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RISK ASSESSMENT OF CULTURAL HERITAGE IN CENTRAL EUROPE IN FACING EXTREME EVENTS

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With contribution of all partners

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Undoubtedly, cultural heritage is effectively a non-renewable resource, both in terms of socio-cultural and economic capital.

Thus evaluating the risk assessment of cultural heritage in facing extreme events is mandatory in order to identify all the possible solutions for protecting and transmitting our tangible and intangible knowledge, culture and traditions to future generations.

In the last decades, several works have been published on the issue of climate change impact on cultural heritage, especially in Europe. Indeed, as stated by Fatorić and Seekamp (2017), the highest number of publications on cultural heritage at risk from climate change is related to European contexts (59%). Considering merely the environmental impact on built cultural heritage the situation is similar, the majority of investigations regards Europe and the Mediterranean Basin (e.g. Bonazza et al. 2009a-2009b; Gomez-Bolea et al. 2012; Grossi et al. 2011; Ozga et al. 2011-2013; Sabbioni et al. 2012).

A recent study, commissioned by European Commission (Bonazza et al.,2018), realized a comprehensive overview of the existing knowledge, at European and international level, on safeguarding cultural heritage from the effects of natural disasters and threats caused by human action. This work highlighted that cultural heritage suffers from the fact that it is not considered a priority in risk management planning for emergency situations. Furthermore, cultural heritage is persistently omitted in the collective approach to creating and promoting fully effective resilience policies, therefore there is a need to address it.

The here present Deliverable underlines the past, current and overall the future projections of extreme events that can affect cultural heritage, as ***heat waves***, ***heavy precipitation***, ***droughts***, ***floods*** and ***fires***.

RENT AND FUTURE EUROPEAN AN MEDITERRANEAN EXTREME EVENTS

2.1. General Overview

The latest Report of IPCC (Intergovernmental Panel on Climate Change), the AR5 (Fifth Assessment Report) states that since about 1950 changes in many extreme weather and climate events have been observed, as a decrease in cold temperature extremes and an increase in warm temperature extremes, in extreme high sea levels and in the number of heavy precipitation events.

Precisely, it is reported:

> *“There are likely more land regions where the number of heavy precipitation events has increased than where it has decreased. Recent detection of increasing trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (medium confidence). It is likely that extreme sea levels (for example, as experienced in storm surges) have increased since 1970, being mainly a result of rising mean sea level.*
>
> ***Impacts from recent climate-related extremes**, such as **heat waves**, **droughts**, **floods**, **cyclones and wildfires**, **reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability** (very high confidence).”* (IPCC, 2014)

The historical temperature reconstructions of the European region date back to several past centuries, allowing researchers to highlight as some areas have experienced a disproportionate number of **extreme heat waves** in recent decades. Future projections of this phenomenon show that it will occur with a higher frequency, duration and/or intensity, since it can be amplified by drier soil conditions resulting from warming. In fact, the Panel declares that it is very likely that temperatures will continue to increase throughout the 21st century over all of Europe and the Mediterranean region.

Furthermore, also the frequency or intensity of **heavy precipitation events** has probable increased in Europe, in addition, the intensification in precipitation extremes has been evidenced consistent with a warmer climate. Thus, in future, there is a high confidence that extreme precipitation events will be more intense and more frequent along with warming, over most of the mid-latitude land masses, which include also Europe.

Land-based observations have shown an association between earlier snow melt at high northern latitudes and an increase of **extreme rainfall events** and **flooding**, however there is strong regionality in the trends.

Furthermore, we have to bear in mind that trends in floods are also strongly influenced by changes in river management as accounted by AR5 Working Group II (devoted to Impacts, Adaptation and Vulnerability).

Considering **drought**, even if it is a complex variable and there are uncertainties in its regional projections, there are indications of a likely increase of its frequency and intensity (reflecting also the length) in the Mediterranean area.

extremes are strongly connected, indeed in future the rainfall change will produce seemingly contradictory effects that are: more intense downpours, leading to more floods, yet longer dry periods between rain events, leading to more drought (IPCC, 2013).

A brief summary of extreme weather and climate events affecting Europe and Mediterranean regions and their related changes is reported in Table 1 and Table 2.

Table 1. Extreme weather and climate events: Global-scale (extracting specifically the European situation) assessment of recent observed changes, human contribution to the changes, and projected further changes for the early (2016–2035) and late (2081–2100) 21st century (extracted from Table SPM.1, B.1 Atmosphere, Summary for Policymakers, IPCC, 2013).

Phenomenon and direction of trend	**Assessment that changes occurred (typically since 1950 unless otherwise indicated)**	**Assessment of a human contribution to observed changes**	**Likelihood of further changes**	
			Early 21st century	**Late 21st century**
Warmer and/or fewer cold days and nights over most land areas	Very likely	Very likely	Likely	Virtually certain
Warmer and/or more frequent hot days and nights over most land areas	Very likely	Very likely	Likely	Virtually certain
Warm spells/heat waves[1]. Frequency and/or duration increases over most land areas	Likely in large parts of Europe	Likely	Not formally assessed	Very likely
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	Likely more land areas with increases than decreases	Medium confidence	Likely over many land areas	Very likely over most of the mid-latitude land masses and over wet tropical regions {12.4}
Increases in intensity and/or duration of drought	Low confidence on a global scale Likely changes in some regions (e.g. Mediterranean one)	Low confidence	Low confidence	Likely (medium confidence) on a regional to global scale Medium confidence in some regions (e.g. Mediterranean one)
Increases in intense tropical cyclone activity	Low confidence in long term (centennial) changes Virtually certain in North Atlantic since 1970	Low confidence	Low confidence	More likely than not in the Western North Pacific and North Atlantic
Increased incidence and/or magnitude of	Likely (since 1970)	Likely	Likely	Very likely

level				

ean observed changes in a range of climate indices since the middle of the 20th c
(extracted from Table 2.13, Observations: Atmosphere and Surface, Chapter 2, IPCC, 2013).

Warm Days (e.g. TX90pa)	Cold Days (e.g. TX10pa)	Warm Nights (e.g. TN90pa, TRa)	Cold Nights/Frosts (e.g. TN10pa, FDa)	Heat Waves / Warm Spells	Extreme Precipitation (e.g., RX1daya, R95pa, R99pa)	Dryness (e.g., CDDa)/ Drought
High confidence: Likely overall increase	High confidence: Likely overall decrease	High confidence: Likely overall increase	High confidence: Likely overall decrease	High confidence: Likely increases in most regions	High confidence: Likely increases in more regions than decreases but regional and seasonal variation	Medium confidence: spatially varying trends High confidence: Likely increase in Mediterranean

Finally, another catastrophic event that can have an impact on cultural heritage is undoubtedly **fire**. Even though the analyses of data in the European Forest Fire Information System (EFFIS) show that over 95% of the fires in Europe are human-induced (San-Miguel-Ayanz et al., 2012), their propagation is due to environmental conditions, among them also climatic variables, as maximum and minimum temperature, relative humidity, precipitation and wind speed (Marsala et al., 2012).

The combination of extreme weather conditions previously mentioned, as extended heat waves, drought, and strong winds, which are observing an increase in future in several European areas, can increase also the possibility of fire occurrence and diffusion, especially the large-scale ones, the “catastrophic megafires”.

According to Barbosa Ferreira et al. (2008), wildfires significantly affect the regions across Central and Southern Europe. In particular, two-thirds of the total European fires (in the period 2000-2005) occurred in 5 European Union Mediterranean countries (France, Greece, Italy, Portugal, and Spain). For this reason, the EU is very actively engaged in this thematic, indeed since 2000 EFFIS within the Copernicus programme, have published annual reports on forest fires in Europe. The most recent one is referred to 2016, and it reported that during this year “13 of the EU28 countries were affected by fires of over 30 ha: (Belgium, Bulgaria, Cyprus, France, Germany, Greece, Ireland, Italy, Portugal, Romania, Slovenia, Spain, United Kingdom), burning 327 503 ha in total (around twice the amount that was recorded in 2015, and above the long term average)” (San-Miguel-Ayanz et al., 2017).

During 2016, several countries of Central Europe registered the highest damage during the period April/May and July/August/September (Croatia, Germany, Italy, Slovenia), nevertheless both Croatia and Italy were interested by fires until December.

While considering specifically the reports developed by each country, it was specified also the type of fire, which can be forest, non-forest, agricultural, artificial surfaces, etc., even sometimes identifying the different type of forest (e.g. coniferous/ broadleaved forest in Germany), as deciduous species are less flammable than conifer species (Terrier et al., 2013).

Therefore, the development of fires is very complex and depends by several factors, for this reason it is difficult to have a long-term projection of them. Nevertheless, in 2009, Krawchuk et al. realized a first step to quantify potential change in global wildfire. Indeed, they realized a multivariate quantification of environmental drivers for the observed, current distribution of vegetation fires using statistical models of the relationship among fire activity and resources to burn, climate conditions, human influence, and lightning flash rates at a coarse spatiotemporal resolution (100 km, over one decade). Thus, they highlight current and future “pyrogeography”, a concept that referred to the spatial distribution of fire across the planet, in order to illustrate geographically the fire-prone and fire-free areas, combining jointly the urn and environmental conditions that conduct to combustion. Cons specifically Europe, projections show an increase of fire-prone areas across northern Europe by the end-of-century, under both the A2 (mid-high) and B1 (low) emissions scenarios (in Figure 1 the A2 scenario).

