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MiCHe project

Flood risk to cultural heritage in Florence

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Summary

1.Introduction

Florence has experienced several floods during its history (Fig. 1) and some were catastrophic like the 1333 one, which destroyed most of the bridges, and the 1966 one, the latest, which had a worldwide resonance for the number of artworks affected and damaged.

Florence is still prone to floods, although several interventions have been made after the 1966 catastrophic event. Currently a system of retention basins is under construction upstream of the city and changes in dam crest elevation in the Levane and La Penna reservoirs are under evaluation to reduce the hazard.

The city of Florence concentrates valuable monuments, artworks and built asset which pose the city at serious risk for the high degree of exposure and vulnerability.

An effective flood risk assessment requires the estimation of its three components: hazard, exposure and vulnerability. Exposure measures the number and value of elements located in a flood-prone area (e.g. number of cultural buildings, people etc.). Vulnerability measures the expected relative degree of loss for a given hazard parameter (e.g. flood depth, flood velocity etc).

Depending on the target and on the scale of analysis the complexity of such an estimate may vary significantly due to modelling approaches, and availability of input data.

Figure 1: Marble plates showing the flood levels for two historical floods (1933 bottom and 1966 top)(Di Sailko - Opera propria, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=1064982).

This document describes the analysis of flood risk to cultural heritage at site scale for the city of Florence and the risk of the historic centre in terms of Annual Average Loss and number of visitors lost per year. First the hazard evaluation is presented, second, the exposure and vulnerability of cultural heritage are analysed. A new method is developed to understand the resilience of the system and evaluate the indirect impacts on tourism. The results of risk assessment are presented for cultural buildings, for artworks and for all buildings in the site.

2.Methodology

The methodology is summarized in Fig. 2. The first step of risk assessment is the understanding of hazard. Flood hazard is the probability of a flood to occur in a certain time and space with a certain severity (i.e. magnitude).

The second step is the analysis of exposure, which consist in the evaluation of the number and typology of cultural heritage affected for different hazard scenarios. The analysis is conducted on a geographical basis by intersecting the inundation map with the position of the asset. The monetary exposure of the buildings in the historic centre is evaluated based on market values, footprint areas and replacements costs

The third step assigns to an asset class (e.g. religious building, theatre etc.) a degree of expected damage due to the flood. The degree of expected damage for buildings is represented by means of vulnerability curves.

2.1 Flood Hazard analysis

Flood hazard estimation usually requires (i) a statistical analysis of precipitation recorded at rain gauges, (ii) a hydrologic model transforming the precipitation into river discharge, (iii) a hydrodynamic model of the river and its surrounding floodplain areas. The results of this analysis are described in flood hazard maps in terms of several parameters of intensity

- Inundation extent

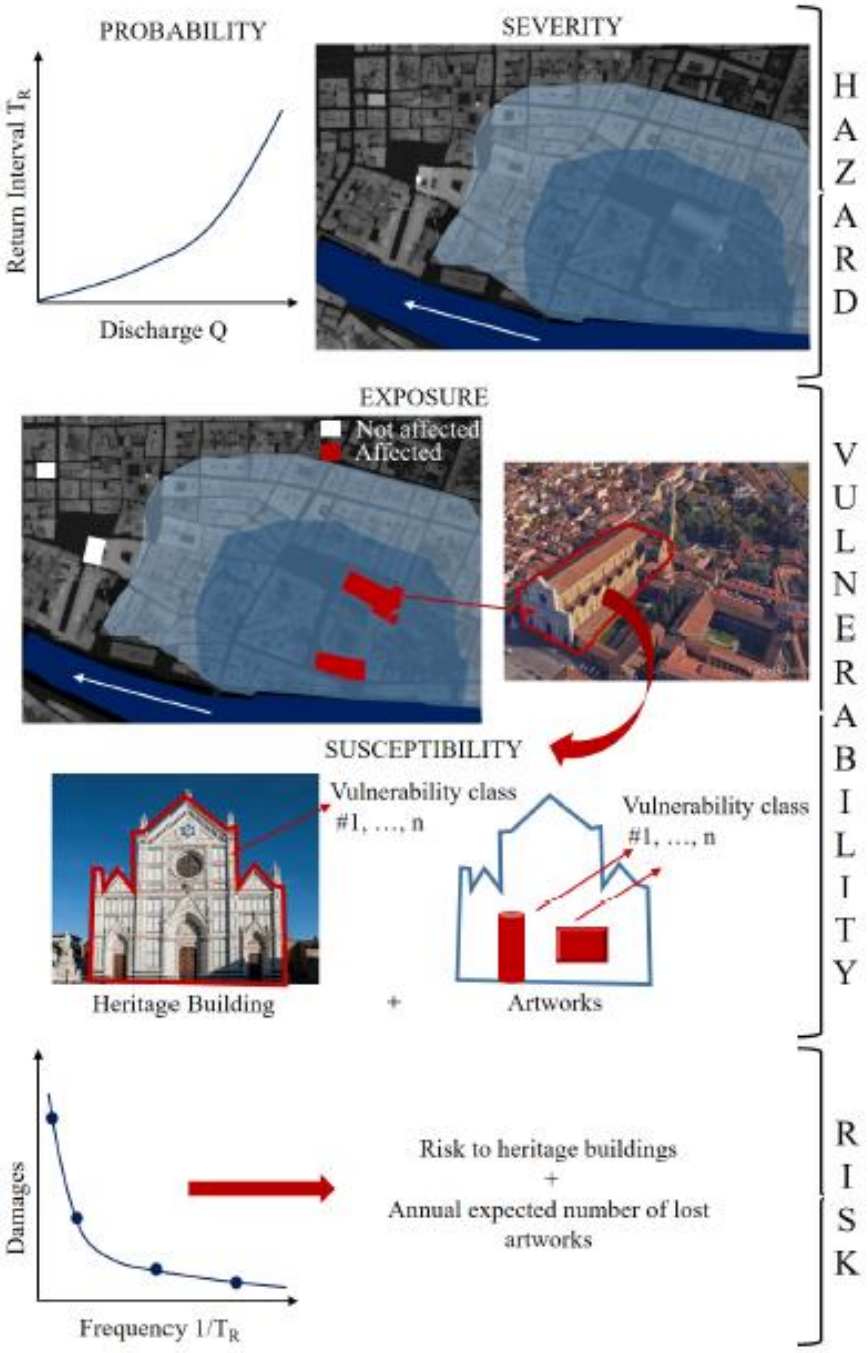

Figure 2: Sketch of the flood risk assessment methodology for cultural heritage

(Arrighi et al., 2016)

- Spatial distribution of flood depths
- Spatial distribution of flow velocities

for a defined probabilistic scenario. Several probabilistic scenarios must be analysed, from frequent to rare events.

The European "Floods Directive" 60/2007/EC requires member states to assess flood hazard at catchment scale as a priority for flood risk management plans. The local authority responsible for the implementation of the Directive is the District of the Northern Appennines, formerly the Arno River Catchment Authority, which freely distributes flood hazard maps on their website. The data are updated to May 2016 and account for the new topographic surveys and hydrologic studies.

The methodology used by the District to produce the flood hazard maps is composed by two parts:1-D unsteady flow model for the river and a quasi-2-D storage cell model for the urban flood prone area. This model is a refinement of the current instrument for flood hazard mapping

in the Arno river basin which now includes the LiDAR-derived Digital terrain Model for the detailed (streets/buildings scale) representation of the flow domain. The DTM of the study area is characterised by a horizontal resolution of 1m by 1m and a vertical accuracy of 0.15 m.

The computation of the flood propagation and corresponding water profile along the Arno river is performed through a standard solver of the 1-D general equation of unsteady flow, such as the one provided in the well known HEC-RAS (Hydrologic Engineering Centers River Analysis System) package.

The quasi-2-D hydraulic model for the floodplain consist of several storage areas

(cells) whose effective geometry is estimated from a meter-scale DTM. Buildings are, by default, considered as waterproof blocks. A certain level of porosity can be also added for those non-waterproof buildings with relevant storage capacity. Water levels within cells and flow between them are computed using the continuity equation, the DTM-based stage–storage relationships and the weir law for the conceptual elements connecting neighbouring cells. The continuity equation provides the evolution in time of the water volume V of each cell. For equations and more details about the inundation modelling please refer to Arrighi et al (2013).

The results of the hazard analysis are shown as flood depth maps of the study area from Fig. 3 to Fig. 5 for three scenarios (Return periods Tr equal to 30, 100 and 200 years). In Fig. 3 the map shows the flood depths in meters for an inundation with a 30 years recurrence interval (high frequency event). For this recurrence interval the inundation occurs downstream of the city centre in the Mantignano area.

In Fig.4 the map shows the flood depths in meters for an inundation with a 100 years recurrence interval (medium frequency event), which affects The Cascine Park, Mantignano, Scandicci and Quaracchi areas. Upstream of the city centre small effects are seen in the Bellariva and varlungo districts. In Fig. 5 the map shows the flood depths in meters for an inundation with a 200 years recurrence interval (medium-low frequency event) which would affect the whole city centre, particularly the S. Croce and cathedral areas and the area of borgo Ognissanti with water depths largely above 2 m.

Fig. 6 shows an event of magnitude similar to the 1966 flood which is considered having a return period of 500 years.

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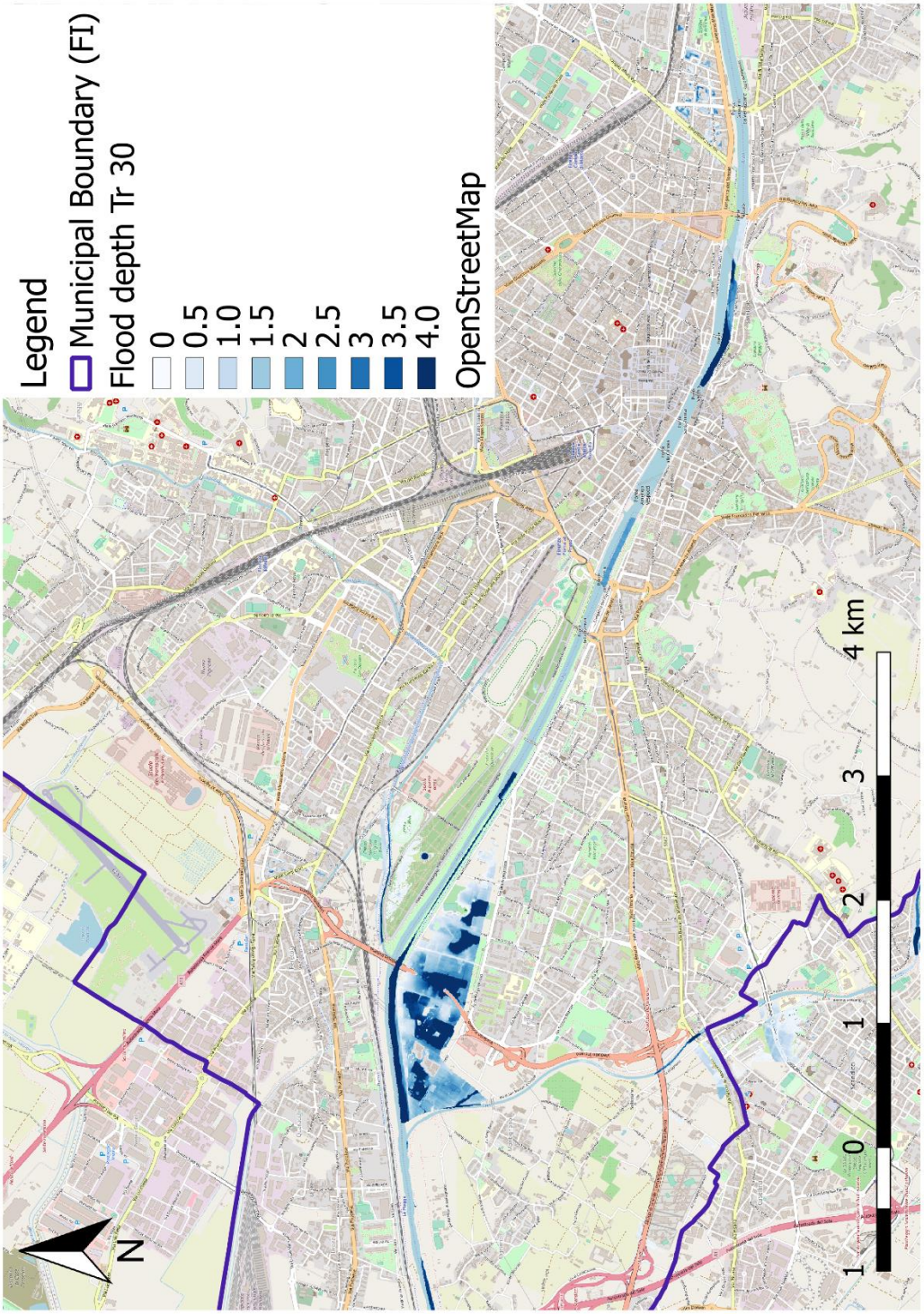

Figure 3: Flood hazard map for a 30 year return period event (elaborations from data distributed by District of the Northern Appennines), flood depth expressed in meters.

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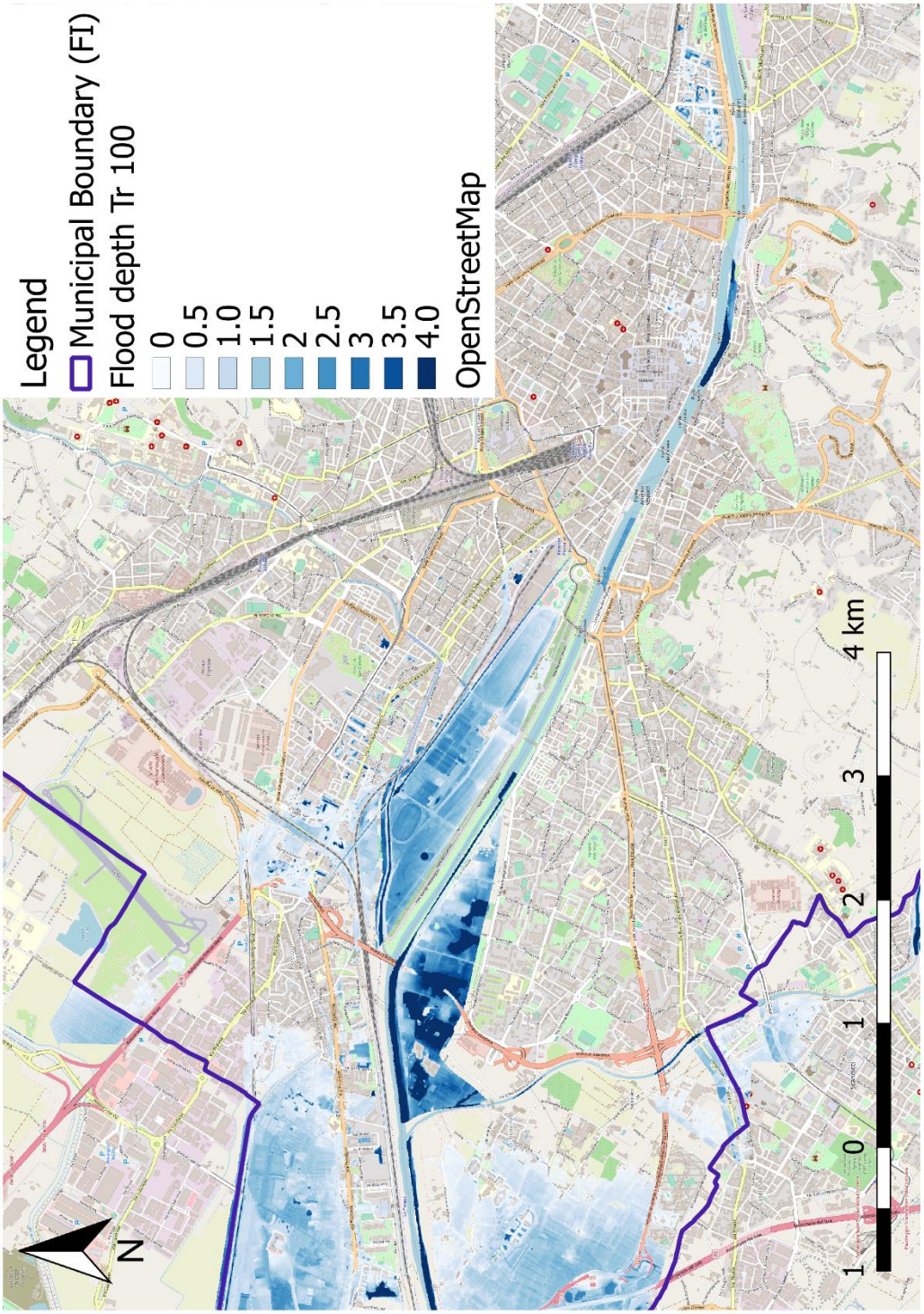

Figure 3: Flood hazard map for a 100 year return period event (elaborations from data distributed by District of the Northern Appennines) flood depth expressed in meters.

