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Two dimensional Hydrodynamic Modelling for Urban Flood Hazard Assessment

Application to the hillside area of Turin

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Abstract

This thesis focuses on the flood hazard assessment of the hillside and foothill area of Turin. Placed right behind the Po River, this area is characterized by steep slopes that end in the highly urbanized context of the neighborhoods of Borgo Po and Madonna del Pilone. The presence of secondary watercourses with transitions to underground culverts shifts the hydraulic domain directly onto the street network, exposing the entire territory to extreme flood events. To address this issue, a two-dimensional hydrodynamic model of the catchment was created using Iber, a software developed by the Universitat Politècnica de Catalunya and the Universidade da Coruña.

The workflow started with a detailed hydrological analysis and catchment characterization. A Digital Terrain Model (DTM) and land-use datasets were used to define the morphology, soil permeability, and surface roughness of the basins, while the design rainfall was obtained through the elaboration of official hydrological data from ARPA Piemonte. This allowed the creation of a high-resolution 2D numerical model, capable of simulating the effects of an urban flood within a complex topography.

To ensure the reliability of the model, a calibration process was carried out using a historical flooding event that occurred on June 20th, 2007, which is extensively documented in reports by ARPA Piemonte. The soil permeability parameters were iteratively adjusted by comparing the simulated water depths against real field observations documented in the historical reports.

The calibrated model was then implemented to run the design rainfall scenarios. Instead of just mapping simple water depths, the study evaluated urban safety through advanced stability criteria developed by Martínez-Gomariz, Gómez, and Russo. By processing the maximum water depth and velocity outputs, these criteria define three different hazard levels based on analytical-experimental thresholds and real-scale human trials. The output maps, generated with QGIS, are able to highlight the most critical areas and road intersections in the analyzed catchments and provide practical insights for urban planning, emergency management, and risk mitigation strategies in the city of Turin.

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Chapter 1

Introduction

In recent years, urban areas have become increasingly vulnerable to catastrophic flooding, which now represents one of the primary threats to public safety in inhabited zones. These floods are driven by extreme rainfall events combined with urban drainage networks that are inadequate to manage such volumes. Indeed, the widespread soil sealing of these areas drastically reduces the ground's infiltration capacity, generating rapid surface runoff that surcharges traditional sewer systems. When the drainage network is underdimensioned for these massive water volumes, the excess flow surcharges onto the streets, endangering citizens and damaging infrastructure. Furthermore, climate change is drastically increasing both the frequency and intensity of extreme rain events, shifting flash floods from sporadic anomalies into recurring seasonal challenges that demand systematic mitigation.

For this reason, the development of prevention and protection strategies from such events is more than necessary, and must be based on an in-depth study of the dynamics and effects generated by extreme rainfall events. One of the objectives of this thesis is precisely to face this challenge, applying a numerical model to a specific case study to simulate an urban flood and observe its effects.

Once the effects are known, a hazard assessment must then be made to define which are the most critical areas of a city. This step is necessary to implement suitable prevention and protection mechanisms, where necessary. The second part of this project aims precisely to do this type of evaluation, applying a series

of criteria that are able to associate a specific degree of hazard to the effects of a flood.

For this project, the chosen case study is the foothill area of Turin, located between the neighborhoods of Borgo Po and Madonna del Pilone. Indeed, this area represents an ideal case study for this type of analysis since, as will be discussed in the following chapters, it has been affected by frequent flash flood events over the last few decades, making an in-depth study of the territory strictly necessary.

1.1 Study Area and Geomorphological Framework

The area examined in this study lies within the foothill belt of Turin, on the right bank of the Po River. The territory has a distinctive geomorphological character that plays a decisive role in determining how the ground responds to intense rainfall events. The Turin hill presents a markedly asymmetric profile: on the southern side the slope descends gently toward the Chieri plain, while on the north-western flank, the one directly facing the urban core, gradients become steep.

From a hydrographic point of view, this hillside hosts a dense network of secondary watercourses and minor streams, reported in Table 1.1 and Figure 1.1. The short distance between the hilltop and the Po River, combined with the significant elevation differences, results in extremely short concentration times. The hydrological response is consequently of a torrential nature: brief but sufficiently intense rainfall events can generate extremely high peak flows almost instantaneously, turning small streams into fast-moving channels.

This geomorphological fragility was further aggravated during the twentieth century by progressive urbanization. The city gradually spread along the lower part of the hill, filling in the entire transitional zone between the steep slopes and the urban fabric in the flat area below. Today, this area coincides with densely populated districts such as Borgo Po and Madonna del Pilone. To accommodate urban development, the terminal reaches of nearly all minor streams have been altered over time, being enclosed within underground conduits buried beneath the road surface.

Table 1.1: Main watercourses of the Turin hillside and their catchment areas.

Watercourse	Area [km²]
Rio Sappone	2.27
Rio degli Alberoni	0.15
Rio Pattonera	2.15
Rio Salino	0.85
Rio Isabella–San Vito	0.16
Rio San Severino	0.26
Rio Pavese o Val Salice	5.50
Rio Val San Martino	2.47
Rio Val Piana	0.28
Rio Reaglie	5.57
Rio Sassi–Mongreno–Cartman	9.70
Rio Costa Parigi	1.35

These conditions create a far from negligible hydraulic risk for the surrounding urban environment. During more severe weather events, the underground channels tend to reach full capacity rapidly, to the point of being no longer able to drain all the water beneath the street network. This causes a violent surge of flow back to the surface, shifting the hydraulic domain entirely: it is no longer the streams that carry the water, but the street network. This effect is considerably amplified by obstructions caused by debris inside the underground channels. Indeed, the high velocities generated along the full extent of the hillside transport large quantities of sediment and debris downstream, which not only pose a direct hazard to citizens, but also contribute to reducing the capacity of the channels, worsening the displacement of the hydraulic domain toward the surface. Roads, hemmed in on both sides by buildings and boundary walls, effectively function as open channels, funneling fast-moving flows down the slopes and pooling large volumes of water at low points, intersections and squares.

The recurrence of these phenomena over time and the disastrous effects they generate are well documented both in local historical records and in official technical sources, including the Turin Municipal Archives and reports produced by ARPA Piemonte. Among the most significant and well-known episodes, the flood of 20 June 2007 stands as a key reference point: an exceptionally intense

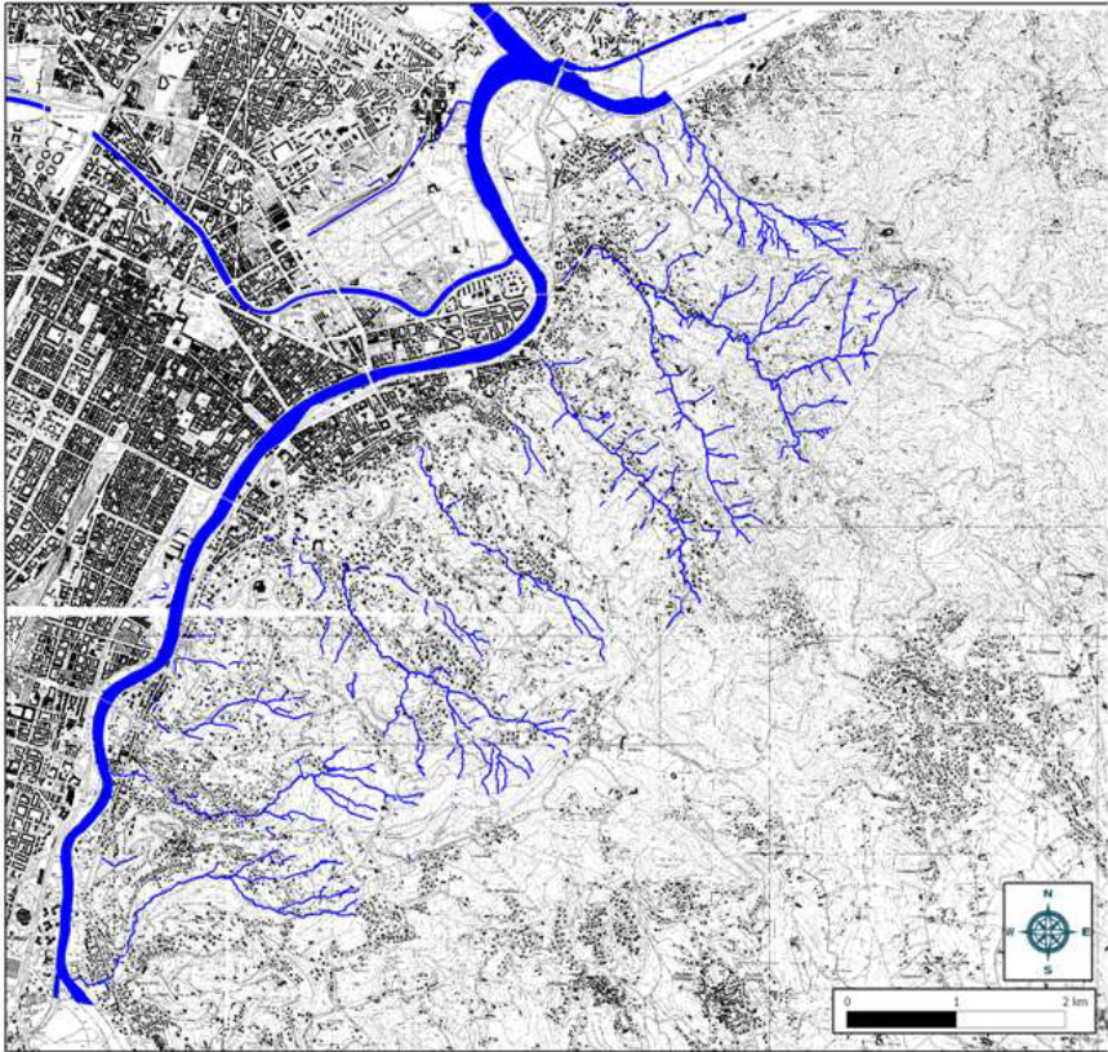


Figure 1.1: Carta Tecnica Regionale del Piemonte, with the watercourses highlighted in blue

rainfall event that caused severe damage, flooded streets and basements and trapped numerous vehicles.

In order to examine these dynamics in detail, this study focuses on three specific catchments, considered representative of the vulnerability of the Turin hill slopes. The first is the Rio Val Salice and Rio Pavese catchment: located in the southern part of the study area, it is characterised by high residential density interacting with deeply incised natural drainage lines. Historical critical points

have been concentrated along road axes such as Viale Thovez and Corso Lanza. The second, immediately to the north, is the Rio Val San Martino catchment: this is characterised by significant hydraulic bottlenecks at the terminal culverted sections, which have in the past been responsible for serious flooding along Strada Val San Martino and Corso Gabetti. Finally, the Rio Valpiana catchment is considered: it is the smallest of the three and is notable for the particularly abrupt transition between natural gradients and the fully impervious surfaces of the city, resulting in a very high propensity for flash runoff generation at critical road junctions. The Figure 1.2 highlights the selected area composed by the three basins.

1.2 Objectives and methodological approach

As previously anticipated, this research project develops around two primary objectives: to generate a two-dimensional hydrodynamic model of the study area capable of simulating urban flood effects and providing detailed information on the hydrodynamic behavior of the catchments with high spatial resolution; to utilize the numerical outputs of the model to develop a hazard mapping for pedestrians and vehicles, following stability criteria that are well-established in literature and engineering practices.

Consequently, these represent two strictly interconnected working phases, since the hazard assessment directly depends on the numerical results derived from the 2D hydrodynamic simulation.

The workflow implemented to build the model and achieve reliable numerical results consisted of five steps:

1. Collection and processing of data regarding the geomorphological characteristics of the basins, including the Digital Terrain Model (DTM), the network of the main streams, and land-use maps. Additionally, georeferenced data regarding interfering infrastructure (roads, buildings, bridges, and underground culvertes) were collected. These datasets were obtained from the Geoportale of Regione Piemonte (2026), previous hydrological studies of the area (Ponzio 2013; Yepes 2020), and, where necessary, satellite imagery

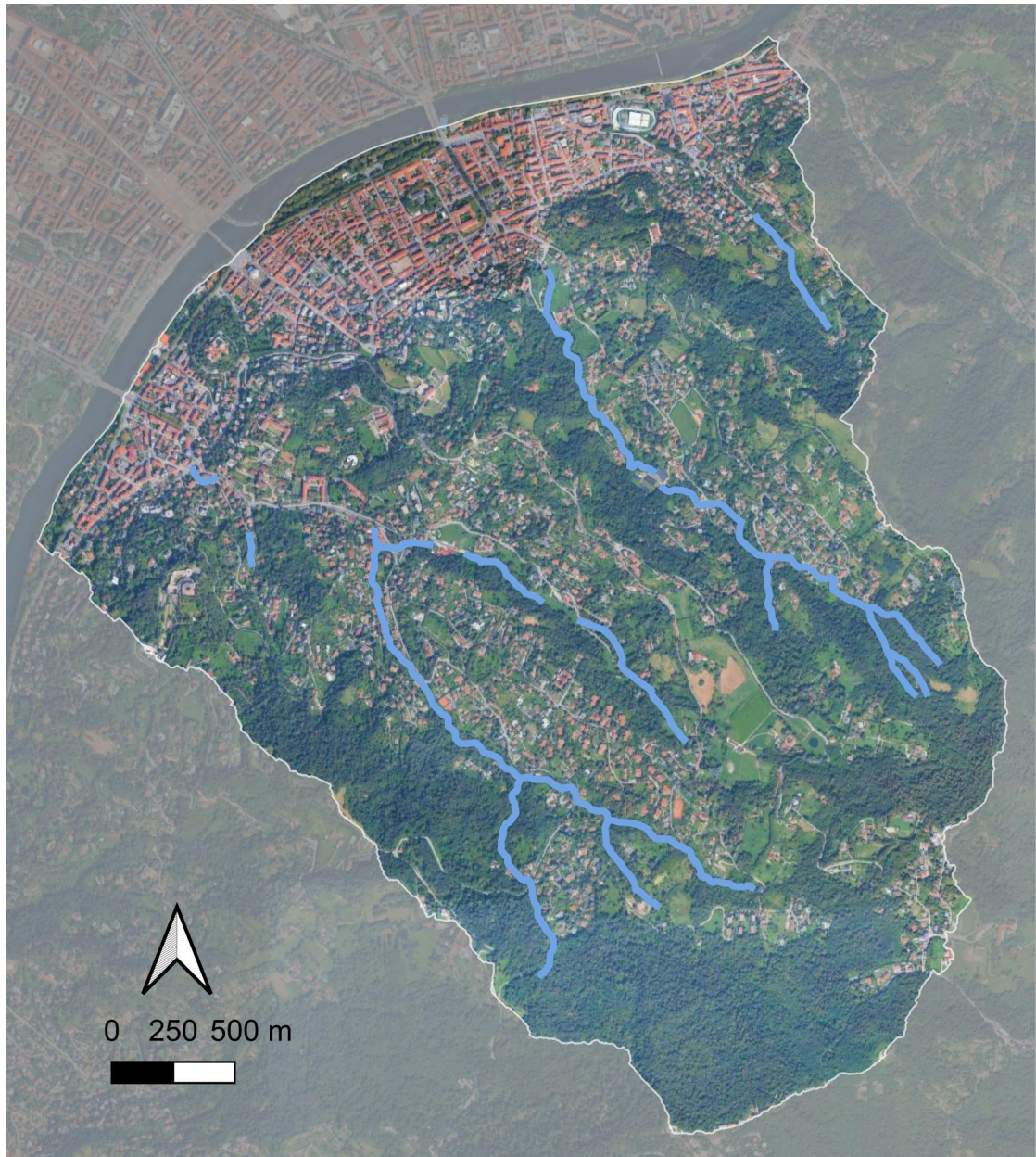


Figure 1.2: Study area selected for this project, comprising three catchments shown from south to north: Rio Val Salice e Rio Pavese, Rio Val San Martino, and Rio Valpiana. Watercourses are shown in blue. Satellite imagery: Google Earth.

analysis.

2. Creation of design hydrographs to define the intensity, duration, and temporal evolution of rainfall during potential extreme events. Five scenarios were developed for different return periods (2, 5, 10, 100, and 200 years) based on official pluviometric data from ARPA Piemonte (2026b).
3. Integration of all processed geometric and hydrological data into the Iber software (Bladé et al. 2014; Sanz-Ramos et al. 2025), setting up a 2D hydrodynamic model capable of delivering high spatial resolution within acceptable computational times.
4. Calibration of the model, selecting the parameters governing soil permeability to be optimized, specifically the Curve Number (CN). This process was based on the analysis of a major historical flash flood that occurred on June 20th, 2007. After reconstructing the historical rainfall hyetograph, the event was simulated in Iber, comparing the computed water depths with real field observations documented in an official report from ARPA Piemonte (2007). The iterative adjustment of these parameters resulted in a highly reliable model, capable of replicating the actual hydraulic response of the catchments.
5. Execution of design scenarios to generate the final outputs by running the calibrated model under the action of the calculated design rainfall events.

The numerical simulations provided several georeferenced outputs across the entire study area. Among these, maximum flow velocity and maximum water depth represent the most critical variables. Not only do they provide the essential input for the subsequent hazard assessment phase, but they also fully describe the hydraulic dynamics of the three analyzed catchments, establishing a fundamental baseline for future risk mitigation and urban planning studies.

The second phase of the project concerns the hazard mapping of the study area according to specific evaluation criteria for both pedestrians and vehicles. Once the maximum water depth and maximum flow velocity values were extracted from Iber, they were processed using QGIS software to apply the hazard criteria and construct the final maps.

Regarding pedestrian hazard, the criteria adopted in this study are primarily based on the experimental work of Martínez-Gomariz et al. (2016), who conducted real-scale human trials to identify the limits of stability against sliding and toppling mechanisms. The classification distinguishes three distinct hazard levels based on the hydrodynamic momentum, defined as the flow product of velocity and depth, as well as independent structural limits for maximum depth and velocity to ensure safety even under low-momentum conditions.

For the assessment of vehicle stability, this study adopts the experimental framework proposed by Martínez-Gomariz et al. (2017), which overcomes the rigidity of traditional static guidelines by deriving stability thresholds based on the specific physical characteristics of a vehicle. A popular commercial model was selected as the "design vehicle" to ensure a safety-biased and conservative analysis. Similar to the pedestrian approach, the resulting classification identifies three hazard levels determined by the hydrodynamic momentum and independent structural limits, specifically focusing on the buoyancy threshold beyond which the vehicle loses contact with the ground and is washed away.

The final output consists of 10 comprehensive hazard maps, equally divided between pedestrian and vehicle hazards for each of the five return periods analyzed in the first phase. These maps constitute a crucial decision-making tool for urban pluvial flood mitigation. This typology of cartography should be used as a fundamental baseline for resilient urban planning, the design of flood protection structures, and the development of civil protection emergency plans that guarantee public safety.