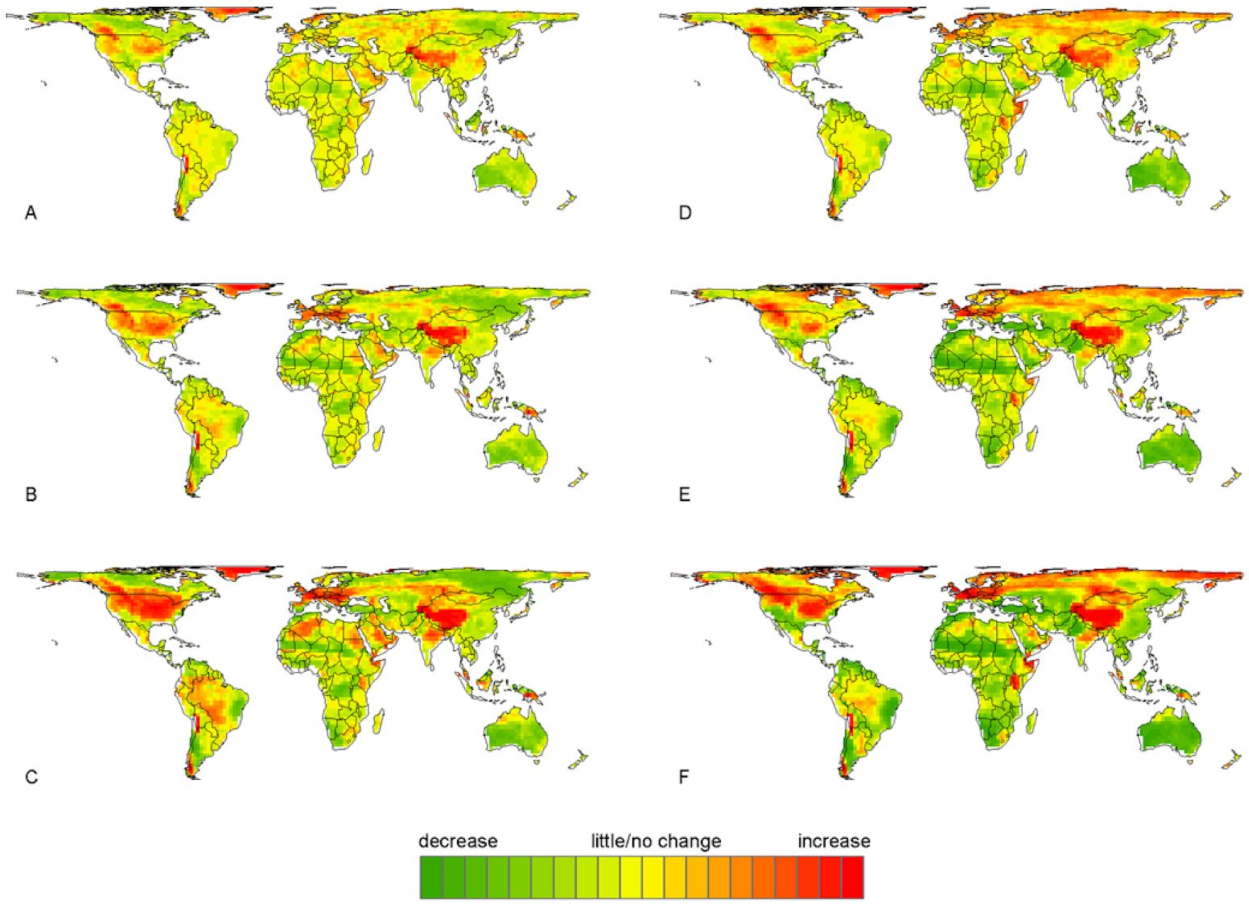

Figure 1. Changes in the global distribution of fire-prone pixels under the A2 (mid-high) emissions scenario. An increase from current conditions (red) is indicated by a PΔ (change in future fire probabilities) greater than unity, little or no change (yellow) is indicated by a PΔ around unit, and a decrease (green) is indicated by a PΔ less than unity. Panels show the mean PΔ for the ensemble of ten FIRENPP (A–C) and FIREnoNPP (D–F) sub-models. Climate projections include 2010–2039 (A, D), 2040–2069 (B, E) and 2070–2099 (C, F). (From Krawchuk, 2009, doi:10.1371/journal.pone.0005102.g002)

Always regarding the future situation, as cited in the AR5 of IPCC (2014 and related references), r**egional studies for boreal regions suggest an increase in future fire risk.** Nevertheless, models predict spatially variable responses in fire activity, due to regional variations in the climate-fire relationship, and anthropogenic interference, in fact fire activity is also related to land use change. For instance, wetter conditions can reduce fire activity, but increased biomass availability can intensify fire emissions.

Urban Areas

A recent study of Guerreiro et al. (2018) investigated 571 European cities, analysing 50 climate model projections from the CMIP5 (RCP8.5) ensemble in order to evaluate climate impacts for heat waves (HW), droughts and flooding, considering high, medium and low scenarios (future period 2051-2100).

Considering the selected pilot sites of Protech2save Project, which are located in Ferrara (IT), Troja (CZ), Kastela (HR), Kocevje (SL), Krems (AT), Pècs (HU) and Bielsko-Biala (PL), an extract of data obtained by this research work and referred to Protech2save-case studies is reported in Table 3.

Table 3. Indices results for all analysed cities. (i) Δ % of Heatwave Days: difference in percentage of summer (May-September) days classified as heatwaves days. (ii) ΔMax (Tmax): Difference in the maximum daily maximum temperature for days classified as heat waves days. (iii) DSI change factor: Future maximum DSI-12 divided by historical maximum DSI-12 (HMD). (iv) P (DSI-12> HMD): Probability for any given month in the future being above HMD. (v) Q10 change factor: Future Q10 divided by historical Q10, cities without a river (with at least 500 km$_2$ of catchment area) within their boundary are not applicable (NA) for this index.

City	***Scenario***	***Δ % of Heat wave Days***	***ΔMax (Temp)***	***DSI change factor***	***P(DSI-12> MHD)***	***Q10 change factor***
	High	36.80	11.90	2.40	9.40	NA
	Low	8.30	5.00	0.39	0.00	NA
	Medium	19.30	8.80	1.09	0.50	NA
	High	49.70	12.20	3.42	31.10	1.26
	Low	19.40	5.90	0.86	0.00	0.84
	Medium	31.00	8.40	1.81	6.30	1.01
	Low	15.30	6.40	0.68	0.00	0.66
	Medium	28.90	8.50	1.54	5.90	0.98
	High	47.60	12.30	2.77	23.50	1.59
	High	42.30	11.40	2.99	16.80	NA
	Low	12.20	5.60	0.54	0.00	NA
	Medium	26.80	8.50	1.43	3.70	NA
	High	33.90	12.00	1.60	6.20	1.15
	Low	7.70	5.40	0.42	0.00	0.86
	Medium	18.00	9.50	0.88	0.00	1.04
	High	51.00	10.30	3.73	27.10	NA
	Low	23.30	4.80	0.76	0.00	NA
	Medium	36.20	7.20	1.67	7.30	NA
	High	40.40	11.90	2.50	14.70	1.20

		11.40	5.20	0.54	0.00	
	Medium	23.30	8.70	1.13	1.00	1.02

With mention to heat waves, the research work highlighted that **in general more frequent and hotter heat waves are expected for all the European cities considered**. While considering **heat wave days**[1], **the largest increase will interest the southern cities** (as much as 69%). Nevertheless, authors remind that central European cities, which show the largest increase of maximum heat waves temperature (up to 14 °C), are generally not adapted to extreme heat both considering infrastructures and population. Moreover, **drought** conditions will increase in cities belonging to South Europe, showing in the high-impact scenario a worsening of future droughts (up to 14 times worse than the ones in the historical period).

Referring to **flooding**[2], an **increase** is indicated, **mostly prevalent in North-West Europe**, particularly worrying for the British Isles and several other European cities, which could observe more than a 50% increase of their 10 year high river flow. For instance, “Ljubljana (Slovenia) and Leeds, Cardiff, Exeter and Newport in the UK are in the top 20% of changes in both flooding and HWTmax indices”, always according to this study.

2.3. Evaluation of Damages in Cost Terms

Another contemporary study, always concerning the projections and impact of this extreme events (Alfieri et al., 2018), compared estimates of river flood risk in Europe (Fig. 1), calculating economic damages for several economic sectors (residential, commercial, industrial, infrastructure, and agriculture). By combining inundation depth with damage functions[3], Gross Domestic Product and land use maps, the research work highlights as **“most of the Central and Western Europe is consistently projected to experience substantial increase in flood risk, with the magnitude of the change increasing for higher levels of warming”**. Although results generally demonstrate a correlation between global warming and flood impacts, the authors also add that a “considerable increase in flood risk is predicted in Europe even under the most optimistic scenario of 1.5°C warming as compared to pre-industrial levels”.

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[1] Defined as three consecutive days where both the maximum and the minimum temperature exceed their respective 95th percentile from the historical period.

[2] Changes in river flooding, assessed by the 10 year high flow (Q10).

[3] Flood damage functions describe the relation between inundation depth and the corresponding direct economic damage per unit surface.