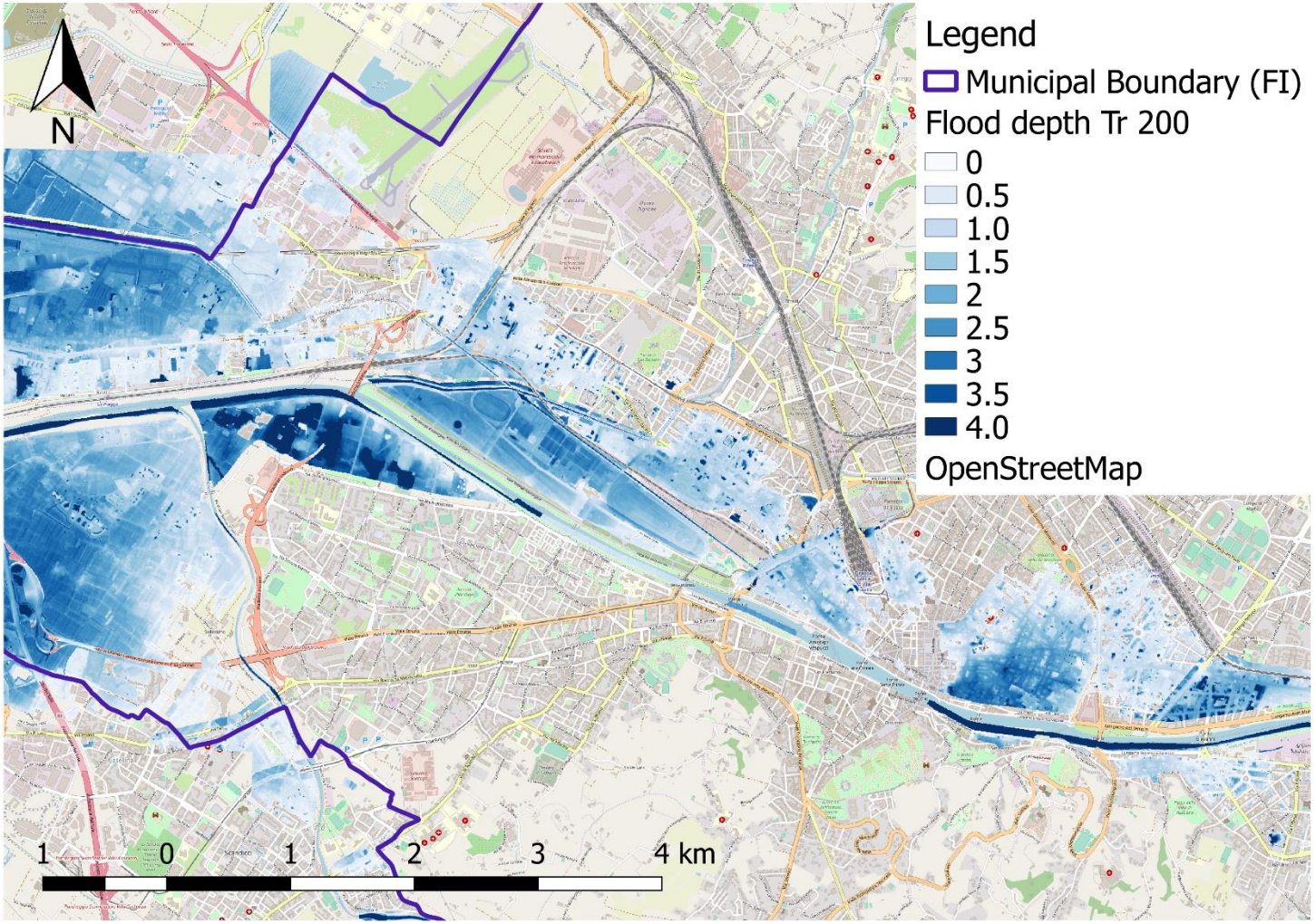

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Figure 5: Flood hazard map for a 200 year return period event (elaborations from data distributed by District of the Northern Appennines), flood depth expressed in meters.

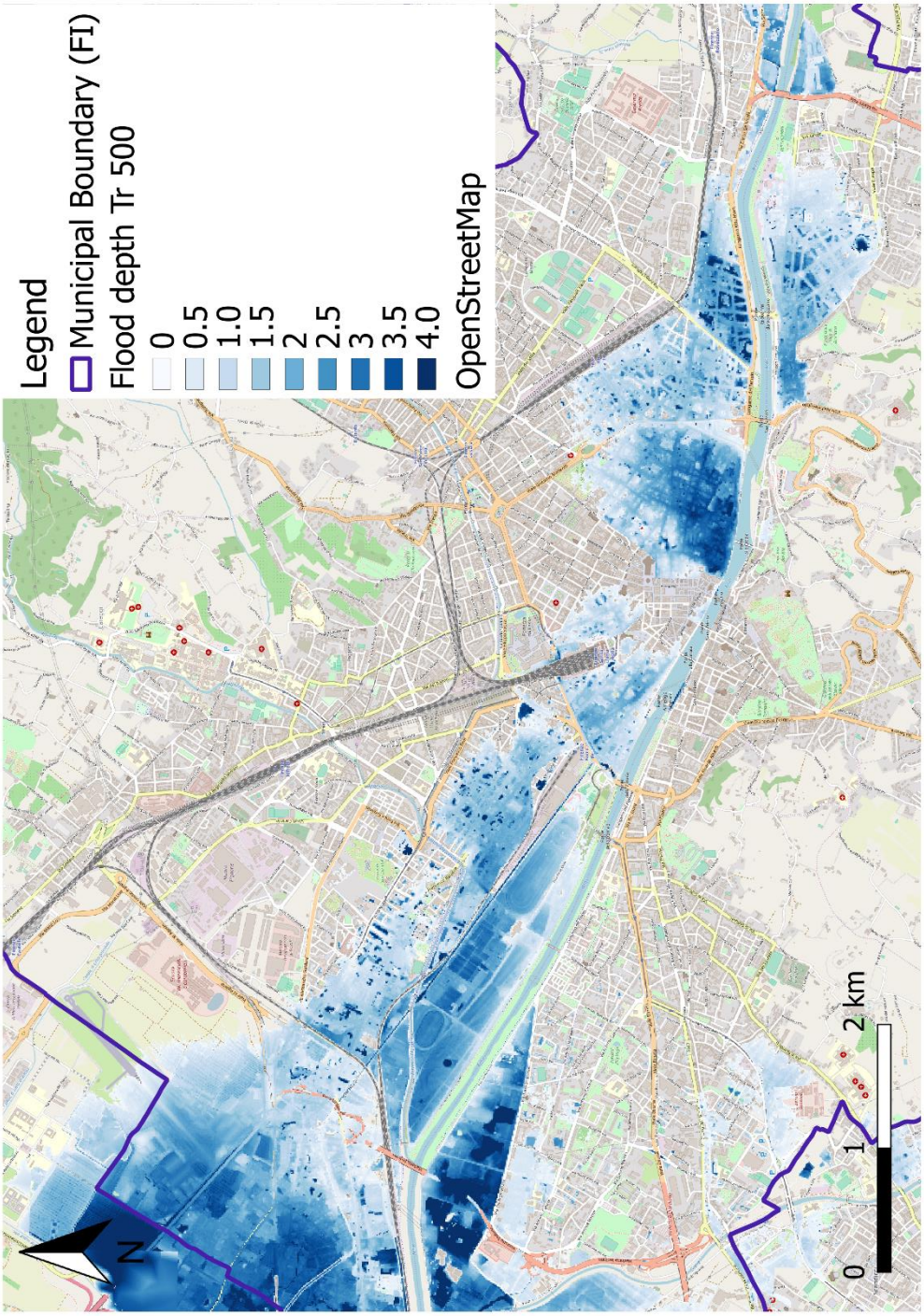

Figure 6: Flood hazard map for a 500 year return period event (elaborations from

data distributed by District of the Northern Appennines), flood depth expressed in meters.

2.2 Flood exposure analysis

The exposure analysis is carried out using the official cultural heritage shapefile obtained by the Arno River Authority and the recognition sheets of the artworks. The intersection of the cultural heritage layer with the inundation area for different probability (i.e. return period) scenario, gives the cultural asset exposed to floods.

For the 30 years recurrence interval none of the cultural buildings is affected in the municipal boundary, since the inundation covers a small portion of the Scandicci municipality.

For the 100 years return period only the Library of technology of the Faculty of Agrarian studies is potentially affected, but it is presumed that water levels are very low and that the area is not a ponding area (Fig.7).

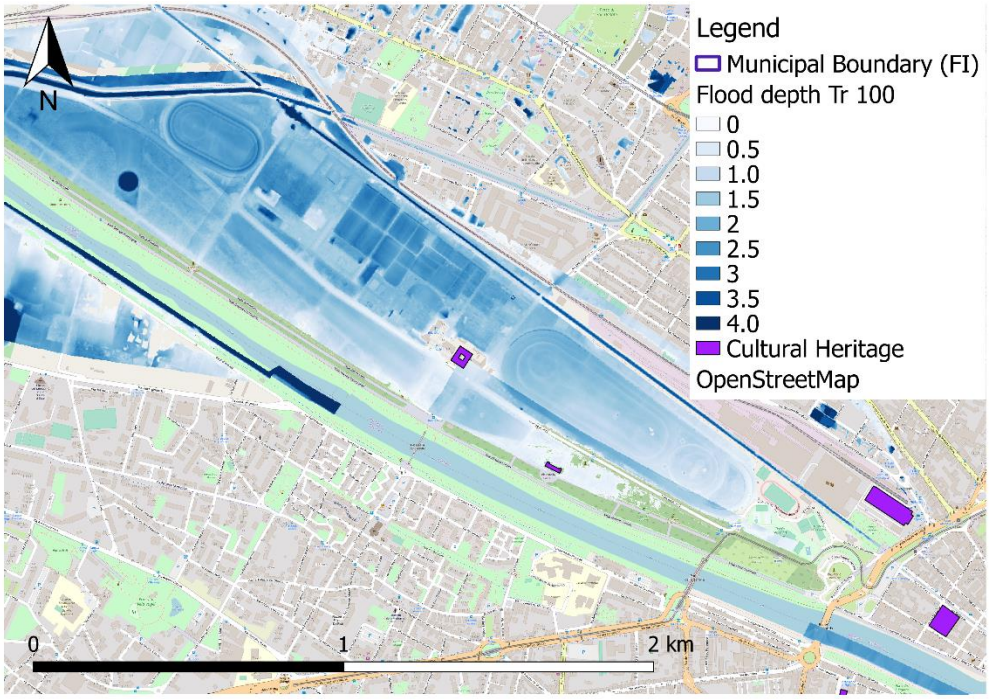

Figure 7: Flood exposure for return period 100 years (detail of the Cascine district in Florence).

This result updates the previous analysis (Arrighi et al., 2018) where for the 100 years return period also the city centre of Florence was affected (Fig. 8). This is due to the hydraulic revision carried out in 2016 by the District of the Northern Appenines.

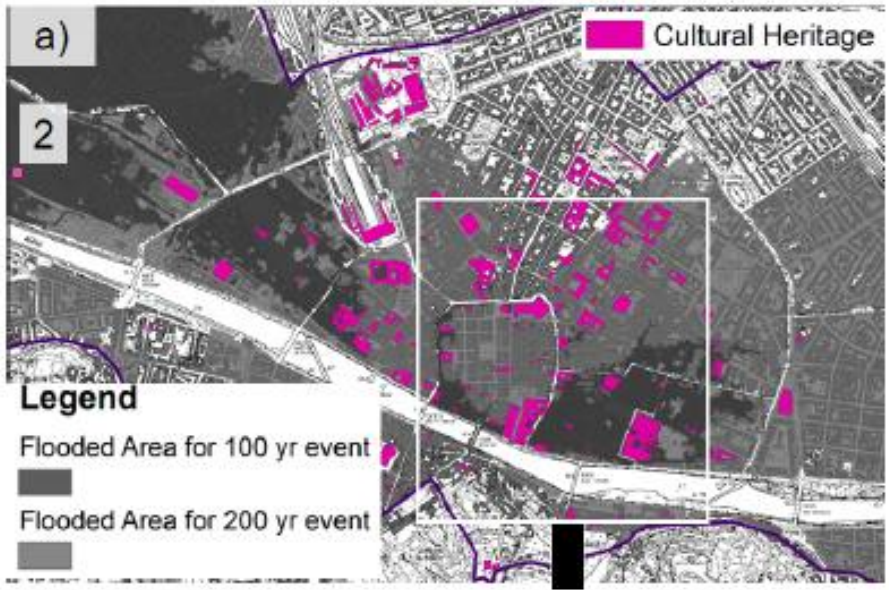

Figure 8: Flood exposure for return period 100 and 200 years (with the previous hydrologic-hydraulic data) (Arrighi et al., 2018).

For the 200 years return period event 79 cultural buildings are affected. They are listed in Table 1 and shown in Fig. 9.

