a geometrical point of view for the masses could have potentially changed according to how reliable and detailed the informational component of LOD was; at this point, having established the parameters to be implemented and then numerically defined, it is evident how more detailed they would be on a parametrical point of view. It is therefore necessary to rely on another regulation that deals with what is called Level of Information Need (LOIN), which is defined as 'framework which defines the extent and granularity of information' and it 'should be described by different concepts: geometrical information, alphanumeric information and documentation' (UNI EN 17412-1, 2021). Generally speaking, UNI recommends to consider different aspects when specifying a level of information, such as the purposes of the information, the delivery milestones that have to be completed, who is going to have access to the information and the possible breakdown structures of the objects involved. Each mass could be detailed in terms of level of information need through Table 4, which is inspired by Annex B of UNI EN 17412-1 (2021).

Information delivery milestone	Thesis
Purpose	Visualization
Actor	Author
Object	“Mass”
Geometric information	
Detail	Simplified volume representation including roof
Dimensionality	3D
Location	Absolute
Appearance	Selected by material “General Mass”
Parametric behaviour	Not requested
Alphanumerical information	
Identification	BLD_NN
Information content	Type, family, quantity, area, volume, material, DTR_Height_ DTR_Distance, DTR_Rainfall_Accumulation, DTR_River_Flow, DTR_Hydrometric_Level, DTR_Risk
Documentation	Possible implementation in the Hydrogeological Plan of Rosazza

Table 4 Level of Information Need for masses in the project (Personal elaboration based on Annex B of UNI EN 17412-1, 2021)

11 Data enrichment

The model that has been detailed needs to be integrated with parameters that can be useful in the paradigm of prevention and administration of flood events. For this reason, a dual system of detailing was introduced to define parameters that could be used to label each building in the model to evaluate its vulnerability against these natural phenomena. The dual approach was based off two different data settings:

- *Piano di Assetto Idrogeologico* (PAI): Hydrogeological Plan, which maps the city of Rosazza and surroundings on a hydro-geological point of view to highlight the most fragile areas and detail the planification of a water body. It was introduced by law 183/89 and it is defined as the 'the cognitive, regulatory, and technical-operational tool through which actions, interventions and rules of use concerning defence against hydrogeological risk of the territory are planned and programmed' (Regione Piemonte, 2023),
- Local data gathered by the owner of building that had been the most damaged during 2020 flood (mentioned in Chapter 4.6), Anna Valz Blin, who provided the report that was sent to Piedmont Region to ask for damaged compensation.

As explained in Chapter 4.4.2 and according to a widely used formula, the risk is determined through:

$$Risk = Vulnerability * Hazard$$

Where:

Vulnerability: relative measure to the degree to which the building is susceptible to damage from the event of a flood, in this case geometrical distances from a point on a sensor,

Hazard: correlation of the previously stated monitoring parameters, *ergo* the possibility of the phenomenon to happen due to external conditions such as weather and hydrological parameters.

The hazard of the flood happening could be obtained through the implementation of the monitored parameters as previously specified, so the:

- Rainfall accumulation (R): amount of total precipitation in mm recorded over a given period of time,
- River flow (F): flow of the river in mc/s,
- Hydrometric Level of the river (L): level of the river from his riverbed expressed in m.

The vulnerability of the single building could be obtained through different parameters:

- Height of the ground plane of the building from the ground place of the first hypothesized sensor (H) expressed in m,
- Horizontal distance from the sensor (D) expressed in m.

The final formula should consider all these parameters and combine them to generate a percentage of risk of a specific building according to its nature (vulnerability) and the general danger present and detected by the monitoring system at a given moment (hazard). Each parameter has been given a value between 1 and 4, where 4 is the higher risk, to grade them on a common scale and correlate them better between one another. In the following table it is possible to see the different scales and the description. The values attributed to the different scales have been gathered through a research based both on data from the Municipality of Rosazza regarding previous floods and natural disasters and more generic information about floods.

All considered, the final formula will be:

$$\boldsymbol{Risk = HD * RVL}$$

The paragraphs that follow will deepen the understanding of the above-mentioned parameters to understand how the risk values were attributed.

The methodology through which risk ranges were defined can theoretically refer to the Prediction Phase of an Early Warning System: it is the preliminary, historical study of a phenomenon to determine alert zones is here used in order to establish ranges in which risk operates and could potentially signify alarming danger for a portion of land or, in this case, a building.

11.1 Weather parameters

11.1.1 Rain accumulation

In order to determine dangerous values for weather parameters evaluated, i.e., rainfall accumulation in Cervo Valley and more specifically in Rosazza, it is necessary to interpolate different sets of data that had previously been gathered:

- The integrated database detailed in Chapter 4.2,
- Rainfall data related to the two nearest weather stations of Piedicavallo and Oropa found in ARPA Piedmont website.

The dates specified in the integrated datasets of Chapter 4.2 will be searched in that of ARPA Piedmont, which offers a list of the rainfall accumulation for every single day since 1988, in order to understand which was the accumulation of dangerous dates and create a set of ranges of dangerous levels of rainfall that could lead to floods.

As far as the ARPA Piedmont database is concerned, the weather stations of interest under Biella Province are two, Piedicavallo and Oropa, which are the closest to Rosazza.

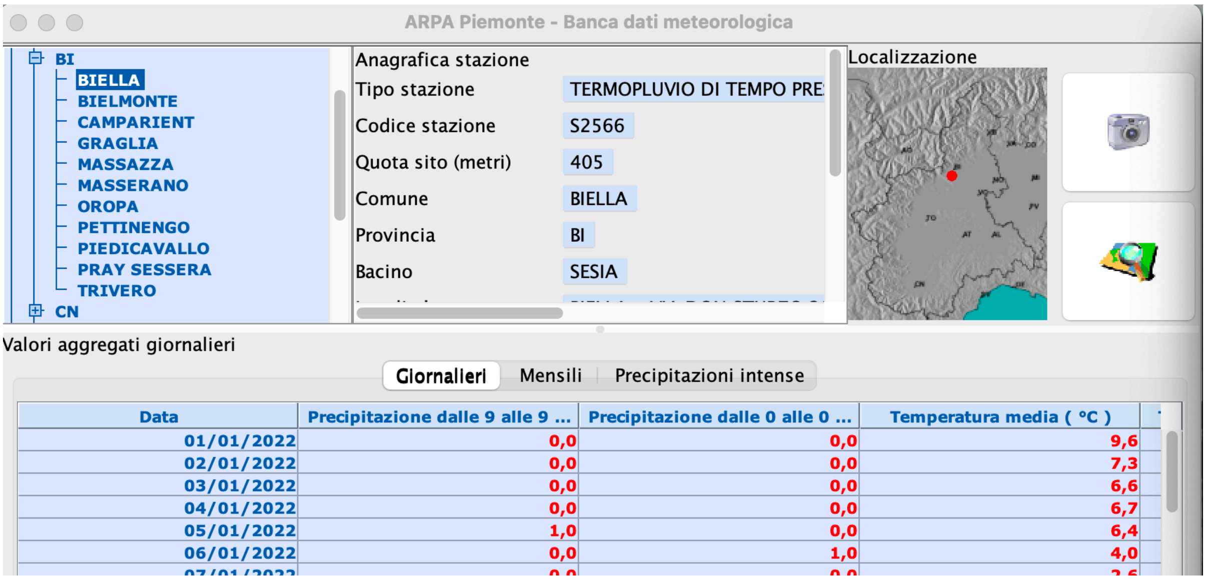

Figure 60 ARPA Piedmont database for rain accumulation (ARPA, 2023b)

Figure 61 Map that shows the proximity of Oropa, Piedicavallo and Rosazza (Google, 2023)

It was possible to download the data in .cvs and then .xlsx format to have daily data over a larger period of time (1988-2022) and therefore study the correlation between the event of floods and the accumulation of rainfall in those days.

As for the heavy rainfalls of November 1994, the heaviest rains have accumulated between 5th and 7th November 1994, with the following data:

Date	**Rainfall accumulation from 9 to 9**		**Rainfall accumulation from 0 to 0**	
	Oropa Weather Station	Piedicavallo Weather Station	Oropa Weather Station	Piedicavallo Weather Station
05/11/94	155,6	-	95,8	-
06/11/94	331,4	-	314	-
07/11/94	50,2	-	140,8	-

Table 5 Table extracted by Arpa's data related to the 1994 flood (ARPA, 2023b)

As for the flood of 4th – 6th June 2002, the data is recorded as follows:

Date	Rainfall accumulation from 9 to 9		Rainfall accumulation from 0 to 0	
	Oropa Weather Station	Piedicavallo Weather Station	Oropa Weather Station	Piedicavallo Weather Station
04/06/02	0,4	3,8	0,6	3,8
05/06/02	99,8	103,2	19,2	9
06/06/02	200	237,6	280,4	330
07/06/02	10,2	11,2	10,4	13

Table 6 Table extracted by Arpa's data related to the 2002 flood (ARPA, 2023b)

As for the flood of 2nd and 3rd October 2020, the data is reported as follows:

Date	Rainfall accumulation from 9 to 9		Rainfall accumulation from 0 to 0	
	Oropa Weather Station	Piedicavallo Weather Station	Oropa Weather Station	Piedicavallo Weather Station
02/10/20	24,6	40,6	3,6	4,8
03/10/20	457	552,8	427,4	476,8
04/10/20	2,4	5,8	53	117,2
05/10/20	21	14,2	21	14,6

Table 7 Table extracted by Arpa's data related to the 2020 flood (ARPA, 2023b)

More information could be obtained through data about the flood of 2020 in different weather stations to understand hourly parameters (and not only daily as showed in the previous tables).

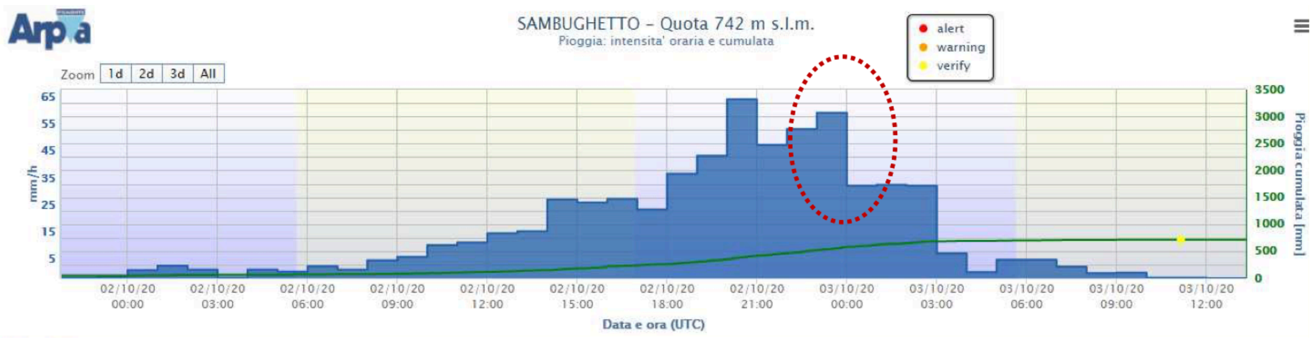

Figure 62 Rain intensity and accumulation between 02/10/2020 and 03/10/2020 for Sambughetto (VB) (Arpa, 2020)

Based on this data and of the alerting system already used by the Civil protection for similar situations (Odor, 2019), we can assume certain levels of risk due to the accumulation of rainfall. 1 is the lowest risk and 4 is the highest, considering the fact that floods happened on the days where rainfall accumulation accounted for more than 100/200mm/h.

Level of risk	Meaning	Rainfall Accumulation in 24h	Rain accumulation in one hour	Motivation
1	Low risk of flood. Low accumulation of rain, very low risk for persons and things	0-30 mm	0-5 mm/h	Rain accumulation in this range were frequent in the registered data, therefore determining a high probability of this happening without possible damage.
2	Medium risk of flood. Medium level of accumulation of rain, low risk for persons and things	30-50 mm	5-15 mm/h	Fewer data was concentrated in the medium range, signifying the event of heavy rains. This kind of accumulation was registered during the considered flood events as well as during multiple other occasions.
3	High. High accumulation of rain, risk for persons and things. Similar scenarios in the past have led to flooding phenomena	50-150 mm	15-35 mm/h	This range was way rarer than the previous ones and similar levels could potentially lead to a flooding event.
4	Very high. Very high accumulation of rain, high risk for persons and things. Similar scenarios in the past have led to highly damaging flooding phenomena	> 150 mm	> 35 mm/h	The highest levels were recorded in the first days of a flood and they reached very high rain accumulation of more than 400 mm over a period of 24h.

Table 8 Risk Level associated to Rain Accumulation (Personal elaboration)

11.2 Hydrological parameters

Data about flow and hydrometric level of Torrent Cervo and its affluents can be found in a similar way. As it is possible to find on Arpa Piedmont's portal, the already existent and close hydrological stations that monitor hydrological parameters of the Torrent Cervo are located downstream with respect to the city of Rosazza (in Passobreve and Vigliano), which makes their data less useful for relating them to Rosazza (ARPA, 2023). Nevertheless, since it is necessary to proceed with a study that is similar to the one done before, in order to assess possible hazardous level of speed of the torrent, the data related to the closest station of Passobreve Cervo were taken into consideration.