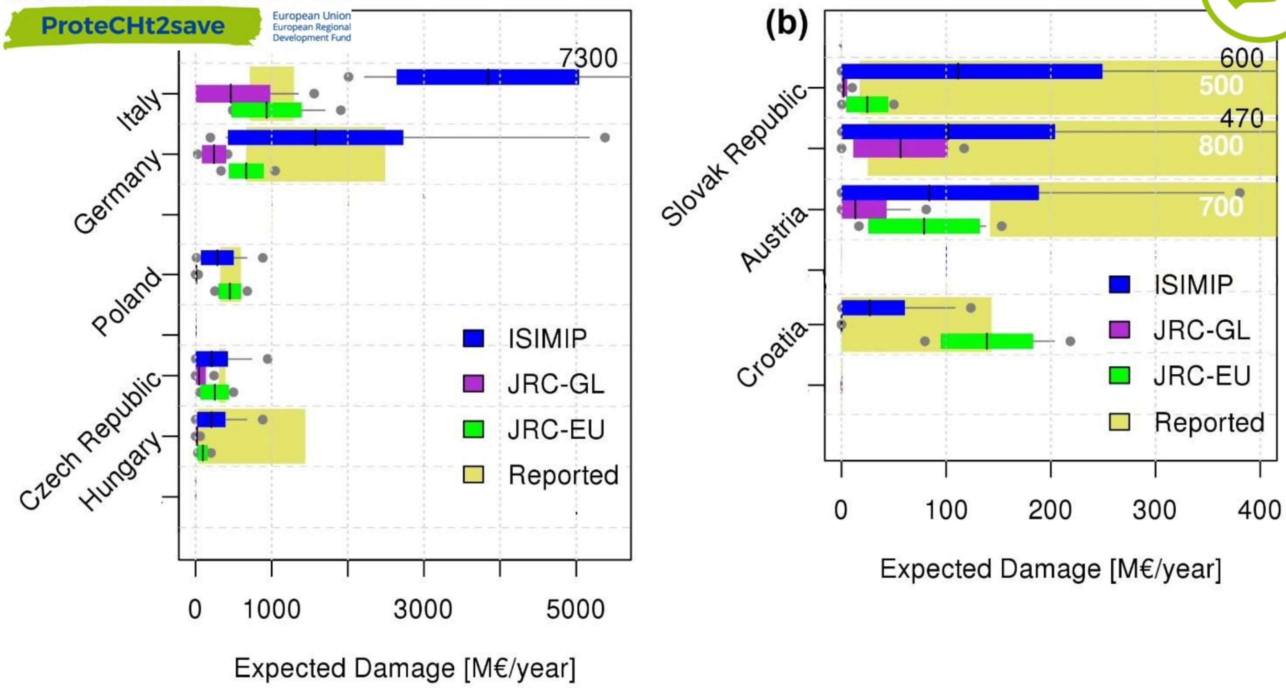


Figure 2. Modified from Fig. 2, Alfieri et al. (2018), extracting only the countries belonging to Central Europe. The figure compares the simulated impact of the three ensemble estimates for the **baseline period 1976-2005**, with the range of available reference datasets including data from the GAR, EM-DAT, and Munich RE for recorded losses and only EM-DAT for reported population affected. "Economic damage computed for the baseline period for each country by the ensembles of the three case studies (a,b). Plots show the average (black dash), ±1 standard deviation (colored bar), and minimum and maximum values (whiskers) of each ensemble. The gold bars show the range of reported impact values (minimum and maximum)."
Legend: Inter-Sectorial Impacts Model Intercomparison Project (ISIMIP); JRC-GL and JRC-EU Flood Hazard Maps at Global and European Scale.

Always considering the possible damages due to climate extremes, another recent study (Forzieri et al. 2018) analysed the damage from climate hazards (heat and cold waves, river and coastal floods, droughts, wildfires, and windstorms). These are derived for 1981–2010 (baseline), 2011–2040 (referred to as the 2020s for short), 2041–2070 (2050s) and 2071–2100 (2080s), for an ensemble of bias-corrected climate projections under the A1B emissions scenario. The damages are referred to critical infrastructures, namely energy, transport, industry and social sector (Fig. 3).
Specifically, the considered assets include the following sectors:

- Energy sector: non-renewable energy production (coal/oil/gas/nuclear power plants), renewable energy production (biomass and geothermal/hydro/solar/wind power plants) and energy transport systems (electricity distribution/transmission and gas pipelines);
- Transport sector: roads, railways, inland waterways, ports, and airports;
- Industry sector: heavy industries (metal/mineral/chemical/refineries) and water/waste treatment systems;
- Social sector: education and health infrastructures (e.g. schools and hospitals).

According to this research work, entire Europe will likely experience a **progressive increase in multi-hazard losses**, **in particular Southern Europe** will be progressively more prominently affected by future climate extremes than the rest of continent.
Specifically, **droughts will strongly intensify in southern parts of Europe** and become less severe in northern regions (Forzieri et al., 2014), also **heatwave impacts are projected to rise significantly all**

e south. While considering **river and coastal floods, they will rema** most critical hazard in W**estern, Central, and Eastern Europe**, including the British Isles, Poland, the Czech Republic, Bulgaria, Romania, and northern coastlines of the Iberian Peninsula.

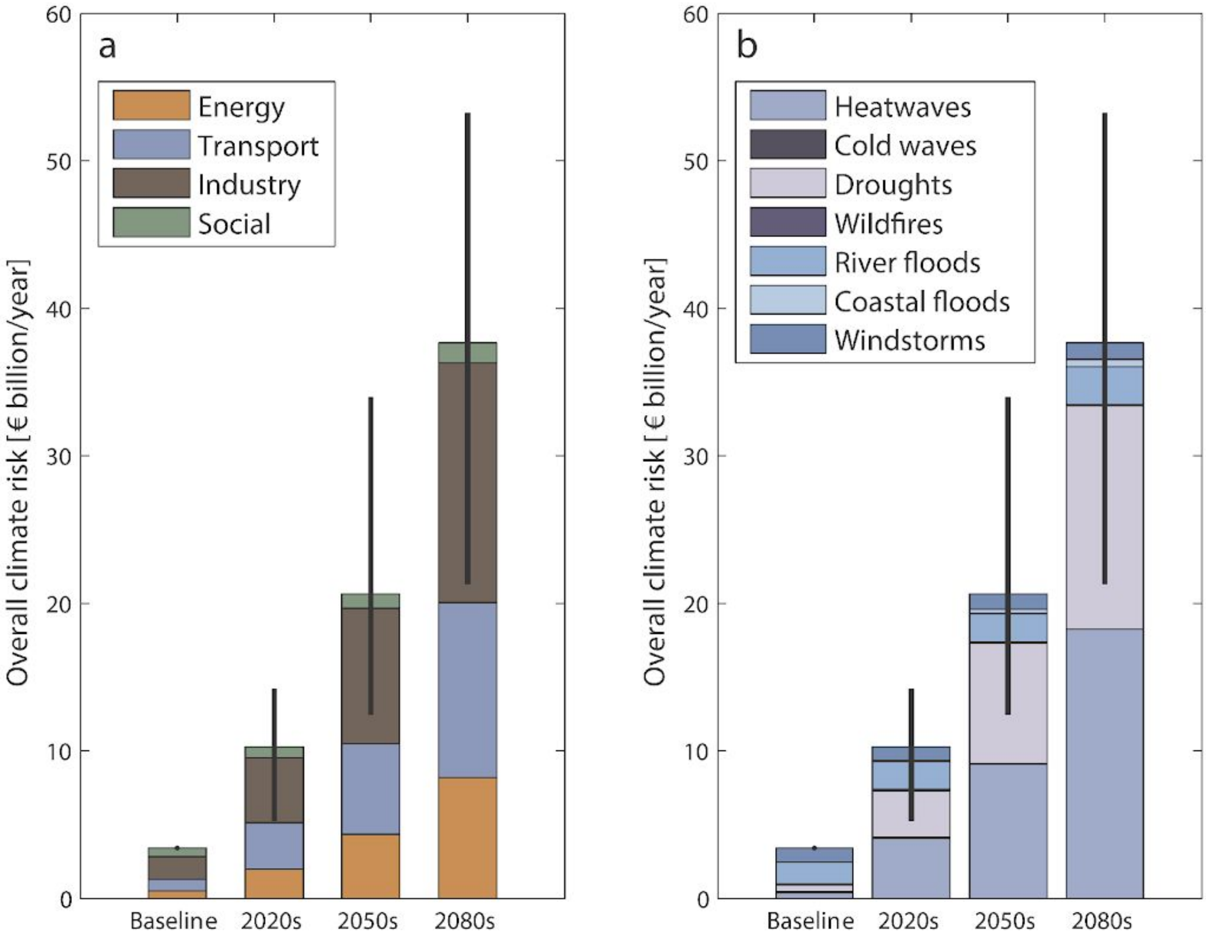


Figure 3. Overall climate hazard risk to critical infrastructures aggregated at European level (EU+) for each time period: a) distribution of damage by sector; b) distribution of damage over the seven hazards. For wind, projections of hazard are not available for 2020 s and 2050s; damage for these periods was obtained by linearly interpolating between the baseline and the 2080s. Whiskers reflect the inter-model climate variability (from Forzieri et al. 2018).

The following table (Tab. 4) collects the expected annual damage (from 2000 to 2080) and cost adaptation for multi-hazard multi-sectors, taking into account only short-term projected changes in climate. Specifically, countries considered in Protecht2save project are extracted from Forzieri et al. (2018), where authors highlighted that countries in southern Europe will be exposed to higher risk levels, thus they could potentially have to direct a significant proportion of their investments in fixed capital to abating the future impacts from climate hazards on critical infrastructures.