Table 1. Cultural heritage exposed to floods with a return period of 200 years

Id_Edifici	**Denominazione Edificio**
41	Basilica Di San Lorenzo
11	Battistero Di San Giovanni A Firenze
111	Chiesa Di San Giuseppe
36	Biblioteca Medicea Laurenziana - Ambienti Monumentali

195	Cassa Di Risparmio Di Firenze
12	Campanile Di Giotto
191	Istituto Gramsci Toscano
68	Cappelle Medicee
67	Cenacolo Del Conservatorio Di Fuligno
24	Casa Buonarroti
183	Convento Dei Frati Francescani
52	Casa Rodolfo Siviero
197	Educatorio Di Fuligno
198	Chiesa Della Badia Fiorentina
164	Chiesa Di S. Francesco Della Confraternita Dei Vauchet
200	Archivio Fratelli Alinari
25	Museo Archeologico
69	Museo Di Arte E Storia Ebraica
199	Museo Di Case Martelli
202	Museo Della Misericordia Di Firenze
16	Museo Del Bigallo
173	Accademia Toscana Di Scienze E Lettere "La Colombaria"

15	Museo Casa Di Dante
62	Museo Dell'opera Di Santa Maria Del Fiore
175	Biblioteca Delle Oblate
113	Chiesa Di Sant'ambrogio
102	Archivio Di Stato
126	Palazzo Ginari Venturi
77	Archivio Storico
90	Biblioteca Umanistica Punto Di Servizio Storia Dell'arte
30	Museo Di Storia Naturale Dell'universita' (Antropologia) - Palazzo Nonfinito
84	Biblioteca Di Scienze Tecnologiche Dip. Tecnologie Dell'architettura E Design "Pierluigi Spadolini"
87	Biblioteca Di Scienze Tecnologiche Fondo Dip. Di Economia Agraria E Delle Riso Territoriali
88	Biblioteca Umanistica Punto Di Servizio Lettere
83	Biblioteca Di Scienze Tecnologiche Dipartimento Di Progettazione Dell'architett
119	Mercato Di Sant'ambrogio
104	Cattedrale Di Santa Maria Del Fiore
137	Galleria Corsi

153	Scuola Del Cuoio Dell’opera Di Santa Croce
151	Deposito Di Santa Croce
152	Cripta Della Chiesa Di Santa Croce
160	Chiesa Di Santa Maria In Campo
9	Cenacolo Del Ghirlandaio - Museo Di San Salvatore A Ognissanti
155	Chiesa S. Margherita In S. Maria De’ Ricci
156	Compagnia Di San Niccolo’ Del Ceppo
157	Chiesa Di San Simone E Giuda
43	Chiesa S. Maria Maddalena De' Pazzi
165	Chiesa Di S. Michele Visdomini
26	Galleria Degli Uffizi
167	Chiesa Di San Remigio
168	Chiesa Di S. Lucia Sul Prato
169	Chiesa Di Sant'egidio In S. Maria Nuova
171	Basilica Della Santissima Annunziata
174	Accademia Dei Georgofili
177	Biblioteca "Libero Beghi"
182	Biblioteca Dell'istituto Degli Innocenti

147	Chiesa Di San Firenze
185	Biblioteca Nazionale Centrale (Laboratorio Di Restauro)
186	Biblioteca Nazionale Centrale (Ex Caserma Curtatone E Montanara)
44	Museo Storico Topografico "Firenze Com'era"
45	Museo Della Fondazione Herbert Percy Horne
8	Istituto E Museo Di Storia Della Scienza
50	Chiesa Di Santa Maria Novella
5	Museo E Chiostri Monumentali Di Santa Maria Novella
38	Museo Nazionale Del Bargello
34	Palazzo Vecchio - Quartieri Monumentali
105	Chiesa Di San Salvatore A Ognissanti
128	Stazione Leopolda (Porta Al Prato)
117	Le Pavoniere
118	Mercato Centrale
103	Camera Di Commercio
131	Teatro Verdi
79	Biblioteca Nazionale
112	Chiesa Di San Niccolo'

124	Palazzo Dei Congressi
120	Antico Ospedale San Giovanni Di Dio
123	Palazzo Corsini Al Prato - Palazzo Sonnini
130	Teatro Della Pergola
129	Teatro Comunale

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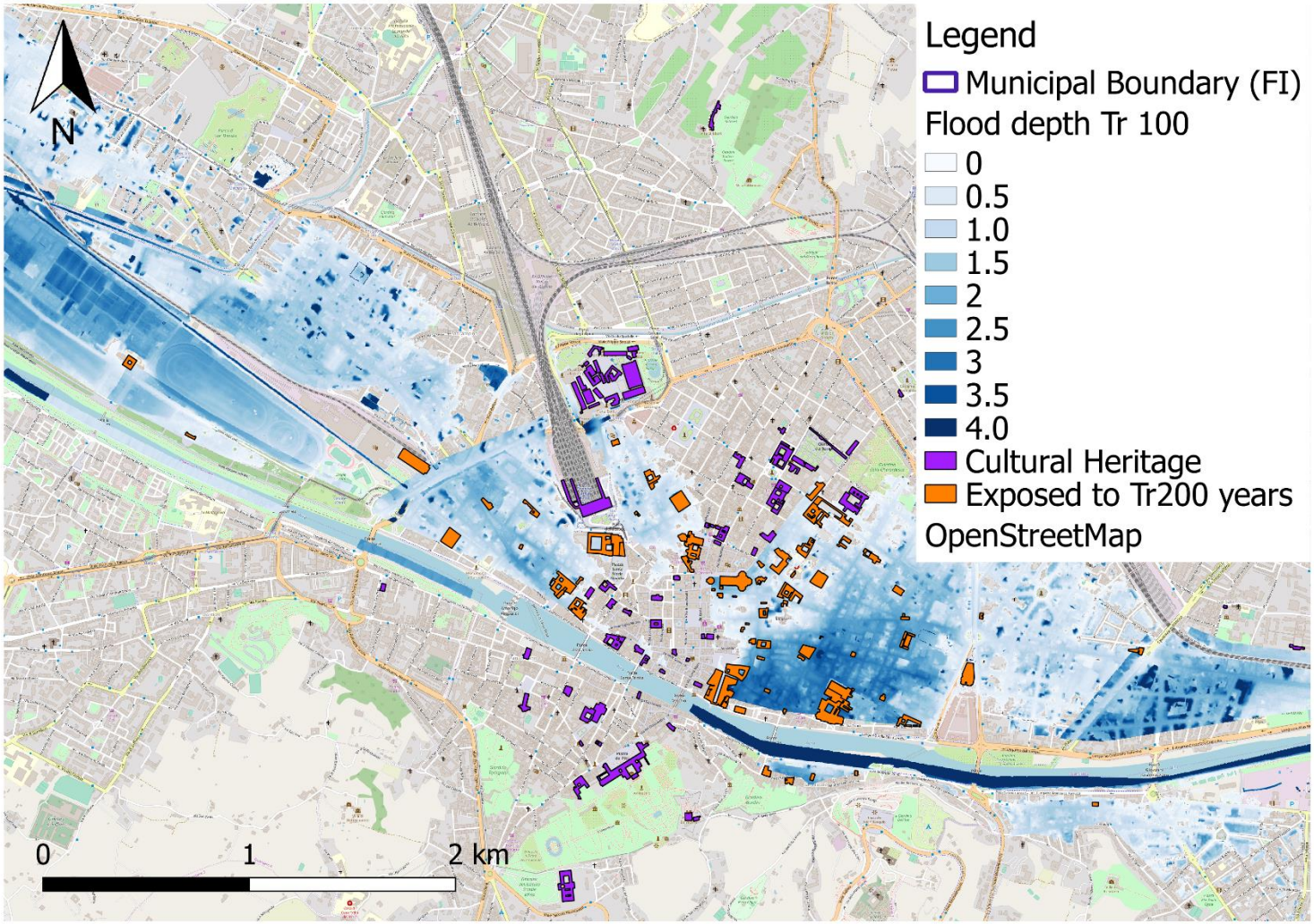

Figure 9: Current Flood exposure of cultural heritage for return period 200 years

For the 500 years return period event 94 cultural buildings are exposed. They are listed in Table 2 and shown in Fig. 10.

Table 2. Cultural heritage exposed to floods with a return period of 500 years (similar to 1966 event)

Id_Edifici	**Denominzaione Edificio**
41	Basilica Di San Lorenzo
11	Battistero Di San Giovanni A Firenze
36	Biblioteca Medicea Laurenziana - Ambienti Monumentali
111	Chiesa Di San Giuseppe
195	Cassa Di Risparmio Di Firenze
12	Campanile Di Giotto
68	Cappelle Medicee
191	Istituto Gramsci Toscano
67	Cenacolo Del Conservatorio Di Fuligno
24	Casa Buonarroti
183	Convento Dei Frati Francescani
52	Casa Rodolfo Siviero
197	Educatorio Di Fuligno

198	Chiesa Della Badia Fiorentina
164	Chiesa Di S.Francesco Della Confraternita Dei Vauchet
200	Archivio Fratelli Alinari
21	Galleria Dell'istituto Degli Innocenti
25	Museo Archeologico
199	Museo Di Case Martelli
69	Museo Di Arte E Storia Ebraica
202	Museo Della Misericordia Di Firenze
16	Museo Del Bigallo
173	Accademia Toscana Di Scienze E Lettere "La Colombaria"
15	Museo Casa Di Dante
189	Archivi Delle Famiglie Bartolommei, Bicchierai, Fenzi (C/O Istituto Di Studi Sul Risorgimento)
62	Museo Dell'opera Di Santa Maria Del Fiore
7	Museo Fiorentino Della Preistoria
175	Biblioteca Delle Oblate
20	Fondazione Scienza E Tecnica - Planetario
113	Chiesa Di Sant'ambrogio

91	Biblioteca Umanistica Punto Di Servizio Psicologia
102	Archivio Di Stato
203	Museo Stefano Bardini
126	Palazzo Ginari Venturi
77	Archivio Storico
90	Biblioteca Umanistica Punto Di Servizio Storia Dell'arte
30	Museo Di Storia Naturale Dell'universita' (Antropologia) - Palazzo Nonfinito
84	Biblioteca Di Scienze Tecnologiche Dip. Tecnologie Dell'architettura E Design "Pierluigi Spadolini"
86	Biblioteca Di Scienze Tecnologiche. Punto Di Servizio Agraria. (Facolta' Di Agraria
87	Biblioteca Di Scienze Tecnologiche Fondo Dip. Di Economia Agraria E Delle Risor Territoriali
88	Biblioteca Umanistica Punto Di Servizio Lettere
83	Biblioteca Di Scienze Tecnologiche Dipartimento Di Progettazione Dell'architettu
119	Mercato Di Sant'ambrogio
104	Cattedrale Di Santa Maria Del Fiore
133	Chiesa Di S. Paolino
137	Galleria Corsi

153	Scuola Del Cuoio Dell’opera Di Santa Croce
150	Archivio Dell’opera Di Santa Croce
151	Deposito Di Santa Croce
14	Basilica Di Santa Croce
152	Cripta Della Chiesa Di Santa Croce
160	Chiesa Di Santa Maria In Campo
9	Cenacolo Del Ghirlandaio - Museo Di San Salvatore A Ognissanti
155	Chiesa S. Margherita In S.Maria De’ Ricci
156	Compagnia Di San Niccolo’ Del Ceppo
157	Chiesa Di San Simone E Giuda
43	Chiesa S. Maria Maddalena De' Pazzi
165	Chiesa Di S.Michele Visdomini
166	Chiesa Dei Ss. Apostoli - S.Biagio
26	Galleria Degli Uffizi
167	Chiesa Di San Remigio
168	Chiesa Di S.Lucia Sul Prato
169	Chiesa Di Sant'egidio In S.Maria Nuova
171	Basilica Della Santissima Annunziata

174	Accademia Dei Georgofili
177	Biblioteca "Libero Beghi"
179	Capitolo Metropolitano Fiorentino
182	Biblioteca Dell'istituto Degli Innocenti
147	Chiesa Di San Firenze
185	Biblioteca Nazionale Centrale (Laboratorio Di Restauro)
186	Biblioteca Nazionale Centrale (Ex Caserma Curtatone E Montanara)
44	Museo Storico Topografico "Firenze Com'era"
45	Museo Della Fondazione Herbert Percy Horne
8	Istituto E Museo Di Storia Della Scienza
50	Chiesa Di Santa Maria Novella
5	Museo E Chiostri Monumentali Di Santa Maria Novella
76	Ex-Case Martelli
38	Museo Nazionale Del Bargello
33	Museo Salvatore Ferragamo
34	Palazzo Vecchio - Quartieri Monumentali
105	Chiesa Di San Salvatore A Ognissanti
128	Stazione Leopolda (Porta Al Prato)

117	Le Pavoniere
118	Mercato Centrale
103	Camera Di Commercio
131	Teatro Verdi
79	Biblioteca Nazionale
112	Chiesa Di San Niccolo'
124	Palazzo Dei Congressi
120	Antico Ospedale San Giovanni Di Dio
123	Palazzo Corsini Al Prato - Palazzo Sonnini
130	Teatro Della Pergola
129	Teatro Comunale
122	Archivio Della Famiglia Corsini (Palazzo Corsini Al Parione)

With the analysis of exposure, the buildings are assigned an hazard degree P_class (Tab. 3):

- Exposed to Tr 500 or higher, P_class is 1 (low hazard)
- Exposed to Tr 200 or higher, P_class is 2 (medium hazard)
- Exposed to Tr 30 or higher, P_class is 3 (high hazard)

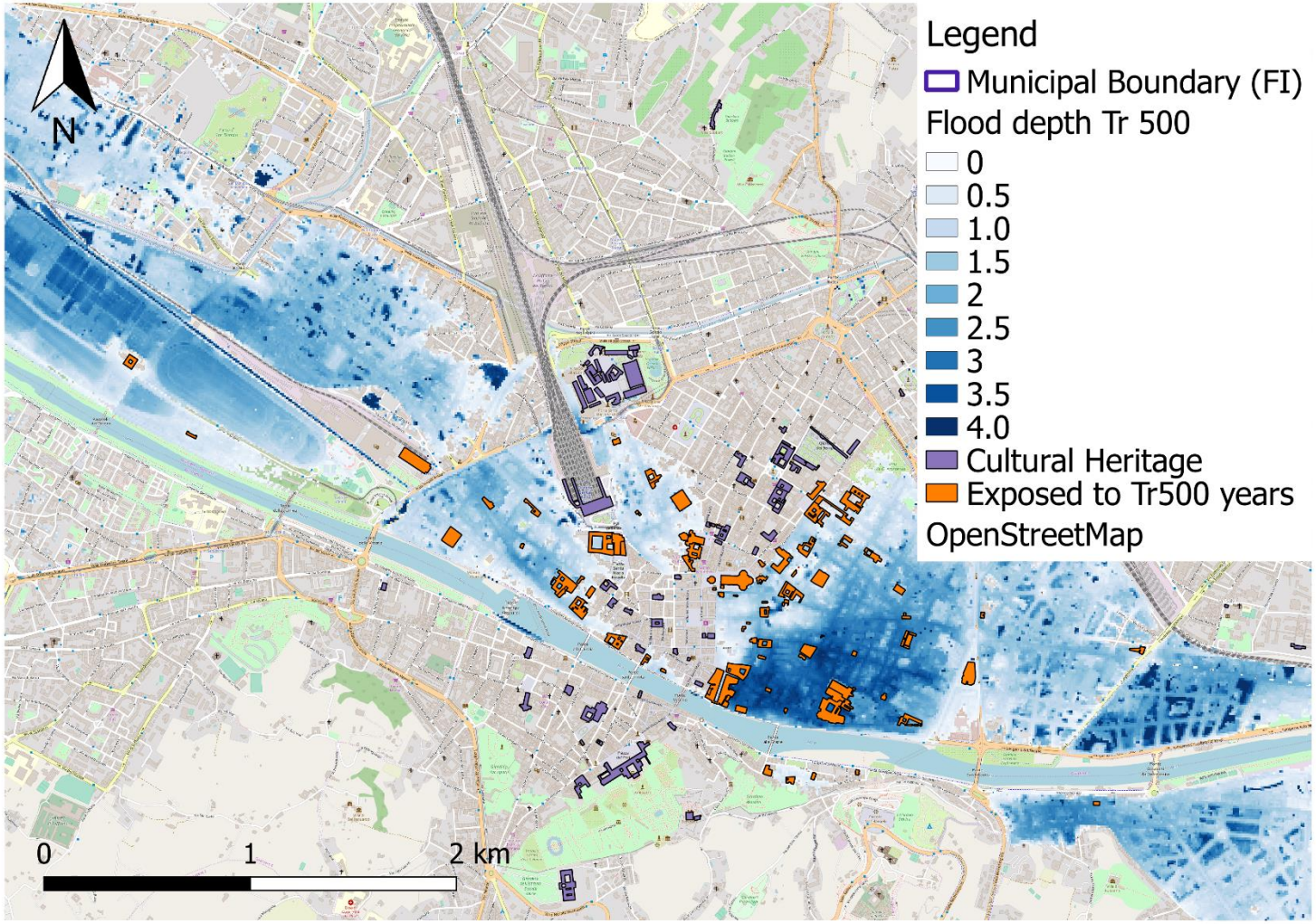

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Figure 10: Current Flood exposure of cultural heritage for return period 500 years

2.3 Flood vulnerability for the cultural heritage

To assign a vulnerability level cultural heritage is divided into two main classes: buildings and artworks. For the buildings, three vulnerability classes have been assigned (see Tab. 3 V_class):

- Churches and religious buildings have high vulnerability
- Noble Palaces, Museums and theatres have medium vulnerability
- Libraries and archives have low vulnerability

These are assumptions at site scale based on the main characteristics of the cultural heritage. Usually in the area, the religious structures are those with a higher level of refinement of the structures (e.g. frescoes or sculptures in the facades). Libraries and archives are mainly valuable for their contents and not for their structures.