1.3 Two Dimensional Modelling with Iber

Iber is a two-dimensional hydraulic simulation software for the resolution of problems in hydraulic and environmental engineering. Originally developed in 2010 to satisfy the requirements of Spanish regulations and directives regarding water, themselves largely based on European directives, Iber is now a simulation software that combines a hydrodynamic module, a turbulence module and a sediment transport module (Bladé et al. 2014), with other plug-ins for water quality simulations, hydrological processes at the rural and urban watershed

level, eco-hydraulics and more.

The development of this freeware software was an initiative of the Centro de Estudios y Experimentación de Obras Públicas (CEDEX), through a consortium of academic and research institutions, including the Universidade da Coruña (UDC), the Universitat Politècnica de Catalunya (UPC) and the Centro Internacional de Métodos Numéricos en Ingeniería (CIMNE). The resulting software was built from the integration of three already existing tools: Turbillion (Cea, 2005) and CARPA (Bladé, 2005), for the simulation of the water free surface, and GiD (Coll et al., 2018) for pre- and post-processing (Bladé et al. 2014). The Iber software has undergone significant development over the last decades, evolving into a robust platform for two-dimensional free-surface flow simulation (Sanz-Ramos et al. 2025).

For the hydrodynamic resolution, Iber uses the Shallow Water Equations (SWE), also known as Saint-Venant equations. These non-linear partial differential equations are implemented to account for phenomena such as bed friction, turbulence effects and surface friction due to wind. The model resolves these differential equations using the Finite Volume Method on unstructured meshes. This methodology is preferred because it ensures mass conservation across the entire computational domain and offers flexibility in mesh generation. The resolution of these equations requires the definition of appropriate boundary conditions for the model domain, which can be implemented in many different ways.

The hydrological module transforms Iber into a distributed hydrological-hydraulic model, capable of directly simulating the rainfall-runoff transformation over urban catchments or rural basins. The core of this module is the DHD (Decoupled Hydrological Discretization) scheme (Cea and Bladé 2015), developed specifically for overland flow applications where water depths are extremely shallow, on the order of millimetres. The advantages it provides are greater numerical stability over irregular topographies, increased efficiency through a reduction in computational cost, and the ability to handle both subcritical and supercritical flow regimes. The module implements the most common models for the computation of hydrological losses: Green-Ampt, Horton, the SCS Curve Number method, and linear constant-rate infiltration models (Aranda et al. 2023).

The integration of Iber with the Storm Water Management Model (SWMM 5.1) allows the modelling of dual urban drainage: the interaction between the surface system (major system) and the underground sewer network (minor system). The exchange of water between the surface (Iber) and the network (SWMM) is bidirectional and occurs through two main mechanisms: inlets and manholes, through which surface mesh elements are linked to the nodes of the sewer network, and building roofs, which transfer rainfall to the nearest SWMM manhole or to other adjacent mesh elements (Sañudo et al. 2020).

A further characteristic of the software is the integration of High Performance Computing (HPC) techniques, in particular parallelisation through GPGPU (General Purpose Computing on Graphics Processing Units), which is capable of accelerating computation times by over 100 times compared to a traditional hydrodynamic simulation running on a CPU (Sanz-Ramos et al. 2025).

Chapter 2

Hydrological analysis and hydrodynamic model setup

This chapter describes the process of constructing the two-dimensional hydrodynamic model of the catchment, structured around two main phases. The first concerns the collection and processing of all the data required for the model implementation: the morphological characteristics of the territory, the hydrological parameters, and the properties of the infrastructure present in the study area. The second phase describes the actual construction of the model within the Iber software, illustrating the operational choices made and the configuration of the internal parameters, with the aim of obtaining a simulation that reproduces the reality of the analysed territory as closely as possible.

It should be noted that the hydrodynamic model developed in this study does not include the urban sewer network, due to the lack of data on its geometry and characteristics. The absence of this element inevitably introduces a simplification into the simulation, since in a real scenario part of the surface runoff would be conveyed into the sewer network, in addition to the volume coming from building roofs, which is also normally intercepted by the network. Consequently, the simulated water depths and flow velocities tend to be overestimated with respect to those that would occur in the presence of a functioning drainage system. However, this simplification is considered acceptable for the purposes of this thesis, for two main reasons: firstly, during high-intensity flood events the sewer

network tends to reach saturation in the early stages of the event, progressively losing its drainage capacity; secondly, the resulting simulation does not describe the expected real scenario, but rather a more severe one, which by definition is on the side of safety. The hazard maps produced therefore represent a conservative estimate of the hydraulic risk.

2.1 Catchment Hydrology and Morphological Data

Before proceeding to build the model in Iber, it is necessary to prepare all the data that will need to be fed into the software. This preparation is carried out on two categories of information: morphological and hydrological. The former concern the geometry of the model, the elevation, the surface roughness and soil permeability, the characteristics of the buildings, and the data related to the culverts. Each of these inputs and the processing workflow followed are described in detail below.

2.1.1 Domain Geometry and Mesh Zonation

The geometry is a fundamental component of the model in Iber, as it defines the boundaries of the catchment and allows it to be subdivided into different areas, to which different mesh resolution values will be assigned. It must indeed be considered that the finer the mesh, the greater the computational time required for the simulation. It is therefore of fundamental importance to assign different resolution values to the different areas of the catchment, in order to speed up the computation where it is not necessary to know the results with extreme spatial precision.

The construction of the geometry began with the definition of the outermost boundary of the considered area. This operation was made possible by processing the DTM (Digital Terrain Model) with a 1-metre grid, provided by the Municipality of Turin, which covered a larger area than the one selected for the analysis. Using the GRASS tools within the QGIS software, the boundaries of the catchments contained in the DTM were delineated, and only the three selected in Section 1.1 were retained: the Rio Val Salice and Rio Pavese catchment, the

Rio San Martino catchment, and the Rio Valpiana catchment. By merging them, the boundary of the entire geometry to be inserted into the model was obtained, in the form of a shapefile.

The definition of the internal areas was carried out following a precise hierarchy criterion among the different zones of the catchment, distinguishing three levels of spatial resolution for the results: 2 metres for roads, rivers, and densely populated areas, 5 metres for sparsely populated areas, and 15 metres for natural areas (woodlands, fields, pastures, ...). This choice, which will allow the simulation times to be considerably reduced, was made by considering the possible future uses of the results. The information that will be extracted from them (water velocity and water depth), in most cases and in this one in particular, is used for hydraulic hazard analyses of urban areas. It is therefore important to have a fine resolution in densely populated urban areas and along roads, while coarser results can be used in natural areas, where there is no interest in computing hydraulic hazard levels. The footprints of the buildings are then subtracted from the final geometry, as they will be implemented in the model separately from all other areas. The result, shown in Figure 2.1, is a shapefile containing the catchment on which the simulation is to be performed, subdivided into secondary areas to which a variable-resolution mesh will be assigned.

2.1.2 Digital Terrain Model

The elevation data for the model must be contained in a raster file (in `.tif` format), and in this case the DTM provided by the Municipality of Turin will be used directly.

2.1.3 Surface Roughness

The surface roughness data are entered into Iber using two separate files: a `.csv` file containing a list of the land cover types that can be found within the catchment, to each of which an ID and a Manning's roughness coefficient value are assigned; a raster file (in `.asc` format) covering the entire model area, which assigns to each pixel a number representing the ID of the land cover type to which it belongs. To obtain these files, a series of processing operations were carried

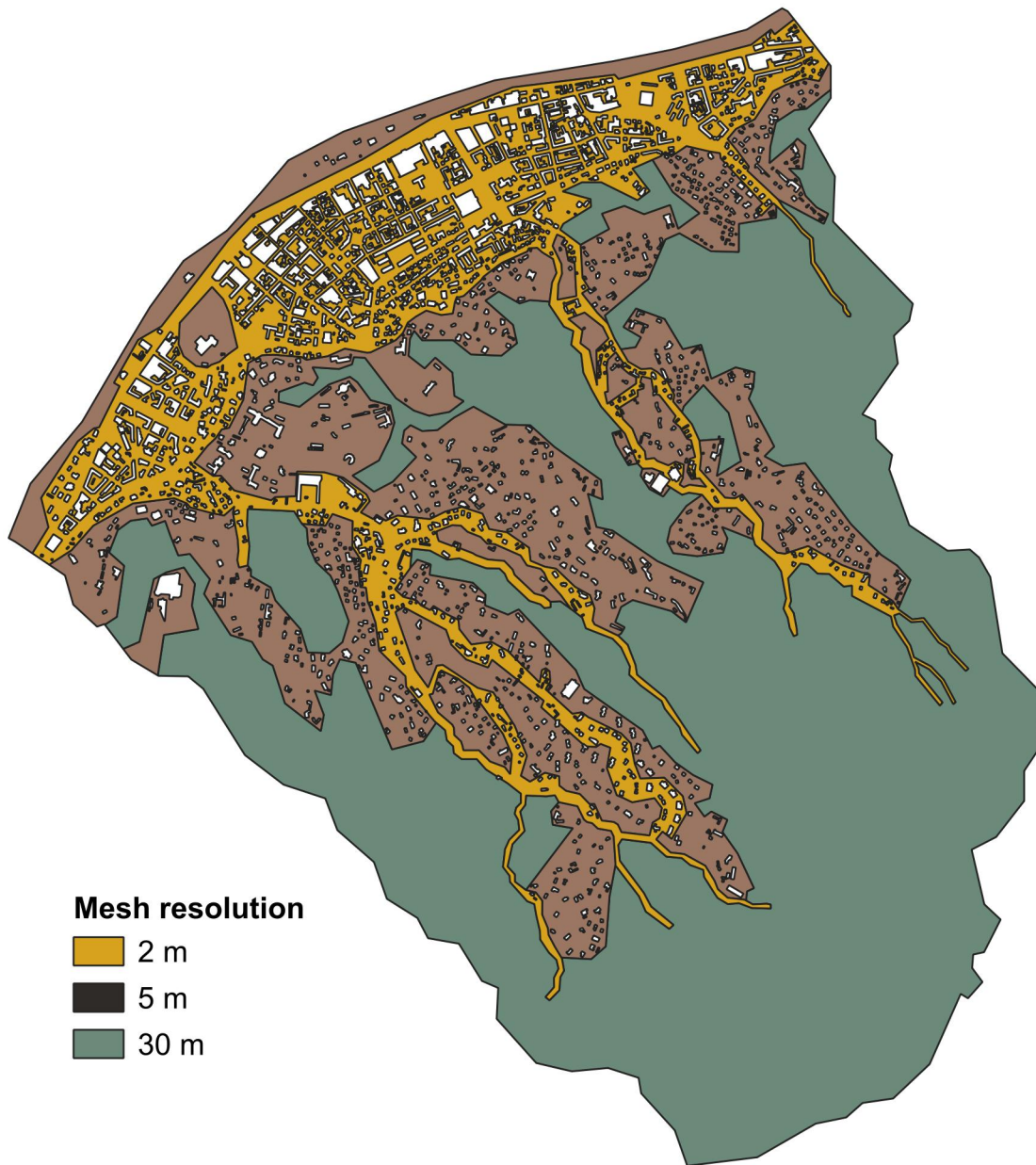


Figure 2.1: Spatial subdivision of the catchment domain into mesh resolution zones: 2 m for roads, rivers, and densely populated areas; 5 m for sparsely populated areas; 15 m for natural areas. Building footprints are excluded from the domain and treated as separate elements.

out in QGIS, starting from the land use map of the BDTRE (Base Dati Territoriale di Riferimento degli Enti), downloaded from the Geoportale of Regione Piemonte

(2026). All land use categories were grouped into five classes: infrastructure, river, sparse vegetation, forest, and residential, to each of which a Manning's roughness coefficient value was assigned. The chosen values can be observed in Table 2.1. The assignment was carried out on a shapefile, within its attribute table, then converted into a raster file, so that it could be read by Iber. The resulting map can be seen in Figure 2.2.

ID	Land use class	Manning's
1	Infrastructure	0.020
2	River	0.025
3	Sparse vegetation	0.080
4	Forest	0.120
5	Residential	0.020

Table 2.1: Manning's roughness coefficients assigned to each land use class for the surface roughness characterisation of the catchment.

2.1.4 Soil Permeability and Curve Number

Soil permeability was assessed following the criteria of the Curve Number (CN) method, originally developed by the Soil Conservation Service (SCS). The hydraulic modelling software Iber allows the spatialisation of this parameter by requiring as input a raster file (in .asc format) that assigns to each pixel the corresponding CN value. It should be noted that the soil permeability data are those that will be refined during the calibration phase. It is indeed complex to assign exact CN values to each land cover type within the catchment; for this reason, the values computed at this stage will differ from the final ones.

In the Curve Number method, the first step concerns the selection of the hydrologic soil group (HSG). The starting point was therefore the Soil Map of the Piedmont Region (scale 1:250,000), obtained from the Geoportale of Regione Piemonte (2026), which contains the pedological information system. This map shows that the study area falls entirely within a protective retention capacity class of *A-Alta* (A-High), described as follows:

“Soils with absent or negligible coarse fragments, with texture ranging



Figure 2.2: Spatial distribution of surface roughness classes across the catchment domain. Each zone is assigned a Manning's roughness coefficient.

from clay loam to clay or silty, free from reversible or irreversible cracking, and without hydromorphic horizons within 150 cm depth.”

Although the designation *A-Alta* defines the protective retention capacity of the

soil with respect to subsurface contaminants, the pedological description indicates the presence of fine fractions (silt and clay) that result in low surface hydraulic conductivity. Consequently, in accordance with the criteria defined in Chapter 7 of the National Engineering Handbook (United States Department of Agriculture, Natural Resources Conservation Service 2009), the soil was classified within Hydrologic Soil Group C, defined as follows:

“Group C — Soils in this group have moderately high runoff potential when thoroughly wet. Water transmission through the soil is somewhat restricted. Group C soils typically have between 20 percent and 40 percent clay and less than 50 percent sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures. [...] The saturated hydraulic conductivity in the least transmissive layer between the surface and 50 centimeters is between 1.0 micrometers per second and 10.0 micrometers per second. The depth to any water impermeable layer is greater than 50 centimeters. The depth to the water table is greater than 60 centimeters.”(United States Department of Agriculture, Natural Resources Conservation Service 2009)

The tabular Curve Number values were then determined based on the USDA-NRCS Technical Release 55 (United States Department of Agriculture, Natural Resources Conservation Service 1986), Chapter 2: “Estimating Runoff”. This manual catalogues CN values as a function of the hydrologic soil-cover complex. The tables (from Table 2-2a to Table 2-2d) are structured according to the macro land use category and the type of vegetation cover, distinguishing between cultivated agricultural lands, other agricultural lands (pasture or woodland), urban and sub-urban areas, and arid and semi-arid rangelands. Within each table, the different land use entries are further differentiated according to the hydrologic condition, which can be classified as poor, fair, or good. This parameter estimates the capacity of the vegetation cover and the soil to promote infiltration and reduce surface runoff. Finally, the tables show a specific CN value for each of the four Hydrologic Soil Groups, which in the present case is always Group C. For the assignment, the descriptions of all land cover types defined within the catchment by the BDTRE land use map were examined, and a tabular value was associated

with each of them, as can be seen in Table 2.2. A map showing the spatial distribution of the values will be given in the Chapter 3, after the calibration process.

Table 2.2: Curve Number values assigned to each BDTRE land use class, for Hydrologic Soil Group C and average antecedent runoff condition (ARC II).

BDTRE land use class	CN
<i>Urban areas</i>	
Zone residenziali a tessuto continuo (S.L. > 80%)	94
Zone residenziali a tessuto discontinuo (S.L.: 50%–80%)	90
Zone residenziali discontinuo a media densità (S.L.: 30%–50%)	83
Zone residenziali discontinuo a bassa densità (S.L.: 10%–30%)	80
Zone residenziali discontinuo a densità molto bassa (S.L. < 10%)	77
Zone residenziali isolate	77
Aree industriali, commerciali e dei servizi	91
Aree industriali	91
Aree commerciali	94
Aree a servizi pubblici o privati	94
Reti stradali, ferroviarie e infrastrutture tecniche	98
Altre reti stradali	89
Cantieri	91
Aree verdi urbane	74
Incolti in aree urbane	79
Aree ricreative e sportive	74
<i>Agricultural areas</i>	
Seminativi in aree non irrigue	82
Foraggiere avvicendate	78
Vivai	82
Orticole	82
Vigneti	82
Frutteti e frutti minori	72

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BDTRE land use class	CN
Arboricoltura da legno	70
Prati da sfalcio a bassa e media altitudine	71
Incolti	79
Aree agroforestali	72
<i>Forest and semi-natural areas</i>	
Boschi di latifoglie	70
Robinetto	70
Querceto-carpineto	70
Querceto di Rovere	70
Pascolo naturale e praterie (continue)	74
Pascolo naturale con arbusti (discontinue)	76
Vegetazione boschiva e arbustiva in evoluzione	70
Rimboschimento di latifoglie	73
<i>Water bodies and bare areas</i>	
Spiagge, dune, isole fluviali e greti	100
Corsi d'acqua, canali e idrovie	100
Bacini d'acqua	100

The final consideration concerns the antecedent runoff condition (ARC). This parameter, introduced in the National Engineering Handbook, Section 4 (United States Department of Agriculture, Soil Conservation Service 1972), defines the soil moisture state in the days immediately preceding the rainfall event under consideration. The method defines three possible levels. ARC I represents a dry condition, in which the soil is below the wilting point, promoting maximum infiltration and reducing surface runoff to a minimum. ARC II is the average condition, representing the mean moisture state of the catchment and serving as the standard reference condition to which all CN values tabulated in the technical manual TR-55 (United States Department of Agriculture, Natural Resources Conservation Service 1986) refer. ARC III, finally, describes a wet or near-saturated state, resulting from heavy rainfall in the five preceding days: in this scenario,

infiltration capacity is minimal and the catchment responds by generating the maximum volume of surface runoff. Should the catchment be in an ARC I or ARC III condition, the CN values can be corrected using empirical formulae. At this stage, however, the average condition (ARC II) was preferred, without modifying the tabular CN values, bearing in mind that this choice may be revised during the calibration phase.

2.1.5 Buildings

The Iber software, through the Iber-SWMM plug-in, allows the roofs of buildings to be defined as separate geometries, equipped with their own mesh disconnected from the rest of the domain. This makes it possible to treat them as independent elements and to associate with them simplified hydrodynamic equations, which reduce the simulation times of the model, as described in Section 1.3.

All data related to the roofs are stored within a single shapefile, containing the geometry of each building. The characteristics associated with it are found in the attribute table, built according to a specific schema shown in Table 2.3.

Table 2.3: Format and characteristics of the attribute table of the buildings shapefile, as required by the Iber-SWMM plug-in.

#	Field name	Type	Options
1	ROOF_ID	String	—
2	SLOPE	Real	—
3	WIDTH	Real	—
4	MANNING	Real	—
5	STATE	String	100%_Connected Partially_connected Disconnected
6	MH_ID	String	—
7	VOL_2_MH	Real	% or 0
8	VOL_2_STRE	Real	% or 0
9	VOL_INFIL	Real	% or 0

The main parameters are described below:

- SLOPE: indicates the slope of the roof surfaces; a value of 20% is assigned

to all buildings.