Table 4. Expected annual damage (EAD) and cost of adaptation (in 2010 constant euro prices or percentage of 2010 GFCF) for multi-hazard multi-sector analysis. Values for different time windows refer to results obtained by adding up single-hazard multi-model medians and reflect the EAD and adaptation costs assuming climate conditions of the time window imposed on present infrastructures. (Extracted from Forzieri et al. 2018)

Country	EAD (€ million)				EAD (% of GFCF)				Capital cost (€ million)			Capital cost (% of GFCF)			Annual O&M (e million)		
	2000s	2020s	2050s	2080s	2000s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s

					0.11	0.21	0.35	0.76	223	771	2260	0.35	1.21	3.54	17.3	30	
					0.21	0.28	0.24	0.34	112	163	362	0.27	0.39	0.86	8.7	6.3	
DE	579	1039	1788	2956	0.12	0.21	0.36	0.59	1657	6010	14,569	0.33	1.2	2.91	129	234	378
HR	21	55	163	499	0.22	0.57	1.7	5.21	122	635	2,357	1.28	6.63	24.62	10	25	61
HU	47	56	112	169	0.23	0.28	0.56	0.85	35	269	712	0.18	1.35	3.56	2.7	10.5	18
IT	460	2,617	4,901	8,939	0.14	0.82	1.53	2.79	7,768	23,756	54,282	2.43	7.42	16.96	604	924	1,407
PL	206	277	240	260	0.28	0.38	0.33	0.35	257	379	576	0.35	0.52	0.78	20	14.7	14.9
SI	17	39	72	233	0.23	0.5	0.93	3.01	77	274	1,050	1	3.55	13.59	6	11	27
SK	19	27	82	208	0.13	0.18	0.55	1.39	29	258	938	0.19	1.73	6.29	2.2	10	24
EU+	3,410	10,304	20,621	37,632	0.12	0.38	0.75	1.37	24,820	86,778	209,977	0.9	3.16	7.65	1,930	3,375	5,444

Cultural heritage, along with representing a “cultural capital”, should also be considered as an economical source. Indeed, it will be necessary to evaluate also the damages and the adaptation costs in facing extreme events in heritage sector, thus including this field in research works as the ones previously mentioned.

ESSMENT OF EXTREME EVENTS CULTURAL HERITAGE

3.1. Deterioration Patterns on Materials belonging to Cultural Heritage

According to the EwaGlos (Weyer et al., 2016), several deterioration sources can affect historical architectural surfaces and wall paintings, and they can cause consequently deterioration phenomena as summed up in Figure 4 (for the definitions of stone deterioration patterns see also ICOMOS-ISCS, 2008).

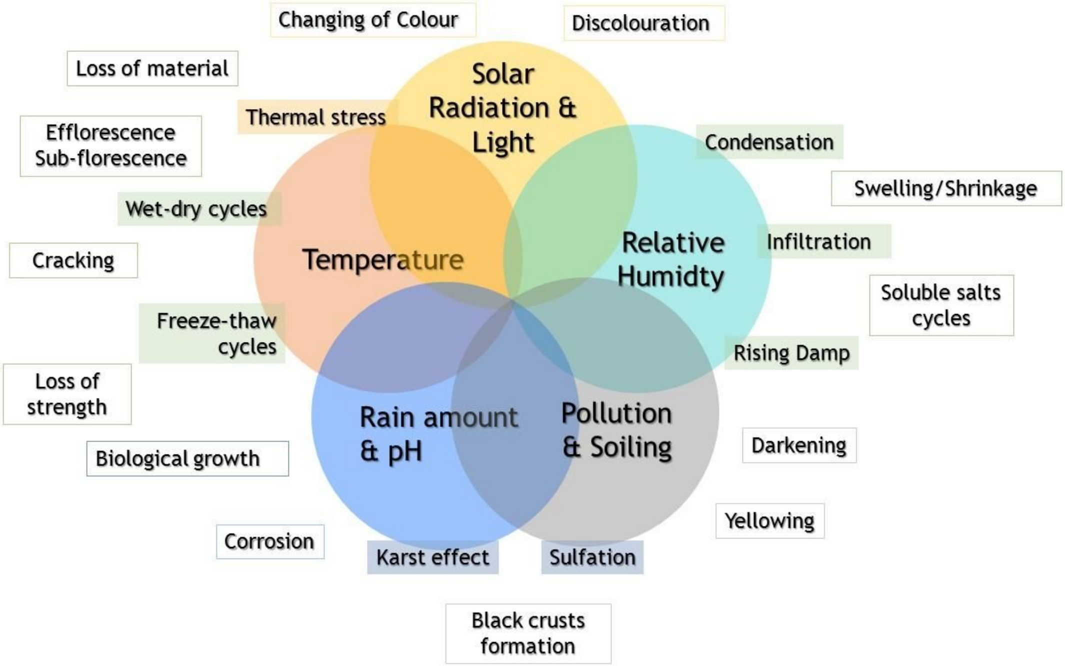
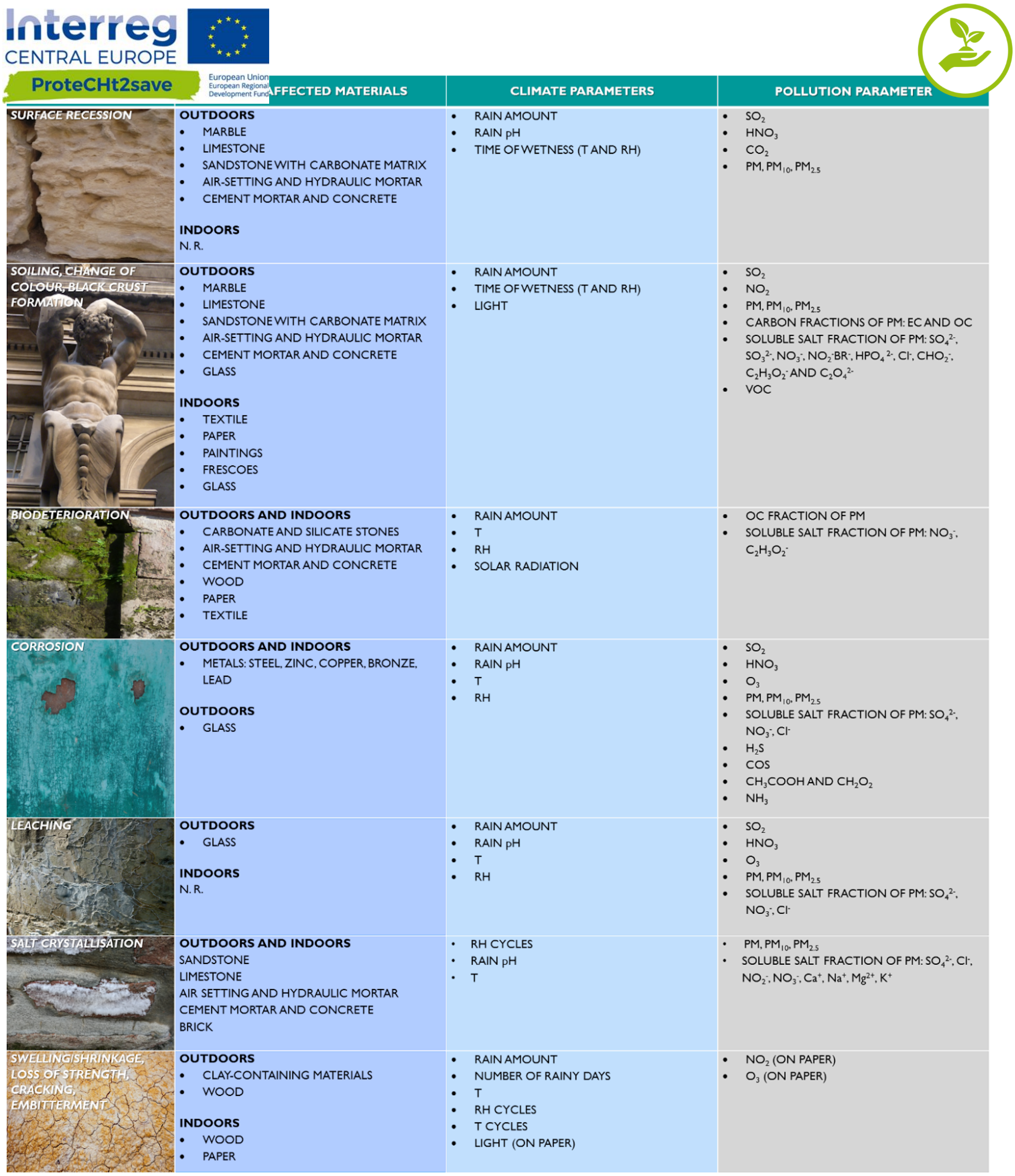


Figure 4. Scheme representing environmental parameters (coloured circles) responsible of processes (in coloured rectangles) that cause materials deterioration phenomena.

Specifically, the main damage processes of materials belonging to cultural heritage due to climate and pollution parameters are reported in Table 5.

Table 5. Summary of the climate and pollution parameters involved in damage processes on cultural heritage materials (immovable and movable) (n. r. = not relevant). Selecting the deterioration phenomena due to the action of climatic parameters in conjunction with pollutants. (Modified by Bonazza et al., 2018). Legend: Acetates = $C_2H_3O_2^-$; Acetic acid = CH_3COOH; Ammonia = NH_3; Bromides = Br^-; Calcium = Ca^+; Carbon dioxide = CO_2; Carbonyl sulphide = COS; Chlorides = Cl^-; Elemental carbon = EC; Formates = CHO_2^-; Formic acid = CH_2O_2; Hydrogen sulphide = H_2S; Magnesium = Mg_2^+; Nitrates = NO_3^-; Nitric acid = HNO_3; Nitrites = NO_2^-; Nitrogen dioxide = NO_2; Organic carbon = OC; Oxalates = $C_2O_4^{2-}$; Ozone = O_3; Particulate matter = PM; Phospates = HPO_4^{2-}; Potassium = K^+; Sodium = Na^+; Sulphates = SO_4^{2-}; Sulphites = SO_3^{2-}; Sulphur dioxide = SO_2; Volatile organic compounds = VOC. Relative Humidity = RH and Temperature = T.