A single building-scale analysis would be capable of determining specific vulnerability values to each building, but this is out of the scope (Arrighi et al., 2018).

Regarding the artworks/books contained inside these buildings, the Arno River Basin Authority together with the local and government authorities responsible for museums, libraries, etc. developed recognition sheets with the number of exposed objects classified into four categories:

- paintings on canvas and wood;
- books, archive documents, art prints;
- sculptures (wood, stone, clay . . .);

- goldsmith's art, coins, medals.

The above categories have been selected to assign an average vulnerability in terms of expected degree of loss according to the damages experienced during the 1966 flood.

Paintings on canvas and wood have been reported to have suffered on average a 60% of loss of the painted surface (as the famous Cimabue's crucifix) (Batini, 1967; Sebregondi, 2009). A report available about the two most important manuscript collections of the National Library (Fontana, 2002) states that approximately 50–60% of the books have not been restored yet.

Sculptures and goldsmith's art have suffered lower damages, so the degree of loss has been chosen equal to 15% (Corradetti, 2014; Giusti, 2015).

2.4 Flood risk to cultural heritage in the city of Florence

Table 3 shows the vulnerability degree assigned to cultural buildings V_class and the risk obtained combining hazard level (P_class) with vulnerability through a standard risk matrix.

Risk values between 1-2 are considered low, 3 is medium, between 4-6 are high and 9 is very high (Tab. 3).

Table 3. Hazard class (P_class), vulnerability class (V_class) and risk to cultural buildings

Id_Edifici	Den_Ed	P_Class	V_Class	Riskedif
41	Basilica Di San Lorenzo	2	3	6

11	Battistero Di San Giovanni A Firenze	2	3	6
111	Chiesa Di San Giuseppe	2	3	6
36	Biblioteca Medicea Laurenziana - Ambienti Monumentali	2	1	2
195	Cassa Di Risparmio Di Firenze	2	2	4
12	Campanile Di Giotto	2	3	6
191	Istituto Gramsci Toscano	2	1	2
68	Cappelle Medicee	2	3	6
67	Cenacolo Del Conservatorio Di Fuligno	2	3	6
24	Casa Buonarroti	2	2	4
183	Convento Dei Frati Francescani	2	3	6
52	Casa Rodolfo Siviero	2	2	4
197	Educatorio Di Fuligno	2	2	4
198	Chiesa Della Badia Fiorentina	2	3	6
164	Chiesa Di S.Francesco Della Confraternita Dei Vauchet	2	3	6
200	Archivio Fratelli Alinari	2	1	2
25	Museo Archeologico	2	2	4

69	Museo Di Arte E Storia Ebraica	2	2	4
199	Museo Di Case Martelli	2	2	4
202	Museo Della Misericordia Di Firenze	2	2	4
16	Museo Del Bigallo	2	2	4
173	Accademia Toscana Di Scienze E Lettere "La Colombaria"	2	1	2
15	Museo Casa Di Dante	2	2	4
62	Museo Dell'opera Di Santa Maria Del Fiore	2	2	4
175	Biblioteca Delle Oblate	2	1	2
113	Chiesa Di Sant'ambrogio	2	3	6
102	Archivio Di Stato	2	1	2
126	Palazzo Ginari Venturi	2	2	4
77	Archivio Storico	2	1	2
90	Biblioteca Umanistica Punto Di Servizio Storia Dell'arte	2	1	2
30	Museo Di Storia Naturale Dell'universita' (Antropologia) - Palazzo Nonfinito	2	2	4
84	Biblioteca Di Scienze Tecnologiche Dip. Tecnologie Dell'architettura E Design	2	1	2

	"Pierluigi Spadolini"			
87	Biblioteca Di Scienze Tecnologiche Fondo Dip. Di Economia Agraria E Delle Risorse Territoriali	2	1	2
88	Biblioteca Umanistica Punto Di Servizio Lettere	2	1	2
83	Biblioteca Di Scienze Tecnologiche Dipartimento Di Progettazione Dell'architettura.	2	1	2
119	Mercato Di Sant'ambrogio	2	1	2
104	Cattedrale Di Santa Maria Del Fiore	2	3	6
137	Galleria Corsi	2	2	4
153	Scuola Del Cuoio Dell'opera Di Santa Croce	2	1	2
151	Deposito Di Santa Croce	2	2	4
152	Cripta Della Chiesa Di Santa Croce	2	3	6
160	Chiesa Di Santa Maria In Campo	2	3	6
9	Cenacolo Del Ghirlandaio - Museo Di San Salvatore A Ognissanti	2	3	6
155	Chiesa S. Margherita In S.Maria De' Ricci	2	3	6
156	Compagnia Di San Niccolo' Del Ceppo	2	3	6

157	Chiesa Di San Simone E Giuda	2	3	6
43	Chiesa S. Maria Maddalena De' Pazzi	2	3	6
165	Chiesa Di S.Michele Visdomini	2	3	6
26	Galleria Degli Uffizi	2	2	4
167	Chiesa Di San Remigio	2	3	6
168	Chiesa Di S.Lucia Sul Prato	2	3	6
169	Chiesa Di Sant'egidio In S.Maria Nuova	2	3	6
171	Basilica Della Santissima Annunziata	2	3	6
174	Accademia Dei Georgofili	2	1	2
177	Biblioteca "Libero Beghi"	2	1	2
182	Biblioteca Dell'istituto Degli Innocenti	2	1	2
147	Chiesa Di San Firenze	2	3	6
185	Biblioteca Nazionale Centrale (Laboratorio Di Restauro)	2	1	2
186	Biblioteca Nazionale Centrale (Ex Caserma Curtatone E Montanara)	2	1	2
44	Museo Storico Topografico "Firenze Com'era"	2	2	4
45	Museo Della Fondazione Herbert Percy Horne	2	2	4

8	Istituto E Museo Di Storia Della Scienza	2	2	4
50	Chiesa Di Santa Maria Novella	2	3	6
5	Museo E Chiostri Monumentali Di Santa Maria Novella	2	3	6
38	Museo Nazionale Del Bargello	2	2	4
34	Palazzo Vecchio - Quartieri Monumentali	2	2	4
105	Chiesa Di San Salvatore A Ognissanti	2	3	6
128	Stazione Leopolda (Porta Al Prato)	2	1	2
117	Le Pavoniere	2	1	2
118	Mercato Centrale	2	1	2
103	Camera Di Commercio	2	1	2
131	Teatro Verdi	2	2	4
79	Biblioteca Nazionale	2	1	2
112	Chiesa Di San Niccolo'	2	3	6
124	Palazzo Dei Congressi	2	2	4
120	Antico Ospedale San Giovanni Di Dio	2	1	2
123	Palazzo Corsini Al Prato - Palazzo Sonnini	2	2	4
130	Teatro Della Pergola	2	2	4

129	Teatro Comunale	2	2	4
33	Museo Salvatore Ferragamo	1	2	2
133	Chiesa Di S. Paolino	1	3	3
122	Archivio Della Famiglia Corsini (Palazzo Corsini Al Parione)	1	1	1
166	Chiesa Dei Ss. Apostoli - S.Biagio	1	3	3
20	Fondazione Scienza E Tecnica - Planetario	1	2	2
179	Capitolo Metropolitano Fiorentino	1	1	1
91	Biblioteca Umanistica Punto Di Servizio Psicologia	1	1	1

Table 4 shows the expected losses to artworks based on the information of "Ricognizione Beni Culturali - Città di Firenze - 2007-2010" (Autorità di Bacino del Fiume Arno, 2013). Blank cells are missing data of the recognition sheets. In the Table the column *Tot artworks* shows the total number of artworks exposed in the building, the column *loss 200* and *loss 500* show the potential losses to the artworks for the two recurrence interval scenarios, the column *Risk artwork* is the expected annual loss of artworks and the *risk %* is the annual expected loss in percentage with respect to the total number of objects.

According to the risk assessment, the cultural artworks most at risk are manuscripts and books, in particular the highest annul average loss is obtained for Biblioteca di Scienze tecnologiche (dipartimento di progettazione

dell'architettura), Biblioteca Umanistica (punto di servizio storia dell'arte), Archivio Fratelli Alinari. This is especially due to the high vulnerability of books and manuscripts. In percentage with respect to the total number of artworks the S. Niccolò church is the cultural building which suffer the high annual expected loss. Fig. 12 shows a map with the relative annual expected loss of artworks.

For the site of Florence, the overall annual expected loss of artworks is about 427, which sums up the annual expected losses for each record.

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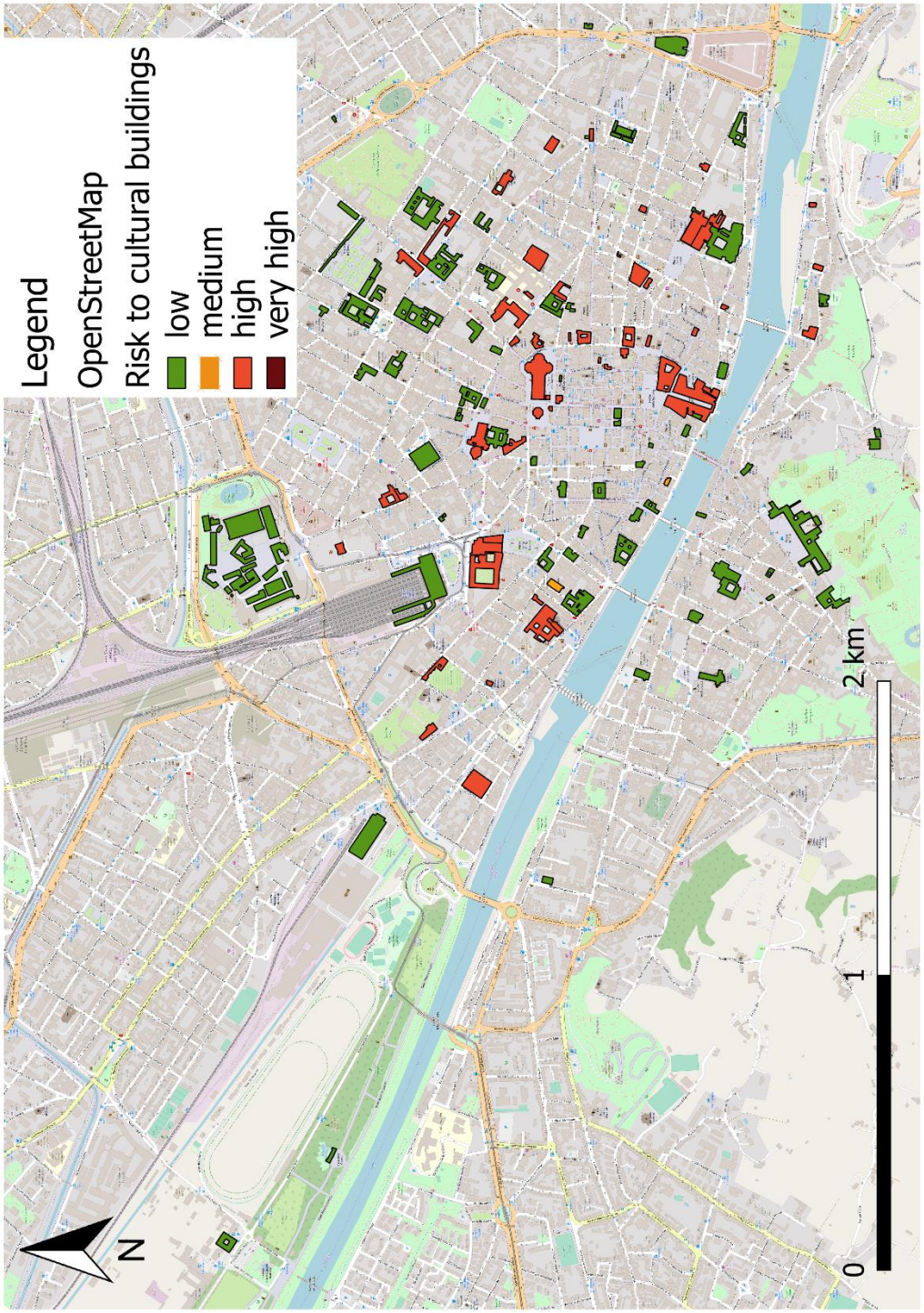

Figure 11: Risk to cultural buildings

Table 4. losses for the 200 and 500 years return period and risk to artworks

Denominazione Edificio	Tot Artworks	Loss 200	Loss 500	Risk Artwork	Risk %
Museo Salvatore Ferragamo	0	0			0
Chiesa Di S. Paolino	0	0			0
Archivio Della Famiglia Corsini (Palazzo Corsini Al Parione)	0	0			0
Chiesa Dei Ss. Apostoli - S.Biagio	30	0	0	0	0
Fondazione Scienza E Tecnica - Planetario	3000	0	0	0	0
Capitolo Metropolitano Fiorentino	100	0	39.6	0.059	0.1
Biblioteca Umanistica Punto Di Servizio Psicologia	12000	0	7200	10.8	0.1
Basilica Di San Lorenzo	0	0	0	0	0
Battistero Di San Giovanni A Firenze	10	2	2	0.011	0.1
Chiesa Di San Giuseppe	8	4.8	4.8	0.026	0.3