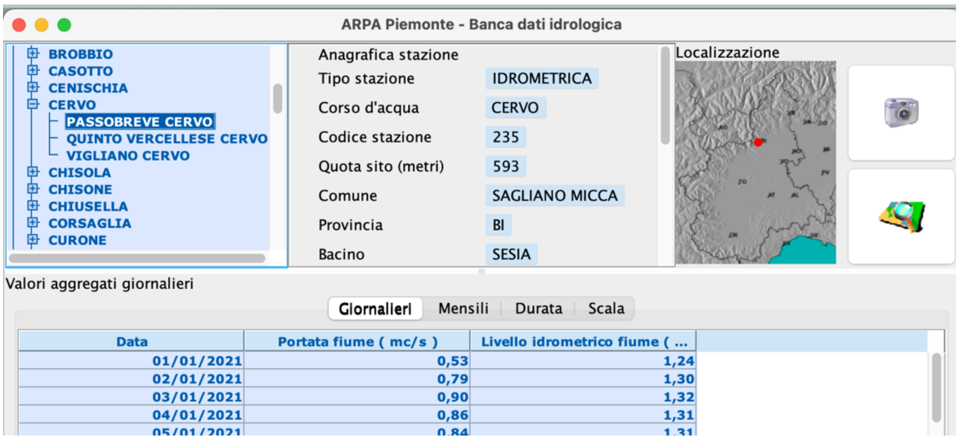

Figure 63 Database of hydrological data by Arpa Piedmont (ARPA, 2023a)

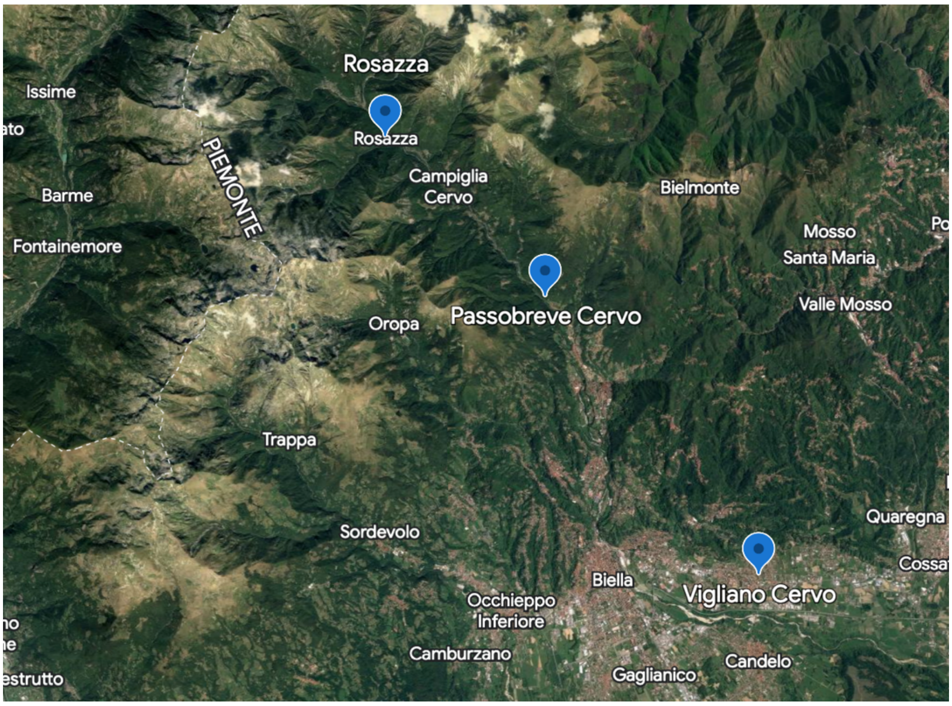

Figure 64 Localization of the nearest hydrological stations (Google Earth, 2023)

As previously, it was possible to download the .csv and .xlsx of hydrological data related to that station and analyse the dates in which the event of a flood occurred in Rosazza or the Cervo Valley. In this case, since the data available is only between 2003 and 2022, it was possible to openly study just the flood of 2020. Indeed, even if the station is located downstream with respect to Rosazza, large margins of difference between certain levels of these metrics with respect to more regular scenarios were noted.

Date	River Flow (mc/s)	Hydrometric Level of the river (m)
02/10/20	123	2,33
03/10/20	182	3,52
04/10/20	16,8	2,07
05/10/20	11	1,9

Table 9 Table extracted from Arpa's data (ARPA, 2023a)

According to these metrics and giving a more complete look at those registered by Passobreve station, certain risk levels based on River flow and Hydrometric Level of the River can be assumed.

11.2.1 River flow

Level of risk	Meaning	River flow (mc/s)	Motivation
1	Low risk of flood. Low river flow, very low risk for persons and things	< 2 mc/s	Most of the data gathered has been found to stay below 2mc/s.
2	Medium risk of flood. Medium level of river flow, low risk for persons and things	2-15 mc/s	Less data can be found in this range, leading to think that the risk is slightly higher. These numbers haven't been proved to eventually lead to a flood event.
3	High. High accumulation of rain, risk for persons and things. Similar scenarios in the past have led to flooding phenomena.	15-70 mc/s	Much fewer data belonged to this range. Also, a river flow of 16.8 mc/s has been recorded on 4th October 2020, the day after the major flood of 2020.
4	Very high. Very high river flow, high risk for persons and things. Similar scenarios in the past have led to highly damaging flooding phenomena	> 70 mc/s	River flows higher than 20mc/s were almost non-existent except for the exceptional 123 and 182 mc/s registered on 2nd and 3rd October 2020, the days of the flooding event.

Table 10 Risk levels associated to River flow (Personal elaboration)

11.2.2 Hydrometric Level of the River

Level of risk	Meaning	Hydrometric Level of the River	Motivation
1	Low risk of flood. Low river level, very low risk for persons and things	< 0-1.5m m	Most of the data gathered between 2003 and 2022 show a level between these numbers. It must be considered that during the summer period, the river proceeds to reach a much lower level with respect to autumn or winter, therefore a wide margin is to be expected.
2	Medium risk of flood. Medium level of river level, low risk for persons and things	1.5-1.7 m	Fewer data were registered in this range, but they still didn't belong to dangerous scenarios.
3	High. High accumulation of rain, risk for persons and things. Similar scenarios in the past have led to flooding phenomena.	1.7-2 m	A level of 1.9m has been registered on the last day of the flood, which led to think that this could be a more dangerous level.
4	Very high. Very high river flow, high risk for persons and things. Similar scenarios in the past have led to highly damaging flooding phenomena	> 2 m	On the days of the floods, levels of 2.33m and 3.52m were registered, determining a high hazardousness of this range.

Table 11 Risk levels associated to the Hydrometric Level of the River (Personal elaboration)

11.3 Geometric parameters

As for Height and Distance, the parameters had to be extracted from the model. Dynamo® was implemented, a graphical programming interface that enables the possibility of customizing a model through infinite possible combinations of coding blocks (Autodesk, 2023). These blocks are of different nature and purpose, from the setting of parameters to geometrical properties, from recognition of different parts of an item, family or category to numerical expression or python scripts inserted through a so-called "CodeBlock". Dynamo® was used in this project twice, in one case for the calculation of the geometrical parameters identifying the Vulnerability of the masses and in the other case to determine the different colours of the masses according to different levels of risks, which will be explored in the following chapter.

In order to calculate vertical and diagonal distance from a source of monitoring data to every single mass, it was first of all necessary to define the source. This source will be a monitoring sensor of similar typology to those described in Chapter 4.5 and for the purpose of this thesis only one is hypothesized, and it was modelled as a cylindric mass. Its location in the model was selected on the side of the torrent that is the closest to the municipality of Rosazza and the location where the flood of 2020 created the most damage, destroying *Ponte delle Cave*.

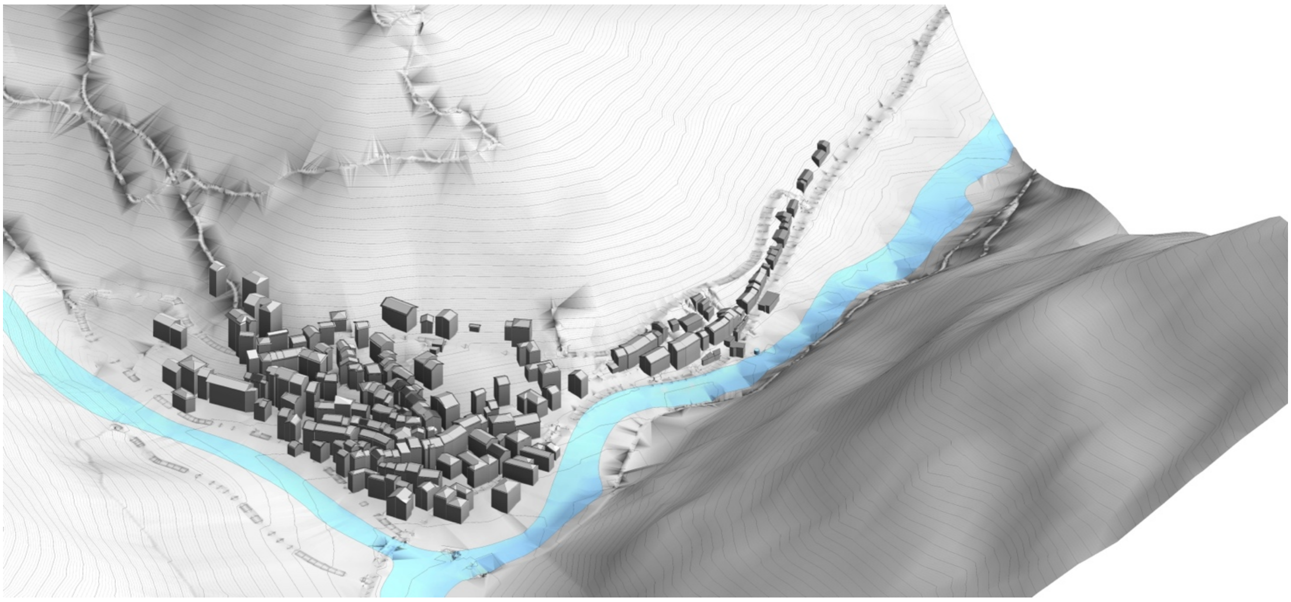

Figure 65 Location of the sensor (Personal elaboration)

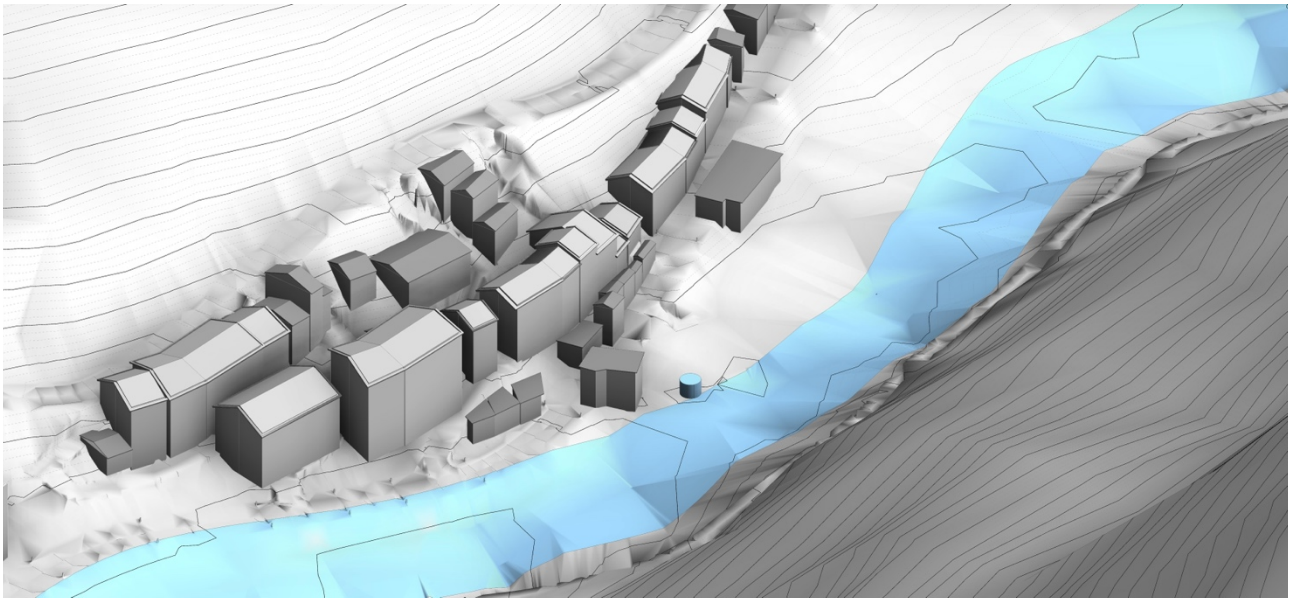

Figure 66 Detail of the location of the sensor (Personal elaboration)

At this point, it was necessary to open Dynamo® through the Manage panel and detect the necessary parameters. Height and distance were measured in two different ways in the same script, but the first step was the same: extracting the faces of the masses. All of them were enlisted through their category first, then the lower one was identified through a difficult coding elaboration; the lower face was necessary in order to be compared to a point in the sensor to extract the needed data, measuring the distance between face and point in the case of the distance and the difference between the z of said face and that of the point of the sensor for the height.