	FFECTED MATERIALS	CLIMATE PARAMETERS	POLLUTION PARAMETER
SURFACE RECESSION	**OUTDOORS** • MARBLE • LIMESTONE • SANDSTONE WITH CARBONATE MATRIX • AIR-SETTING AND HYDRAULIC MORTAR • CEMENT MORTAR AND CONCRETE **INDOORS** N. R.	• RAIN AMOUNT • RAIN pH • TIME OF WETNESS (T AND RH)	• SO_2 • HNO_3 • CO_2 • PM, PM_{10}, $PM_{2.5}$
SOILING, CHANGE OF COLOUR, BLACK CRUST FORMATION	**OUTDOORS** • MARBLE • LIMESTONE • SANDSTONE WITH CARBONATE MATRIX • AIR-SETTING AND HYDRAULIC MORTAR • CEMENT MORTAR AND CONCRETE • GLASS **INDOORS** • TEXTILE • PAPER • PAINTINGS • FRESCOES • GLASS	• RAIN AMOUNT • TIME OF WETNESS (T AND RH) • LIGHT	• SO_2 • NO_2 • PM, PM_{10}, $PM_{2.5}$ • CARBON FRACTIONS OF PM: EC AND OC • SOLUBLE SALT FRACTION OF PM: SO_4^{2-}, SO_3^{2-}, NO_3^-, $NO_2^-$$BR^-$, HPO_4^{2-}, Cl^-, CHO_2^-, $C_2H_3O_2^-$ AND $C_2O_4^{2-}$ • VOC
BIODETERIORATION	**OUTDOORS AND INDOORS** • CARBONATE AND SILICATE STONES • AIR-SETTING AND HYDRAULIC MORTAR • CEMENT MORTAR AND CONCRETE • WOOD • PAPER • TEXTILE	• RAIN AMOUNT • T • RH • SOLAR RADIATION	• OC FRACTION OF PM • SOLUBLE SALT FRACTION OF PM: NO_3^-, $C_2H_3O_2^-$
CORROSION	**OUTDOORS AND INDOORS** • METALS: STEEL, ZINC, COPPER, BRONZE, LEAD **OUTDOORS** • GLASS	• RAIN AMOUNT • RAIN pH • T • RH	• SO_2 • HNO_3 • O_3 • PM, PM_{10}, $PM_{2.5}$ • SOLUBLE SALT FRACTION OF PM: SO_4^{2-}, NO_3^-, Cl^- • H_2S • COS • CH_3COOH AND CH_2O_2 • NH_3
LEACHING	**OUTDOORS** • GLASS **INDOORS** N. R.	• RAIN AMOUNT • RAIN pH • T • RH	• SO_2 • HNO_3 • O_3 • PM, PM_{10}, $PM_{2.5}$ • SOLUBLE SALT FRACTION OF PM: SO_4^{2-}, NO_3^-, Cl^-
SALT CRYSTALLISATION	**OUTDOORS AND INDOORS** SANDSTONE LIMESTONE AIR SETTING AND HYDRAULIC MORTAR CEMENT MORTAR AND CONCRETE BRICK	• RH CYCLES • RAIN pH • T	• PM, PM_{10}, $PM_{2.5}$ • SOLUBLE SALT FRACTION OF PM: SO_4^{2-}, Cl^-, NO_2^-, NO_3^-, Ca^+, Na^+, Mg^{2+}, K^+
SWELLING/SHRINKAGE, LOSS OF STRENGTH, CRACKING, EMBITTERMENT	**OUTDOORS** • CLAY-CONTAINING MATERIALS • WOOD **INDOORS** • WOOD • PAPER	• RAIN AMOUNT • NUMBER OF RAINY DAYS • T • RH CYCLES • T CYCLES • LIGHT (ON PAPER)	• NO_2 (ON PAPER) • O_3 (ON PAPER)

Extreme events can worsen these phenomena, even causing more serious damages, as described in the following subchapter (3.2).

Considering the outlines of Chapter 2, in the future Central Europe and Mediterranean Area will experience an increase of extreme events, such as downpours and floods. In large parts of Europe warm spells and heat waves will likely rise in frequency and/or duration, while drought intensity and/or duration will probably increase especially in some regions, as Southern Europe and Mediterranean ones. Finally, it has been also observed that wildfires significantly affect the regions across Central and Southern Europe and in the future it is likely that this trend will continue, even if it is highly dependent on anthropogenic interferences and land use.

Therefore, their effects on cultural heritage could produce several deterioration processes, depending also by the material compounds of masonries, structures, monuments, work of arts, etc. present at the sites.

In the following Tables (6-8) the deterioration processes of outdoor structures are described, divided by materials, according with the most diffused in the pilot sites. These are natural and artificial stone masonries and monuments (Tab. 6), wooden structure (Tab. 7) and metals (Tab. 8).

Table 6. Effects of extreme events on brick and stone masonries and on natural and artificial stone monuments and works-of-art.

Masonries, natural and artificial stone monuments and works-of-art		
Extreme event	Effects	Description
Heavy rainfalls ***cause both physical-chemical deterioration processes (due to the prolonged exposure to rain that increases the presence of moisture in the structures)***	*Erosion*	The mechanical action of wind driven rain can cause loss of material.
	Wet-dry cycles/Salts weathering	Cyclical absorption and desorption of moisture in a building material, responsible of salt crystallization problems: efflorescence (on surfaces) and/or subflorescence (beneath surfaces). They can cause cracks, fractures, detachments and loss of materials (Grossi et al., 2011; Arnold and Zehnder, 1989).
	Freeze-thaw cycles	Cyclical formation of ice crystals when temperature fluctuates above and below 0 °C, which can cause cracks, fractures, detachments and loss of materials (Sabbioni et al., 2012).
	Biological growth	The persistent presence of humidity, in conjunction with favourable temperature and substrate conditions, can foster the biological colonization (mold, moss, lichens, algae, fungi and even vascular plants) (Gomez-Bolea, 2012; Caneva et al., 2009).
	Surface recession	On areas exposed to rain wash out, loss of material, in terms of recession of the surface, can occur. It is due to chemical attack induced by the effect of clean rain (karst effect), acid rain (due to presence of sulphuric and nitric acid) and dry deposition of gaseous pollutants (especially SO_2 and NO_X). It occurs between precipitation events, mainly affecting carbonate stones of low porosity (marbles and compact limestones) (Bonazza et al., 2009a).
	Soiling	Deposit of soot that can change the colour of architectonical surfaces, depending on its nature (e.g. diesel soot in proximity of a busy road can blacken the surfaces of buildings). This has an aesthetic impact, depending on the direction and the magnitude of colour change, indeed the rain-washing can lead to disfiguring patterns on cultural surfaces. It can have also economic implications due to changes in the approach to cleaning and maintaining buildings (Sabbioni et al., 2012; Brimblecombe and Grossi, 2005).

	Black-crusts formation	The deposit of soot can originate, on areas partially protected agai direct rainfall or water runoff in urban environment, black crusts. They are formed by gypsum (that is calcium sulphate, through the sulphation process of the calcium carbonate substrate), which traps particles from the atmosphere. (Ruffolo, 2015; La Russa et al., 2013; Török, 2003).
	Eventual structural problems	In conjunction with the surroundings, heavy rainfall can also lead to landslides and ground instability, thus consequently structural instability for the whole heritage complex.
Floods ***cause both physical-chemical deterioration processes (due to the moisture penetration within the structures)***	*Erosion*	Due to the mechanical action of water and eventual debris carried by flood (e.g. in case of river and coastal/sea flood);
	Damage due to horizontal static pressure of raised water	It typically destroys light shutters of building openings, e.g. doors and windows, especially glazing, and it can destroy freestanding walls and fences, in many cases together with dynamic action of streams and flows.
	Saturation of materials with water	It causes a wide variety of actions and damage related to volumetric changes, chemical action, loss of strength, etc.
	Wet-dry cycles/Salts weathering	Cyclical absorption and desorption of moisture in a building material, responsible of salt crystallization problems: efflorescence (on surfaces) and/or subflorescence (beneath surfaces). They can cause cracks, fractures, detachments and loss of materials (Grossi et al., 2011; Arnold and Zehnder, 1989).
	Structural problems	Hydrostatic pressure can uplift floors or whole objects, decreases their stability against overturning and facilitates their damage by horizontal forces;
		Dynamic low velocity stream action is typically observed inside closed buildings where floated objects move and are displaced;
		Collapse of historic retaining walls: long lasted action can even wash out subsoil or clay mortar from masonry;
		Dynamic high velocity stream action represents one of the most dangerous actions on structures and it is responsible for the majority of severe damage on bridges, on earth structures, (e.g. dams), destruction of masonry by washing out joint mortars (the effect can be worsened by the effect of also water pollution)
Warm spells, heat waves and drought	*Thermoclastism*	Process caused by differential thermal expansion and contraction of surface mineral grains and interstitial salt deposits in response to long- and short-term temperature fluctuations at the material surface, due to solar radiation effect (Bonazza et al., 2009b).
	Wet-dry cycles/Salts weathering	Cyclical absorption and desorption of moisture in a building material, responsible of salt crystallization problems: efflorescence (on surfaces) and/or subflorescence (beneath surfaces). They can cause cracks, fractures, detachments and loss of materials (Grossi et al., 2011; Arnold and Zehnder, 1989).
Fires	*Macro-decay*	*Cracking* of stone at high temperatures;

propagation can be enhanced by prolonged period of warm spells and drought		*Coating by soot;*
		Colour change in stones containing iron;
	Micro-decay	Mineralogical and textural changes, which can lead to subsequent processes that act at a greater scale, as changes in porosity, mineralogy and micro-cracking.
	Structural instability of the stone	Main effects that fire has in porous materials with an intergranular matrix (mainly sandstones) are related to chemical changes within the matrix (clay minerals are especially sensitive to temperature increase).
		In dense materials (low porous materials) the breakdown of stone due to fire is evident.
	Material deformation	Spalling and loss of material.
	Longer-term effects	Patterns of decay may be influenced by a combination of weaknesses inherited from the fire with background environmental factors like salt-weathering/temperature cycling (Gomez-Heras et al., 2009)

Table 7. Effects of extreme events on wooden structures.