Biblioteca Medicea Laurenziana - Ambienti Monumentali					
Cassa Di Risparmio Di Firenze					0
Campanile Di Giotto					0
Istituto Gramsci Toscano					0
Cappelle Medicee	35	7.2	7.2	0.04	0.1
Cenacolo Del Conservatorio Di Fuligno	122	69.8	69.8	0.384	0.3
Casa Buonarroti	175	43.2	43.2	0.238	0.1
Convento Dei Frati Francescani	35	2.2	2.2	0.012	0
Casa Rodolfo Siviero	211	68	68	0.374	0.2
Educatorio Di Fuligno	12	7.2	7.2	0.04	0.3
Chiesa Della Badia Fiorentina					0
Chiesa Di S.Francesco Della Confraternita Dei Vauchet	1	0	0	0	0
Archivio Fratelli Alinari	20000	12000	12000	66	0.3
Museo Archeologico	15020	3004	3004	16.522	0.1
Museo Di Arte E Storia Ebraica	300	120	120	0.66	0.2
Museo Di Case Martelli	59	14.2	14.2	0.078	0.1

Museo Della Misericordia Di Firenze					
Museo Del Bigallo	42	17.2	17.2	0.095	0.2
Accademia Toscana Di Scienze E Lettere "La Colombaria"	4308	2540.2	2540.2	13.971	0.3
Museo Casa Di Dante					0
Museo Dell'opera Di Santa Maria Del Fiore	212	48.2	48.2	0.265	0.1
Biblioteca Delle Oblate	10000	6000	6000	33	0.3
Chiesa Di Sant'ambrogio	2	1.2	1.2	0.007	0.4
Archivio Di Stato	0	0	0	0	0
Palazzo Ginari Venturi					0
Archivio Storico					0
Biblioteca Umanistica Punto Di Servizio Storia Dell'arte	21000	12600	12600	69.3	0.3
Museo Di Storia Naturale Dell'universita' (Antropologia) - Palazzo Nonfinito	0	0	0	0	0
Biblioteca Di Scienze Tecnologiche Dip. Tecnologie Dell'architettura E Design "Pierluigi Spadolini"	8500	5100	5100	28.05	0.3

Biblioteca Di Scienze Tecnologiche Fondo Dip. Di Economia Agraria E Delle Risorse Territoriali	2500	1500	1500	8.25	0.3
Biblioteca Umanistica Punto Di Servizio Lettere	8125	4875	4875	26.813	0.3
Biblioteca Di Scienze Tecnologiche Dipartimento Di Progettazione Dell'architettura.	45000	27000	27000	148.5	0.3
Mercato Di Sant'ambrogio					0
Cattedrale Di Santa Maria Del Fiore	5782	98	98	0.539	0
Galleria Corsi					0
Scuola Del Cuoio Dell'opera Di Santa Croce	35	6.4	6.4	0.035	0.1
Deposito Di Santa Croce	984	198.8	198.8	1.093	0.1
Cripta Della Chiesa Di Santa Croce	139	18.6	18.6	0.102	0.1
Chiesa Di Santa Maria In Campo	20	0	0	0	0
Cenacolo Del Ghirlandaio - Museo Di San Salvatore A Ognissanti					
Chiesa S. Margherita In S.Maria De' Ricci	40	0	0	0	0
Compagnia Di San Niccolo' Del Ceppo	0	0	0	0	0

Chiesa Di San Simone E Giuda	0	0	0	0	0
Chiesa S. Maria Maddalena De' Pazzi	0	0	0	0	0
Chiesa Di S.Michele Visdomini	857	264.8	264.8	1.456	0.2
Galleria Degli Uffizi	10	6	6	0.033	0.3
Chiesa Di San Remigio	19	9	9	0.05	0.3
Chiesa Di S.Lucia Sul Prato	0	0	0	0	0
Chiesa Di Sant'egidio In S.Maria Nuova	0	0	0	0	0
Basilica Della Santissima Annunziata					
Accademia Dei Georgofili					0
Biblioteca "Libero Beghi"					0
Biblioteca Dell'istituto Degli Innocenti					
Chiesa Di San Firenze	0	0	0	0	0
Biblioteca Nazionale Centrale (Laboratorio Di Restauro)	0	0	0	0	0
Biblioteca Nazionale Centrale (Ex Caserma Curtatone E Montanara)	0	0	0	0	0
Museo Storico Topografico "Firenze Com'era"	0	0	0	0	0

Museo Della Fondazione Herbert Percy Horne	0	0	0	0	0
Istituto E Museo Di Storia Della Scienza	125	9	9	0.05	0
Chiesa Di Santa Maria Novella					0
Museo E Chiostri Monumentali Di Santa Maria Novella	131	18.6	18.6	0.102	0.1
Museo Nazionale Del Bargello	65	13	13	0.072	0.1
Palazzo Vecchio - Quartieri Monumentali	0	0	0	0	0
Chiesa Di San Salvatore A Ognissanti	100	0	0	0	0
Stazione Leopolda (Porta Al Prato)					
Le Pavoniere					0
Mercato Centrale					0
Camera Di Commercio					0
Teatro Verdi					0
Biblioteca Nazionale	0	0	0	0	0
Chiesa Di San Niccolo'	19	10.8	10.8	0.059	0.3
Palazzo Dei Congressi					0

Antico Ospedale San Giovanni Di Dio					
Palazzo Corsini Al Prato - Palazzo Sonnini					
Teatro Della Pergola	2	0	0	0	0
Teatro Comunale					

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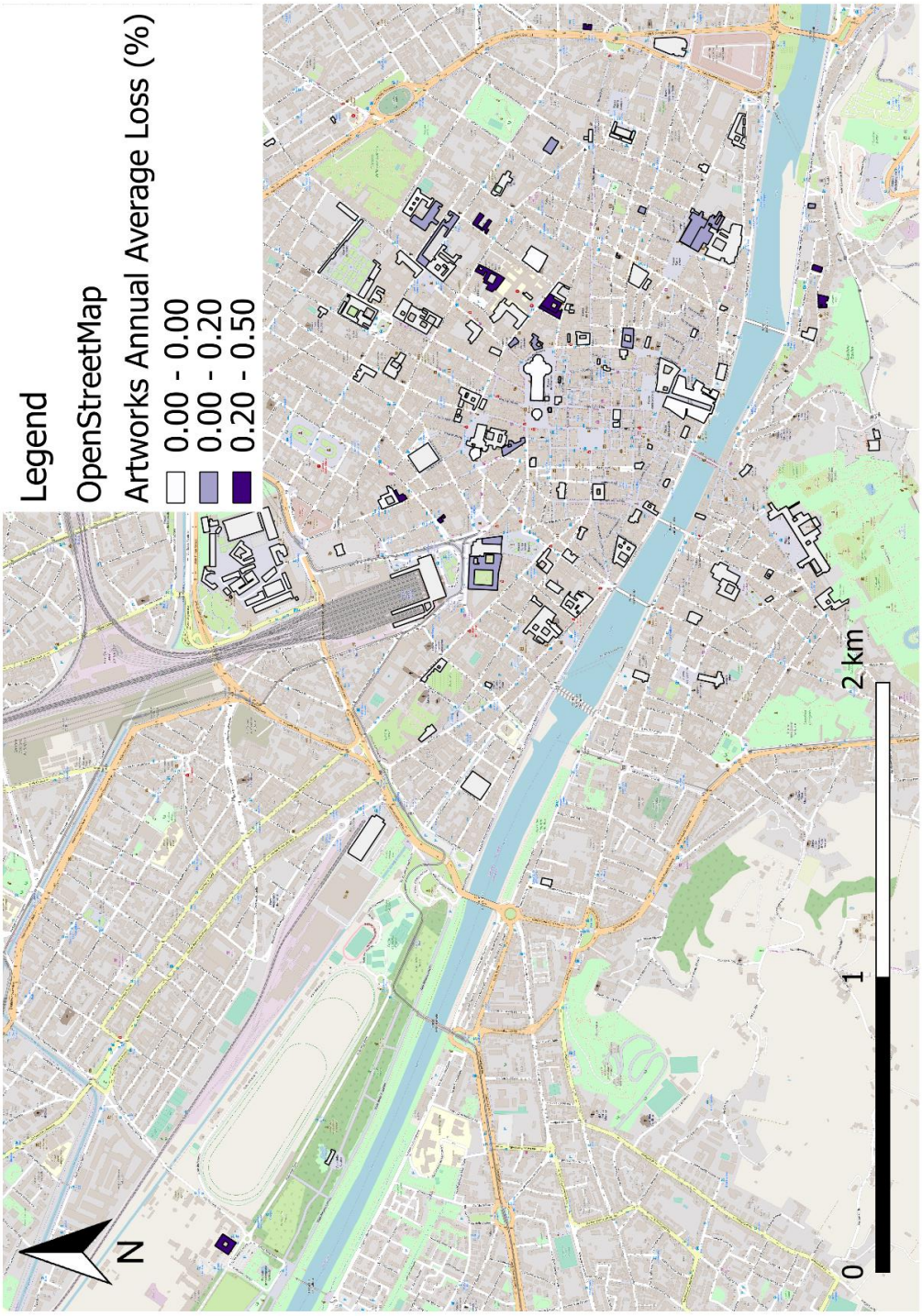

Figure 12: Risk to artworks (annual expected loss) expressed as percentage over the total exposure

2.5 Indirect flood impacts on tourism and resilience of the historic city

Direct flood impacts are usually defined as those damages directly caused by the physical contact with floodwaters (e.g. damages to wooden floors or loss of painted surfaces in frescoes). Indirect impacts instead occur outside the flooded area in space or time, i.e. losses occur several days or months after the event or in boundary areas which were not affected directly by an inundation. A typical example is the damage of a road branch in the flooded area which has repercussions also in other branches of the road network given the interdependencies of infrastructural systems.
In these cases, indirect impacts are sensitive to the recovery speed of the systems, i.e. the ability to restore the previous condition and business as usual. The evaluation of indirect impacts is thus strongly connected to the concept of resilience. **"Resilience** refers to the ability of individuals, societies or socio-economic systems to cope with the sudden impact of crises or **disasters**, and to restore as quickly as possible their ability to function and their capacity to act" in the definition by Munich Re.

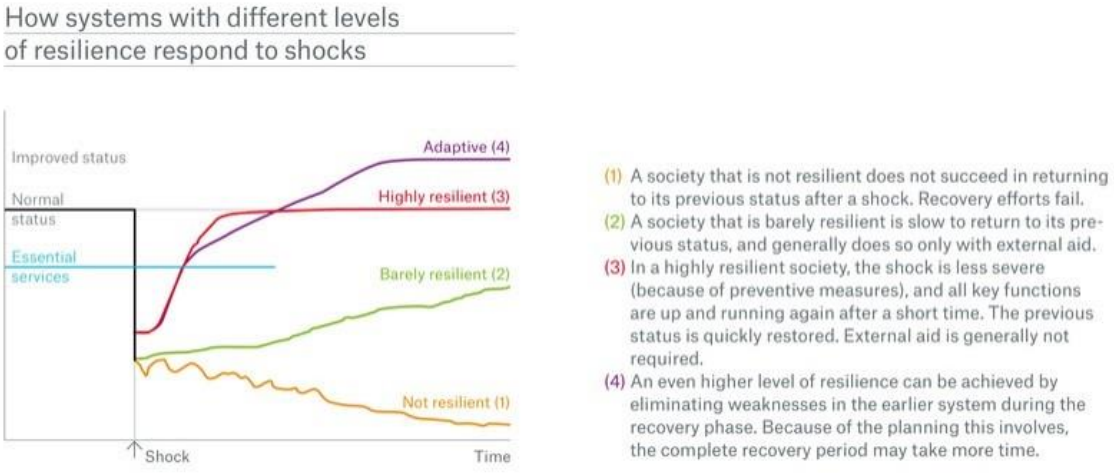

Figure 13: Responses to shocks of different systems (Munich Re)

The response of a system to a shock (Fig. 13) is measured through a state variable versus time. The shock is intended here as the natural hazard (i.e. the flood) which cause the sudden drop of the state variable. The ability to recover determines the

shape of the curve (Fig. 13) according to different assumptions: not resilient, barely resilient, highly resilient and adaptive.
In case of an art city with exceptional cultural heritage, a measure of the state of the system can be the number of visitors in museums and attractions (Fig. 14). Indirect losses can be thus expressed in terms of lost visitors in the historic city. In fact if a museum is flooded, although artworks can be displaced and saved from damages, it is not accessible to visitors for a certain time.

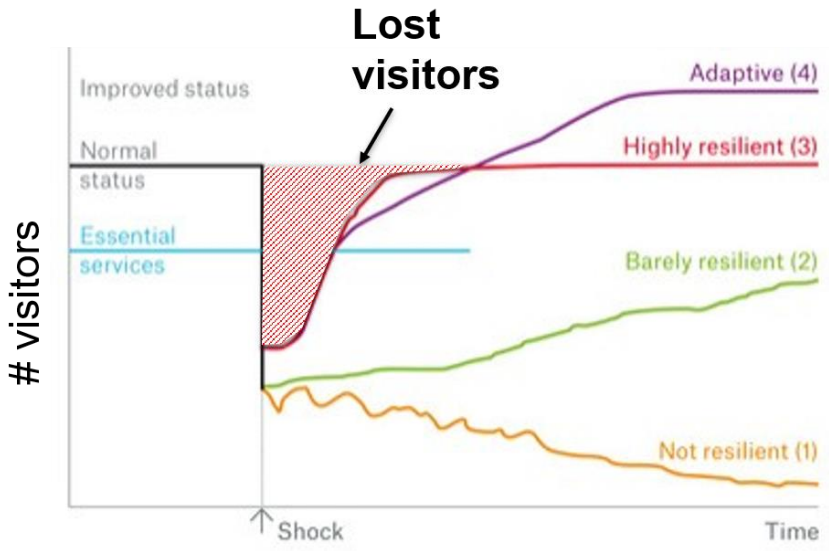

Figure 14: A resilience metric for art cities (adapted from Munich Re)

To estimate the shape of the resilience curve a function relating direct and indirect impacts has to be defined. The steps required to obtain a resilience curve are:

1. determination of the 'normal status' in terms of visitors (to single attraction/museum $\mathbf{V_{ni}}$ and in the whole historic district $\mathbf{V_N}$)
2. determination of the physical flood damage of the attraction/museum for each probabilistic flood scenario $\mathbf{D_{\%}}$
3. Assumption of the maximum closure time $\mathbf{T_{max}}$
4. Estimation of the most probable re-opening time $\mathbf{T_o}$

5. Assessment of the site attractivity **A(t)**
6. Estimation of the visitors **V(t)**
7. Estimation of the losses to number of visitors $\mathbf{V_{loss}}$ with respect to the potential visitors $\mathbf{V_{pot}}$