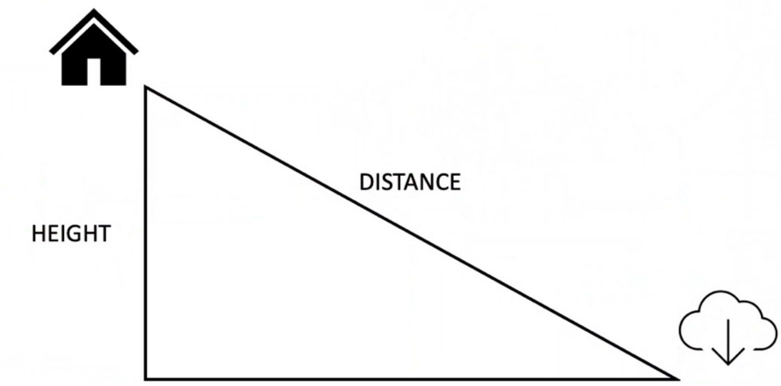

Figure 67 Visual representation of geometrical meaning of DTR_Height and DTR_Distance (Personal elaboration)

The identification of the lower face was an issue because various methods could be implemented. At first, a list of all the face was created and then only one face per mass was extracted through its index, creating another list through the common index that face had on every mass. The issue that arose with this methodology was that, since not all the masses were created in the same way and their geometries were different, not every lower face of every mass had the same index, which resulted in confused and not reliable results. This also led to believe that for the purpose of this thesis, a simple paralleled shape for the masses could have been sufficient to define data enrichment phase, which is the most important of the process.

The second method was the identification of that face through its normal. What was known about that face, which is the lowest and adhering to the ground, is that its normal would have been the Vector Z, which is an identifiable object in Dynamo®. In this case, from the list of all the faces their normal vectors were extracted, creating another nested list that was then shortened identifying all the faces whose normal vectors were parallel to Vector Z, therefore those who had -1 as their z component. This was proven to be a successful method to identify all the lower faces. Then, this new list was put through two different elaborations to find Height and Distance.

In the first case, a point on the lower face of the mass representing the sensor was identified. Then, a list of the same number of indices as the list of the building masses was created. Eventually, every z component of the lower face’s vector was subtracted from the z of the sensor point, generating the distance between the mass and the sensor.

In the second case, it was necessary to measure the distance between the lower face of each mass, which had already been enlisted, and the point on the sensor.

Finally, these calculations were applied to the parameters concerning Height and Distance through a final block.

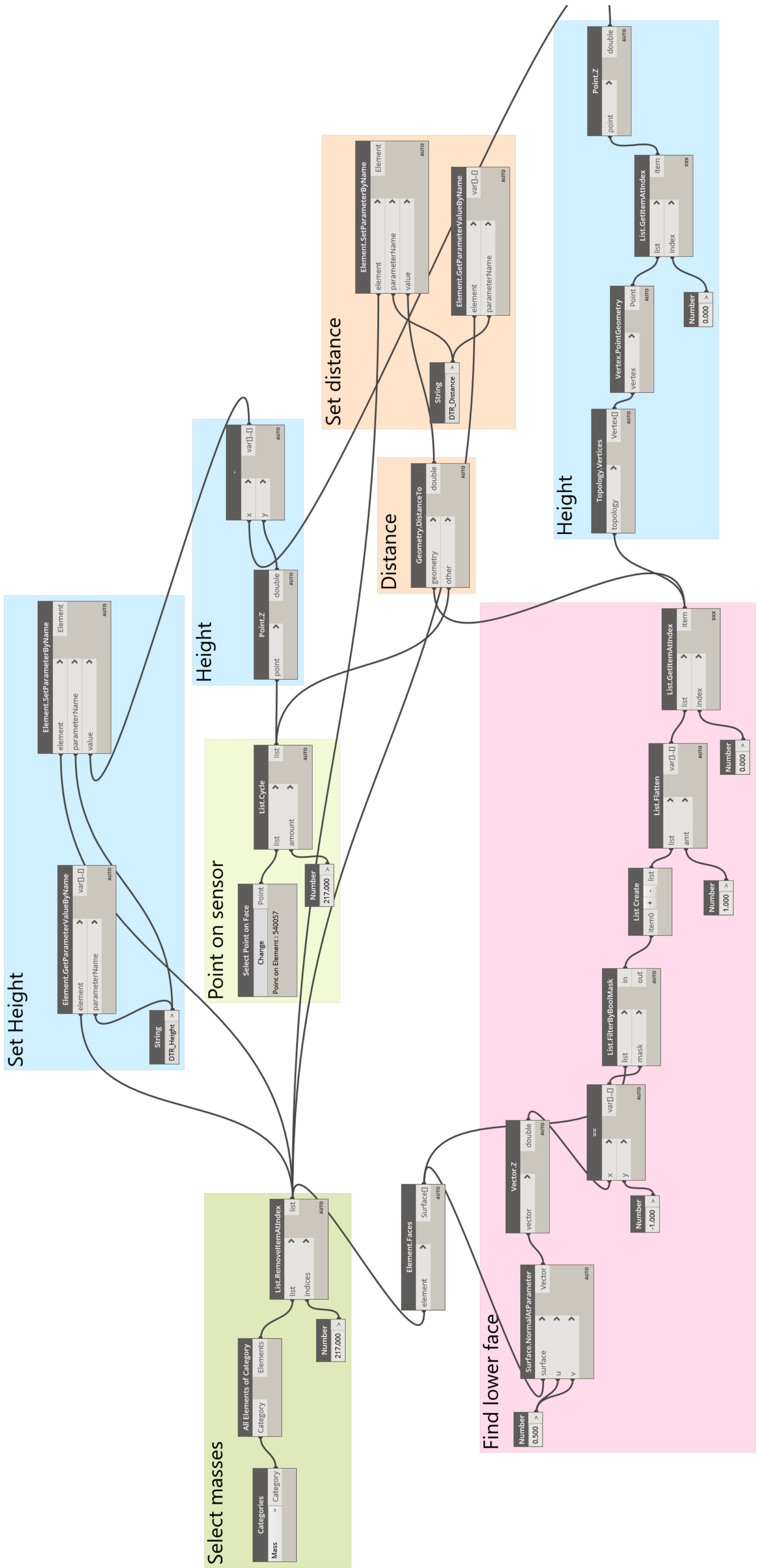

Figure 68 First Dynamo® script. Different parts of the code are highlighted in order to better navigate the script (Personal elaboration)

After Dynamo® was successfully ran, a Mass Schedule including all the parameters was created. In order to do so, the previously created parameters were created, generating a schedule with the following information:

- Family
- DTR_Distance
- DTR_Height
- DTR_Rainfall_Accumulation
- DTR_River_Flow
- DTR_Hydrometric_Level

Thanks to the Dynamo® script, data regarding Geometric parameters was already listed. Studying this data allowed to give further definition of the levels of risk associated to these parameters, which was done in a similar method as previously, considering the frequency of data and the already existent knowledge about the building that were damaged in the last floods.

11.3.1 Distance

In the case of the distance, as in that of the height, the Risk levels held an inverse proportion with that of the risk: a higher distance determined a lower risk, because the considered mass was further away from the source, which is theorized as the point in which the torrent could potentially overflow, causing damage. Therefore, the ranges were defined as follows.

Level of risk	Meaning	Distance	Motivation
1	Low risk of flood. High distance of the mass, very low risk for persons and things	> 50 m	Most of the data gathered through Dynamo® presents values of distance from the sensor that are higher than the considered ranges. These data are associated to masses that are further downhill or completely unrelated to the designated sensor in terms of distance, therefore that will unlikely be affected by an overflow of the river in that point.
2	Medium risk of flood. Medium level of distance, low risk for persons and things	50-25	Fewer data were registered in this range, but they still didn't belong to dangerous scenarios.
3	High. Lower distance, risk for persons and things. Similar scenarios in the past have led to flooding phenomena.	25-15	These levels belong to masses that are closer to the source of information, determining a higher danger for them in the case of a flood.
4	Very high. Very low distance, high risk for persons and things. Similar scenarios in the past have led to highly damaging flooding phenomena	< 15	This data belongs to the closest masses and to the one that has already been highly damaged by a flood.

Table 12 Risk levels associated to Distance (Personal elaboration)

11.3.2 Height

In this case, data was complicated to analyse, since many masses located further downhill held a distance from the sensor that was negative and lower than the buildings that were closer and more at risk. Through a manipulation of the masses, it was possible to create more reliable data and therefore more reliable Risk levels.

Level of risk	Meaning	Height	Motivation
1	Low risk of flood. High height of the mass, very low risk for persons and things	> 3 m and < -1	Most of the data gathered through Dyn presents values of vertical distance from the sensor that are either much higher or much lower than the considered ranges. These ranges belong to masses that are further downhill or completely unrelated to the designated sensor in terms of distance, therefore that will unlikely be affected by an overflow of the river in that point.
2	Medium risk of flood. Medium level of height, low risk for persons and things	3-2 m	Few data was registered in this range, but they still didn't belong to dangerous scenarios.
3	High. Lower height, risk for persons and things. Similar scenarios in the past have led to flooding phenomena.	2-1 m	These levels belong to masses that are closer to the source of information, determining a higher danger for them in the case of a flood.
4	Very high. Very low height, high risk for persons and things. Similar scenarios in the past have led to highly damaging flooding phenomena	< -1 m	This data belongs to the closest masses and to the one that has already been highly damaged by a flood.

Table 13 Risk levels associated to Height (Personal elaboration)

11.4 Data elaboration

11.4.1 Export phase

In order to establish the different levels of risk related to geometric properties, the results coming from Dynamo® were to be analysed. A Mass Schedule with all these parameters had to be exported in Google Drive™ to be able to work on it in real time. This was possible thanks to DiRoots One, a plug-in that has already been mentioned when talking about the elaboration of the point cloud. Through SheetLink, which is an option that enables various Schedule creations, it was possible to directly Export the previously set Mass Schedules in a folder in Google Drive™ (called DTR as the main one in Dropbox). In this way, the Geometric and Hydrological parameters were visible in a Google Sheet™ (named DTR00_EXC_RSZ_01) together with the identifier of each mass. At this point though, the Hydrological Parameters were still to be filled in through the second web-implementation.

Element ID Custom Parameter	Family ElementId Instance Other	DTR_Distance Double Instance Other	DTR_Height Double Instance Other	DTR_Rainfall_Accumulation Double Instance Other	DTR_Risk Double Instance Other	DTR_River_Flow Double Instance Other	DTR_Hydrometric_Level Double Instance Other
335404	BLD_01	432,5941825	4,19202307				
336176	BLS_02	418,2791042	4,19202307				
337024	BLD_03	414,469514	4,19202307				
337910	BLD_04	377,276113	4,19202307				
338761	BLD_05	432,5077019	4,19202307				
339049	BLD_06	386,0037704	4,19202307				
340701	BLD_07	364,3563987	-3,54685483				
342817	BLD_08	351,0309575	-4,65885321				
343206	BLD_09	333,2367921	-4,65885321				
344858	BLD_10	349,541027	-6,35072832				
345217	BLD_11	366,8347842	-3,80797693				
345724	BLD_12	362,5360956	-1,32337318				
347134	BLD_13	331,5688433	-13,04995018				
347574	BLD_14	329,4628918	-13,74014465				
347928	BLD_15	318,7747193	-15,20838746				
348663	BLD_16	308,537287	-12,32351123				
349096	BLD_17	292,420844	-13,84014465				
350909	BLD_18	300,6274331	-13,84014465				
351379	BLD_19	289,7874117	-13,07849363				
351757	BLD_20	256,1239659	-15,20838746				
352083	BLD_21	249,1894555	-13,84014465				
352406	BLD_22	230,0850766	-10,46373185				
352749	BLD_23	210,8372463	-8,07965784				
353109	BLD_24	206,7614711	-8,07965784				
354228	BLD_25	197,3314701	-10,46373185				
355181	BLD_26	213,5853525	-9,4622267				
355591	BLD_27	235,0756535	-9,4622267				
355974	BLD_28	236,8327688	-6,49076946				
356258	BLD_29	224,8904405	-11,11286885				
356620	BLD_30	222,916021	-10,46373185				

Figure 69 Google Sheet™ after the first Export through SheetLink (Personal Elaboration)

11.4.2 Risk computation

As for the Hydrological Parameters, their elaboration was completely done online. Since the sensor will be able to detect three different metrics, Rainfall Accumulation, River Flow, and Hydrometric Level of the River, a potential dashboard for a sensor was created in a separate Google Sheet™ (named DTR00_EXC_REF) to show possible interoperability among internet sources. In this dashboard, the three parameters are shown in a real-time way, with their date and hour of detection.