- **WIDTH:** represents the width of the roof. This parameter is used by Iber to compute the time taken by water to flow along the roof surfaces; in order to avoid measuring each building individually, it was estimated as the square root of the footprint area. It should be noted that this parameter affects exclusively the timing of stormwater discharge from the roofs to the streets: the error introduced by this approximation therefore only partially influences the final result, by shifting the discharge hydrograph of some buildings slightly forward or backward in time.
- **MANNING:** is the Manning's roughness coefficient of the roof surfaces, assumed equal to 0.02 for all buildings.
- **STATE:** indicates the level of connection between the roof and the urban drainage network. Three options are available: `100%_connected`, in which all water is directed to the drainage network; `Partially_connected`, in which a percentage of the water is directed to the drainage network and the remainder is discharged onto the street; `Disconnected`, in which all water is discharged directly onto the street. In this project, all roofs were set to `Disconnected`, as the urban drainage network is not included in the model.
- **MH_ID:** is used to indicate which manhole the roof water should be conveyed to. In the present case, no manhole was assigned, as all water is discharged directly onto the street.
- **VOL_2_MH, VOL_2_STRE, VOL_INFIL:** represent respectively the percentage of water directed to the manholes, that discharged onto the street, and that lost to infiltration, set to 0%, 100%, and 0% respectively.

The construction of this file was carried out using QGIS, starting from the building footprint shapefile, part of the BDTRE dataset downloaded from the Geoportale of Regione Piemonte (2026). The first operation was the cleaning and simplification of the geometries, which in their original state would have been excessively complex for Iber to handle. Buildings with a footprint area smaller than 10 m² were removed, as they were considered negligible for the purposes

of the simulation. In densely urbanised areas, some geometries were further simplified by removing protrusions smaller than 2 metres, considered geometric details irrelevant for hydrodynamic purposes. This process yielded a shapefile with sufficiently simple geometries to be handled effectively by Iber. The second step was the construction of the attribute table, populated with the parameters described above. The final result is a shapefile containing all the buildings present in the study area, ready to be imported directly into Iber as input.

2.1.6 Culverts

In Iber, culverts are defined as structures having an inlet and an outlet connected by a straight segment. The characteristics required by the software are the positions of the inlet and outlet, the shape and dimensions of the cross-section, and the Manning's roughness coefficient of the channel, which was set to 0.015 for all culverts.

While the Manning's coefficient was assigned uniformly to all culverts, the remaining characteristics had to be determined individually for each structure. As no official datasets were available, all information was obtained by combining two main sources: Google Earth and the data contained in the thesis by Yepes (2020). In particular, the latter includes the photogrammetric survey of the inlets of two of the main underground channels, ensuring high geometric accuracy for these structures. The thesis material also contained images of the inlets and outlets of other channels, without survey data, which allowed the dimensions of those sections to be estimated by comparison with objects of known size present in the photographs. For the remaining culverts, the estimation was carried out based on the observation of satellite imagery and the three-dimensional visualisation of Google Earth, which allowed their approximate cross-section to be identified.

Regarding the positioning, since the culverts are inserted manually directly within Iber, the precise location of each structure will be defined during the model implementation phase, taking into account in particular the layout of the mesh generated in the surrounding area. At this stage, an approximate position is defined, derived from the observation of satellite imagery. A map showing all the culverts included in the model can be found in Figure 2.3.



Figure 2.3: Location of the drainage network within the study area.

It should be noted that the information collected through the methods described above inevitably introduces some errors into the model results. Inaccuracies in the dimensions of some cross-sections may affect the results in a non-negligible manner in cases where large volumes of water completely fill the culvert, causing

it to flow under pressure: this scenario is expected to occur only at high return periods (100 and 200 years). Further sources of error, which are difficult to eliminate given the inaccessibility of such information, concern the possibility that the culvert cross-section varies along its length, the presence of internal obstructions due to debris or other material, and the fact that the actual alignment may not be straight, making the schematisation adopted by Iber a simplification of the actual geometry. These uncertainties are considered acceptable for the purposes of this analysis, also in view of the fact that the information needed to resolve them is practically impossible to obtain without a direct on-site investigation. It should be noted, however, that should these uncertainties produce effects that are excessively discordant with the historical observations, they may be identified during the calibration phase as localised anomalies not attributable to the permeability parameters, and will need to be corrected through a revision of the geometry of the affected structures.

2.1.7 Catchment Hydrology

In the hydrological characterisation phase of the catchment, a series of hydrological data were processed in order to construct the design hyetographs capable of describing a rainfall event for each of the five return periods considered.

The source data were obtained from the Atlante delle Piogge Intense of ARPA Piemonte (2026a), a service that provides, at any point within the regional territory, the rainfall probability curves for assigned return periods, covering durations ranging from 10 minutes to 24 hours. The database underlying the service was built from the historical rainfall records of the Piedmont Region, collected between 1938 and 2010. Through the application of ordinary kriging on a 250 m square interpolation grid, maps of the parameters α and n of the rainfall probability curve and the growth factors K_T according to the Gumbel and GEV distributions were generated, for return periods ranging from 2 to 1000 years (ARPA Piemonte 2010).

The first step consisted of downloading all data related to the rainfall probability curves from the Atlante delle Piogge Intense (ARPA Piemonte 2026a), covering an area larger than the one under study. Using QGIS, the data grid was then

clipped to the extent of the catchment, so as to isolate exclusively the values contained within the project area, which were subsequently exported to a .csv file.

The subsequent processing phase was carried out using MATLAB, which allowed the development of a script capable of performing all the operations required to obtain the final hyetographs.

The script begins by extracting the variables needed to construct the design rainfall probability curves, following the criteria set out in the Atlante documentation (ARPA Piemonte 2010). In particular, the parameters a and n of the rainfall probability curve are extracted as the spatial average of all values in the selected grid, yielding $a = 29.20$ and $n = 0.26$. The growth factor K_T of the GEV distribution is also extracted for each of the five return periods considered, likewise as a spatial average. From these parameters, the script generates the rainfall probability curves following the formulas provided in the documentation. The result is shown in Figure 2.4, where all five curves are represented.

The script then proceeds with the construction of the design hyetographs using the alternating block method (Chow et al. 1988). This method allows the temporal distribution of rainfall intensity to be derived from the rainfall probability curve, ensuring that the cumulative rainfall depth over any sub-interval of the resulting hyetograph is consistent with that provided by the curve for the same duration. The operating principle is as follows: given the rainfall probability curve, the cumulative rainfall depth $P(d)$ is computed for multiples of the time interval Δt ; the difference between consecutive cumulative values gives the rainfall depth associated with each block. The blocks are then reordered so as to place the largest one at the centre of the hyetograph, arranging the subsequent ones alternately to the right and left of the peak in decreasing order, thus producing a hyetograph with a pronounced central peak, representative of an intense rainfall event.

The input parameters provided to the script are the total duration of the design rainfall and the time interval Δt of each block, set to 5 minutes. Regarding the total duration, the alternating block method requires it to be at least greater than the concentration time of the catchment. The latter was therefore estimated by applying four formulas available in the literature: Giandotti, Kerby–Hathaway,

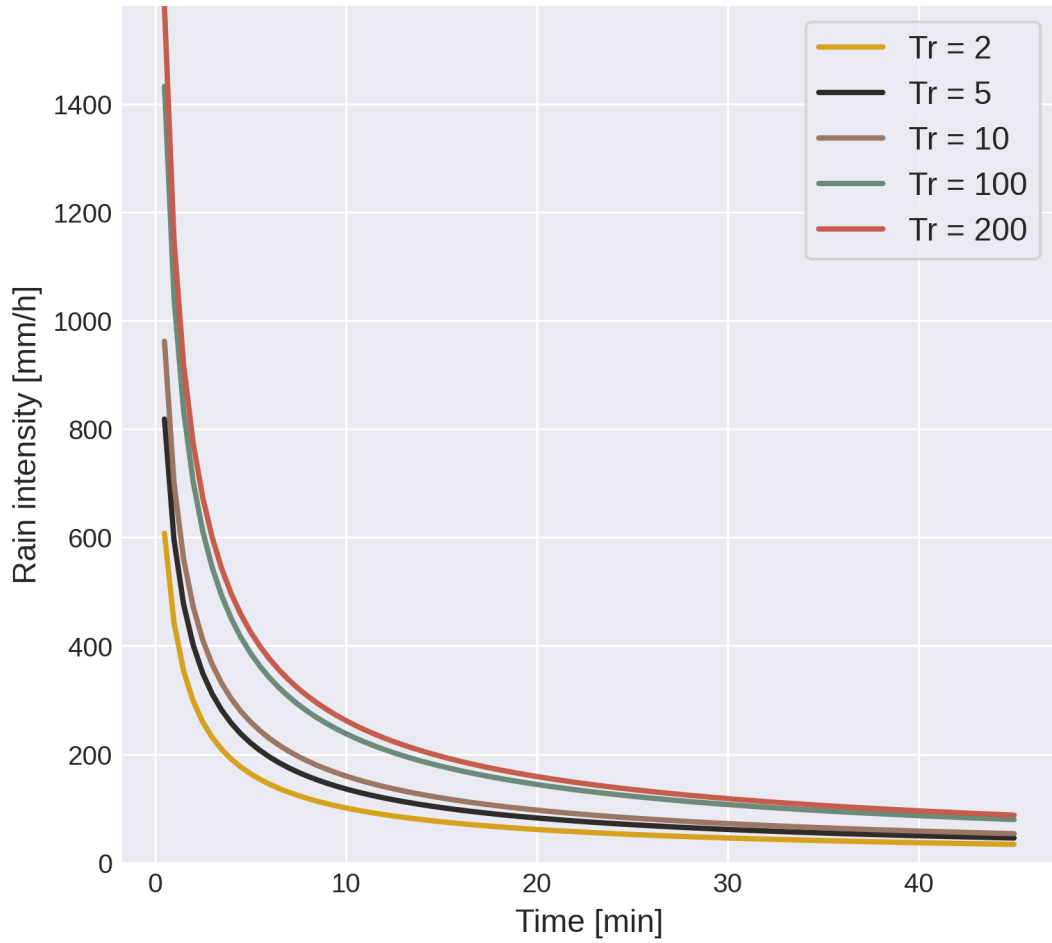


Figure 2.4: Rainfall probability curves (IDF curves) obtained for the catchment, for return periods of 2, 5, 10, 100, and 200 years.

Temez, and Kirpich. Each of these formulas computes this parameter following different criteria and requiring specific morphological data of the catchment. A detailed analysis of the application of each formula falls outside the scope of this thesis; the results are therefore simply reported in Table 2.4.

The mean of the four values amounts to approximately 46 minutes. A total design rainfall duration of 50 minutes was therefore adopted, rounded to the nearest multiple of Δt .

Upon applying the method, it was observed that the steep initial slope of the

Formula	T_c [min]
Giandotti	60.41
Kerby–Hathaway	37.87
Temez	50.38
Kirpich	37.83
Mean	46.62

Table 2.4: Concentration times estimated with the four adopted formulas.

rainfall probability curve generates a central peak that is excessively high relative to the rest of the hyetograph. In order to obtain a more regular distribution, more representative of a realistic rainfall event, it was decided to smooth this peak: the two largest central blocks were replaced by their arithmetic mean, thus ensuring a more gradual transition around the maximum. The five design hyetographs obtained, one for each return period, are shown in Figures 2.5, 2.6, 2.7, 2.8, 2.9.

It should finally be noted that the results of the processing were not exported to any specific file format, as the hyetographs will need to be entered manually into Iber during the model implementation phase.

2.2 Iber Model Implementation

Once all the necessary data and files have been collected, the construction of the model in Iber can begin. This phase does not consist only of feeding the previous information into the software, but also involves the configuration of a large number of internal parameters and model settings, as well as a series of choices to be made in order to obtain a simulation that reproduces reality as closely as possible.

The first step is the creation of the geometries defining the catchment to be analysed, which are divided into two categories: the areas representing the ground surface and those representing the buildings. The former are generated by importing the corresponding shapefile into Iber, assigning each element to a layer named *Terrain*. The buildings, on the other hand, are generated following a different procedure, through a dedicated Iber-SWMM command that imports

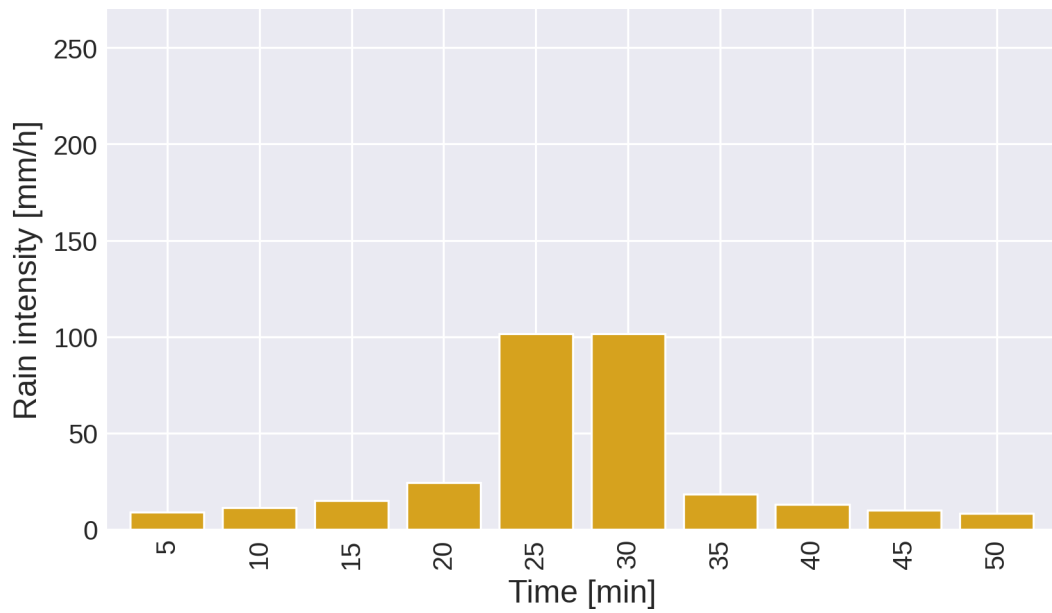


Figure 2.5: Design hyetographs obtained for 2 years return period.

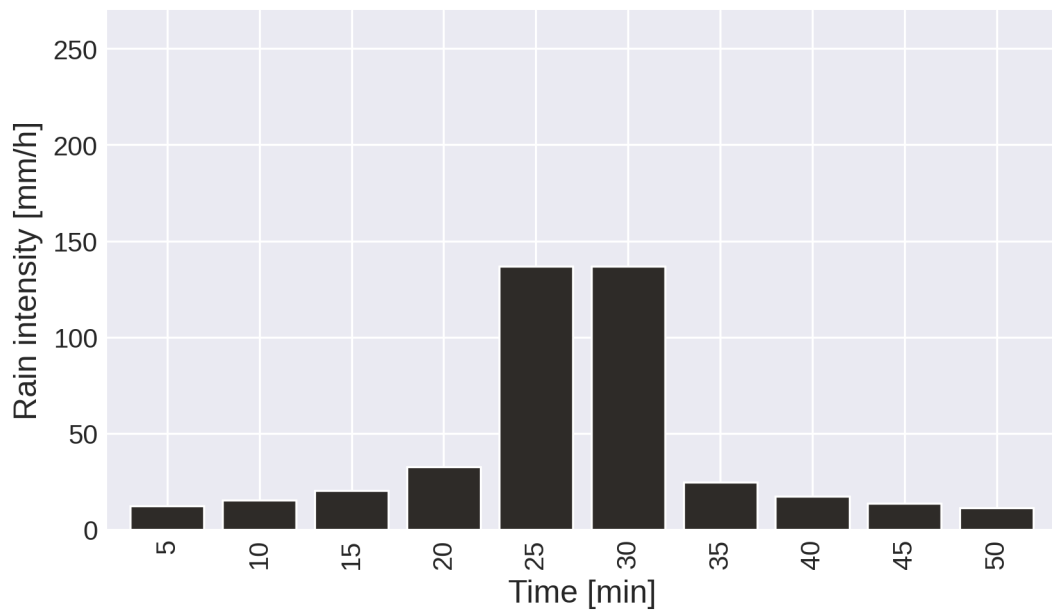


Figure 2.6: Design hyetographs obtained for 5 years return period.

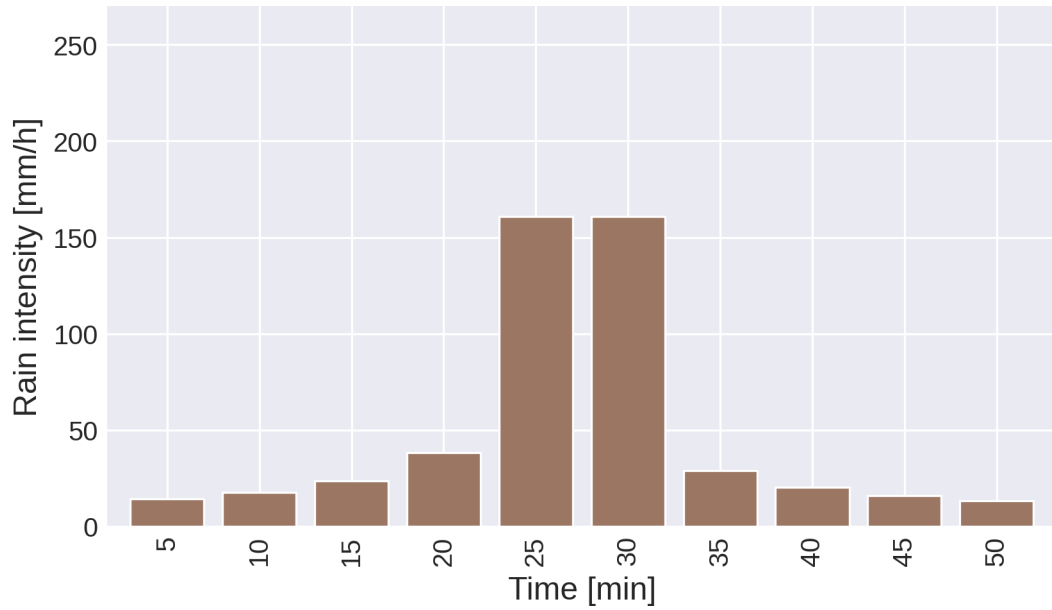


Figure 2.7: Design hyetographs obtained for 10 years return period.