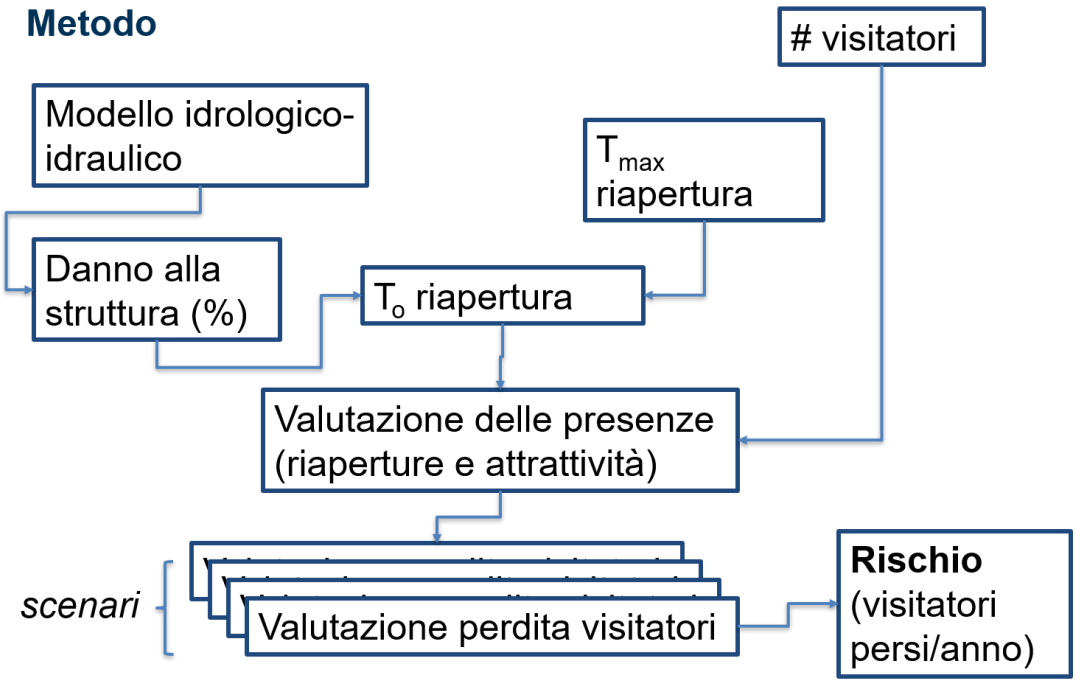

Figure 15: methodology for resilience and indirect impact assessment

The most probable re-opening time called T_o is dependent on the assumed maximum closure time T_{max} and physical damage $D_{\%}$ suffered by the art building according to vulnerability curves

$$T_o = T_{max} \cdot D_{\%} \quad (1)$$

The number of open museums at t, $M_o(t)$ in the site is

$$M_o(t) = \sum_{i=1}^{n} M_i(t) \quad (2)$$

where i is the i-th attraction and n is the total number of museums/attraction in the site and $M_i(t)$ is

$$M_i(t) = \begin{cases} 0 \ \ if \ t < T_{oi} \\ 1 \ if \ t > \ T_{oi} \end{cases} \quad (3)$$

The number of potential actual visitors at t, is the sum of the 'normal' visitors of the open attractions

$$V_{act}(t) = \ \sum_{i=1}^{n} \ v_i \cdot M_i(t) \quad (4)$$

Where v_i is the specific number of visitors in normal conditions of the attraction i.

The number of visitors in the historic district depends not only by the accessibility of single attractions but also on the attractivity of the overall site since special museums might be a 'must see' attraction that affect the decision to make or not a trip to the site. Attractivity is here considered dependent on the ratio between potential (i.e. 'normal' when no flood occurs, M_i=1 for each i) and actual visitors V_{act}

$$A(t) = \frac{V_{pot}}{V_{act}} \quad (5)$$

The number of visitors is thus a function of attractivity according to a power law

$$V(t) = V_{pot} \cdot A(t)^k \quad (6)$$

Where k is an exponent determining the weight of the attractivity factor.

The loss in terms of visitors $\mathbf{V_{loss}}$ is then the difference between V_{pot} (t) and V(t)

$$V_{loss} = V_{pot} - V(t) \quad (7)$$

The overall impact L(T_R) depends on the overall recovery time in the integral form

$$L(T_R) = \int_{Tshock}^{Tend} V_{loss}(T_R, t)\, dt \quad (8)$$

Where T_R is the recurrence interval of the flooding, T_{end} is the time where all the attractions become open, i.e. the end of the recovery phase.

If the estimation of the overall impact is carried out for several probabilistic scenarios with different T_R the risk can be estimated as

$$Risk = \int_0^1 L(T_R)\, d\left(\frac{1}{T_R}\right) \quad (9)$$

2.6 Flood risk prevention and mitigation

The reduction of flood risk is achieved by prevention and mitigation, which are crucial steps in the risk management cycle. Prevention is the reduction of hazard, i.e. in the case of a flood, the reduction of the probability of occurrence of an inundation or reduction of expected flood depths. It is usually achieved by means of hydraulic works like dikes or retention basins.

Mitigation is the reduction of exposure and vulnerability, i.e. the reduction of potential losses, achieved by means of waterproofing, relocation or self-protection

strategies during warning.

2.6.1 Flood hazard reduction

To understand how the reduction of hazard affects the risk in Florence, the flood damage assessment is carried out for the same probabilistic scenarios of inundation but accounting for the effects of the retention basins under construction upstream of the city.

2.6.2 Flood vulnerability reduction

To understand how the reduction of vulnerability affects the risk in Florence, the flood damage assessment is carried out for the same probabilistic scenarios of inundation but accounting for the effects of the protection of underground floors. This effect is obtained by changing the shape of the vulnerability curve.

3.Results

3.1 Flood exposure analysis for the historic centre of Florence

For the buildings of the historic centre of Florence, delimited by the Middle Ages walls in agreement with the UR DIDA-UNIFI, exposure is evaluated by intersecting flood depths with building position and second, to calculate the value of the exposed buildings. The total number of buildings in the historic centre is 560, based on the regional dataset scale 1:2000. For the 30 years return period the historic centre is not affected since flooding occurs downstream of the city and mostly affects the municipality of Scandicci. For the 100 years return period the inundation only marginally affects the historic centre in the area of Piazza del Grano, only 5 buildings are affected with water depths higher than 0.2 m (average on the building footprint).

For the 200 years return period, 222 buildings are exposed with water depths higher than 0.2 m (Fig. 16, buildings highlighted in yellow).

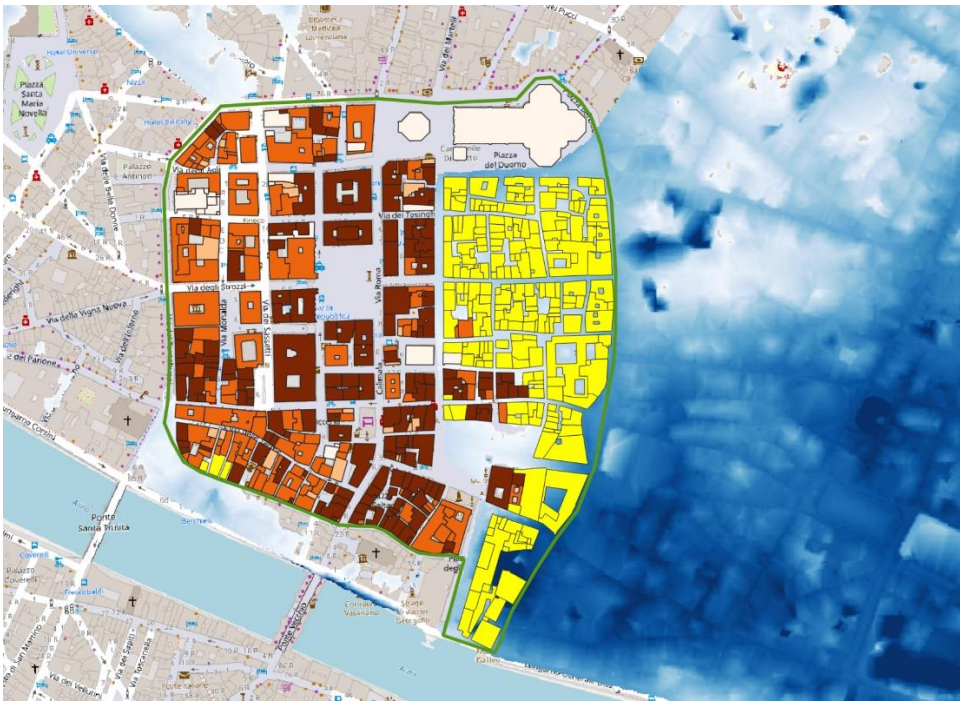

Figure 16: Buildings exposed for return period 200 years highlighted in yellow

The total exposed value is 223.6 Mio € accounting only for the flooded floors (i.e. basements and ground floor).

For the 500 years return period (i.e. an event similar in magnitude to the 1966 flood) 256 buildings are exposed, with water depths higher than 0.2 m (Fig. 17, buildings highlighted in yellow). Although the number of exposed buildings does not change significantly, water depths are increasing for this scenario. The total exposed value is 293.9 Mio € accounting only for the flooded floors (i.e. basements and ground floor).

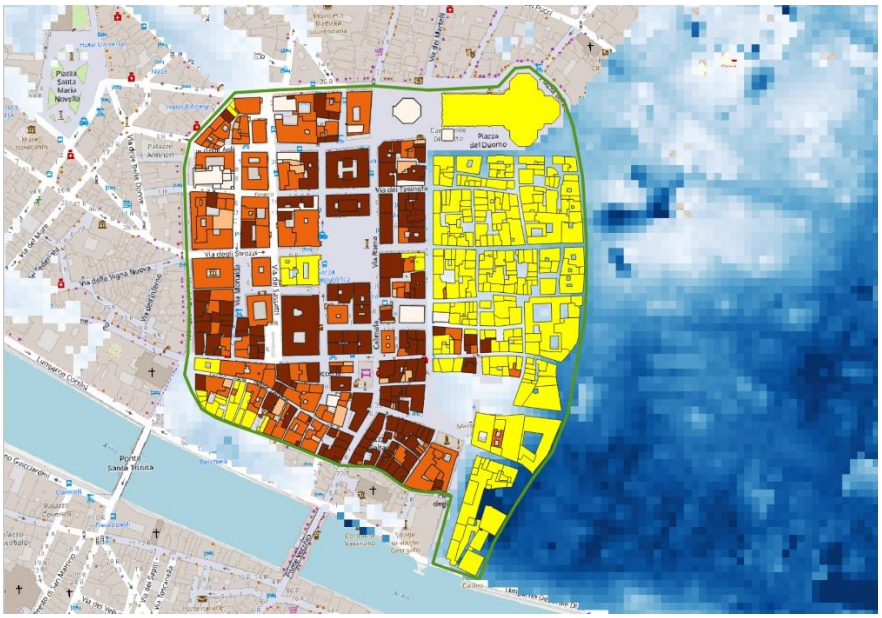

Figure 17: Buildings exposed for return period 500 years highlighted in yellow

Table 5. Summary of exposure for the different probabilistic scenarios

	Tr 30	Tr 100	Tr 200	Tr 500
Exposed buildings (#)	0	5	222	256
Exposed value (Mio €)	0	10.8	223.6	293.9
Total building stock in the historic centre Bn € 2.67				

3.2 Flood vulnerability analysis and losses for the historic centre of Florence

To assign the vulnerability to the buildings of the historic centre a simple linear piece-wise stage-damage curve has been selected (Fig. 18). Since the majority of

buildings has an underground floor, a vulnerability function which has a non zero damage for the threshold of 0.25 m is selected. This assumes that basements can be flooded due to backwater effects. The curve also considers only basement and ground floor, i.e. it reaches the 100% for 3.5 m of flood depth. The percent physical damage is then multiplied by a recovery cost equal to one fifth of the exposure, based on market analysis.

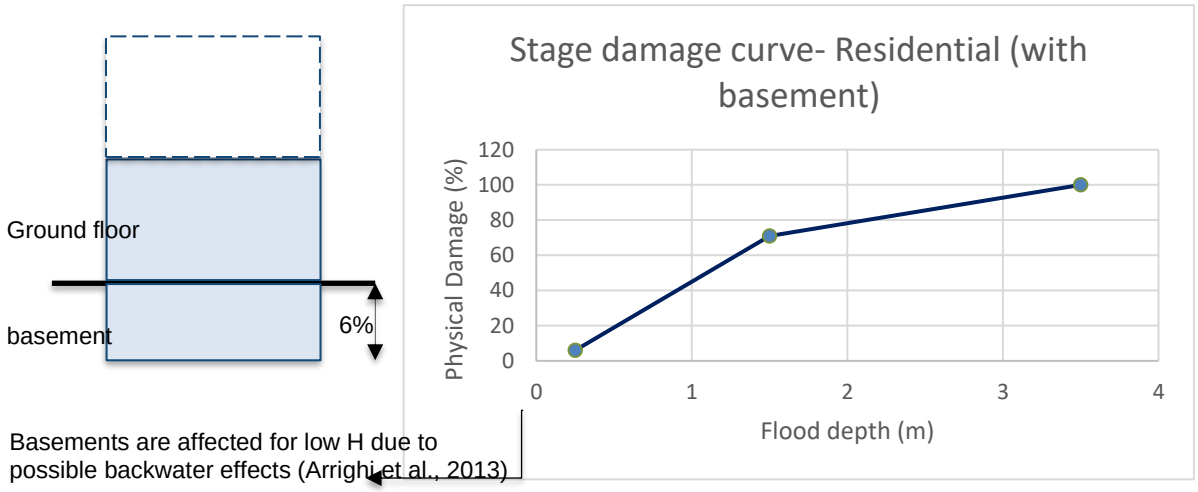

Figure 18: Vulnerability function selected for the buildings of the historic centre

The application of the above vulnerability curve for each recurrence interval scenario leads to a cumulative damage per event. An example of flood damages for the 500 years return period is shown in Fig. 19.

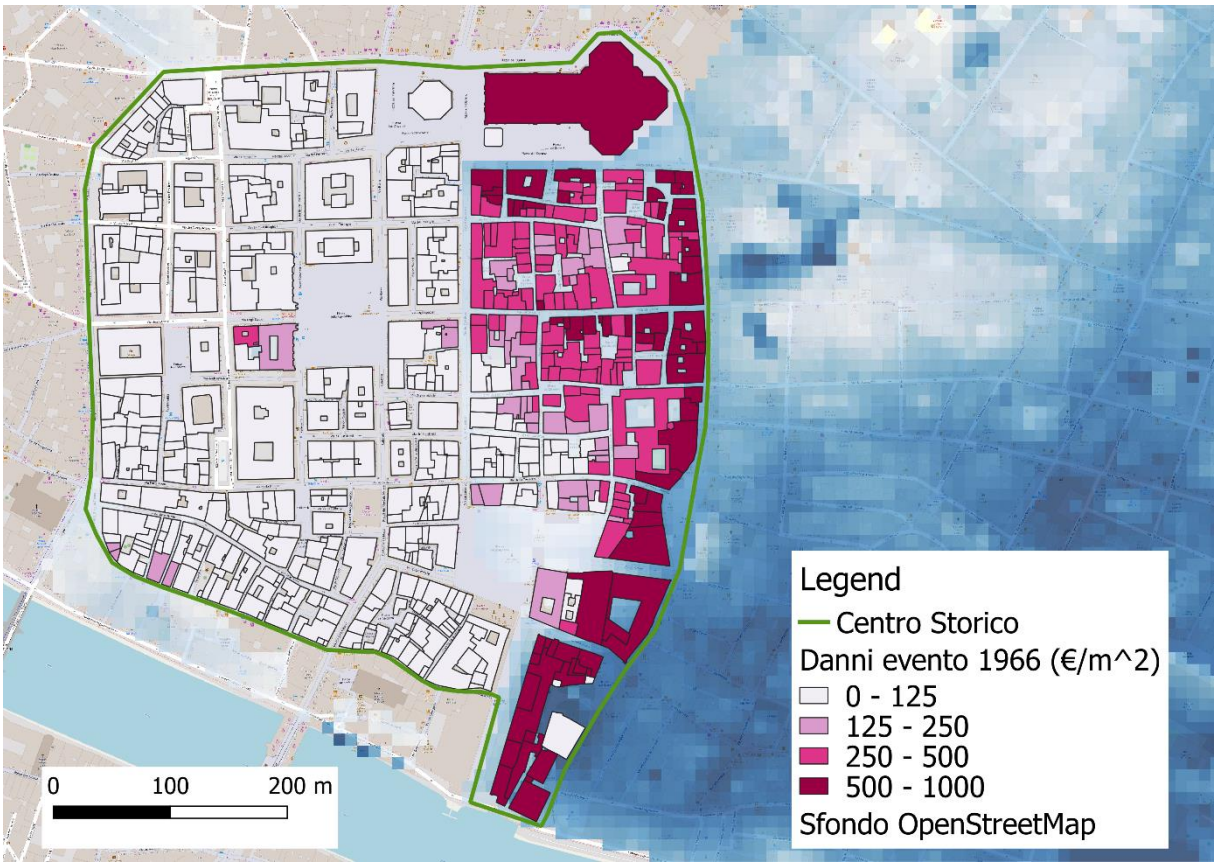

Figure 19: Flood losses for an event similar in magnitude to the 1966 flood

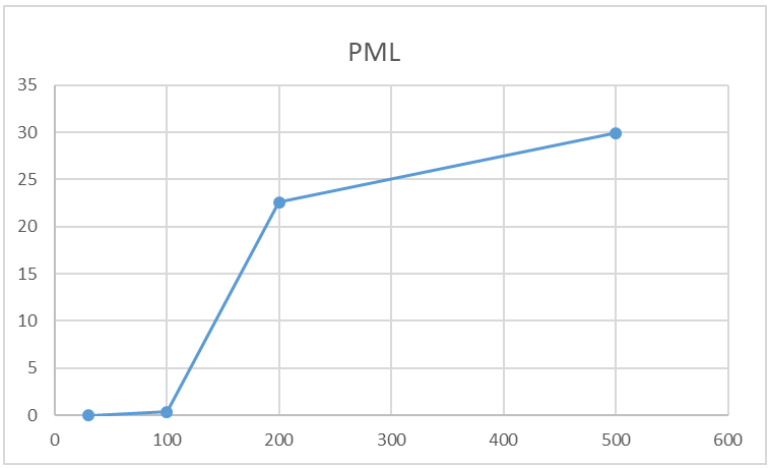

Figure 20: Flood losses (Mio €) associated to the four recurrence intervals (years)