Date	Time	Rainfall Accumulation [mm/24h]	River Flow [mc/s]	Hydrometric Level [m]
DD/MM/YYYY	*HH:MM*			

Table 14 Hypothesised real-time dashboard of the sensor (Personal elaboration)

DTR00_EXC_RSZ01 was then implemented with the data that has been inserted in DTR00_EXC_REF. the two databased were linked through the function IMPORTRANGE_, which allows to insert in a Google Sheet data coming from a range of cells in another Google Sheet.

At this point, the only operation left was the definition of the Level of Risk. In order to do so, it was necessary to create another Google Sheet™ that could easily interoperate with the other two, because it is not possible to create different sheets on the same exported file (this will create issues in the import phase). The new file is names DTR00_EXC_RSZ_02 and it holds the same structure as DTR00_EXC_RSZ_01:

- It imports Geometric data through IMPORTRANGE_ connected to DTR00_EXC_RSZ_01,
- It imports Hydrological data through IMPORTRANGE_ connected to DTR00_EXC_REF.

In a second sheet in the same file, the same table was created (number of masses as rows and parameters as columns) and the data on the first sheet was converted through a series of IF clauses in order to compute the range in which a value fit in the parameter, according to the ranges of Risk given to every parameter previously. For example, for Rainfall Accumulation, the created equation gave these results:

- A cell related to the value of Rain Accumulation for a single Mass was considered. If the value contained in this cell was greater than 150 mm/24h, the value of the risk associated to the rainfall accumulation was to be 4,
- If this value was higher than 50, the risk associated to Rainfall Accumulation for this was to be 3,

- If it was higher than 15, the associated risk would be 2,
- Else, it will be 1.

Through this methodology, each value of each parameter was converted in the associated risk parameter according to the previously explained ranges. Then, for each mass, the values of the parameters were multiplied according to the previous enunciated formula:

$$\boldsymbol{Risk = HD * RVL}$$

In order for the value of risk to still be resulting in a parameter that varied on a scale of 1-4, it was necessary to further create IF clauses to convert the product of the metrics into a range. In this case:

- If the risk was found to be equal or higher than 1024 (if all the risks were to be equal to 4, therefore 4^5), the risk would be of 4,
- If it was equal or higher than 256, the risk associated to the mass would be 3,
- If it was equal or higher than 64, it would be of 2,
- Else, it would be of 1.

Through this implementation, all the masses were associated with their level of risk according to Geometric and Hydrological parameters. Now it was necessary to insert the found value of risk in DTR00_EXC_RSZ_01 through an IMPORTRANGE_ with DTR00_EXC_RSZ_02.

Element ID Custom Parameter	Family ElementId Instance Other	DTR_Distance Double Instance Other	DTR_Height Double Instance Other	DTR_Rainfall_Accumulation Double Instance Other	DTR_Risk Double Instance Other	DTR_River_Flow Double Instance Other	DTR_Hydrometric_Level Double Instance Other
335404	BLD_01	1	1	4	1	4	4
336176	BLS_02	1	1	4	1	4	4
337024	BLD_03	1	1	4	1	4	4
337910	BLD_04	1	1	4	1	4	4
338761	BLD_05	1	1	4	1	4	4
339049	BLD_06	1	1	4	1	4	4
340701	BLD_07	1	1	4	1	4	4
342817	BLD_08	1	1	4	1	4	4
343206	BLD_09	1	1	4	1	4	4
344858	BLD_10	1	1	4	1	4	4
345217	BLD_11	1	1	4	1	4	4
345724	BLD_12	1	1	4	1	4	4
347134	BLD_13	1	1	4	1	4	4
347574	BLD_14	1	1	4	1	4	4
347928	BLD_15	1	1	4	1	4	4
348663	BLD_16	1	1	4	1	4	4
349096	BLD_17	1	1	4	1	4	4
350909	BLD_18	1	1	4	1	4	4
351379	BLD_19	1	1	4	1	4	4
351757	BLD_20	1	1	4	1	4	4
352083	BLD_21	1	1	4	1	4	4
352406	BLD_22	1	1	4	1	4	4
352749	BLD_23	1	1	4	1	4	4
353109	BLD_24	1	1	4	1	4	4
354228	BLD_25	1	1	4	1	4	4
355181	BLD_26	1	1	4	1	4	4

Figure 70 DTR00_EXC_RSZ_02, where it is possible to see the associated Levels of Risk for each parameter. This data refers to 3rd October 2020 (Personal Elaboration)

B	C	D	E	F	G	H	I
Element ID Custom Parameter	Family ElementId Instance Other	DTR_Distance Double Instance Other	DTR_Height Double Instance Other	DTR_Rainfall_Accumulation Double Instance Other	DTR_Risk Double Instance Other	DTR_River_Flow Double Instance Other	DTR_Hydrometric_Level Double Instance Other
335404	BLD_01	432,5941825	4,19202307	552,8	1	182	3,52
336176	BLS_02	418,2791042	4,19202307	552,8	1	182	3,52
337024	BLD_03	414,469514	4,19202307	552,8	1	182	3,52
337910	BLD_04	377,276113	4,19202307	552,8	1	182	3,52
338761	BLD_05	432,5077019	4,19202307	552,8	1	182	3,52
339049	BLD_06	386,0037704	4,19202307	552,8	1	182	3,52
340701	BLD_07	364,3563987	-3,54685483	552,8	1	182	3,52
342817	BLD_08	351,0309575	-4,65885321	552,8	1	182	3,52
343206	BLD_09	333,2367921	-4,65885321	552,8	1	182	3,52
344858	BLD_10	349,541027	-6,35072832	552,8	1	182	3,52
345217	BLD_11	366,8347842	-3,80797693	552,8	1	182	3,52
345724	BLD_12	362,5360956	-1,32337318	552,8	1	182	3,52
347134	BLD_13	331,5688433	-13,04995018	552,8	1	182	3,52
347574	BLD_14	329,4628918	-13,74014465	552,8	1	182	3,52
347928	BLD_15	318,7747193	-15,20838746	552,8	1	182	3,52
348663	BLD_16	308,537287	-12,32351123	552,8	1	182	3,52
349096	BLD_17	292,420844	-13,84014465	552,8	1	182	3,52
350909	BLD_18	300,6274331	-13,84014465	552,8	1	182	3,52
351379	BLD_19	289,7874117	-13,07849363	552,8	1	182	3,52
351757	BLD_20	256,1239659	-15,20838746	552,8	1	182	3,52
352083	BLD_21	249,1894555	-13,84014465	552,8	1	182	3,52
352406	BLD_22	230,0850766	-10,46373185	552,8	1	182	3,52
352749	BLD_23	210,8372463	-8,07965784	552,8	1	182	3,52
353109	BLD_24	206,7614711	-8,07965784	552,8	1	182	3,52
354228	BLD_25	197,3314701	-10,46373185	552,8	1	182	3,52
355181	BLD_26	213,5853525	-9,4622267	552,8	1	182	3,52
355591	BLD_27	235,0756535	-9,4622267	552,8	1	182	3,52
355974	BLD_28	236,8327688	-6,49076946	552,8	1	182	3,52
356258	BLD_29	224,8904405	-11,11286885	552,8	1	182	3,52

Figure 71 DTR00_EXC_RSZ_01 completely filled in with the necessary data. This data refers to 3rd October 2020 (Personal elaboration)

11.4.3 Import phase

At this point, the Google Sheets™ and the parameters were ready to be imported back on Revit®. The procedure was similar to the one used for the export, the first step was opening SheetLink in DiRoots One, then click on Import and select Google Doc™, then select the document to be imported. After the elaboration of the import, a confirming message was sent out and all the parameters were updated.

It was now the time to associate the Risk parameter, called DTR_Risk on the model, with the corresponding colour of alert. In order to do so, another Dynamo® script was elaborated.

As before, the first step was the import of all categories and elements in category mass, since DTR_Risk was to be associated to all the present masses. Then, the mass corresponding to the sensor was removed from the list in order not the change its colour and because it didn't belong to this process. In order to change the colour, a first comparison was necessary: four different lists with the same number of indices as the masses and four different numbers inside were created, one with just 1s, one with just 2s, one with just 3s and one with just 4s. The list of the masses' DTR_Risk parameters was compared to that of just a single value of risk and if the result of this comparison was True, therefore if the value of risk for a mass was corresponding to that of the list, the colour of the mass was to change accordingly through the ColorOverride block. The chosen colours were the same as previously used for the alert ranges, therefore:

- Green for an overall Risk level of 1,
- Yellow for an overall Risk level of 2,
- Orange for an overall Risk level of 3,
- Red for an overall risk level of 4.

This Dynamo® script was set on automatic so that for every import the colour would change without any further manual operation, to make the process more automated. The only input command needed for the final elaborated version will then be to Import the Google Sheet™ (DTR01_EXC_RSZ_01) whenever needed to update the parameters according to the reference file's changes. This will offer the possibility of more control over the model and its parameters, as it would be less cautious to let the model work in complete autonomy, especially considering the possible outputs of the elaboration. If an emergency alert would be given for a miscalculation of the sensor due to technical issues, for example, it would trigger an entire system without needing to.

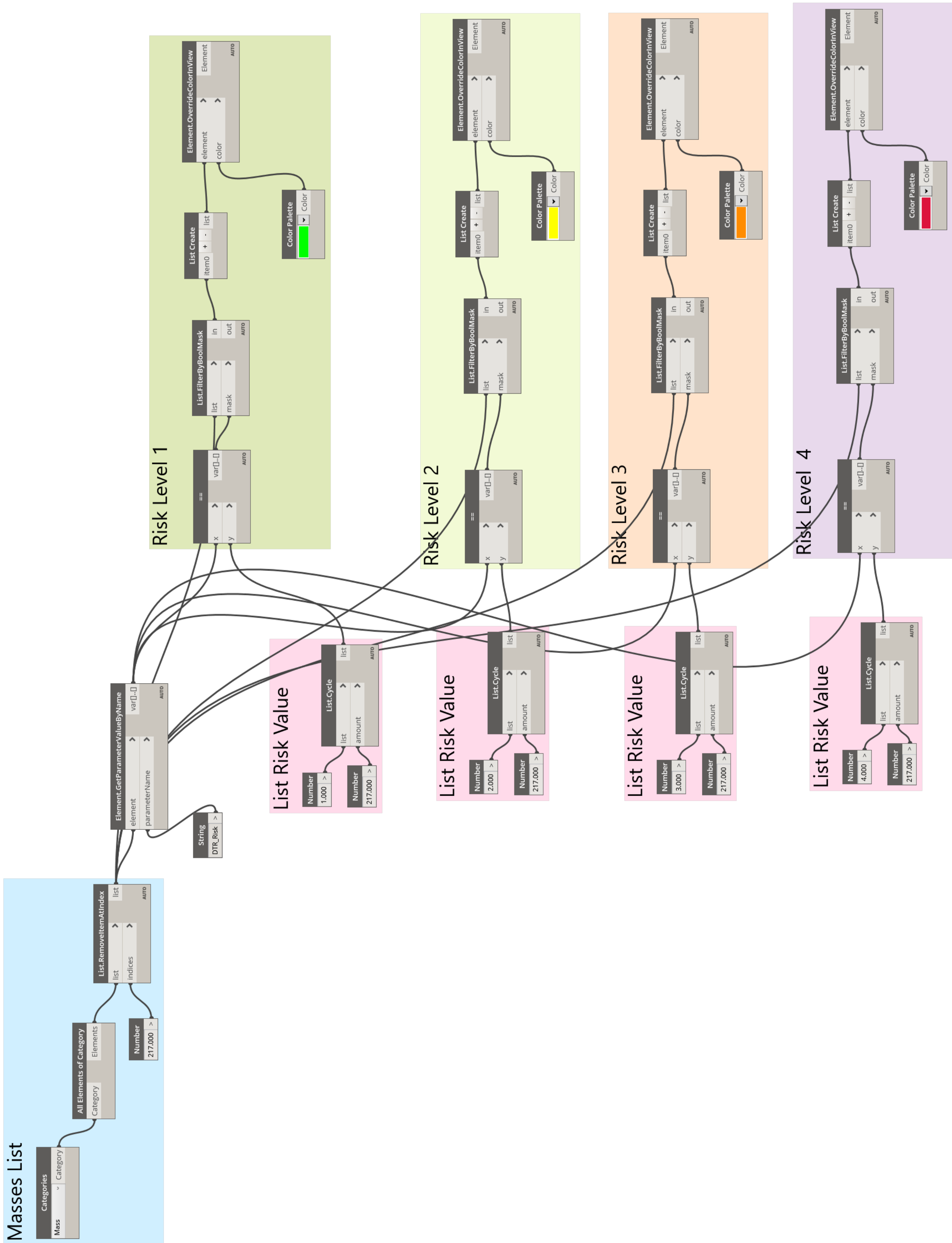

Figure 72 Second Dynamo® script that deals with the changes in colour of the masses according to the imported risk value (Personal elaboration)