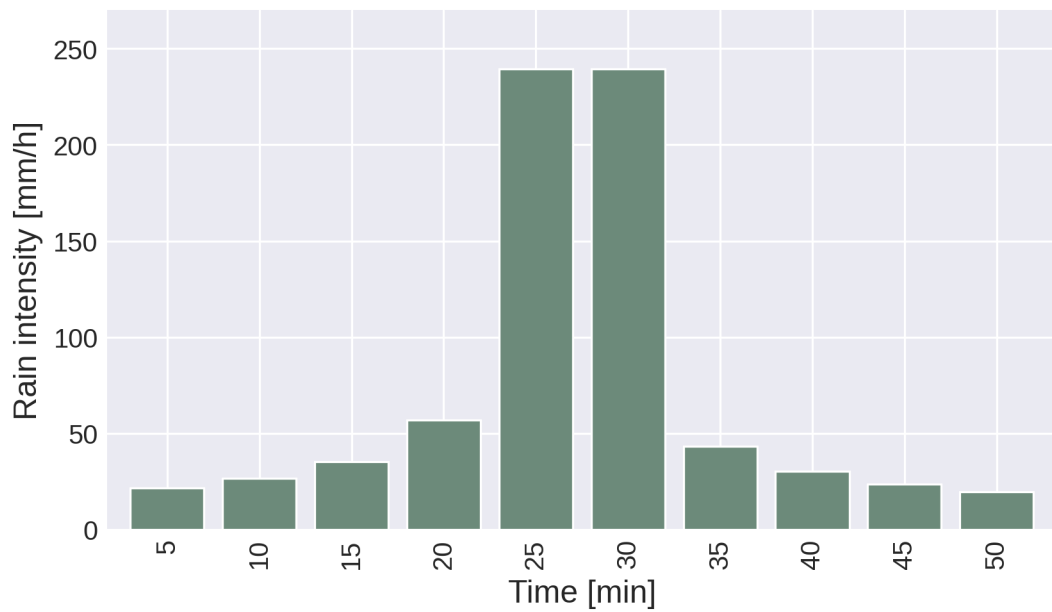


Figure 2.8: Design hyetographs obtained for 100 years return period.

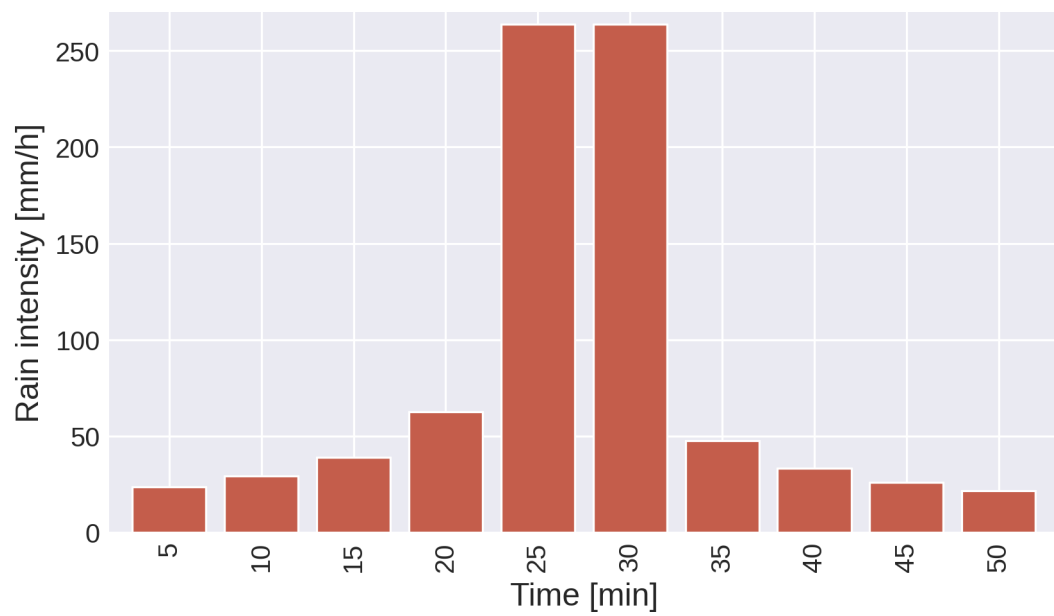


Figure 2.9: Design hyetographs obtained for 200 years return period.

the geometries and associates with them all the characteristics contained in the attribute table, already described in Section 2.1.5. The new elements, now inserted into the model, must be assigned to a different layer, named `Roof`, so that they can be distinguished during subsequent processing.

The boundary conditions are then assigned: the boundary lines between the geometry and the Po River are assigned a 2D outlet condition with supercritical or critical flow. This allows water to exit the model as if it were actually entering the Po River, without the downstream conditions influencing the hydrodynamic behaviour in the areas near that boundary. Indeed, with a supercritical condition, the effects of any flow perturbations propagate only downstream and do not travel back upstream. This condition is the one that most faithfully represents reality, since the Po River, throughout the project area, has a riverbed at a much lower elevation than the model boundary, ensuring that the water surface never reaches a level that could influence the flow conditions near the boundary. Along the entire remaining perimeter of the geometry, no boundary conditions are assigned; in this way, Iber treats these boundaries as impermeable walls. Since all these zones correspond to topographic divides, the morphological nature of the site would not allow water to exit through the boundaries, which would instead flow by gravity within the area, following the natural slopes.

The third phase concerns the generation of the mesh, that is, the actual geometry that Iber will consider during the simulation. This is one of the most critical steps in building the model, as it significantly affects both computation times and the accuracy of the results. The software solves the two-dimensional Saint-Venant equations (SWE) by integrating them locally over each individual element of the grid. Consequently, the adoption of a finer mesh ensures greater accuracy in describing flow fields and water depths, as well as higher spatial resolution of the results, but entails a considerable increase in computational cost and simulation times. It is therefore essential to find an optimal compromise between the desired spatial detail and the numerical complexity of the calculation. The final choice, already discussed in Section 2.1.1, adopted the following spatial resolution: 2 m for roads, rivers, and densely populated areas; 5 m for sparsely populated areas; and 15 m for natural areas (woodlands, fields, pastures, . . .). Given the irregularity of the geometries, an unstructured mesh was adopted, consisting of triangles

with the pre-defined dimensions where possible, but adapting to the shape of the geometry where necessary. The result can be observed in the example at Figure 2.10, and all geometric characteristics are reported in Table 2.5. It can be noted how the mesh is uniformly connected throughout, except at the boundaries between the buildings and the ground. This occurs because the buildings are standalone elements, treated separately also during the simulation phase, and therefore do not require a mesh connected to the rest of the catchment.

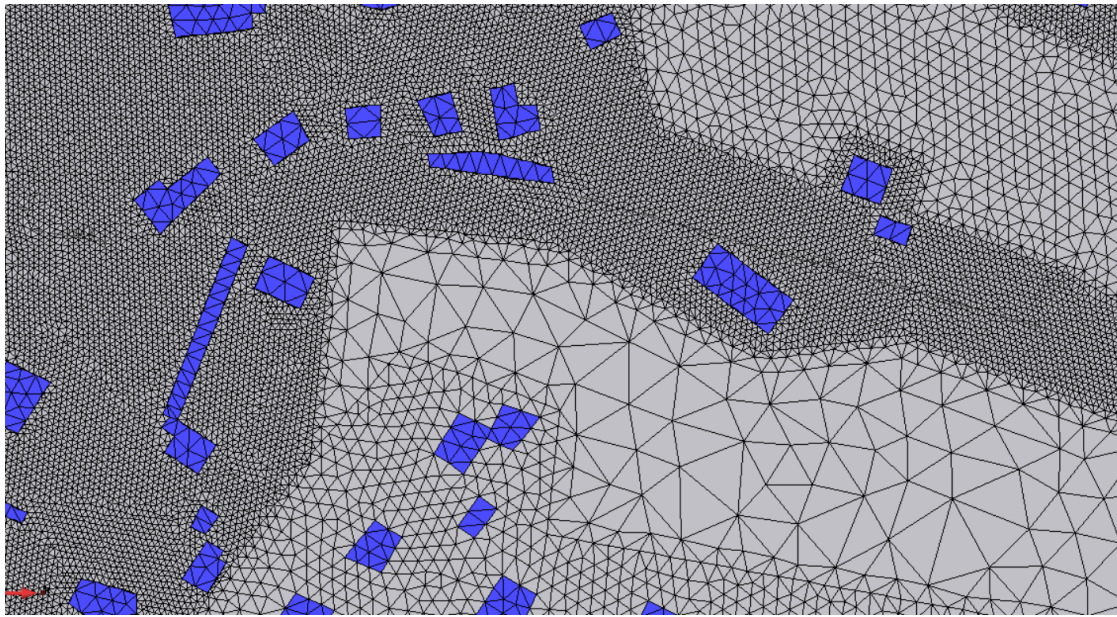


Figure 2.10: Example of the mesh generated in a part of the model. The parts in blue are the buildings.

Table 2.5: Geometric and mesh characteristics of the computational domain.

Parameter	Value
<i>Geometry</i>	
Number of points	26,149
Number of lines	26,212
Number of surfaces	1,769
<i>Mesh</i>	
Number of triangular elements	1,359,201
Number of nodes	730,238

The next step is the assignment of soil characteristics directly onto the generated mesh. Iber allows this operation to be performed automatically by directly importing the raster files processed in QGIS. The data relating to surface roughness (Manning's coefficient) and soil permeability (CN method) were therefore imported using the respective commands available in the software, using the files created previously.

Subsequently, the elevations of the mesh elements are assigned. Iber contains a dedicated function that allows the raster file of the Digital Elevation Model of the catchment to be imported, automatically assigning an elevation to each node of the mesh elements and deforming them along the vertical axis. The resulting three-dimensional model can be seen in Figure 2.11. This operation is performed only for the elements contained in the *Terrain* layer, as the buildings do not require elevation information.

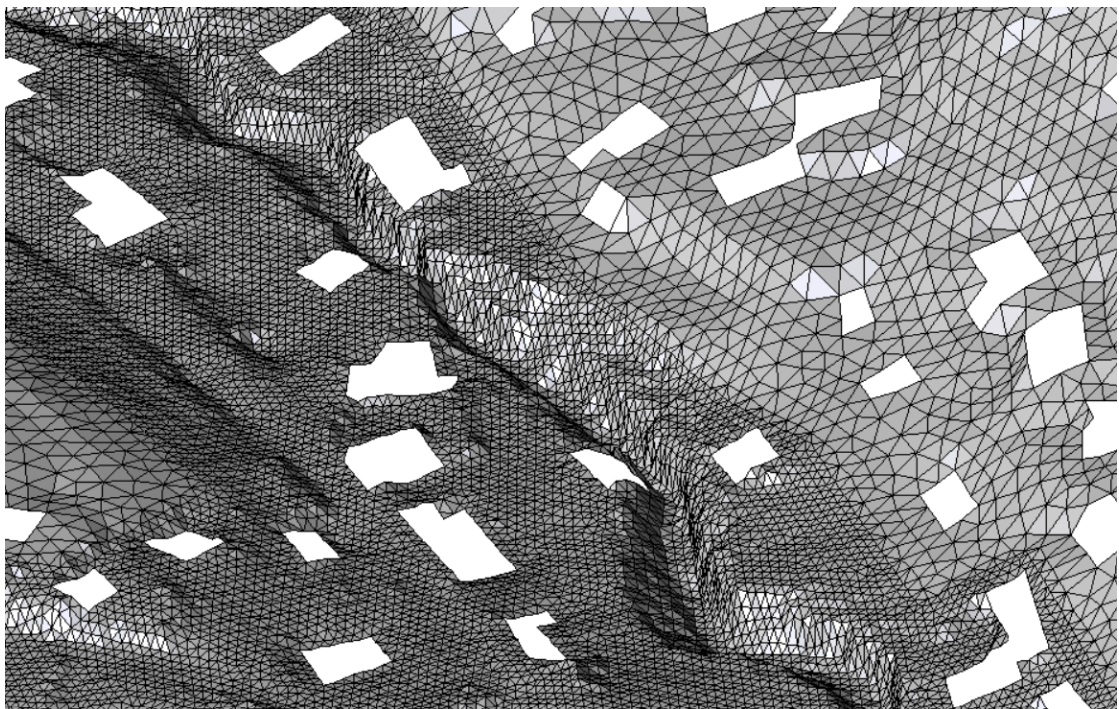


Figure 2.11: Example of the 3D rendering in a part of the model. The white spots are the buildings.

Once the three-dimensional model is ready, the culverts can be inserted. This operation must be performed manually, as their position is determined in relation

to the generated mesh. For each culvert to be inserted, the correct location was identified by comparing the satellite imagery (Figure 2.3) with the Iber model. Using the dedicated command in the software, the mesh elements representing the inlet and outlet were selected, and all the channel characteristics, already specified in Section 2.1.6, were entered.

Regarding the design rainfall, five different hyetographs were defined within the software, one for each return period. For each simulation performed, depending on the scenario under analysis, the corresponding hyetograph was assigned to all mesh elements so as to obtain a spatially uniform rainfall over the entire area.

The final phase concerns the definition of some parameters identified in the software as Problem Data. A detailed explanation of each of these parameters falls outside the scope of this thesis; therefore, only the Time Parameters will be specified. The maximum simulation time was set to 5000 s, a value sufficiently greater than the duration of the design hyetograph (50 minutes, equal to 3000 s) to allow the model to reach fully drained conditions before the end of the simulation. The timeseries time interval, which defines the frequency at which Iber saves the results, was set to 150 s.

The model thus created is complete and ready for computation. To speed up the simulations, the calculations were performed exploiting the power of an external GPU, which allowed the simulation times to be reduced by hundreds of times, reaching a total computation time of between 900 and 1000 seconds. However, as already mentioned, the model must still undergo a calibration process in order to produce reliable results.

Chapter 3

Model calibration

Calibration is a fundamental phase in the development of any hydrodynamic model. However accurate the model construction may be, some parameters cannot be determined with sufficient precision through direct measurements or tabulated values, and therefore require optimisation based on the comparison between simulated results and real observations from documented historical events. In this study, the parameter subject to calibration is exclusively the Curve Number (CN), which governs soil permeability and, consequently, the volume of surface runoff generated by rainfall. As discussed in Section 2.1.4, the tabulated TR-55 values represent an initial reference estimate, but do not account for the local specificities of the catchment; for this reason, they need to be optimised before the model can be considered reliable. The other model parameters (Manning's coefficient, geometry, and culverts) were determined through more direct methods and are considered sufficiently reliable without further adjustment at this stage.

The event chosen as the reference for calibration is the flood of 20 June 2007, which represents the ideal case study for this purpose. This event can be classified as a flash flood, characterised by brief but extremely intense rainfall: in just 90 minutes, the Giardini Reali rain gauge recorded 58.4 mm of precipitation, with a maximum hourly intensity of the same magnitude, corresponding to a return period of over 50 years. From a calibration standpoint, this event has two fundamental qualities. The first concerns the availability of high-resolution

meteorological data: detailed rainfall tables with a temporal resolution of up to 10 minutes are available, along with radar maps from the Bric della Croce system, which allow the spatial distribution and temporal evolution of the convective cell to be reconstructed with precision. The second concerns the richness of the documentation of ground-level effects: the technical report by ARPA Piemonte (2007) provides point measurements of water depth at numerous streets in the study area as well as qualitative descriptions of the flow energy, capable of stripping sections of asphalt and carrying large quantities of debris downstream. This combination of accurate input data and point observations of real-world effects makes the 20 June 2007 event an exceptionally valuable calibration tool, allowing the model to be constrained against a real scenario of extreme criticality, where the interaction between the minor drainage network and the urban fabric is documented in detail.

3.1 Reconstruction of the Historical Rainfall Event

The first step for the simulation of the event is the reconstruction of the historical hyetograph, using rainfall data recorded by the ARPA Piemonte weather stations during the June 20 event 2007.

The ARPA Piemonte report highlights how the rainfall event was characterized by strong spatial variability, and how the most affected area was the city's foothills. The short duration of the event, moreover, is confirmed by the fact that, for all stations, the maximum precipitation recorded in 3 hours is equal to that recorded in 24 hours, indicating that almost all of the rain fell in a very narrow time window. It is therefore important to use as a reference the data recorded by the nearest weather station, i.e. the Turin Giardini Reali station, located approximately 1.5 km from the study area. His position can be observed in Figure 3.1. The sub-hourly rainfall data recorded on the day of the event, downloaded from the official website of ARPA Piemonte, are reported in Table 3.1.

However, the radar data available for this event provide an important correction to the measurements of the rainfall station. The analysis of the maps produced by the Bric della Croce radar system, reported in the technical report of ARPA Piemonte, allows to reconstruct in detail the spatial distribution and evolution

Table 3.1: The sub-hourly rainfall data recorded on the day of the event by the meteorological station of Torino Giardini Reali.

Date	Time	Rain [mm]
20/06/2007	14:50	0.4
20/06/2007	15:00	2.0
20/06/2007	15:10	0.4
20/06/2007	15:20	0.0
20/06/2007	15:30	0.2
20/06/2007	15:40	1.6
20/06/2007	15:50	8.2
20/06/2007	16:00	13.4
20/06/2007	16:10	14.0
20/06/2007	16:20	9.0
20/06/2007	16:30	7.8
20/06/2007	16:40	6.0
20/06/2007	16:50	0.8
Total		63.8

storm cell storm. Below is the exact text contained in the document:

“L’evento pluviometrico trova riscontro anche nell’analisi delle mappe fornite dal Sistema di Rilevamento Regionale Radar Meteorologico che ha rilevato lo sviluppo della cella temporalesca su Torino e ne ha seguito costantemente l’evoluzione. [...] Si può notare il massimo di precipitazione nella zona tra precollina e collina (Madonna del Pilone) intorno a 100 mm, ben superiore ai 63.8 mm registrati dalla stazione di Giardini Reali.”