Wooden Structures		
Extreme event	**Effects**	**Descritpion**
Heavy rainfalls, floods, warm spells, heat waves and drought *Changing of moisture content and temperature*	*Swelling and shrinkage*	The variations of relative humidity, especially relevant for wooden objects inside buildings, cause a dimensional change within the structures, which can lead to irreversible deformation or mechanical damages.
	Biodeterioration	The attack by wood-degrading fungi, mainly relevant for wooden structure exposed to outdoor weather, where wood is wet for sufficiently long periods and mould can grow. Thus, it depends jointly by precipitation amount, temperature and exposure (Sabbioni et al. 2012)
		The increasing rainfall and humid conditions raising the spectre of damage to fabrics or furniture, while enhancing insect growth (Brimblecombe, 2014).
Fire	Material loss	It can referred to a part or to the entire structure depending on the fire extent and the structure features.

Table 8. Effects of extreme events on metals structures and artefacts.

Metals Structures and Artefacts		
Extreme event	**Effects**	**Descritpion**
Heavy rainfalls, floods, warm spells, heat waves and drought	*Atmospheric Corrosion*	This is influenced by two main environmental degradation factors: ● Climatic parameters ● Gaseous air pollutants ● Particulate air pollutants ● Acid rain

moisture content and temperature

According to Sabbioni et al. (2012) the atmospheric corrosion of metal inland areas is expected to increase in Northern Europe and decrease in Southern Europe. In coastal areas, where corrosion is higher due to the effect of chloride deposition, it is expected to be intensified all over Europe due to the increased temperature (T). For instance:

- The combined effect of T and SO_2 pollution, is responsible of carbon steel and bronze corrosion (e.g. on bronze, according to the different exposure to rainfall, the alteration patterns could be formed by cuprum and calcium sulphates and cuprum oxalates, Morigi, 2000);
- The combined effect of T and chloride deposition, including windborne sea salt aerosol, is responsible of zinc, lead and steady state copper corrosion.

corrosion products of Cuprum, Silver, Tin and Lead (modified from Mazzeo, 2005).

	Mineralogical Name	*Formula*	*Colour*
	Cuprum	***Cu***	
Oxides	Cuprite	Cu_2O	Red/Orange
	Tenorite	CO	Grey/Black
Carbonates	Malachite	$CuCO_3\cdot Cu(OH)_2$	Green
	Azurite	$2CuCO_3\cdot Cu(OH)_2$	Blue
	Chalconatronite	$Na_2(CuCO_3)2\cdot 3H2O$	Green/Blue
Chloride	Nantokite	CuCl	Light Green/White
Basic Chlorides	Atacamite	$Cu_2(OH)_3Cl$	Green
	Paratacamite	$Cu_2(OH)_3Cl$	Light Green
	Botallackite	$Cu_2(OH)_3Cl$	Light Green/Blue
Sulphur	Chalcocite	Cu_2S	Black
Sulphate	Brochantite	$CuSO_4\cdot 3Cu(OH)_2$	Green
	Silver	***Ag***	
Oxide	Silver Oxide	Ag_2O	Grey/Dark Brown
Sulphur	Argentite	Ag_2S	Black
Chloride	Chlorargyrite (Cerargyrite)	AgCl	Grey/ Dark Brown
	Tin	***Sn***	

Oxide	Cassiterite	SnO_2	White
Sulphur	Tin Sulphur	SnS	Black
	Lead	***Pb***	
Oxide	Litharge	PbO	Red
Sulphate	Anglesite	$PbSO_4$	Black
Acetate	Lead acetate	$Pb(C_2H_3O_2)_2$	White
Carbonate	Cerussite	$PbCO_3$	Grey

Fire	Material loss	It can be referred to a part or to the entire structure depending on the fire extent and the structure features.

As stated by Leissner et al., 2015, the outdoor climate has a strong influence on cultural heritage structures and surfaces and on the indoor environments in buildings. For example, high temperatures may be amplified in cities where most of cultural heritage is located because buildings, asphalt and other artificial structures absorb more heat during the day than suburban and rural areas. “Higher temperatures and more extreme events will likely affect the rate of degradation and the cost of climatisation (HVAC = Heating, Ventilation, Air Conditioning) of buildings for stable climate conditions of art objects but also for human comfort and health in cities.”

Thus, considering the indoor environment and possible materials exposed to these micro-climate conditions, the extreme events and their relative alteration phenomena on indoor structures and art-works are summarized in Table 9.

Table 9. Effects of extreme events on indoor multi-materials.

Indoor Materials		
Extreme event	**Effects**	**Descritpion**
Heavy rainfalls and floods *Increase of moisture content*	*Swelling and shrinkage*	The variations of relative humidity can cause the swelling and shrinkage in materials as wood, ivory, textiles and several types of glue, provoking cracks and fractures (e.g. wood and ivory) and fragility (e.g. paper, parchment and leather).
	Corrosion	Triggering or acceleration of metals corrosion.
	Biodeterioration	Fungi growing is fostered in warm and slightly aired spaces with RH>65%. Other biological agents responsible to materials deterioration can be microorganisms (bacteria, algae, lichens) and the micro-climatic conditions to avoid the growing of microbiological organisms on organic materials are reported in Table ii.

Table ii. Micro-climatic conditions to avoid microbiological attacks on organic materials, according to Istituto per i beni artistici, culturali e naturali della regione Emilia-Romagna (2007).

Organic artefacts	Relative Humidity (RH)/%	Max daily ΔRH	Temperature (°C)	Max daily ΔT

Paintings	**On canvas**	40-55	6	19-24	1.5
	On wooden panel	50-60	2	19-24	1.5
Paper		40-55	6	18-22	1.5
	Books & Manuscripts	45-55	5	<21	3
Wood		50-60	2	19-24	1.5
Leather, parchment		40-55	5	4-10	1.5
Textiles	**Cellulose based**	30-55	6	19-24	1.5
	Protein based	>50-55		19-24	1.5
Ethnographic collection		20-35	5	15-23	2
Stable materials		35-65		15-30	

		The increasing rainfall and humid conditions raising the spectre of damage to fabrics or furniture, while enhancing insect growth (Brimblecombe, 2014). Indeed, the activity of insects, as thysanurans, blattoidea, psocids and beetles, is also connected with the HR and T conditions.
Warm spells, heat waves and drought	*Changing of moisture content*	● It will influence the biological activity and, consequently, biological attack ● Material discoloration (e.g. for paper, fabrics and paintings) ● Deterioration of specific glass materials (RH < 40%)
Fire	Material loss	It can be referred to a part or to the entire structure depending on the fire extent and the structure features.

9) regarding the biodeterioration of wood, the moisture content is the that mostly determine the attacks by microrganisms and consenquently the durability of wood structures. This was considered by the Italian (UNI) and European (EN) standardization bodies which have drawn up a classification of the durability of wood in relation to wood susceptibility to biological attack (Norm UNI EN 335-1, 1992, now substituted by Norm UNI EN 335:2013), illustrated in Table 10.

Table 10. Class of risk for wood in relation to its susceptibility to biological attack (UNI EN 335-1, 1992) from (Berti et al., 2009).

Class	1	2	3	4	5
General situation	Not in the soil, sheltered	Non in contact with the soil, sheltered	Not in contact with the soil and not sheltered	In contact with soil or fresh water	In salt water
Level of humidity	None	Occasional	Frequent	Permanent	Permanent
Deteriogenic organisms	Colcoptera, termites	Basidiomycetes, chromogenic fungi, coleoptera, termites	Basidiomycetes, chromogenic fungi, coleoptera, termites	Basidiomycetes, soft rut, chromogenic fungi, coleoptera, termites	Basidiomycetes, soft rut, chromogenic fungi, coleoptera, termites, marine organisms

RISK ASSESSMENT OF EXTREME EVEN ON PILOT SITES

ProteCHt2save Project selected seven pilot heritage sites on the basis of the identified risk prone areas, cultural/historic value of the sites and outputs from previous local, national, trans-national, EU projects.
Their complete description will be presented in Deliverable D.T.1.3.2, nevertheless in the following subchapters few notions are reported in order to hypothesize the possible risks to whom these sites are exposed to.

PL)

In Poland, the selected pilot site includes the Roman Catholic Church of the Exaltation of the Holy Cross (early 16th century) and a parish school (18th century), which now serves as Regional Chamber, located in Stara Wieś, a village within Bielsko District, in southern Poland (Fig.5). Specifically, this village is 10 km far from Bielsko-Biała city, in the north direction, while it lies 40 km south of the regional capital Katowice.