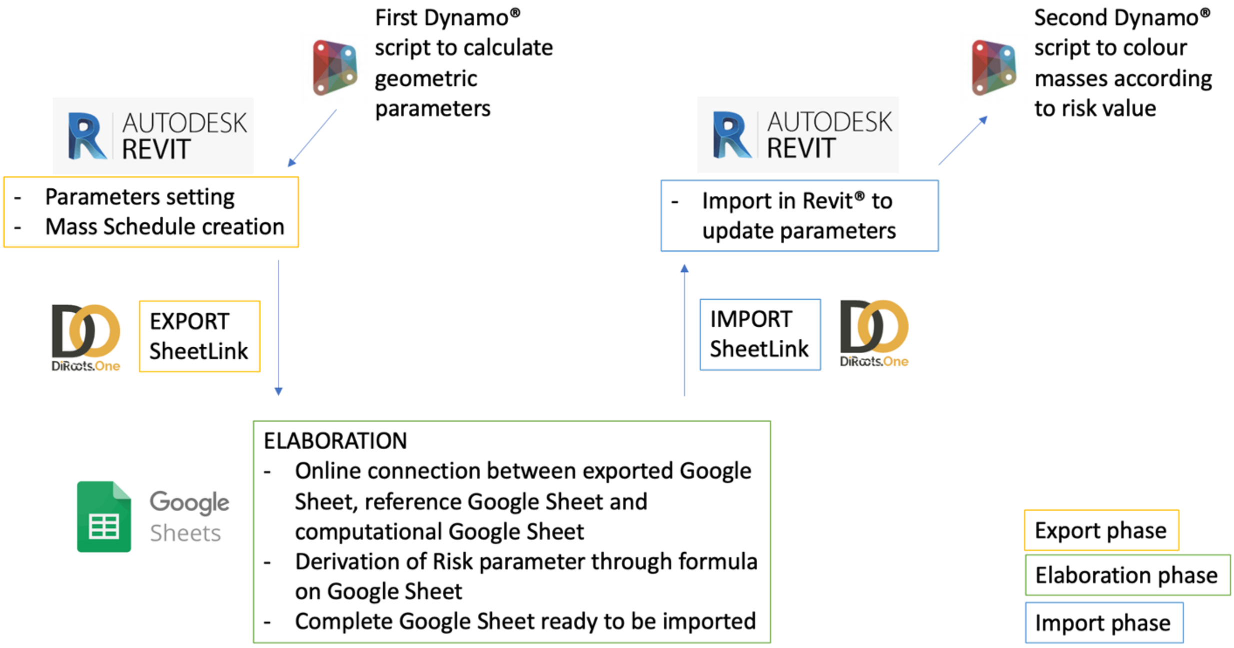

Figure 73 Simplified scheme of Export - Elaboration - Import phases (Personal elaboration)

A video of the Export – Elaboration – Import process is also available on Google Drive™ in the folder DTR00_MOV_RSZ, https://drive.google.com/drive/folders/1CoCb9w47BFYUepauALQ9XowY797kmQ09?usp=share_link, while a QR code of the Google Sheets™ is available in DTR00_EXC_RSZ, https://drive.google.com/drive/folders/1JN7CE5QJA70JmBXvJKAb60iMFXYLPsDG?usp=share_link. DTR00_MOV_RSZ_02 is the complete video related to the whole process, while DTR00_MOV_RSZ_03 shows the automation through the simple Import in Revit®.

12 Results

The following section sum up the results that have been provided during the previous steps, before showing the last part of the digitalization.

First of all, thanks to the data collection, it was shown how all the relevant documents and files have been gathered, as well as what was done with them and how they were stored. Secondly, the stakeholder analysis could give an idea of who the main entities and private citizens involved with this project's development were, as well as what was their role in the process and what kind of information they could provide. Moving onto the modelling phase, planning was essential do establish a preliminary definition of LOD, as well as the Common Data Environment and the selected naming convention. Scan-to-BIM allowed the model space to hold important contextual data to the project, such as a background point cloud, topography and linked masses files that had been previously redacted, all of which could be used as a reference for further modelling. In the last-mentioned phase, the masses were modelled thanks to multiple sources of information, mainly a combination of the masses that had already been created by other students and Open Street Map data generated through InfraWorks®; parameters were also defined in the masses at this point and a more coherent and complete Level of Information Need was established. During the data enrichment phase, the parameters that had only been mentioned were quantitively implemented thanks to a combination of previously gathered data and automated Dynamo® script, which resulted in a complete enrichment of the masses with all the needed parameters to establish the overall level of Risk that each mass held with respect to its level of vulnerability and hazard. After the data for the Hydrological and Weather parameters was imported in Revit® together with the Risk Value, every mass had all the necessary data. Hence, the last Dynamo® script was implemented in an automatic way through its Automatic Running method and the masses changed their colour according to their level of risk.

What is left is now the visualization of the results that have been introduce in the Import Phase, the actual digitalization of the Hydrogeological Plan and the Early Warning System for Rosazza.

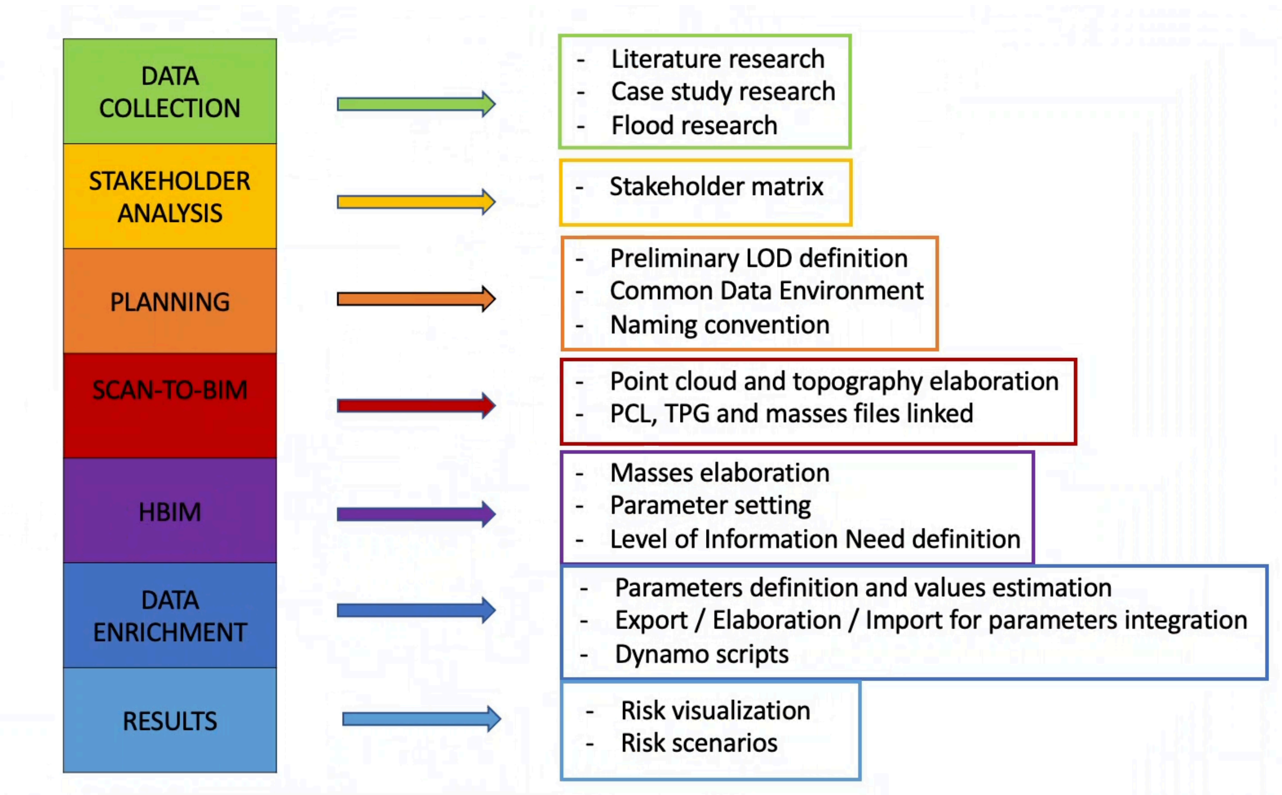

Figure 74 Scheme of results gathered during each step (Personal elaboration)

The following chapters shows different scenarios taken from actual data gathered during the flood of 2020. As for the weather parameters, the weather station that was selected for the data is that of Piedicavallo, because it is closer to Rosazza and its data is therefore more reliable.

This phase belongs to the Monitoring Phase previously explained when referring to Early Warning Systems in Italy: through real-time analysis of parameters and with the addition of implementing said parameters into a HBIM model (the novelty of this thesis), a more detailed risk is defined for specific buildings. Through further developments, the Action Phase could start from the local authorities in order to give official alerts and handle evacuation.

12.1 Scenario 1

This scenario entails data from 2nd October 2020. In this situation, the real-time dashboard of the sensor located in the torrent would show these metrics:

Date	Time	Rainfall Accumulation	River Flow	Hydrometric Level
02/10/2020	21:00	40.6 mm	123 mc/s	2.33 m

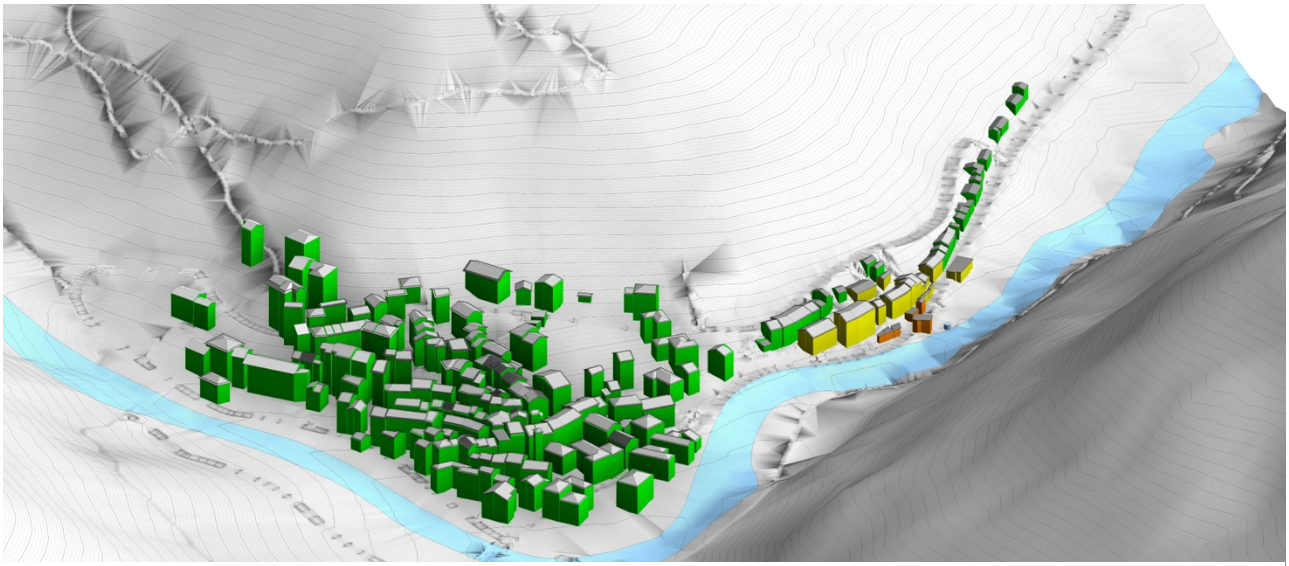

Figure 75 Visualisation of DTR_Risk for 2nd October 2020 (Personal elaboration)

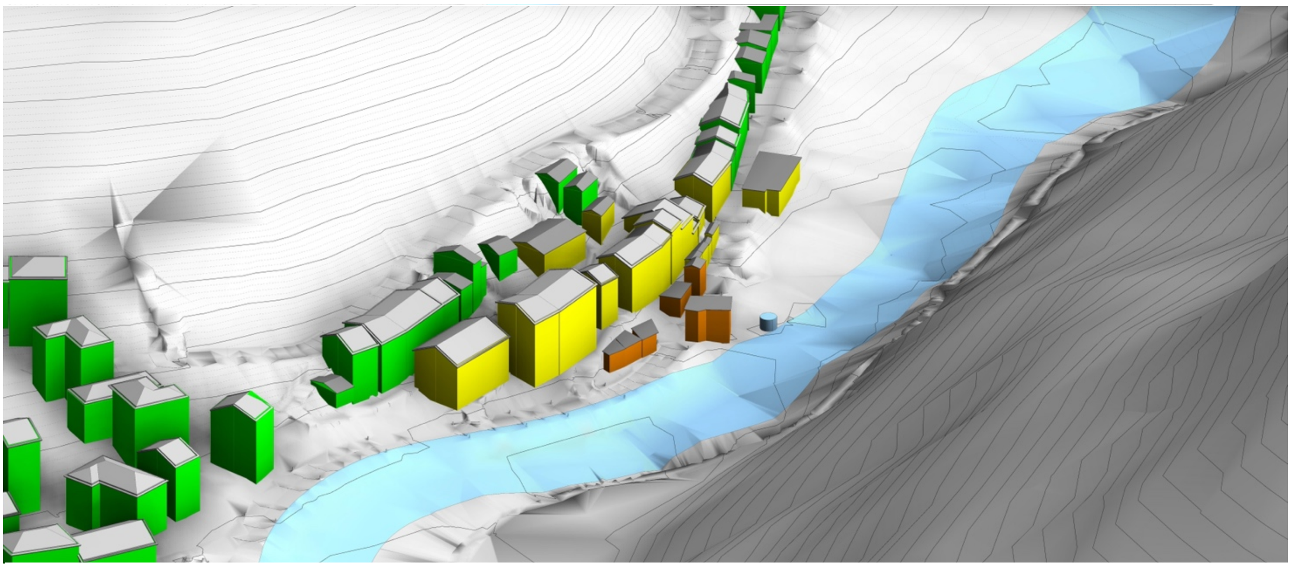

Figure 76 Detail of the area that has been proven to be the most at risk on 2nd October 2020 (Personal elaboration)

This dataset shows the beginning of hazard for the buildings closer to the sensor, which is located close to the building that had been the most damaged. It is clear how an overflow of the torrent in that point could potentially put the orange buildings at risk, which are at High Risk considering the associated ranges.