Here it is clear that in the hillside and foothill area of the city, the maximum precipitation was 100 mm during the event, and not 63.8 mm, as recorded by the Giardini Reali station (see Table 3.1). This discrepancy between the measurement of the rainfall station and the estimation of the radar is attributable to the localized nature of the convective cell, the whose nucleus was centered precisely on the foothill area rather than on the location of the station. To address this data discrepancy, a correction factor K was applied to the raw station data:

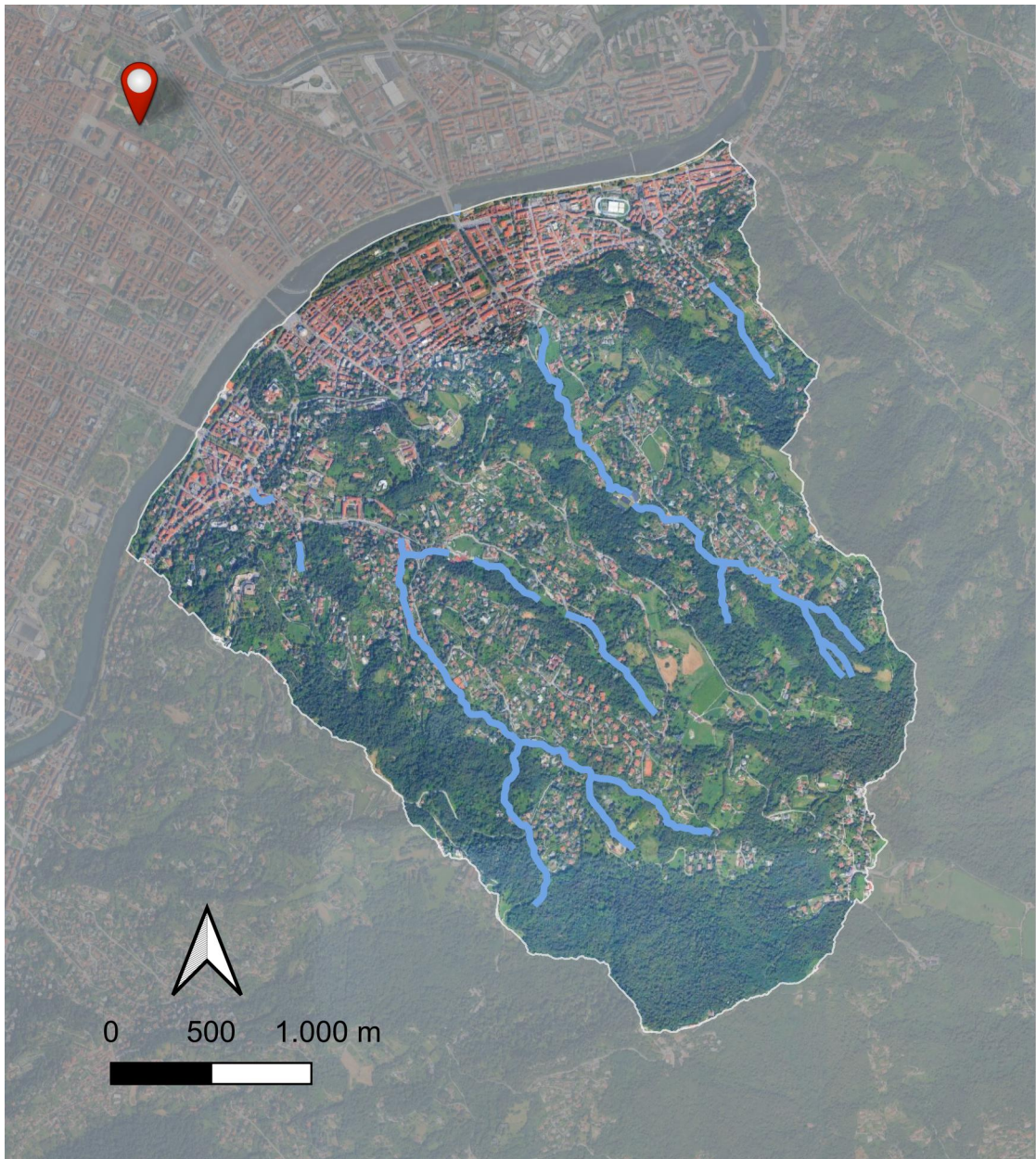


Figure 3.1: Location of the Turin Giardini Reali rainfall station (red marker), with respect to the project basin.

$$K = \frac{100}{63.8} = 1.566 \quad (3.1)$$

Applying this correction factor to the station's sub-hourly rainfall data we obtain

a hyetograph that reflects both the total amount of rain accumulated in the study area and the temporal distribution of the event. The correct data are given in Table 3.2, and the resulting hyetograph can be seen in Figure 3.2.

Table 3.2: Corrected sub-hourly rainfall data used for the calibration, obtained by applying the radar correction factor $K = 1,566$ to the data from the Giardini Reali station.

Time [min]	Rain [mm]	Corrected rain [mm]	Intensity [mm/h]
0	0.40	0.63	3.76
10	2.00	3.13	18.81
20	0.40	0.63	3.76
30	0.00	0.00	0.00
40	0.20	0.31	1.88
50	1.60	2.51	15.05
60	8.20	12.85	77.12
70	13.40	21.00	126.02
80	14.00	21.94	131.66
90	9.00	14.11	84.64
100	7.80	12.23	73.35
110	6.00	9.40	56.43
120	0.80	1.25	7.52
130	0.00	0.00	0.00
Total	63.8	100.0	

3.2 Calibration of the permeability coefficients

Once the hyetograph describing the historical event to be used for the simulation was obtained, it was inserted into the Iber model, already described in Section 2.2, and the simulation was launched. The results obtained describe the effect of the flood on the numerical model, in terms of water depth and flow velocity, at every point of the mesh. The calibration phase consists precisely in comparing these results with the real observations of the effects of the rainfall event, reported in the ARPA Piemonte technical report.

Several locations were therefore selected where the historical report provided

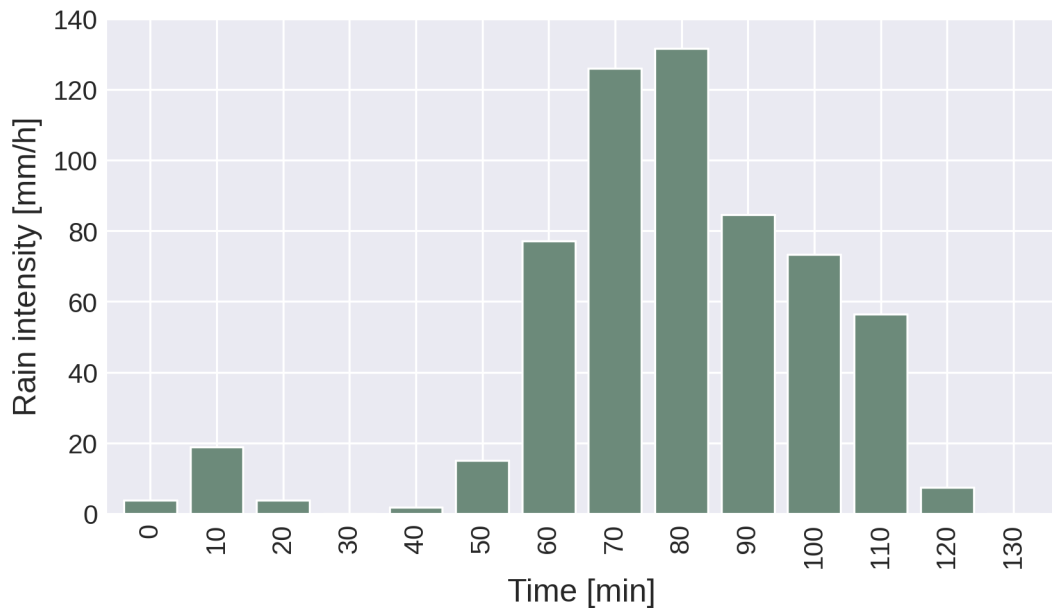


Figure 3.2: Design hyetographs of the rain event of 20 June 2007 used for the calibration.

data comparable with the results of the numerical simulation. By comparable data, it is meant data relating to real observations of water depth along the roads and squares contained in the considered catchment. All the information gathered was collected within a shapefile, processed using QGIS. The map showing the position of each observation point is reported in Figure 3.3. Table 3.3 allows the real water depth observations in these areas to be compared with the results obtained from the first simulation. It should be noted that all the values reported are not precise, but cover the range in which the maximum values are contained. In general, a strong discrepancy is observed between the two cases: the real event reports higher water depths in the majority of the areas, meaning considerably larger volumes of water compared to the numerical simulation. It is therefore clear that the permeability of the catchment, in the current state of the model, is too high with respect to what the reality should be.

To address this discrepancy, the permeability parameters can be modified by shifting from an ARC II condition to an ARC III condition. This operation allows

Table 3.3: Comparison between observed and simulated water depths at the calibration reference points for the event of 20 June 2007.

Location	Observed [cm]	Simulated [cm]
Corso Gabetti — high-middle part	40	20–30
Corso Gabetti — near Piazza Borromini	80	40–45
Corso Fiume — north side	30–40	10–15
Corso Fiume — south side	15–20	5–10
Via Tabacchi	70–80	6–10
Piazza Madonna del Pilone	70–80	70–80
Strada Val San Martino	40	30–35
Piazza Hermada	40	10–20
Via Gassino	30	15–20
Piazza Borromini — Po side	50–90	70–80
Piazza Borromini — hillside	20	10–15
Piazza Borromini — private properties	130	140
Piazza Gran Madre	20–30	15–20
Corso Moncalieri — north side	15	5
Corso Moncalieri — near Via Curtatone	30–40	15–20

all CN values to be increased while maintaining an effective distinction between the different land cover types, as described in Section 2.1.4. However, in order to apply this conversion, it will be necessary to evaluate the cumulative rainfall depth recorded during the 5-day window preceding the simulated event and the seasonal status of the vegetation (dormant vs. growing season) (United States Department of Agriculture, Soil Conservation Service 1972). Given that the event occurred in mid-June, the watershed conditions fall strictly within the “growing season” classification, where higher evapotranspiration rates typically require greater rainfall volumes to achieve full soil saturation. According to the standard SCS criteria, the threshold for shifting from the average ARC II condition to the saturated ARC III condition during the growing season is a cumulative 5-day antecedent rainfall exceeding 53.0 mm (Chow et al. 1988). The daily rainfall depth recorded in the five days prior to the 20 June event is summarised in Table 3.4.

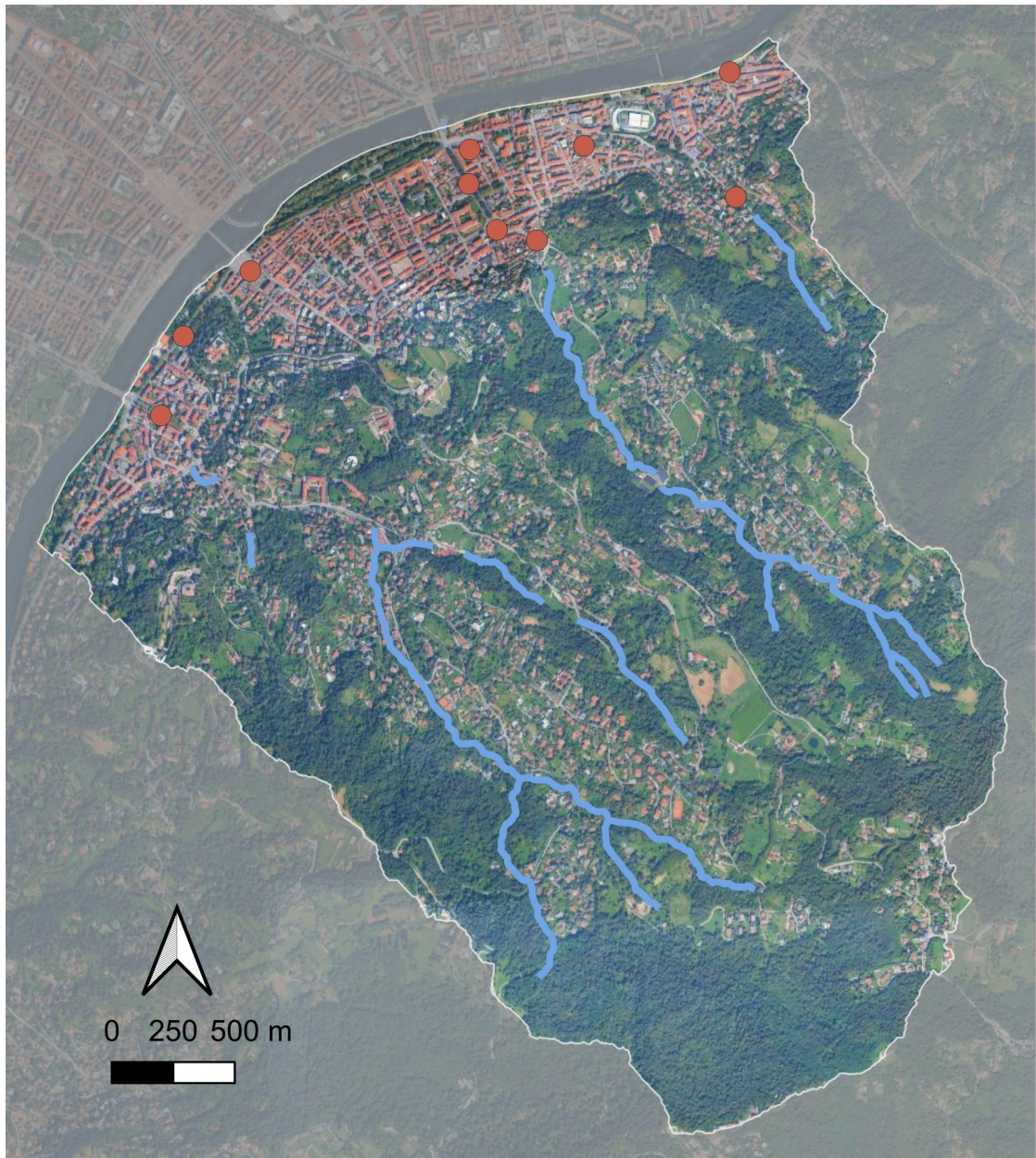


Figure 3.3: Position of the real calibration reference points for the event of 20 June 2007.

The cumulative rainfall strictly within the standard 5-day antecedent window (15–19 June) amounts to 7.0 mm. From a rigid application of the classic SCS tables, this volume would mathematically classify the basin under an ARC II state.

Table 3.4: Rainfall recorded at the Torino Giardini Reali station in the days preceding the event ARPA Piemonte 2026a.

Date	Rainfall [mm]
13 June	5.4
14 June	5.4
15 June	4.4
16 June	1.2
17 June	1.4
18 June	0.0
19 June	0.0
Total	17.8

However, in engineering practice and hydrological safety assessment, a broader temporal context must be evaluated, especially when dealing with consecutive low-intensity rainy days. Extending the observation window slightly to include 13th and 14th June yields an additional 10.8 mm of precipitation. Moreover, these precipitation data were recorded by the Torino Giardini Reali weather station. Although this station is geographically the closest to the study area, it fails to accurately capture the real rainfall distribution and total depth that actually fell over the selected sub-catchments. As previously demonstrated in the analysis of the main event on 20 June, this rain gauge significantly underestimates the real precipitation volumes due to the highly localised and convective nature of the storm. Furthermore, the ultimate objective of this hydrological modelling is to feed a subsequent hydraulic simulation aimed at assessing the flood hazard, where the adoption of an ARC III condition is a standard and highly recommended procedure, as it provides a necessary safety margin. These reasons justify the application of the ARC III condition in order to correctly calibrate the CN values.

The conversion of the values was performed by applying the mathematical formulation of Hawkins, following the formula:

$$CN_{III} = \frac{23 \cdot CN_{II}}{10 + 0.13 \cdot CN_{II}} \quad (3.2)$$

The results are reported in Table 3.5. The map in Figure 3.4 shows the spatial

distribution of the final CN values.

Table 3.5: Curve Number values assigned to each BDTRE land use class, for Hydrologic Soil Group C and calibrated considering an ARC III state

BDTRE land use class	CN
<i>Urban areas</i>	
Zone residenziali a tessuto continuo (S.L. > 80%)	100
Zone residenziali a tessuto discontinuo (S.L.: 50%–80%)	100
Zone residenziali discontinuo a media densità (S.L.: 30%–50%)	100
Zone residenziali discontinuo a bassa densità (S.L.: 10%–30%)	86
Zone residenziali discontinuo a densità molto bassa (S.L. < 10%)	84
Zone residenziali isolate	87
Aree industriali, commerciali e dei servizi	86
Aree industriali	84
Aree commerciali	84
Aree a servizi pubblici o privati	84
Reti stradali, ferroviarie e infrastrutture tecniche	84
Altre reti stradali	85
Cantieri	89
Aree verdi urbane	84
Incolti in aree urbane	84
Aree ricreative e sportive	85
<i>Agricultural areas</i>	
Seminativi in aree non irrigue	91
Foraggiere avvicendate	91
Vivai	91
Orticole	89
Vigneti	91
Frutteti e frutti minori	86
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Once the permeability parameters were updated to the ARC III condition, a new simulation of the 20 June 2007 event was performed. Table 3.6 reports the updated comparison between the observed and simulated water depths: with respect to the simulation prior to calibration, the simulated values increased considerably, approaching the available historical observations in a satisfactory manner.

In some locations, a slight exceedance of the observed values is recorded, which may indicate a local overestimation of the catchment response. It should however be considered that the reference observations do not constitute official instrumental measurements, but direct eyewitness accounts collected during the event, and as such carry an intrinsic uncertainty that cannot be quantified. Taking this limitation into account, together with the other sources of uncertainty already discussed during the model construction phase, the results obtained are considered acceptable for the purposes of this thesis, and the calibrated model

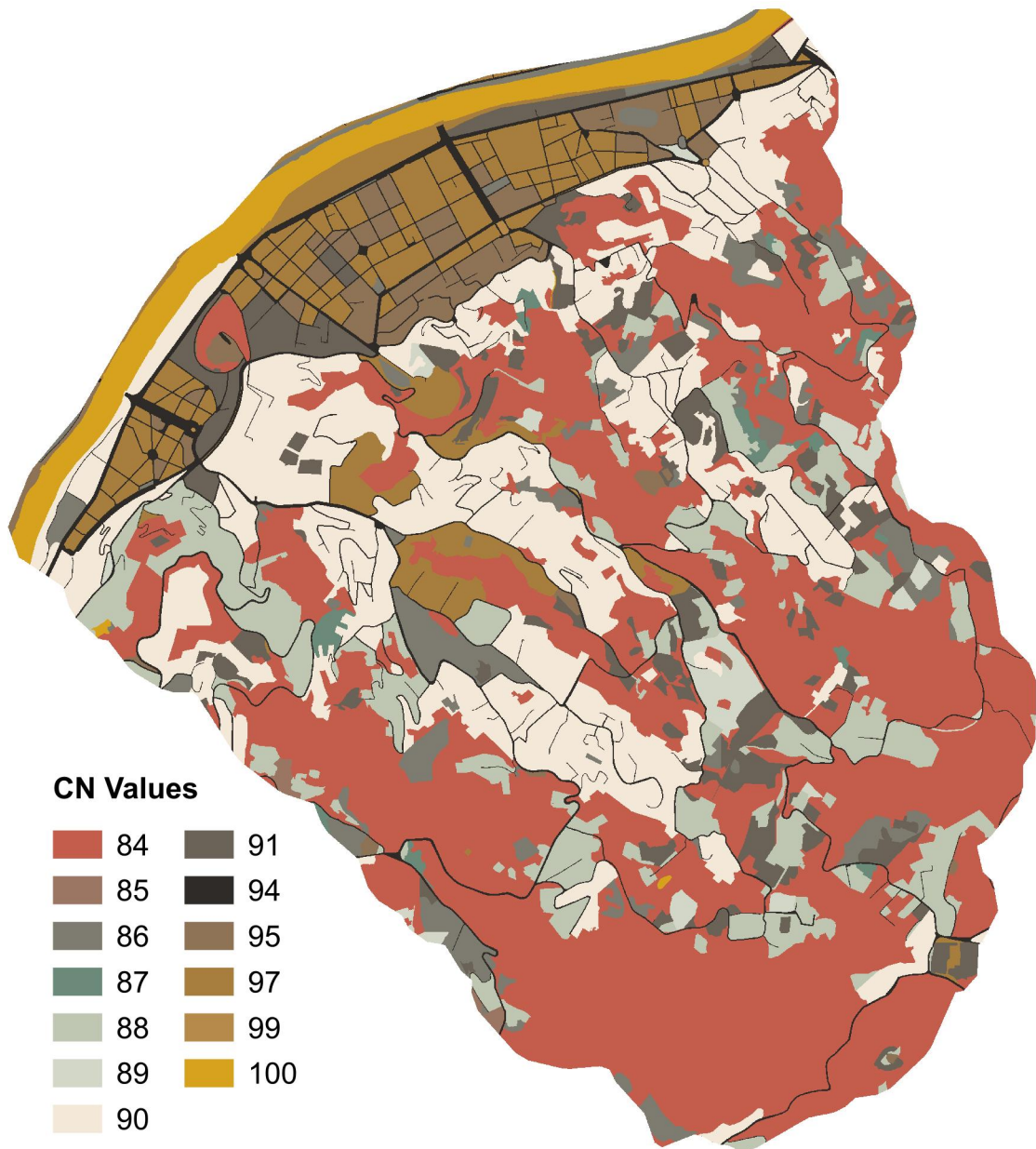


Figure 3.4: Spatial distribution of the calibrated values of Curve Number (CN)

is adopted as the basis for the development of the hydraulic hazard assessment.