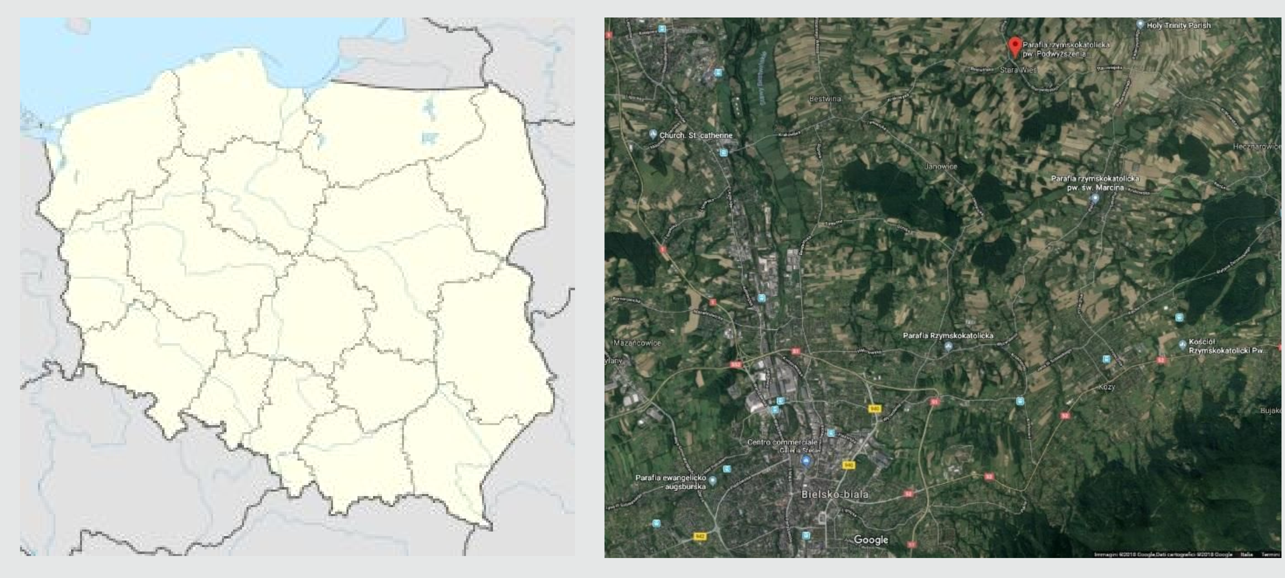


Figure 5. On the left, highlighted with a red dot Bielsko-Biała city; on the right, the location of the Roman Catholic Church of the Exaltation of the Holy Cross in Stara Wieś.

Considering the parish school, separated from the church by a cemetery (Fig.6), it was erected in 1787 and thoroughly rebuilt in 1862, during the past years had maintained its function of school. In recent times, it was also used as seat of the village administrator and place for various meetings, courses, sometimes rented as rooms for tenants. In 1971, the Polish Tourist and Sightseeing Society organized a regional chamber in the old school building, becoming a tourist attraction. Almost 20 years later, in 1994, the building was given back to the local parish.

The church is erected on a hill and surrounded by trees (Fig.6). The structure is composed by a nave, lateral low arcades and a bell tower; this latter one shows square base, with a belfry and an onion-shaped dome with a lantern. Overall, the building is quite high, since the tower measures 30 m of maximum height and the nave 20 m.

In 2011, dendrochronological analysis have been carried out, revealing that the presbytery, nave and tower were built in the same year, which is 1522, thus the original shape has survived until now.

Figure 6. Aerial views of the Roman Catholic Church of the Exaltation of the Holy Cross and the parish school.

Building materials affected

Both buildings are examples of wooden architecture. In particular, the church is made of fir wood on the oak foundation.

The inner decorations of the church are (Fig.7):
- Renaissance polychrome paintings of ceilings;
- Baroque polychrome wall paintings and movable paintings;
- Wooden, richly decorated and painted, baroque altars of the 14th and 15th centuries;
- Wooden, baroque pulpit and baptismal font;
- A Rococo organ;
- Statues;
- A historic confessional;
- A parchment reporting the act of consecration of the church;
- A bell in the belfry dates to 18th century.

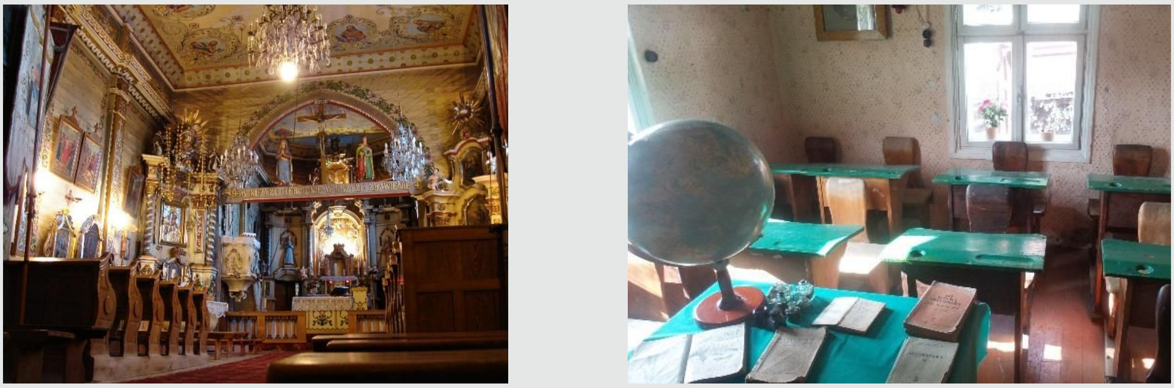


Figure 7. Inner views of: on the left, the Roman Catholic Church of the Exaltation of the Holy Cross, while, on the right, the parish school.

In conclusion, the site shows a predominance of wood structure, but the two buildings can be considered polimateric structures as a whole.

Main risks affecting the Bielsko-Biała site

ned by the negative effects of heavy rains. Indeed, it is located wing of water through the complex during the downpour. In addition, heavy rains can cause landslides and the movement of the ground on which the monuments are situated.

lsko-Biala, PL): extreme events effects on materials and stuctures

The negative effects of heavy rains are responsible of:

- Considering the whole complex: landslides and ground instability;
- Water overflowing through the wooden structures during downpours due to the conformity of the terrain. The presence of persistent moisture in this material can be responsible of:
    - Swelling and shrinkage due to variations of relative humidity, especially relevant for wooden objects inside buildings. This dimensional change can cause irreversible deformation or mechanical damages.
    - Attack by wood-degrading fungi, mainly relevant for wooden structure exposed to outdoor weather, where wood is wet for sufficiently long periods and mould can grow. Thus, it depends jointly by precipitation amount, temperature and exposure (Sabbioni et al. 2012).
- By reference to the other materials present inside the buildings, problems due to the variation of relative humidity can be:
    - In general it can cause the swelling and shrinkage in materials as wood, ivory, textiles and several types of glue, provoking cracks and fractures (e.g. wood and ivory) and fragility (e.g. paper, parchment and leather).
    - Triggering or acceleration of metals corrosion
    - Material discoloration (e.g. for paper, fabrics and paintings)
    - Deterioration of specific glass materials (RH < 40%)
    - Biodeterioration

The city of Ferrara is located in the Emilia-Romagna region, in the Northeast of Italy (Fig. 8). The city and its province has been inscribed in the World Heritage List since 1995, with an extension in 1999, including also the territory of the river Po Delta[4].

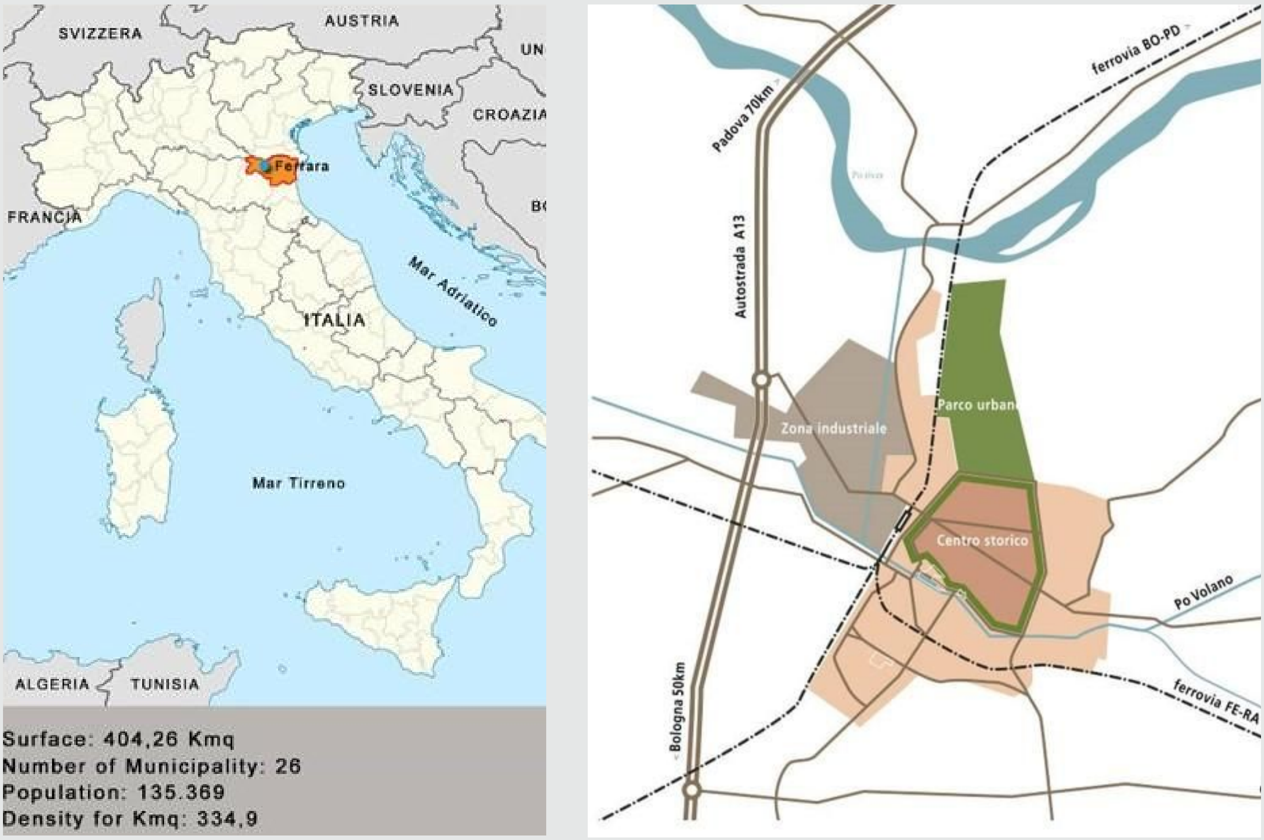


Figure 8. On the left: City of Ferrara and its province; On the right: Urban structure (from: Masterplan per Ferrara. Aree ex Mof, Darsena, ex Amga ed ex Direzionale Pubblico di via Beethoven", September 2008, by Behnisch Architekten in collaboration with Politecnica Ingegneria e Architettura).