12.2 Scenario 2

This scenario entails data from 3rd October 2020. In this situation, the real-time dashboard of the sensor located in the torrent would show this metrics:

Date	Time	Rainfall Accumulation	River Flow	Hydrometric Level
03/10/2020	21:00	552.8 mm	182 mc/s	3.52 m

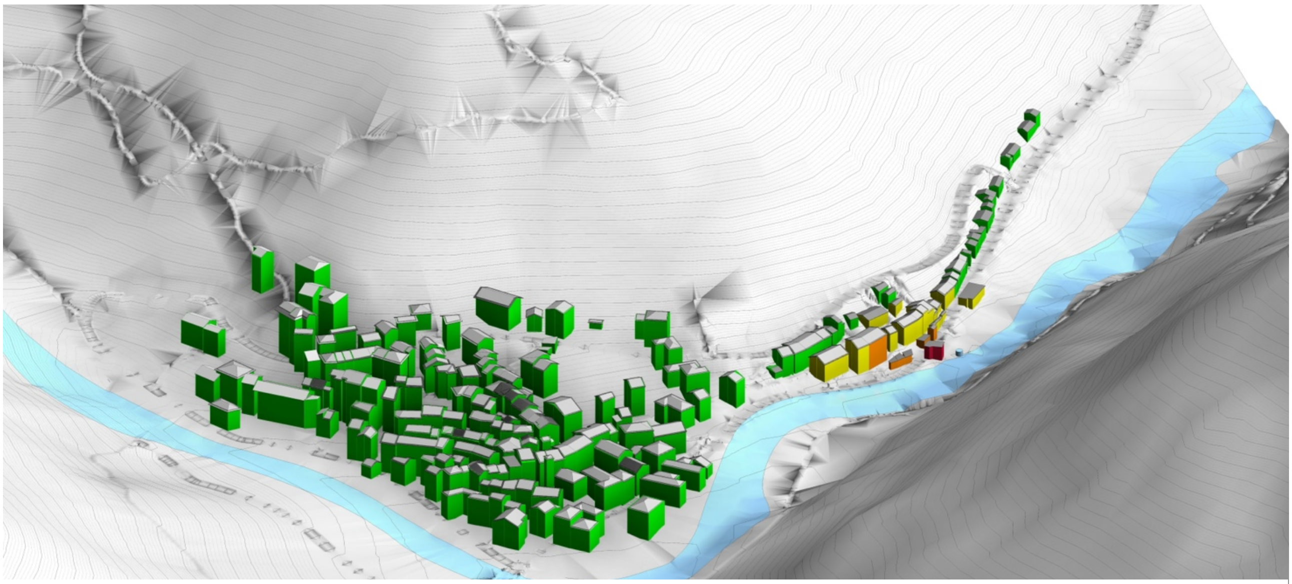

Figure 77 Visualisation of DTR_Risk for 3rd October 2020 (Personal elaboration)

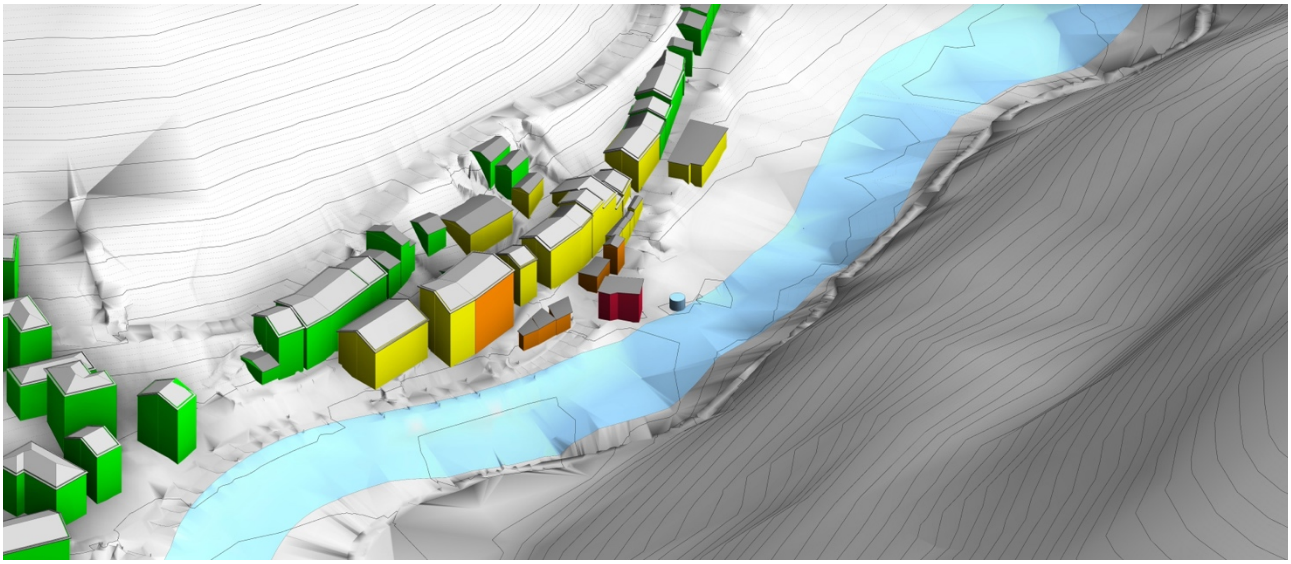

Figure 78 Detail of the area that has been proven to be the most at risk on 3rd October 2020 (Personal elaboration)

In this phase, an overflow of the torrent in that point would damage the buildings nearby. All the Hazard parameters hold a risk value of 4, determining a High Risk for the buildings highlighted in orange and Very High for those in red. Indeed, one of them was highly damaged on this day, the one whose graphical information has already been used in this thesis, for instance in Chapter 4.2.

12.3 Scenario 3

This scenario entails data from 4th October 2020. In this situation, the real-time dashboard of the sensor located in the torrent would show this metrics:

Date	Time	Rainfall Accumulation	River Flow	Hydrometric Level
04/10/2020	21:00	5.8 mm	16.8 mc/s	2.07 m

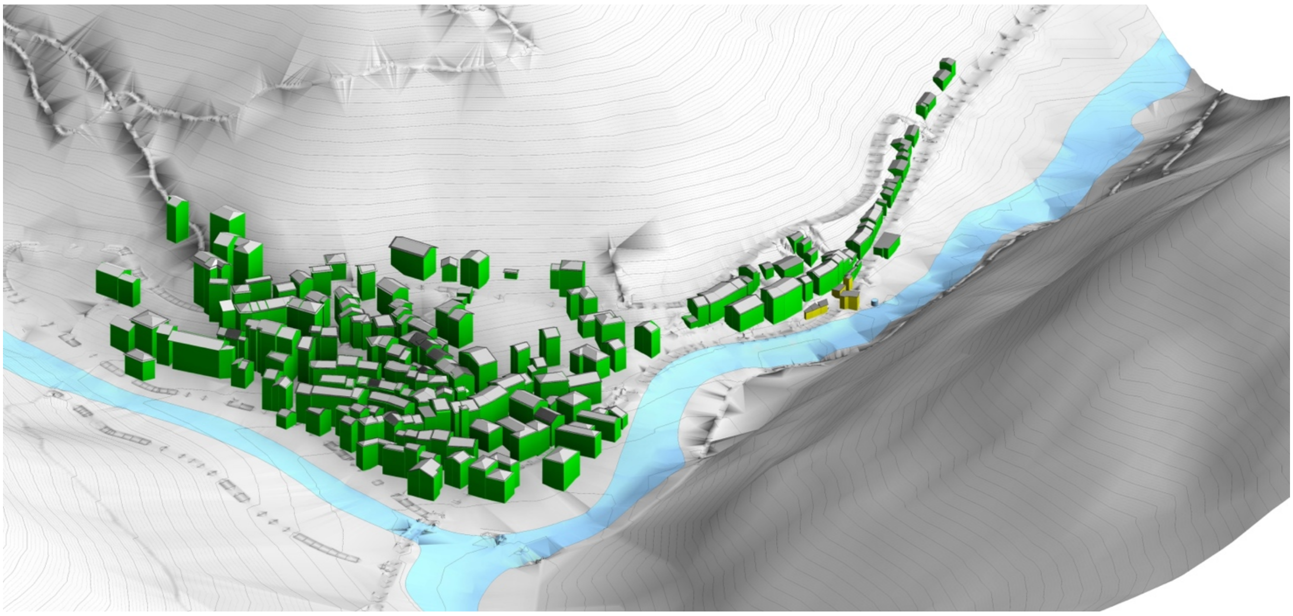

Figure 79 Visualisation of DTR_Risk for 4th October 2020 (Personal elaboration)

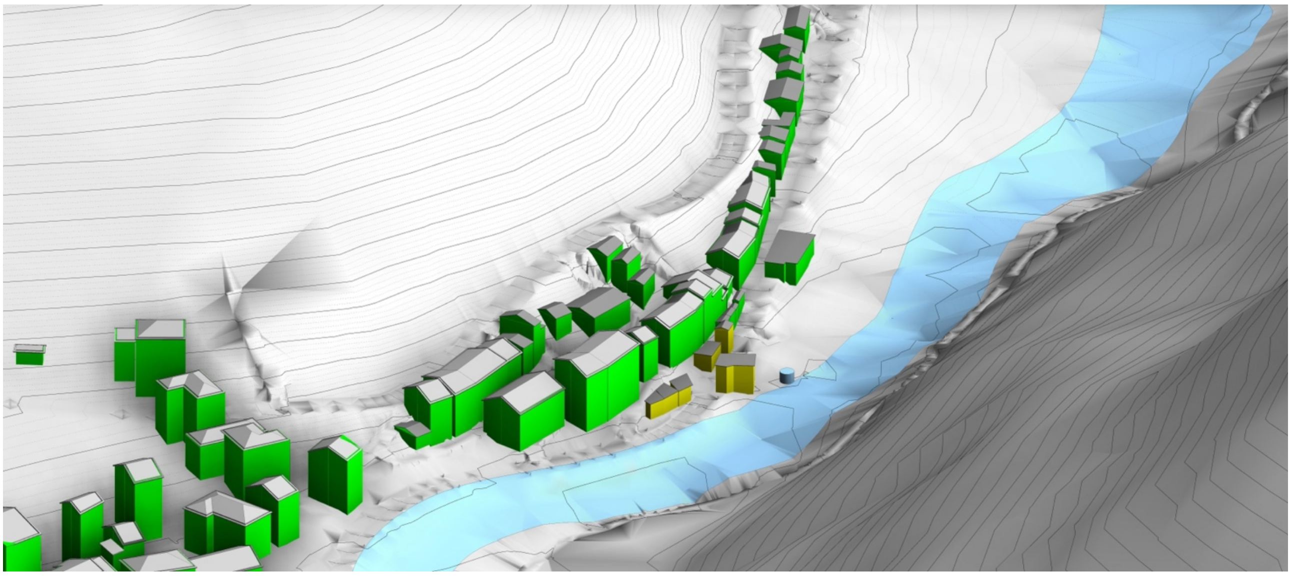

Figure 80 Detail of the area that has been proven to be the most at risk on 4th October 2020 (Personal elaboration)

The risk values are on this day still high for some parameters, such as River Flow and Hydrometric Level, but not for Rainfall Accumulation, which leads the total Risk value to be lower overall. Still, some buildings are at High risk of getting damaged.