Table 3.6: Comparison between observed and simulated water depths using the calibrated Iber model, for the event of 20 June 2007.

Location	Observed [cm]	Calibrated [cm]
Corso Gabetti — high-middle part	40	40–50
Corso Gabetti — near Piazza Borromini	80	70–80
Corso Fiume — north side	30–40	25–35
Corso Fiume — south side	15–20	15–20
Via Tabacchi	70–80	60–70
Piazza Madonna del Pilone	70–80	110
Strada Val San Martino	40	60
Piazza Hermada	40	20–30
Via Gassino	30	20–30
Piazza Borromini — Po side	50–90	90–100
Piazza Borromini — hillside	20	10–15
Piazza Borromini — private properties	130	150–160
Piazza Gran Madre	20–30	20–30
Corso Moncalieri — north side	15	20
Corso Moncalieri — near Via Curtatone	30–40	30–40

Chapter 4

Stability Criteria for Pedestrians and Vehicles

This chapter presents the methodological framework adopted for the hydraulic hazard assessment of the study area. The evaluation is carried out separately for two categories of exposure: pedestrians and vehicles. For each category, a specific set of stability criteria is applied, based on experimental studies that define threshold conditions beyond which the safety of individuals or vehicles can no longer be guaranteed in the presence of flood flows.

The criteria described in the following sections are expressed as functions of the maximum water depth and flow velocity outputs produced by the calibrated hydrodynamic model. Their application to the spatial domain was performed in QGIS through raster algebra operations using the Raster Calculator, processing the output raster files exported from Iber to generate the final hazard classification maps presented in Appendix B.

4.1 Pedestrian hazard criteria

The definition of a hazard criterion for pedestrians in urban environments requires a specific approach capable of adapting to the conditions of the area considered in this analysis. The nature of the basin, in fact, with its steep slopes and the

presence of secondary channels that convey water very rapidly into the highly urbanized foothill zone, causes flooding with shallow water depths accompanied by high flow velocities, typical of urban flash floods. Applying the safety thresholds considered in the most widely used methods, conceived for the fluvial regime, would therefore lead to a systematic underestimation of the actual risk to which the population is exposed in urban environments, making it necessary to adopt more restrictive thresholds calibrated on this specific phenomenon.

The instability of a pedestrian immersed in a water current can manifest itself through two distinct physical mechanisms. The first, defined as sliding, occurs when the hydrodynamic drag force generated by the horizontal flow exceeds the frictional resistance available at the interface between the sole of the footwear and the road pavement. The second mechanism, toppling, occurs instead when the moment induced by the current on the pedestrian's body exceeds the stabilizing moment linked to the individual's own body weight. The experimental studies conducted by Martínez-Gomariz et al. (2016), based on real-scale trials, showed that in urban contexts the dominant mechanism is generally sliding, a condition that is further aggravated by situational factors such as the use of inadequate footwear. A further critical element identified by the authors concerns the so-called *first step*, that is, the transition from the dry sidewalk to the flooded roadway, a phase in which the initial hydrodynamic shock is often more severe than traditional theoretical models take into account.

On the basis of this experimental evidence, obtained from a sample of 26 subjects aged between 6 and 55 years, the stability limit threshold for pedestrian circulation under conditions of urban pluvial flooding was identified as $v \cdot y = 0.22 \text{ m}^2/\text{s}$. This value, together with the independent depth and velocity limits discussed below, forms the basis of the three-level classification adopted in the present work for mapping pedestrian hazard. In the low hazard band, corresponding to $v \cdot y < 0.16 \text{ m}^2/\text{s}$, the hydrodynamic conditions do not impair the ability of the vast majority of the population to move. In the intermediate band, between 0.16 and $0.22 \text{ m}^2/\text{s}$, stability instead begins to be compromised: crossing the flow requires non-negligible physical effort and exposes the most vulnerable categories, such as children or the elderly, to a concrete risk. The high hazard condition is finally reached when at least one of the following circumstances

occurs: $v \cdot y > 0.22 \text{ m}^2/\text{s}$, or $y > 0.15 \text{ m}$, or $v > 1.88 \text{ m/s}$. The depth limit, equal to 0.15 m , was defined independently of the hydrodynamic product because, beyond this threshold, buoyancy and tripping mechanisms make movement nearly impossible regardless of the velocity value; similarly, the limit of 1.88 m/s represents the maximum velocity beyond which the maintenance of physical balance is no longer guaranteed, regardless of the water depth present.

The three hazard levels thus defined, summarized in Table 4.1, constitute the hazard criteria used in this study to obtain the pedestrian hazard maps. A visual representation of the three levels can be seen in Figure 4.1.

Table 4.1: Pedestrian hazard criteria.

Hazard level	Condition
Low	$v \cdot y < 0.16 \text{ m}^2/\text{s}$
Medium	$0.16 \leq v \cdot y \leq 0.22 \text{ m}^2/\text{s}$
High	$v \cdot y > 0.22 \text{ m}^2/\text{s}$ $y > 0.15 \text{ m}$ $v > 1.88 \text{ m/s}$

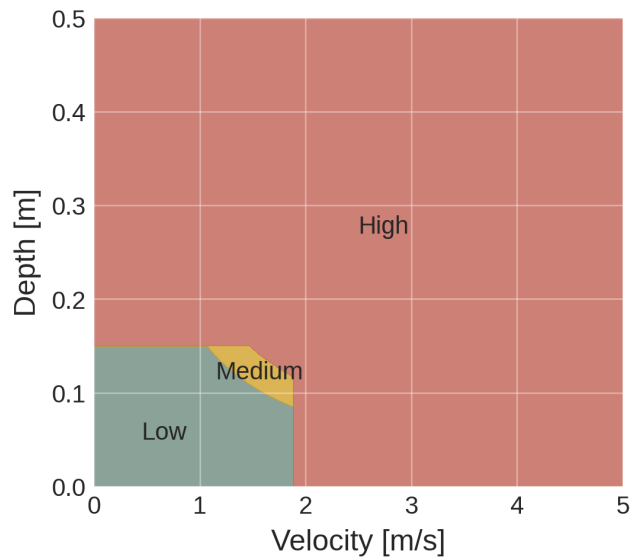


Figure 4.1: Hazard levels for pedestrians

4.2 Vehicle Stability Criteria

The assessment of vehicle stability under urban flooding conditions represents a fundamental component of the multi-level risk analysis adopted in this work, since an unstable vehicle does not only constitute a direct source of economic damage, but can transform into a genuine piece of debris, capable of obstructing drainage infrastructure or compromising the safety of pedestrians. The criteria most traditionally employed in the literature are based on static vehicle classifications, to which fixed thresholds are associated. Such an approach, however, does not account for the large variability in the physical and mechanical characteristics of vehicles actually in circulation. For this reason, the present study adopts the analytical-experimental methodology proposed by Martínez-Gomariz et al. (2017), which allows stability thresholds to be derived from the specific characteristics of a design vehicle.

The resistance of a vehicle to water flow is governed by the balance between the acting hydrodynamic forces and the ground reaction forces, and can fail according to three distinct physical mechanisms. The first, flotation, occurs under hydrostatic or low-velocity conditions, when the vertical upward force exerted by the water, that is the buoyancy force F_b , equals the weight force of the vehicle F_g ; it is worth noting that more recently manufactured vehicles, being increasingly watertight, require lower water depths to reach this condition. The second mechanism, sliding, occurs when the hydrodynamic drag force F_D exceeds the available frictional resistance F_R between the tyres and the road surface, and represents the most frequent failure mechanism in urban flash floods. The third mechanism, overturning, occurs when the moment generated by the drag force exceeds the stabilising moment associated with the vehicle's own weight; although this mechanism is less frequent than the previous ones in urban contexts, it remains a theoretical possibility at the higher velocities typical of the present case study.

To overcome the limitations of the rigid guidelines mentioned above, the present study adopts the methodology based on the Modified Stability Coefficient (SC_{mod}), which serves as a synthetic indicator of the intrinsic stability of a vehicle and is defined as

$$SC_{mod} = \left(\frac{GC \cdot M_c}{PA} \right) \cdot \mu \quad (4.1)$$

where GC represents the ground clearance of the vehicle [m], M_c its kerb weight [kg], PA the plan area (given by the product of length and width) [m²], and μ the friction coefficient between tyre and road surface. The experimental campaigns conducted on scale models (with scale ratios between 1:14 and 1:24) confirmed the existence of a strong linear correlation ($R^2 = 0.93$) between the coefficient SC_{mod} and the critical value of the hydrodynamic product $v \cdot y$ at which instability occurs, according to the relationship

$$(v \cdot y) = 0.0158 \cdot SC_{mod} + 0.32 \quad (4.2)$$

This is complemented by the calculation of the theoretical flotation depth h_b , that is the depth threshold beyond which the vehicle floats regardless of the flow velocity, expressed as

$$h_b = \frac{M_c}{\rho_w \cdot l_c \cdot b_c} + GC \quad (4.3)$$

For the application of this methodology to the specific case of the vehicle fleet in circulation within the study area, the Seat Ibiza was selected as the reference design vehicle. Its technical characteristics, in particular its relatively low kerb weight and ground clearance, make it one of the most widely used and hydraulically vulnerable models, thus ensuring that the resulting assessment is conservative and safety-biased. For this model, the theoretical flotation depth, calculated according to Equation 4.3, amounts to $h_b = 0.28$ m.

Since the friction coefficient μ constitutes the most uncertain parameter of the entire formulation, the hazard classification adopted here introduces an uncertainty zone, delimited by a lower value ($\mu = 0.25$, representative of wet or degraded asphalt) and an upper value ($\mu = 0.75$, representative of dry asphalt in good condition). Applying these two limit values to Equation 4.2 yields the hazard levels employed in the present work: in the low hazard zone, corresponding to $v \cdot y < 0.40$ m²/s, the design vehicle is expected to remain stable both while moving and while stationary; in the intermediate zone, corresponding to the uncertainty

band between 0.40 and $0.55 \text{ m}^2/\text{s}$, stability depends critically on the actual road surface conditions and the effective tyre grip; the high hazard condition is finally reached when $v \cdot y > 0.55 \text{ m}^2/\text{s}$, or when the water depth exceeds the flotation threshold $y > 0.28 \text{ m}$, a situation in which the vehicle, according to Archimedes' principle, tends to float and be carried away by the current, posing a severe risk both to urban infrastructure and to the safety of people.

The three hazard levels thus defined are summarised in Table 4.2 and constitute the criterion applied in the present study to classify the results of the hydraulic simulations performed in Iber. A visual representation of the three levels can be seen in Figure 4.2.

Table 4.2: Vehicle hazard classification criteria.

Hazard level	Condition
Low	$v \cdot y < 0.40 \text{ m}^2/\text{s}$
Medium	$0.40 \leq v \cdot y \leq 0.55 \text{ m}^2/\text{s}$
High	$v \cdot y > 0.55 \text{ m}^2/\text{s}$ $y > 0.28 \text{ m}$

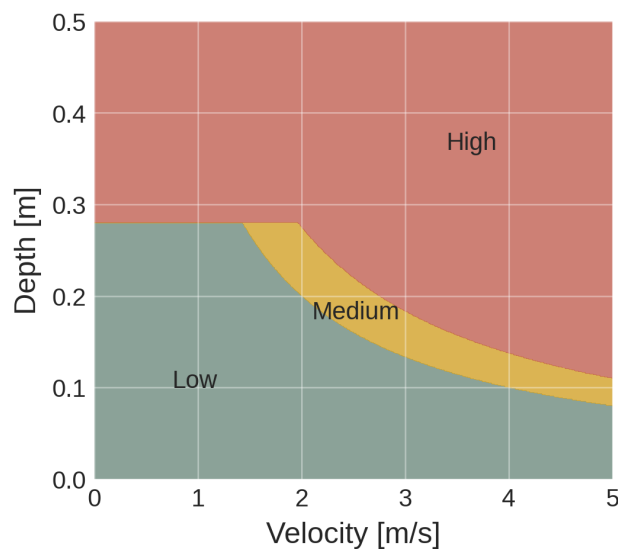


Figure 4.2: Hazard levels for vehicles

Chapter 5

Results and discussion

This chapter presents and discusses the results obtained from the hydrodynamic simulations and the subsequent hazard assessment. The outputs are organised into two sets of maps, both provided in the appendices: the inundation maps, showing the maximum water depth and flow velocity fields for each of the five return periods considered (Appendix A), and the hazard maps for pedestrians and vehicles (Appendix B). Together, these maps provide a comprehensive spatial overview of the hydraulic response of the catchment and allow the most critical areas of the urban fabric to be identified.

The spatial distribution of the flooded areas identified by the model is consistent with the historical records available for the study area. The main reference sources are the ARPA Piemonte technical reports on the floods of 20 June 2007 (ARPA Piemonte 2007) and 7 November 2011 (ARPA Piemonte 2011), as well as the thesis of Ponzio (2013), which collects accounts from historical newspaper articles. The critical areas highlighted by the simulations correspond closely to those historically affected by flooding, providing further confidence in the reliability of the calibrated model.

In all simulated scenarios, three main inundation areas are identified, each located immediately downstream of the culverted terminal section of one of the three analysed watercourses. This confirms that the primary cause of flooding in this area is the limited capacity of the underground channels, which during extreme events reach full capacity and shift the hydraulic domain onto the street

network, as discussed in Section 1.1.

The first of the three areas refers to Rio Val Salice and Rio Pavese. In all the maps it can be clearly observed how, downstream of these streams, very significant flooding forms, involving first and foremost Viale Enrico Thovez, where the velocities generated for a return period of 100 years exceed 5 m/s, leading to a high hazard for both vehicles and pedestrians already at very low return periods. The water then flows along Via Crimea, eventually causing flooding in Corso Fiume, where it is the water depth that causes problems: up to 20 cm for a return period of 100 years. These effects can be clearly observed in Figure 5.1, which shows zoomed-in views of the results for the 100-year return period, displaying the water depth and the water velocity. The hazard generated by this flooding is shown in Figure 5.2.

The second critical area is located downstream of Rio Val San Martino. The first road affected is the terminal section of Strada Val San Martino, where all the water that the underground channel is unable to handle is discharged. Here both the water depth and the velocity reach extremely high values: for a return period of 10 years, more than 20 cm of water is observed with velocities approaching 4 m/s, while for a return period of 100 years, half a metre of water and 5 m/s of velocity are exceeded. The flow runs as far as Piazza Hermada and floods the whole of Corso Gabbetti, whose terminal section is one of the most critical in terms of water depth, as also reported in historical accounts. The water can reach 80 cm in Piazza Borromini for the highest return periods (100 and 200 years), before flowing out onto Corso Casale in a north-east direction. The water depth and water velocity data, for a return period of 100 years, can be observed in Figure 5.3, and the corresponding hazard levels in Figure 5.4.

Finally, Rio Valpiana is the cause of the third critical area: the transition from an open-air channel in a natural environment to a piped channel adjacent to a heavily urbanized area causes flooding that spills onto Via Tabacchi, where strong velocities are generated already at low return periods (2.5 m/s for a Tr of 5 years and 3 m/s for a Tr of 10 years). The slope of this road does not allow water to accumulate, and indeed even at the highest return periods 18 cm is not exceeded. The water flows as far as Piazza Carrara, spilling onto Corso Casale. The latter, located at the end of the basin in an area lower than the rest,

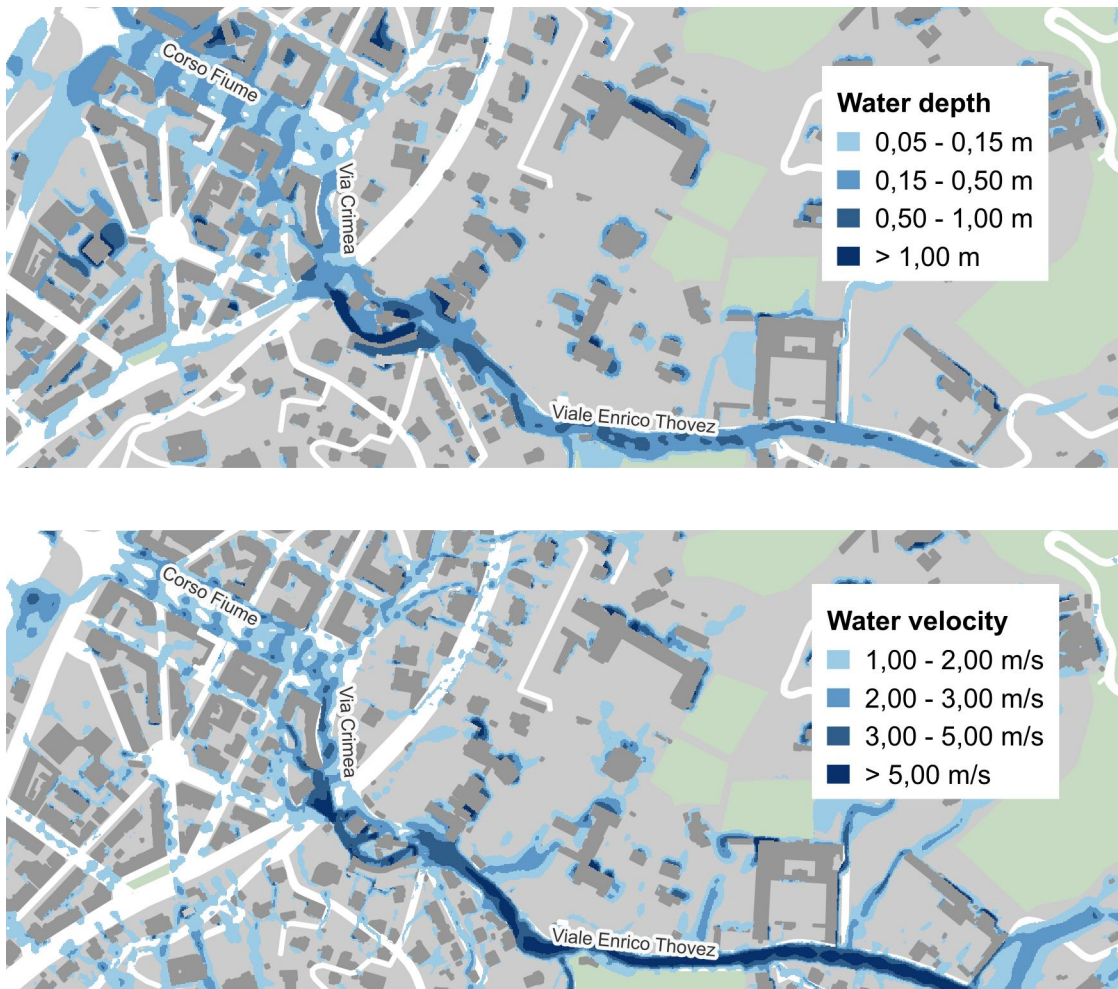


Figure 5.1: Simulated water depth and flow velocity ($T_r = 100$ years) in the area affected by the flooding of Rio Val Salice and Rio Pavese, along Viale Enrico Thovez and Corso Fiume.

undergoes severe flooding phenomena, with high water depth but low velocity, which extend as far as Piazza Madonna del Pilone. Here, for a return period of 100 years, 80 cm is exceeded, as confirmed by historical accounts of the flood of 20 June 2007. Figure 5.5 shows the water depth and water velocity for a return period of 100 years, and the corresponding hazard levels are found in Figure 5.6.