Fig. 20 shows the probable maximum loss curve (PML) that is the value of the largest loss that can occur in a defined return period (e.g. 200 years). For the historic centre of Florence cumulate losses are 0.38, 22.6, 29.9 Mio € for the 100, 200, 500 years recurrence interval respectively.

The annual average loss (AAL) is the loss that we expect annually by weighting all the possible scenarios with their probability of occurrence in one year, it is calculated as the integral of the curve shown in Fig. 21, which represents the damage (Mio €) and the frequency (1/year). The AAL is the flood risk, expressed in monetary terms as €/year.

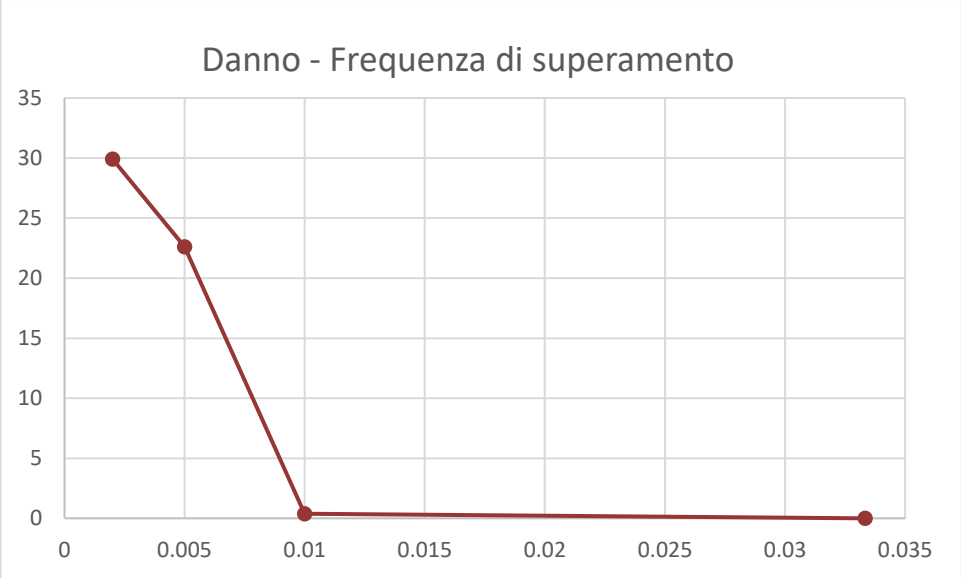

Figure 21: Damage-frequency curve

The risk calculated for the historic centre is about 0.2 Mio €/year. The map in Fig. 22 shows the risk for each building in terms of €/m^{2}year.

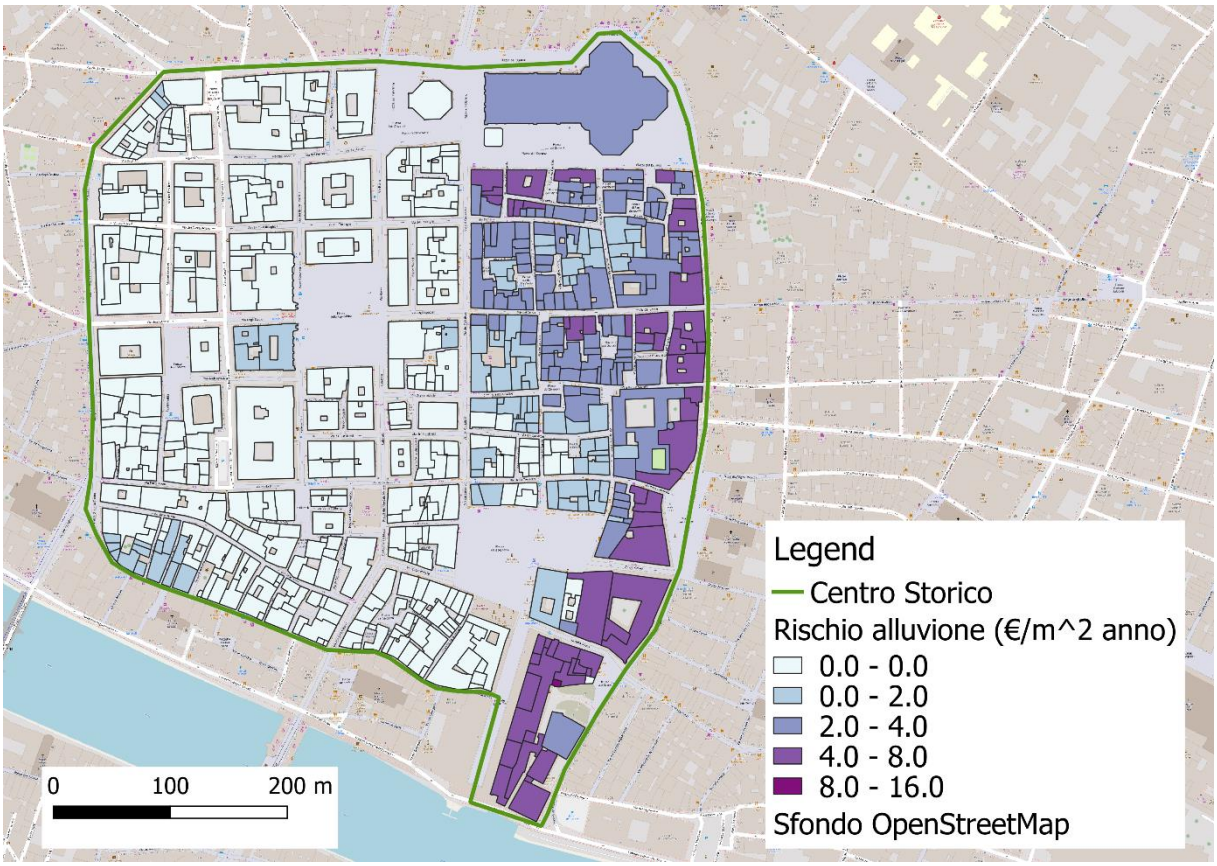

Figure 22: Risk to the historic centre of Florence

3.3 Resilience and indirect impacts on tourism

The application to the historic district of Florence of the methodology described in section 2.5 requires first the evaluation of the number of visitors for each attraction. The sources of the data are the Ministry of Cultural Heritage (MiBACT) and the annual report of museal institutions (Opera del Duomo, Museo della Scienza). For those attractions without data a regression curve with respect to the number of web reviews has been used to estimate the number of annual visitors (Fig. 23).

Beni culturali (visitabili) nel centro storico	Visitatori	# recer
Duomo	636127	
Cripta Santa Reparata	346816	
Campanile di Giotto	626268	
Battistero di S. Giovanni	698069	
Museo del Bigallo		
Chiesa di S. Maria Maggiore		
Chiesa dei SS. Michele e Gaetano		
Museo della Misericordia di Firenze		
Capitolo Metropolitano Fiorentino		
palazzo Strozzi	270000	
Biblioteca gabinetto Vieusseux		
Chiesa S.Margherita in S.Maria dei Ricci		
Museo casa di Dante	80000	
Museo di Orsanmichele	80392	
Palazzo dell'arte della lana		
Chiesa della badia Fiorentina		
Museo di Palazzo Davanzati		
Biblioteca palagio di Parte Guelfa		
Palazzo Vecchio-quartieri monumentali	683000	
Galleria degli uffizi	2219122	
Museo di Storia della scienza	520834	
fuori area di studio (per fitting)		
Galleria accademia	1623690	
Giardino boboli	1000482	
palazzo Pitti	579640	
Cappelle medicee	339870	

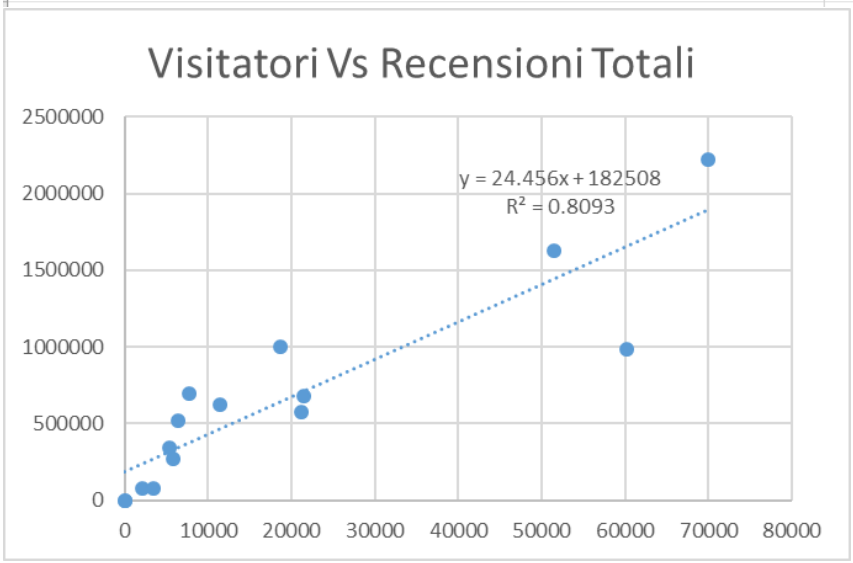

Figure 23: Annual visitors, reviews and regression

For the application T_{max} has been assumed equal to 365 days and the exponent k of Eq. (6) equal to 3. V_{pot} has been assumed equal to the visitors of 2018, neglecting possible trends. The estimation has been resolved at the weekly scale.

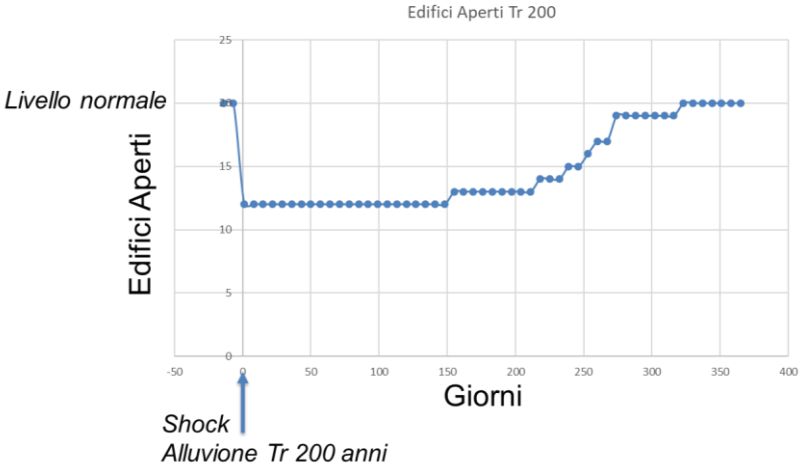

Figure 24: Recovery of the system in terms of number of buildings re-opening

Figure 25: Recovery of the system in terms of number of visitors

By estimating the resilience for each return period scenario L(Tr) (Eq. 8) is obtained

T_R	$1/T_R$	Lost visitors per event $L(T_R)$
30	0.033333	0
100	0.01	649989
200	0.005	3943762
500	0.002	4742540

The total risk from Eq. 9 is equal to 41582 lost visitors/year that is 0.5% of the annual visitors in the historic city.