12.4 Scenario 4

This scenario entails data from 5th October 2020. In this situation, the real-time dashboard of the sensor located in the torrent would show this metrics:

Date	Time	Rainfall Accumulation	River Flow	Hydrometric Level
05/10/2020	21:00	14.2	11 mc/s	1.9 m

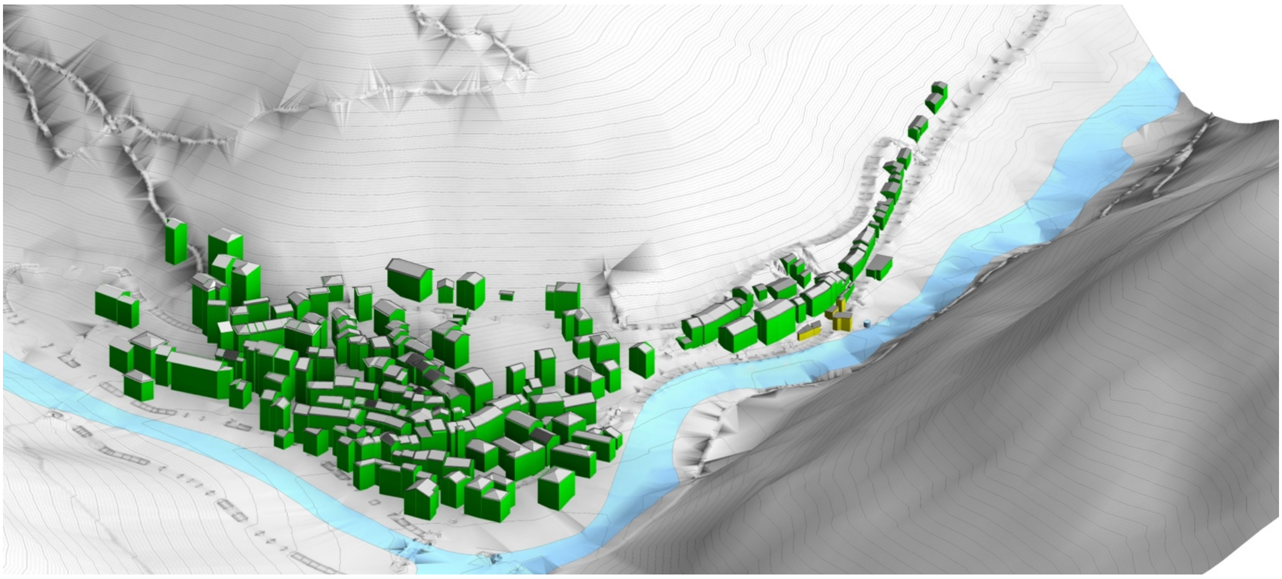

Figure 82 Visualisation of DTR_Risk for 5th October 2020 (Personal elaboration)

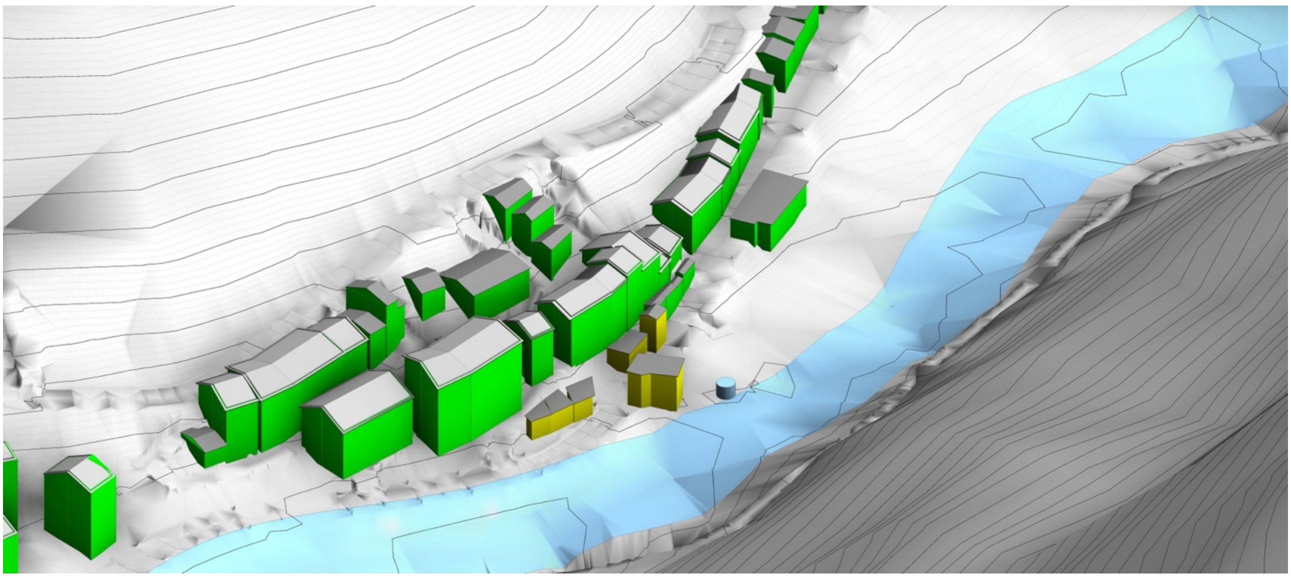

Figure 81 Detail of the area that has been proven to be the most at risk on 5th October 2020 (Personal elaboration)

In terms of Risk, this scenario is showing the same values, hence the same colours of the masses.

12.5 Comparison between results and Hydrogeological Plan of Rosazza

At this point, it should be intuitive to compare the riskiest scenario with the Hydrogeological Plan, to confirm the hypothesis according to which the results of this paper were to digitalise this document through a Digital Twin model.

It is therefore possible to visually relate a picture taken from the top of the model (Figure 83) with the Hydrogeological Plan of Rosazza (Figure 84 and 85) and notice how the masses that are signalled to be the most at danger (Red, Orange and Yellow) are located under a light blue hatch, which refers to "alluvial terrace", defined as a:

'Topographically flat geoform resulting from the accumulation of alluvial materials (alluvial terrace) or from the erosive action exerted by a watercourse on rock (erosion rock terrace) or on a pre-existing alluvial and/or fluvioglacial terrace (terrace system). Generally, the higher terraces are older than those below' (ARPA, 2023c).

Hence, historically, this portion of Rosazza used to be part of the river itself.

Moreover, this alluvial terrace is made of a type of terrain that holds in alluvial deposits directly laying on top of rocks and, as signalled by the geological report of Regulatory Plan for the City of Rosazza (Francini, 2004), this area is considered at risk of flooding in the case of high energy waters coming from Cervo Torrent. This part of Rosazza is labelled as Geological Class 3A, which refers to:

'Modified portions of land that have hydrogeological geomorphological features that make them unsuitable for new settlement (areas that are disrupted, landsliding, potentially unstable or subject to avalanche danger, areas floodable by high-energy floodwaters).' (Specifiche tecniche per l'elaborazione degli studi geologici a supporto degli strumenti urbanistici, 1977).

It is therefore logical for Torrent Cervo to find its way through it once again in the case of flooding phenomena, especially since the area is external to the artificial protection on the right riverbank (Francini, 2004).

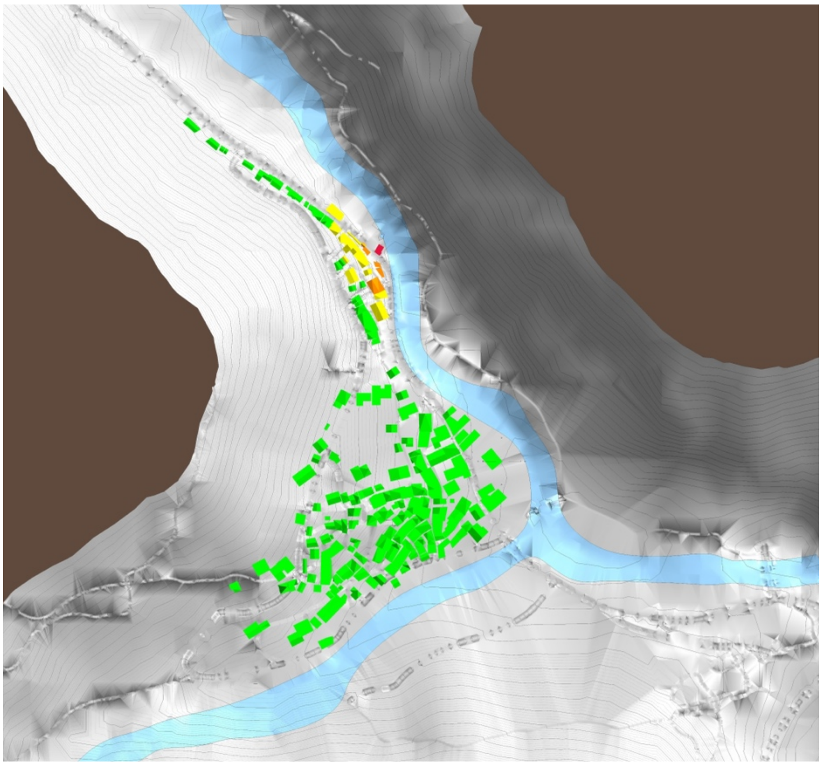

Figure 83 Visualisation of Risk from the top of the model for 3rd October 2020, the riskiest scenario (Personal elaboration)

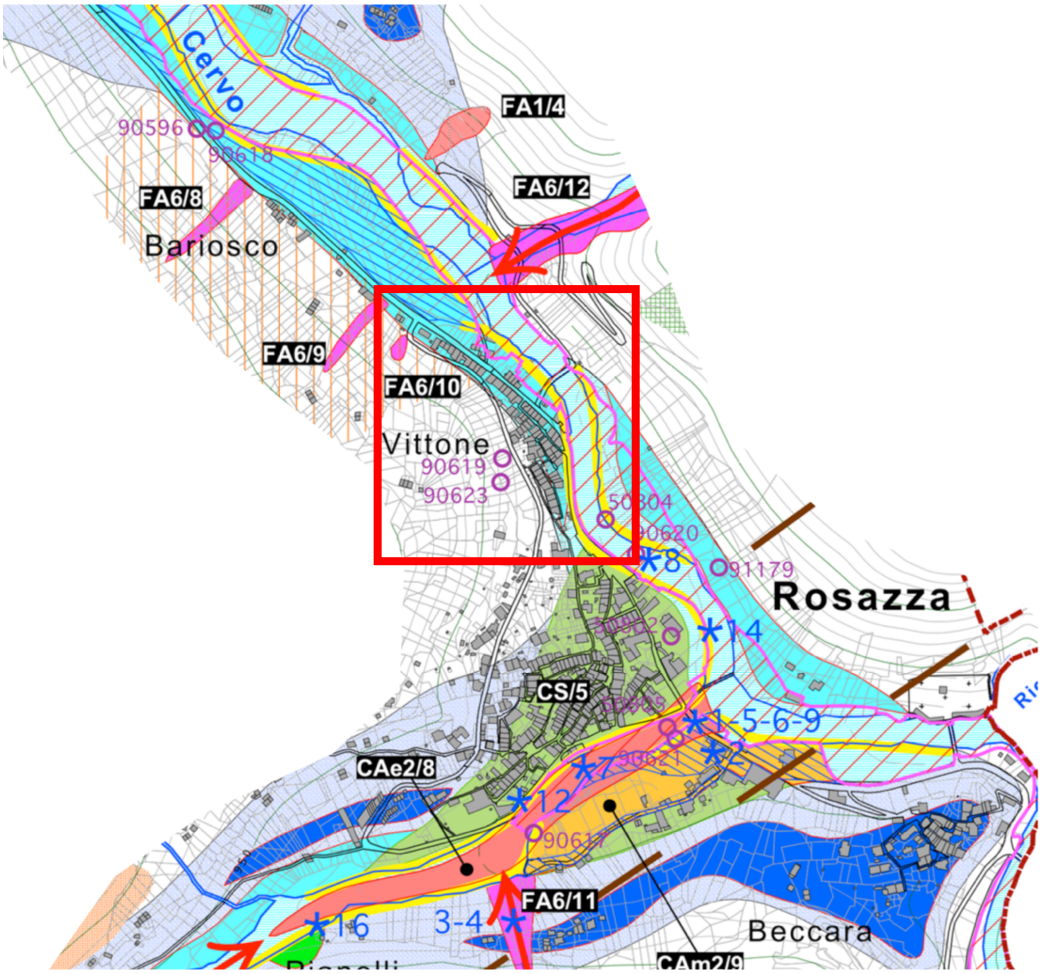

Figure 84 Hydrogeological Plan of the town of Rosazza with indication of the buildings that resulted to be the most at risk (Comune di Rosazza, 2004)