Figure 5.2: Pedestrian and vehicle hazard levels ($T_r = 100$ years) in the area affected by the flooding of Rio Val Salice and Rio Pavese.

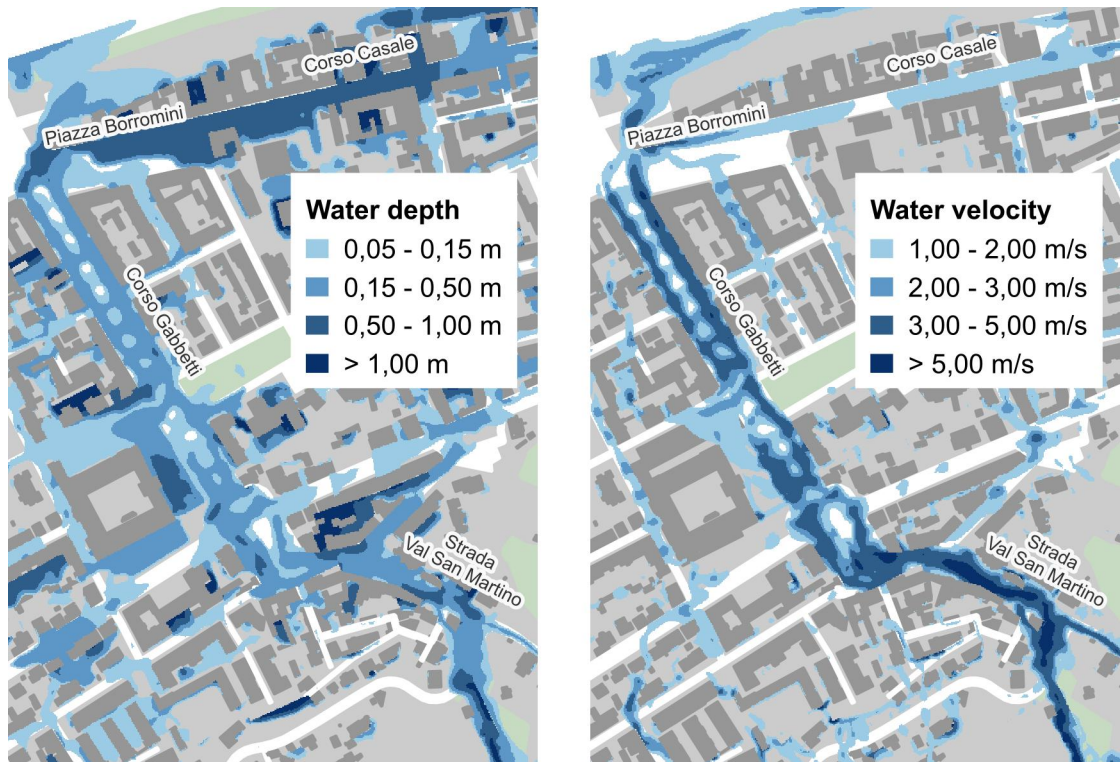


Figure 5.3: Simulated water depth and flow velocity ($T_r = 100$ years) in the area affected by the flooding of Rio Val San Martino, along Strada Val San Martino, Piazza Hermada, and Corso Gabbetti.



Figure 5.4: Pedestrian and vehicle hazard levels ($T_r = 100$ years) in the area affected by the flooding of Rio Val San Martino.

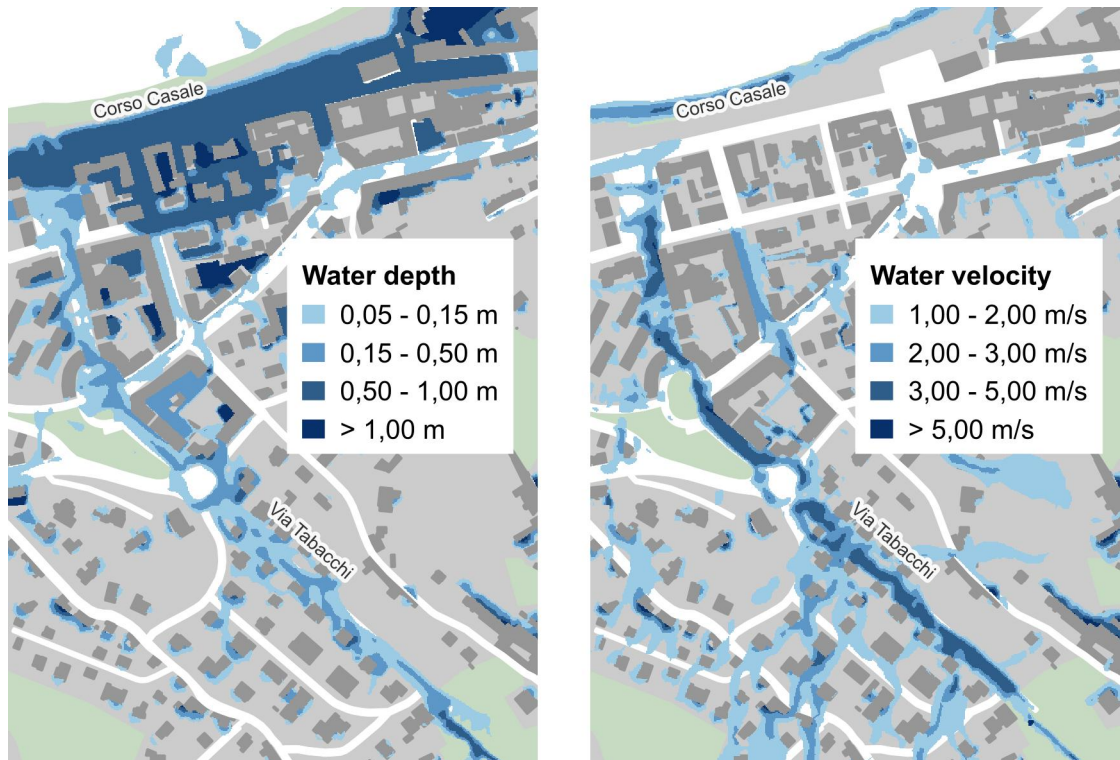


Figure 5.5: Simulated water depth and flow velocity ($T_r = 100$ years) in the area affected by the flooding of Rio Valpiana, along Via Tabacchi, Piazza Carrara, and Corso Casale.

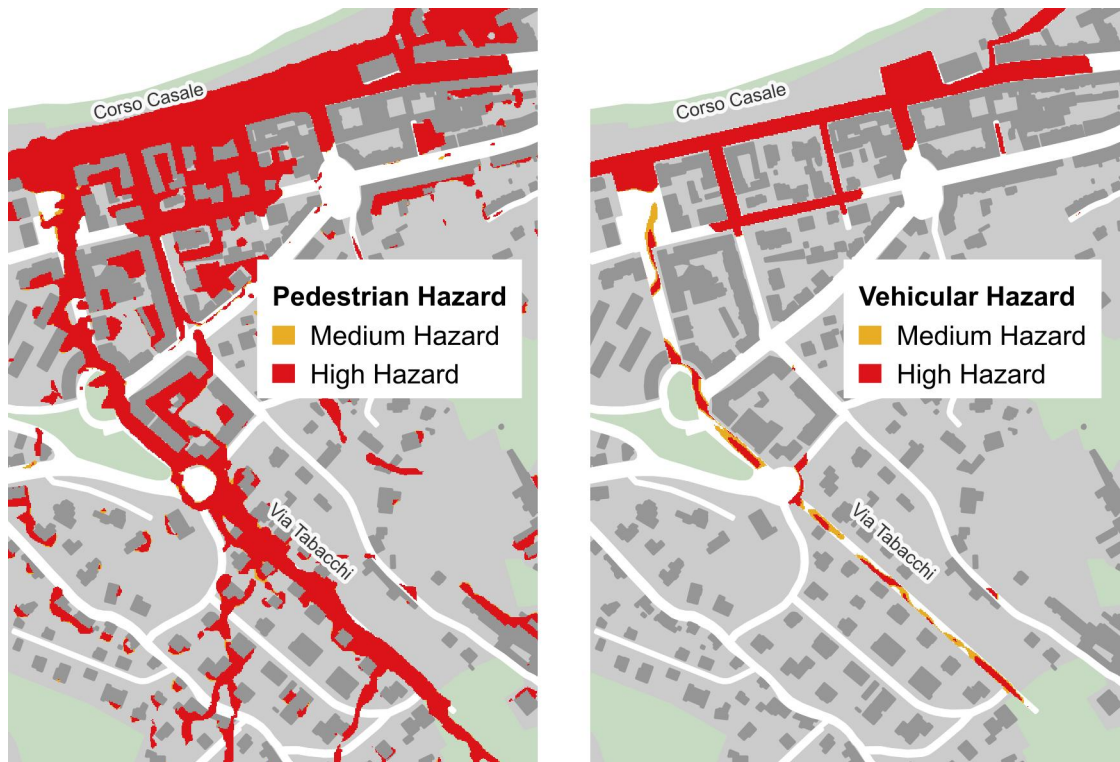


Figure 5.6: Pedestrian and vehicle hazard levels ($T_r = 100$ years) in the area affected by the flooding of Rio Valpiana.

Chapter 6

Conclusions

This thesis has allowed the development of a rigorous methodology for the assessment of hydraulic hazard in an urban context, applied to the foothill belt of Turin. Through the use of Iber, a two-dimensional hydrological modelling software, it was possible to reconstruct the hydrodynamic response of the Rio Val Salice, Rio Pavese, Rio Val San Martino and Rio Valpiana catchments, with a high spatial resolution.

The calibration process, carried out on the basis of the flood of 20 June 2007, proved fundamental in ensuring the reliability of the model. This allowed the optimisation of the soil permeability parameters (Curve Number), based on the comparison between the simulated water depths and the direct observations documented in the ARPA Piemonte reports. The model obtained after calibration is therefore capable of faithfully replicating the flood dynamics of the territory.

The results confirm that the main critical issue of the area lies in the insufficient drainage capacity of the culverted reaches of the secondary watercourses. During intense rainfall events, the obstruction or saturation of these conduits causes the hydraulic domain to shift directly onto the street network, turning the city streets into open channels. The simulations allowed the most critical areas to be identified, such as Viale Thovez, Corso Gabetti and Piazza Madonna del Pilone, where the combinations of flow velocity and water depth generate hazardous conditions even at low return periods.

The integration of the hydrodynamic outputs with the experimental stability

criteria of Martínez-Gomariz et al. for pedestrians and vehicles has made it possible to define hazard in terms of real safety for citizens and urban mobility. The maps produced show how, even at low return periods, large portions of the street network reach high hazard conditions, highlighting the need for targeted interventions aimed at improving flood management capacity.

Although the model contains some limitations, such as the absence of the urban sewer network and the geometric imprecision in the definition of some culverts, the results represent conditions very similar to real ones and conservative by definition, thus constituting a solid basis for territorial planning and civil protection decisions. The maps produced offer a quantitative representation of the hydraulic vulnerability of the Turin foothill belt, a tool that can be updated and refined in future studies, for example through the integration of the sewer network or the extension of the analysis to other catchments of the hillside.

Appendix A

Inundation Maps

Simulated Water Depth 2 Year Return Period



Figure A.1: Water depth map for a return period of 2 years.

Simulated Water Depth 5 Year Return Period



Figure A.2: Water depth map for a return period of 5 years.

Simulated Water Depth

10 Year Return Period



Figure A.3: Water depth map for a return period of 10 years.

Simulated Water Depth 100 Year Return Period

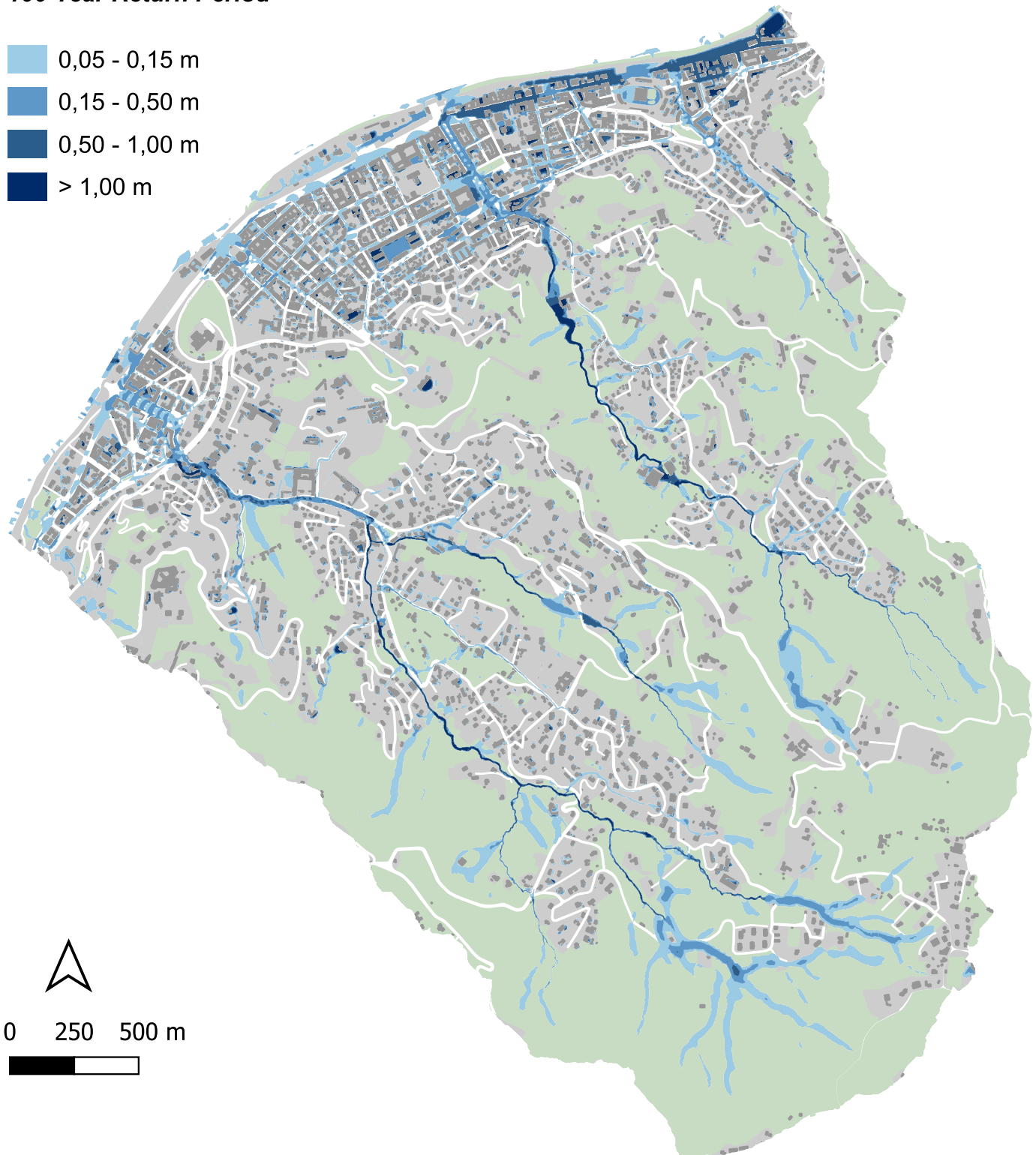


Figure A.4: Water depth map for a return period of 100 years.

Simulated Water Depth 200 Year Return Period

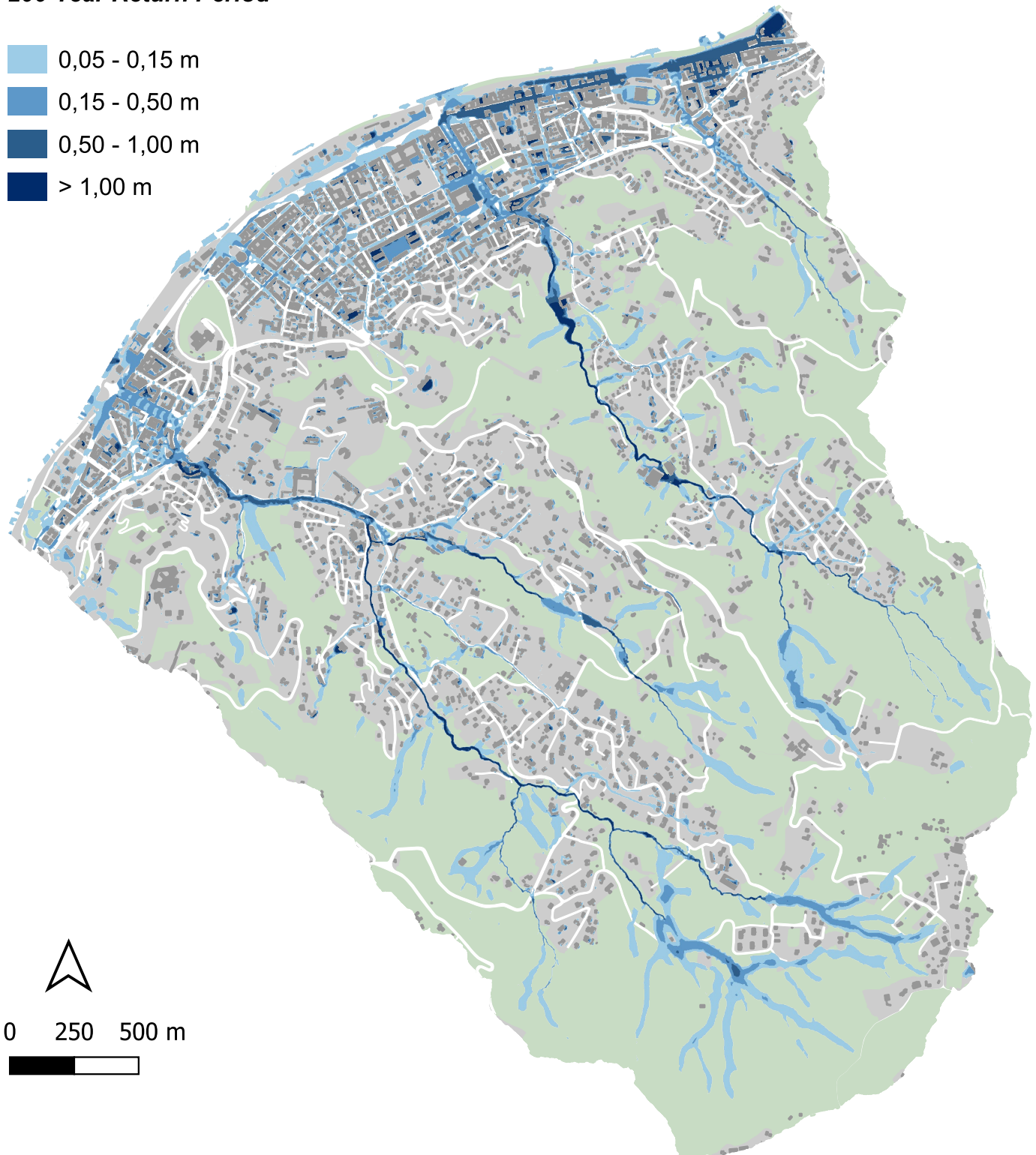


Figure A.5: Water depth map for a return period of 200 years.