3.4 Flood risk prevention and mitigation

The effect of the retention basins upstream of the city can be calculated only for the 200 years return period (Fig.26 and 27)

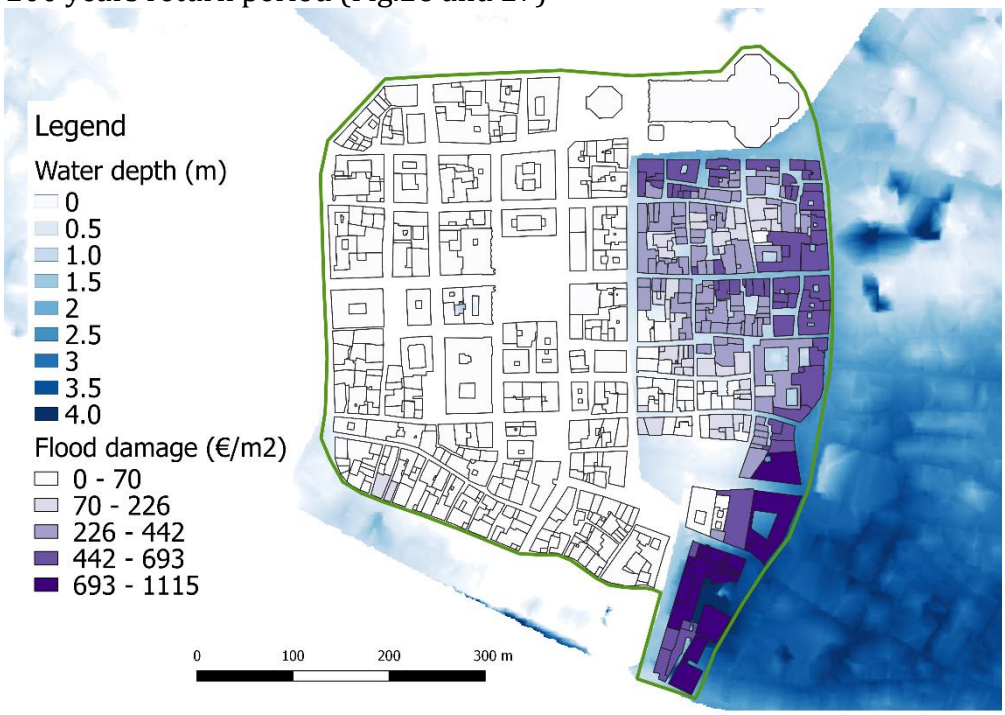

Figure 26: Flood depth and losses for the 200 year flood in current situation

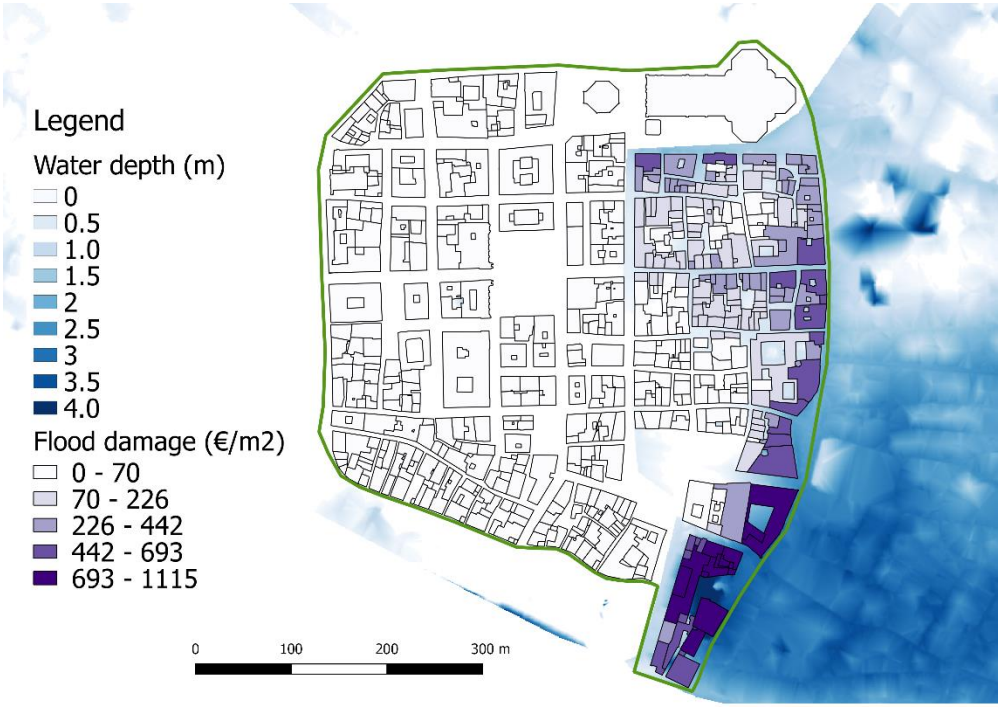

Figure 27: Flood depth and losses for the 200 year flood with retention basins

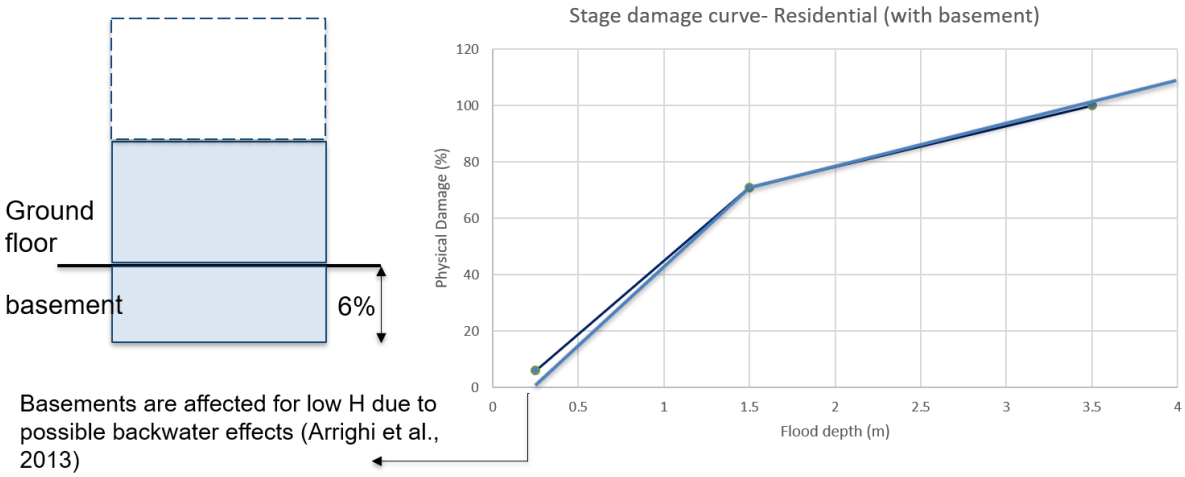

Figure 28: comparison between current vulnerability and protected underground floor

With the application of retrofitting measures the vulnerability curve of Fig. 28

can be applied. The results are shown in Fig. 29-30

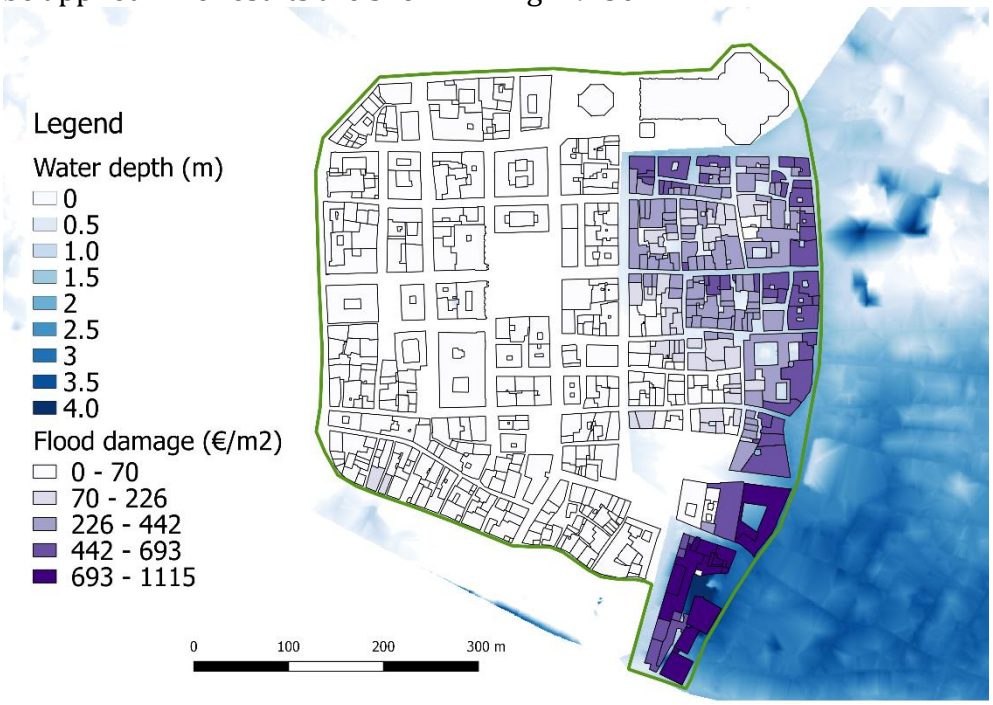

Figure 29: losses for the 200 year flood with mitigation measures

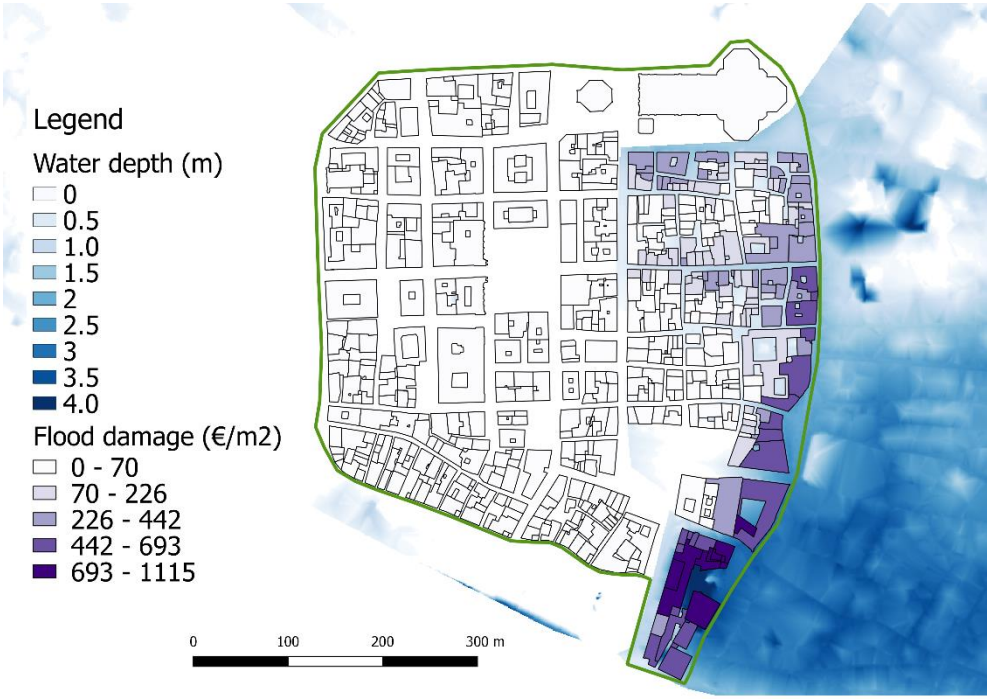

Figure 30: losses for the 200 year flood with mitigation measures and retention basins

The estimation or risk yields the following results:

Scenario	**Risk**
Current state	**209153 €/year**
Retention basin*	146389 **€/year**
Retrofitting	187165 **€/year**
Retention basins+retrofitting	129892 **€/year**

* the risk with retention basins assumes their effectiveness for the 100 and 500 years return period since only the 200 years scenario could be calculated

Mitigation and prevention give also benefits in terms of resilience and indirect impact on tourism. A comparison of resilience is shown in Fig.31 for the 200 years recurrence interval

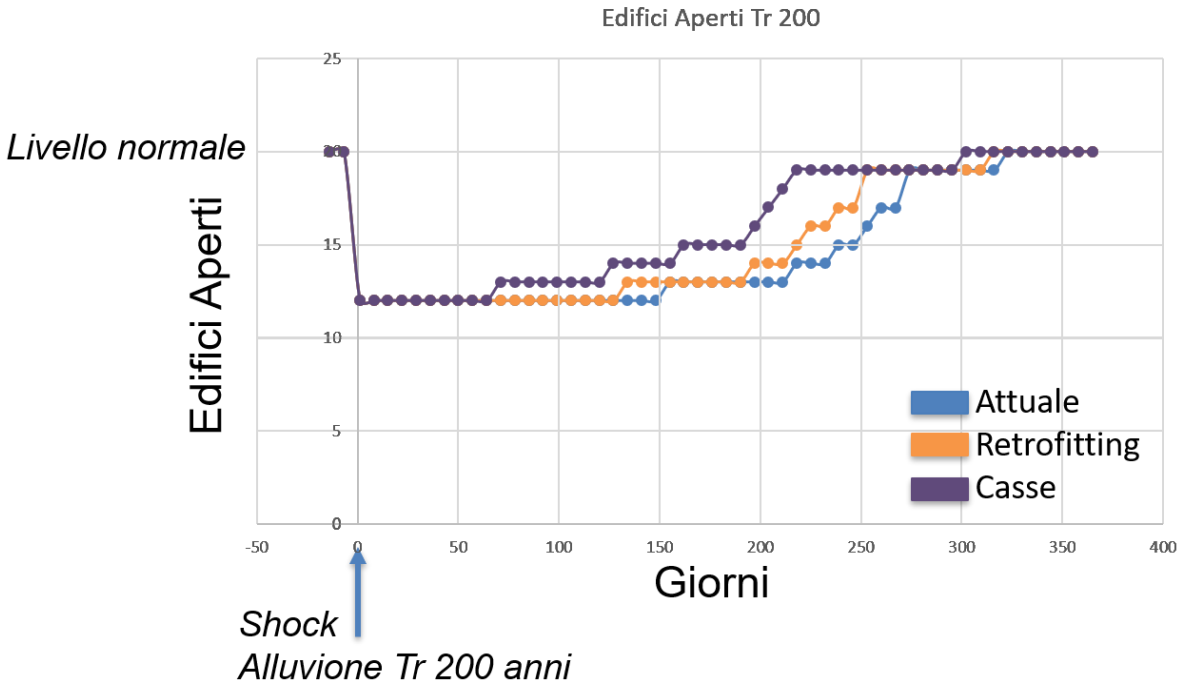

Figure 31: Resilience and recovery for the the 200 year flood with mitigation measures and retention basins with respect to current state

Scenario	**Risk to tourism (lost visitors per year)**
Current state	**41582**
Retention basins	34760

Retrofitting	30713

4.Conclusions

Florence is a UNESCO cultural heritage site prone to floods. The city centre is affected by inundation for return periods higher than 100 years according to hazard maps issued by the District of the Northern Appenines. The overall number of cultural sites considered in the municipality is 176. 76 of them are exposed to a flood with 200 years return period and 94 are exposed to a flood with 500 years return period (i.e. similar in magnitude to the 1966 flood event). The assignment of vulnerability to cultural heritage is spread into two main classes, Buildings and artworks contained inside the buildings. Three vulnerability classes have been selected for buildings and the result of the risk analysis shows that 54 buildings are at high risk of flooding (mainly religious buildings and museums).

For artworks three vulnerability classes have been assigned. The results of the risk assessment shows that libraries and archives suffer the highest annual expected losses, given the high vulnerability of manuscripts combined with hazard levels.

The analysis was carried out at site scale, thus disregarding the peculiarity of each piece of cultural heritage which would require a further investigation at the micro-scale, with high resolution data and increased knowledge of vulnerability.

The analysis assumed the absence of any flood mitigation measure applied to

the sites, so a pessimistic scenario is assumed.

The analysis carried out at building scale for the historic centre contained inside the medieval walls (in agreement with UR DIDA-UNIFI) is mainly focused on a monetary estimation of flood losses caused by the different inundation scenarios. This is the result of the application of vulnerability curves function of water depths and recovery costs based on buildings market values. Moreover, a methodology for the assessment of resilience and indirect impact on the loss of tourism is developed and applied to the historic district of Florence.

The implementation of local protection measures to reduce exposure or vulnerability and the effects of prevention measures upstream of the city are considered to assess the risk reduction under four different scenarios (i) current state, (ii) with retention basins, (iii) with flood-proofing of basements, (iv) with both retention basins and flood-proofing.

For the historic centre of Florence cumulate losses are 0.38, 22.6, 29.9 Mio € for the 100, 200, 500 years recurrence interval respectively. The risk expressed in terms of Annual Average Loss is around 0.2 Mio €/year. The main limitation of this economic analysis is that cultural buildings are considered as 'common' residential buildings in terms of vulnerability and exposure value. With retention basins the risk decreases up to 0.15 Mio €/year, with flood-proofing 0.18 Mio €/year and with both interventions the risk is 0.12 Mio €/year.

In terms of number of visitors lost the current risk is 41582 visitors lost per year, that could decrease up to 30713 with flood-proofing. In monetary terms, this risk can be considered about 6 Mio €/year in current situation and 4.6 with mitigation strategies.

A further research should better investigate at the building scale the actual vulnerability and find a better proxy for renovation costs.

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