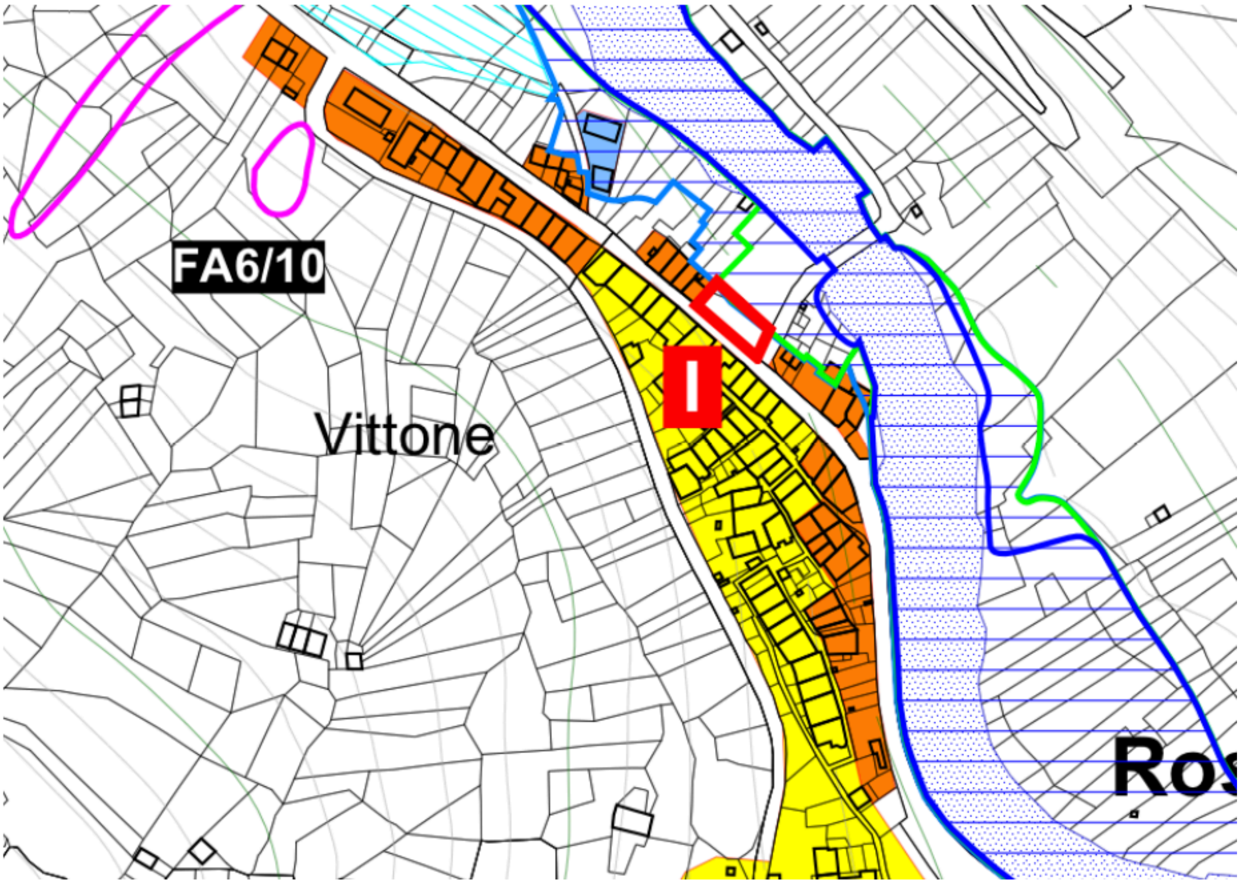

Figure 85 Extract IG7 referring to the Area along Via Roma, the portion of Rosazza which has been labelled to be the most at risk. (Francini, 2004)

13 Conclusion and further development

This thesis aimed to show possible HBIM application and integration for the town of Rosazza, enriching a Digital Twin model with information regarding geometrical properties of the buildings and weather parameters coming from a hypothetical monitoring sensor, and to produce a comprehensive, automated digitalization of the Hydrogeological Plan, generating the structure for prediction and monitoring phases of an Early Warning System for the town.

This has been done through integration between historical, weather, and bibliographical research data, transforming the already existent information in a comprehensive digital model. Research on Digital Twin and HBIM has been carried out bearing in mind the applications of the model, as well as the study of floods and their management worldwide and on a national level when concerning Italy. The model was then planned structuring the methodology with previous examples in mind, then detailing Common Data Environment and the structure of the information. After a preliminary Scan-to-BIM phase in which the context was detailed, the modelling of the town through masses of the buildings started out. Interoperability has been tested out between different software packages, such as ReCap Pro®, InfraWorks®, FormIt® and Revit® in the first phase. Then, Revit® has been further used through the plug-in DiRoots One and the expansion in Dynamo®, connecting it with Google Sheets™ and Google Drive™. After the model was set in terms of geometries and parameters, an Export - Elaboration - Import process allowed every mass and therefore building of Rosazza to be enriched with weather metrics coming from real-time data gathered through a hypothetical sensor, which then generated a visualization of the Risk at which a specific building lied against a possible flood in the area through Dynamo® scripts.

There are many possible future developments for this project, and they can be divided into different themes based on the subject they are focusing on.

Bibliographically speaking, the model and the Dropbox® database could also be used as an integrated BIM database for data regarding Cervo Valley, Rosazza, History of floods, and metrics about real-time situations. The structure of the Common Data Environment has already been specified previously, and it was designed to facilitate understanding and exchange of information among different stakeholders, professionals, and private citizens. The structuring of this database through an open-source Cloud architecture could grant public and private access to the information, so that they are easily reachable by multiple entities for their purposes. The bibliographical research of data regarding the valley has been quite difficult, since this portion of land is very small and not much documentation actually exists, for which it is necessary to mention how hard it was to discover where, who and how exactly held these documents in order to ask for permission to consult them and gather a comprehensive view of these topics in an effective way. A common database for this purpose would be a great help to anyone who would like to deepen their knowledge on these matters.

On a hydrogeological point of view, the model could be enriched with a hydrological model of the torrent Cervo, which could determine a model of flooding scenarios to get more precise metrics of Torrent Cervo and create a more detailed study of the buildings possibly hit by the flood. In addition to this, the torrent could be better monitored through the implementation of not only the sensor that has been used in this thesis, but a monitoring system of multiple sensors located in strategic positions on the riverbanks to gather a more precise study of the behaviour of Cervo and its affluents. The masses could be associated to the sensor that is the closest to them, so that the data coming from a sensor doesn’t interfere with that coming from the closest sensor to the mass; or, even more specifically, data coming from different sensors could be combined mathematically to formulate better scenarios and a more detailed risk assessment.

A further development could also be recognizable with automation and Artificial Intelligence in mind. Weather and Hydrological parameters have been structured in a way that enables connections among different Google Sheets, which already is shown to be a quite real-time implementation. An even more detailed way to exploit this possibility is to implement this data live from Weather and Hydrological sources online, which could be both official stations, or more specifically the more structured monitoring sensors system that has already been proposed. In this way, real-time data could be integrated in the model through the simple Import in Sheetlink with DiRoots One in an even more automated way. This could be done through the simple function IMPORTHTML_, which allows a direct connection between a Google Sheet™ cell and data present a specified website. Revit® could also be installed in a Virtual Machine instead of a personal computer to test out the possibility of running the algorithm without the need of manually selecting Import, even though it has been highlighted how the manual control of this part of the elaboration phase would be useful to avoid monitoring errors. Furthermore, Hazard parameters, as well as the behaviour of watercourses, could be studied through Machine Learning algorithms, so that future predictions could be more specific the more data is gathered. An historical research has already been done, therefore the implementation between historical data, real-time data, and the previously detailed Hydrological Model of Cervo Torrent and its affluents could all lead to a better understanding and extremely accurate predictions for future scenarios thanks to machine learning techniques.

On a BIM point of view, the parameters could be expanded to further detail the integration for HBIM. This could be done more specifically for the metrics concerning the vulnerability, which could be expanded through historical research on Rosazza's buildings, for example with a Building Typology parameter. For example, the technology used for the foundations and for the connections with the ground could be studied and specified in the model to know the fragility of the ground floor in the event of a flood. Since mountain and traditional houses are the main typology present in Rosazza, the main building technologies in this case would be, on a scale that goes from the most to the less vulnerable:

- Sand
- Wood
- Concrete and masonry
- Reinforced concrete.

The risk could then be associated to each case based on the same methodology applied before, giving them a Risk value from 1 to 4 and further the detailing of possible damage.

Furthermore, buildings that have already been damaged (or every single one on a longer term) could be modelled with a higher level of detail in order to define solutions for restoration or refurbishment after the floods. If so, the context, parametric development, and background has already been input on Revit® in this thesis' model, as well as the locations of the buildings through the masses, which results in a solid base from which to expand the model in terms of geometry and information of a more specific nature. Masses hold a geometrical Level of Development of C, as previously pointed out, but they could reach higher LODs that could match their Level of Information Need and Historic BIM requirements, and give the model a higher relevance, especially for future interventions on a public and private scale.

It wouldn't be a technology of the present time if Virtual and Augmented realities could not be included in this process. A more detailed HBIM could lead to the possibility of exploring Rosazza through AR, looking at flooding scenarios first hand and, more importantly, exploring restoration possibilities on-site. VR could then be used to explore the model and discover the state-of-the-art of buildings and their future development, as well as the strengthening of Rosazza against floods, considering the current works that have to be done on *Ponte delle Cave* or possible future embankments of the torrent against floods.

The last but probably most important implementation is on a regulation and administrative level. The model and its real-time results through the visualization of risk could be an effective Early-Warning BIM model for the city of Rosazza. This could allow the municipality to further their Risk Assessment plans accordingly, studying possible damage scenarios and creating evacuation plans that take into consideration everything that's been explained in these chapters. As enunciated in the Abstract, the goal of the project was the digitalization of the Hydrogeological Plan and the detailing of an Early Warning System for the city of Rosazza, therefore this only constitutes the grounding base for administrative interventions based on the data and modelling that has been given through this HBIM model and Digital Twin, whose public exploitation could be of great use to further the safety of Rosazza's people and buildings. On a more specific note, the model could be used by the authorities as a practical digitalization of the Hydrogeological Plan of the town of Rosazza, implementing more geological data on the buildings, such as creating parameters with respect to the fragility of the soil, or creating a parallel visualization of landslide risk. At the same time, the Region could exploit it for EWS purposes, amplifying the already existent network of weather and hydrological stations through the data provided by the sensors. Considering the population of the town as stakeholder, masses that hold a very high flood risk (therefore red) could be automatically sending an email to the owner of said house, so that they are aware of the risk they are under in real-time.

On a greater perspective, this model and its further detailing could help create more sustainable cities, as specified in Sustainable Development Goal number 11, and further innovation, as number 9 hopes for. As BIM and its applications are an extremely valuable tool in nowadays Construction Industry, this application can be used as a methodology ground base for other similar projects, both in terms of HBIM and Digital Twin definition as well as regarding the application phase, structuring Dynamo® scripts in similar ways, exchanging data through a similar process and better integrating project on an informational level. As for sustainability, it is of the utmost importance to reiterate how climate change is currently affecting relevant changes in weather manifestations such as landslides or floods and therefore it is with urgency that international organisations suggest implementing more comprehensive methodologies to consider climate change in everyday processes through a holistic approach. This thesis' main goal was indeed carried out through the study of BIM considering today's needs and technologies, in order to integrate the digital with the historical, the sustainable with innovation.

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In ultimo, vorrei spendere qualche parola per ringraziare la mia tenacia. Chi mi è stato vicino sa bene quanto questi anni siano stati complessi, sia a livello interiore che per eventi che prescindevano dal mio controllo. Non credevo sarei mai arrivata davvero al momento in cui mi sarei potuta guardare indietro ed essere fiera di ciò che ho fatto, del percorso che ho seguito e di tutto quello che ho conseguito in questi anni. Non credevo sarei riuscita a comprendere quale fosse il mio spazio in questo ambito e, a onore del vero, sono piuttosto certa continuerò a cambiare idea, ma se c'è una cosa che ho imparato in questi anni, è che è possibile ritrovarsi. È possibile perdersi, allungare una mano all'esterno e lentamente risollevarsi, ma soprattutto arrivare a capire quando rallentare e offrirsi comprensione; che va bene se il proprio presente non ha la stessa forma che ci si aspettava anni prima e che si può arrivare a ciò che si sognava anche se tutto ciò che c'è stato nel mezzo non è andato secondo i piani. Alla ragazzina che sognava l'università appena iniziato il liceo, voglio dire che siamo arrivate alla fine e che non è stato affatto come ci aspettavamo, ma che va bene comunque. Che alle volte è bene piantarsi a terra e provare a vivere il presente, ma che, in fondo, anche dopo tutti questi anni, non sono poi cambiata così tanto, perché ora che sono sola sulle mie gambe non vedo l'ora di scoprire il mio futuro. Alla me che non sapeva se davvero potesse appartenere a un posto, voglio dire che è anche grazie all'università che ora abbiamo tre città da poter chiamare "casa", e che siamo riuscite a sentirci a casa anche sole con noi stesse. Credo di capire solo adesso, guardandomi indietro, che da bambina avessi deciso che avrei reso dell'architettura la mia passione per scoprire tutti i significati che la parola "casa" può assumere e trovare il mio. Ed è assurdo come una canzone consigliatami da un'amica anni fa sia perfetta per dimostrarlo e concludere questa tesi:

"Perché le case in fondo sono solo scatole
Dove la gente si rifugia quando fuori piove".