Simulated Water Velocity

2 Year Return Period



Figure A.6: Water velocity map for a return period of 2 years.

Simulated Water Velocity

5 Year Return Period



Figure A.7: Water velocity map for a return period of 5 years.

Simulated Water Velocity

10 Year Return Period



Figure A.8: Water velocity map for a return period of 10 years.

Simulated Water Velocity

100 Year Return Period



Figure A.9: Water velocity map for a return period of 100 years.

Simulated Water Velocity 200 Year Return Period

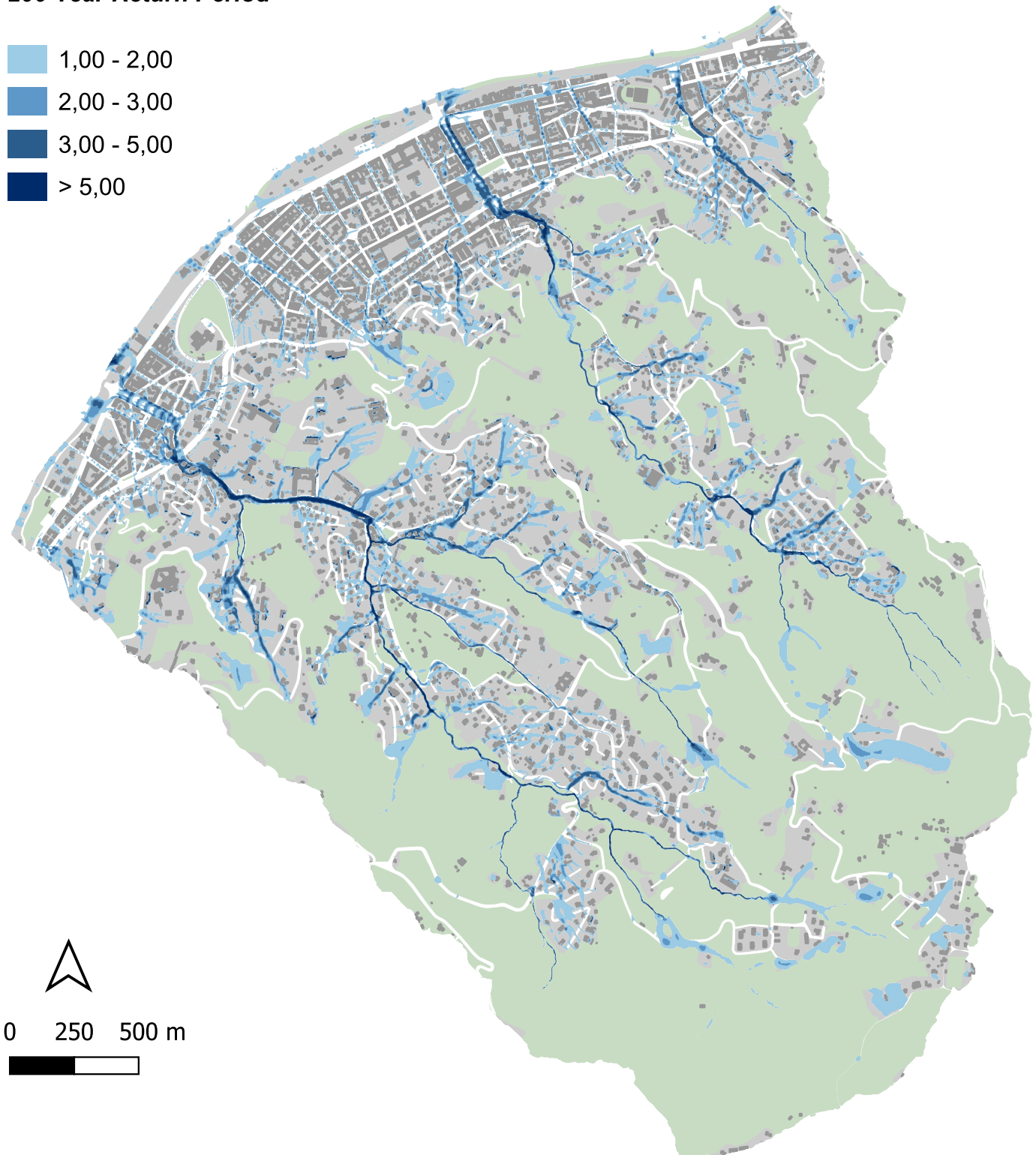


Figure A.10: Water velocity map for a return period of 200 years.

Appendix B

Hazard Maps

Flood Hazard for Pedestrians

2 Year Return Period

Hazard Levels

Medium Hazard

High Hazard



Figure B.1: Pedestrian flood hazard map for a return period of 2 years.

Flood Hazard for Pedestrians

5 Year Return Period

Hazard Levels

Medium Hazard

High Hazard

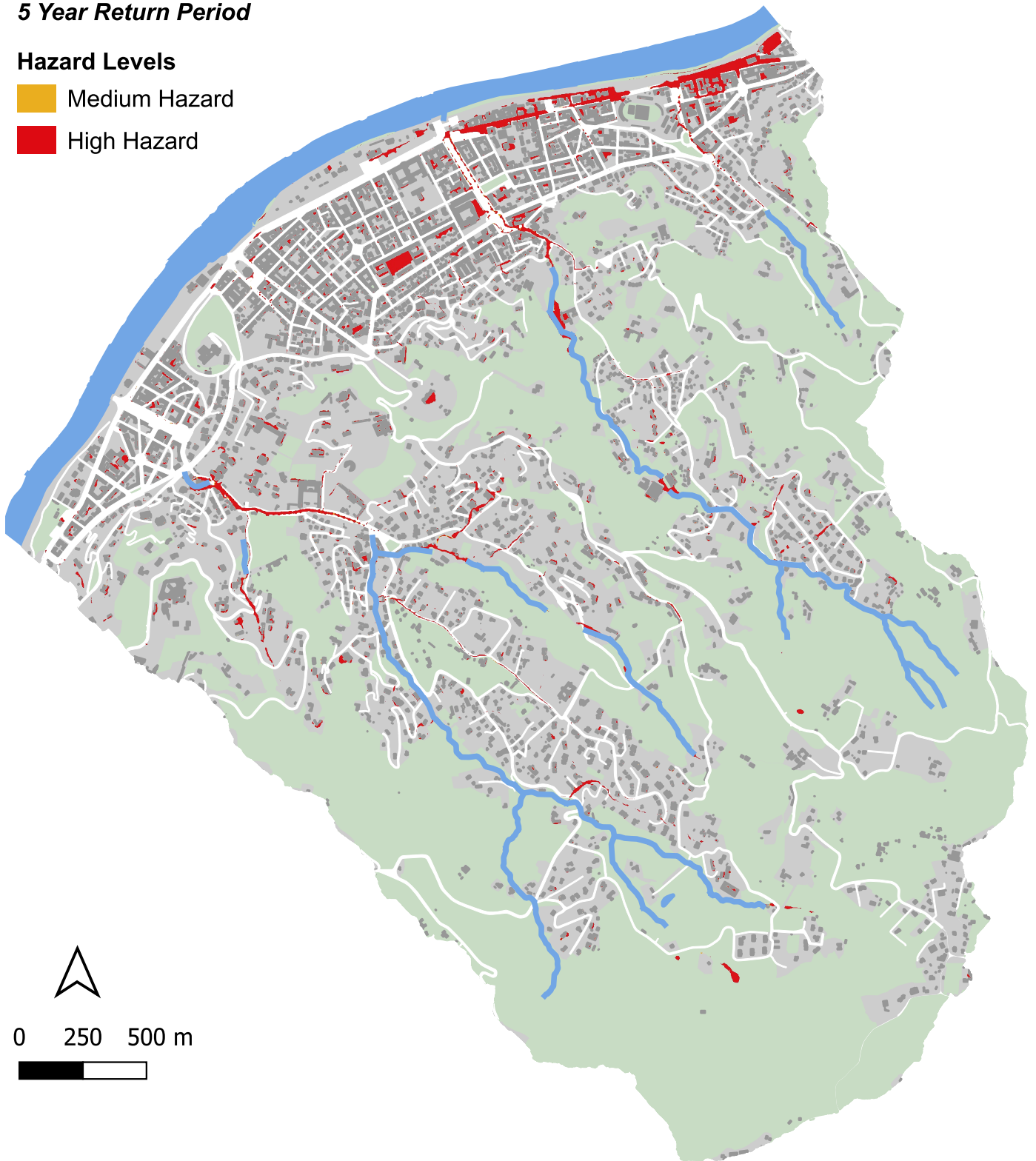


Figure B.2: Pedestrian flood hazard map for a return period of 5 years.

Flood Hazard for Pedestrians

10 Year Return Period

Hazard Levels

Medium Hazard

High Hazard



Figure B.3: Pedestrian flood hazard map for a return period of 10 years.

Flood Hazard for Pedestrians

100 Year Return Period

Hazard Levels

Medium Hazard

High Hazard

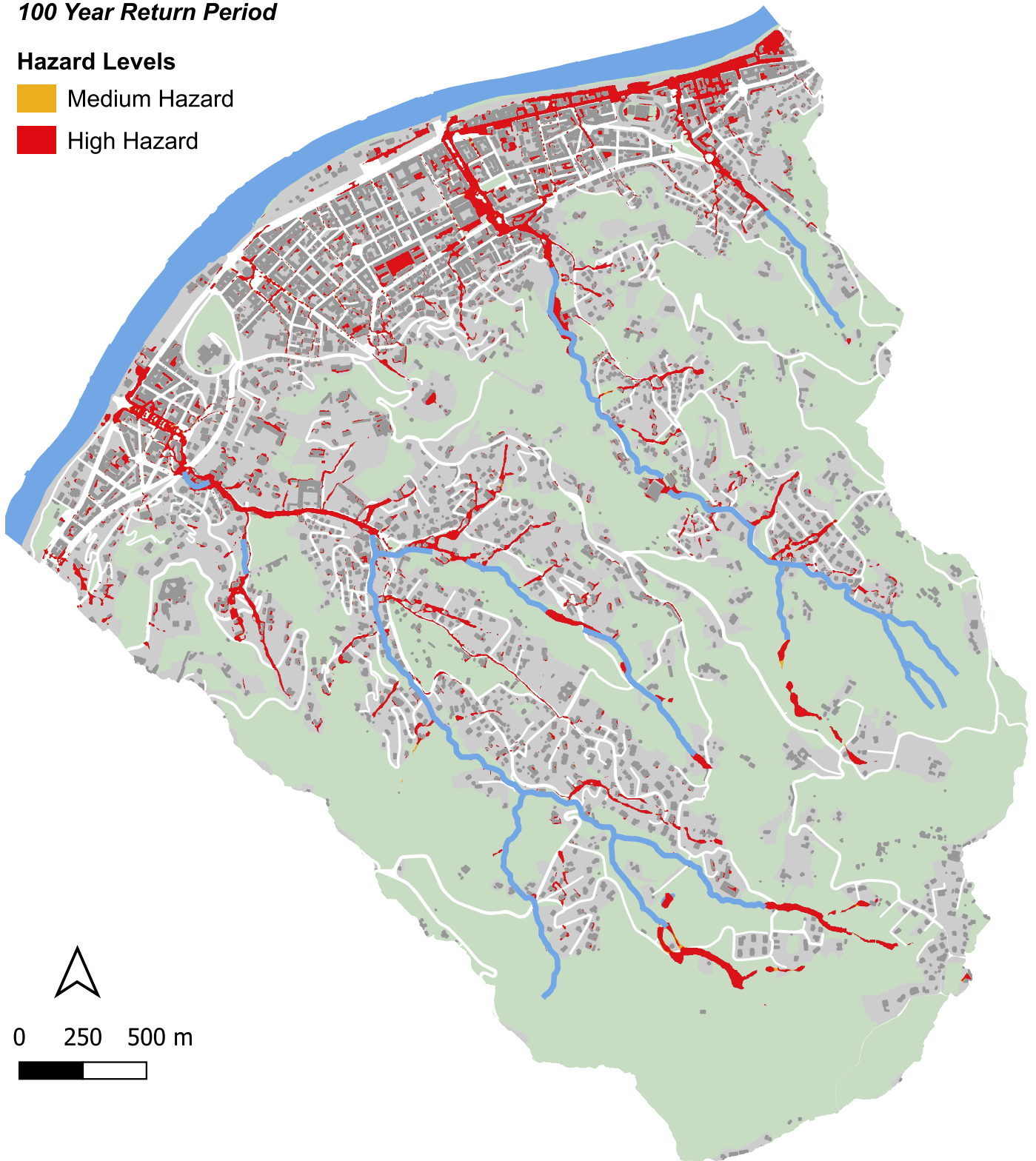


Figure B.4: Pedestrian flood hazard map for a return period of 100 years.

Flood Hazard for Pedestrians

200 Year Return Period

Hazard Levels

Medium Hazard

High Hazard

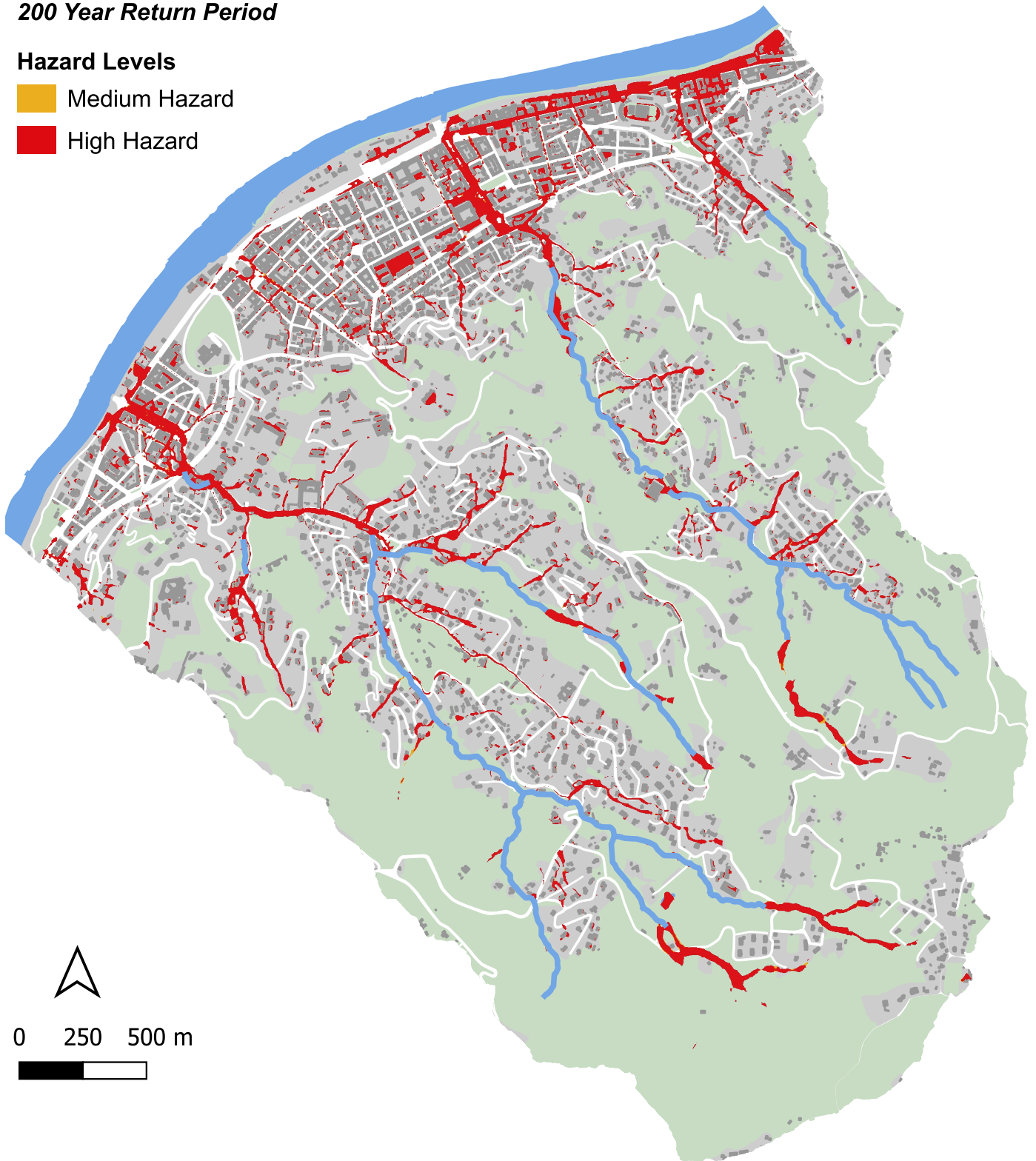


Figure B.5: Pedestrian flood hazard map for a return period of 200 years.

Flood Hazard for Vehicles

2 Year Return Period

Hazard Levels

Medium Hazard

High Hazard



Figure B.6: Vehicular flood hazard map for a return period of 2 years.

Flood Hazard for Vehicles

5 Year Return Period

Hazard Levels

Medium Hazard

High Hazard



Figure B.7: Vehicular flood hazard map for a return period of 5 years.

Flood Hazard for Vehicles

10 Year Return Period

Hazard Levels

Medium Hazard

High Hazard



Figure B.8: Vehicular flood hazard map for a return period of 10 years.

Flood Hazard for Vehicles

100 Year Return Period

Hazard Levels

Medium Hazard

High Hazard



Figure B.9: Vehicular flood hazard map for a return period of 100 years.

Flood Hazard for Vehicles

200 Year Return Period

Hazard Levels

Medium Hazard

High Hazard



Figure B.10: Vehicular flood hazard map for a return period of 200 years.

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