In particular, the case study includes the Cathedral Square and the Trento Trieste Square, where the Cathedral of Saint George the Martyr (of the 12th century) is located. In particular, the façade of the Cathedral, West oriented, faces the Cathedral Square (Fig. 9), while the South side of the church faces Trento Trieste Square (Fig. 10).

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[4] https://whc.unesco.org/en/list/733

ure 9. The main façade of the Ferrara Cathedral, West oriented, faces the Cathedral Square ® Google Maps.

ure 10. The south side of the church and the bell tower face the Trento Trieste Square ® Google Maps.

According to studies aimed at the characterization of construction materials, the stone parts of the Cathedral masonry is composed by limestones, mainly coming from the Veneto Region (in particular from Verona) and Istria. In specific, according to Grillini (2006) the stones utilized in the bell tower, attributed to Leon Battista Alberti and built in 1451-1493, are "*Biancone di Verona*" (belonging to Venetian Alps and Prealps) and "*Istria Stone*" in the wainscoting, while "Rosso Ammonitico Veronese" is present in the stone covering of the bell tower, showing both white and red colours. The columns capitals are made by "*Pietra di Prun*", belonging to the geological formation named "Scaglia Rossa Veneta". There is also the presence of a biocalcarenite, called "*Pietra tenera di Vicenza*", utilized in several emblems present on the southern and western sides. Finally, the central coloumns of northern and southern sides of the bell tower, are made by stones belonging to the Noriglio Grey Limestone Formation.
The brickwork apse, embellished by terracotta arches and marble capitals, was designed by the architect Biagio Rossetti from Ferrara.

The interior of the cathedral was completely refurbished in the 17th century, showing the presence of marbles, plasters, paintings (canvas and mural paintings) and bronze statues.

Main risks affecting the Ferrara site

Ferrara is taken into account as a case study for the heavy rain phenomena that affect the town. Furthermore, in the past the area underwent to flood events, in particular the area in front of the Cathedral Façade after heavy rains events result flooded (Fig.11). Even if no specific damages occurred to the cathedral after the flood, it has to be considered.

ure 11. *On the left*: "Padimetro" of Ferrara. This monumental water gauge indicates the different heights and corresponding years of Po River level at Pontelagoscuro, a locality few kilometers distant from Ferrara city center. It is showed on a coloumn near the Cathedral square. *On the right:* the flooded area in front of Ferrara Cathedral.

Focus on Ferrara: extreme events effects on materials and stuctures

Ferrara is taken into account as case study for the heavy rain phenomena that affect the town and possible flood events.

In particular, considering the Cathedral, the effect of these extreme events on its outdoor materials can cause:

- Erosion due to the synergic action of wind-driven rain. Specifically, "Rosso Ammonitico Veronese" limestone is subjected to differential weathering, due to inhomogeneity in physical or chemical properties of the stone. Thus this kind of alteration pattern will enhanced by this action.
- The prolonged exposure to rain increases the presence of moisture in the masonries, in conjuction with the effect of square flooding, which lead to (polluted) water infiltration within masonries, rising dump, being also a source of:
  - Wet-dry cycles
  - Freeze-thaw cycles
  - Biological growth
  - Thermoclastism

  - blackening
  - Eventual structural problems

Considering the materials present within the church the repercussion of extreme events can lead to the variation of moisture content, causing:

- Cracks, fractures and fragilities within structures, due to swelling and shrinkage in materials as wood, ivory, textiles and several types of glues.
- Metals corrosion
- Biological attack
- Material discoloration
- Deterioration of specific glass materials (if RH<40%)

The city of Kaštela is an agglomeration of seven small settlements in Croatia, located in the eastern Adriatic coast of Croatia, in Central Dalmatia, in the Splitsko-dalmatinska County. In particular, this site is located under mountain, Kozjak, northwest of the city of Split, west of Solin and east of Trogir (Fig.12).

The seven castles, built during the time of Turkish danger in Dalmatia (15th and 16th centuries), are specifically named as follows, listed in order from the nearest to Split and the most far (in the direction of Trogir): Kaštel Sućurac, Kaštel Gomilica, Kaštel Kambelovac, Kaštel Lukšić, Kaštel Stari, Kaštel Novi and Kaštel Štafilić. Then, the town of Kaštela gradually developed around these military fortifications (now it covers 17 km of width), positioned along the coast of the Kaštela Bay, nearby sea (Fig.12). In particular, in this Project only two of these castles will be under study: Kaštel Sućurac and Kaštel Gomilica (Fig.13).

ure 12. On the left: the location of Kaštela in the Splitsko-dalmatinska County, in Croatia. On the right: map showing Kaštela Bay and indicating the locations of the seven castles. On the bottom:

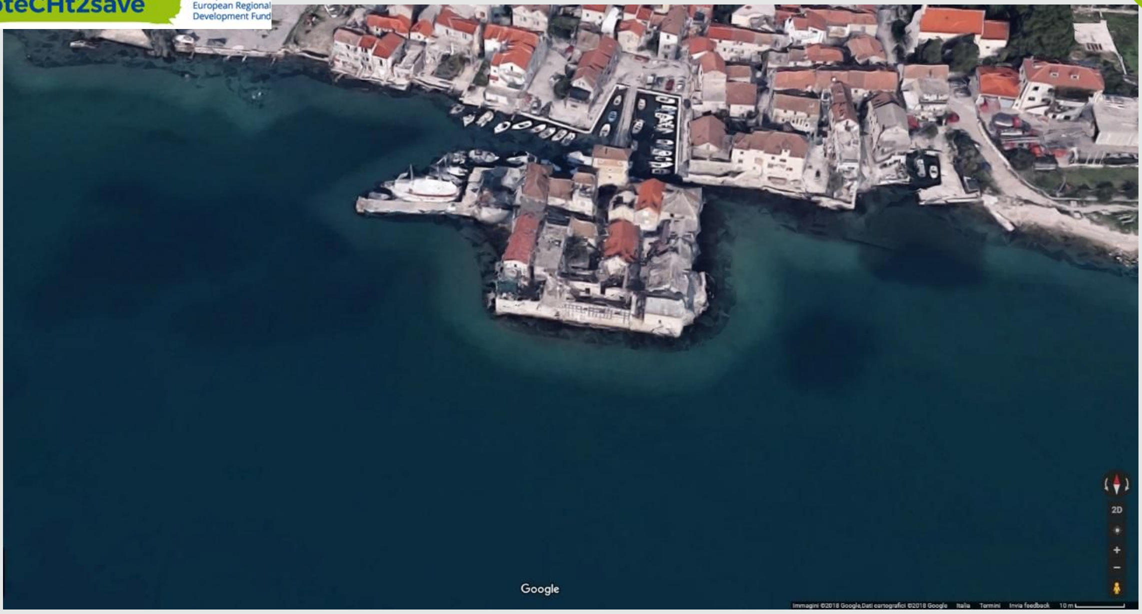


Figure 13. Particular aerial view of Kaštel Gomilica (kaštilac) ® Google Maps.

Building materials affected

All the structures are mainly made by stone masonries and specifically by limestones, also according to the geology of Croatia, which presents about half of its territory as a karst land. In fact, this process originates limestone and dolomite, thus material utilized for the construction of these fortresses are ascribable to these sedimentary stones.

Main risks affecting the Kaštela site

Concerning the coastal position, these settlements result subjected by sea action. For instance, in Kaštel Sućurac, the oldest established settlement on the Kaštela coast, during the 20th century a protective dam with a road were built as an attempt to reduce the sea impact. Nevertheless, the existing drainage system results inadequate in situations of high tide or heavy rain. Indeed, when these phenomena occur, water penetrate in houses foundations and the successive rising damp in the wall of the houses contributes to growth of fungi and mould. While considering Kaštel Gomilica, where the fortress was built on the small island called Gomile, the sea impact during the centuries has caused erosion of the foundation, cracks on buildings and penetration of the seawater into the structure during high tide.
It has to be also underlined that the old town of Kaštela is exposed to tidal waves and drifts that occur under the influence of air and wind pressure, especially in case of strong south wind, which moves the water mass towards the closed end of the Kaštela's bay raising the sea level (Buljan and Zore Armanda, 1976).

Furthermore, since in general more frequent and hotter heat waves are expected in the future, thus probably increasing their duration and consequently being responsible of drought period, another risk can be considered: fire. Indeed, this area has been quite exposed to fire risk even in the past, worsening due also to the *bura* wind action, registering harmful fires in:

- 1971 on Kozjak hill;

a County (Split, Solin and Kaštela City);

reaching also the Gaj area in Kaštel Sućurac;

- 2017 occurred in Plano, at the entrance of the city of Trogir and above the last kaštel, Kaštel Štafilić;

ne events effects on materials and stuctures

Kaštela is highly subjected to the sea impact, in particular to the coastal/sea flood and heavy rain actions (heavy floods have been recently documented in 2005, 2012, 2014). Therefore, their possible effects on these structures, mainly composed by limestone masonries, are:

- Water penetration and infiltration in the masonries provoking:
    - *Erosion* due both to the sea and rain mechanical action;
    - *Salts weathering/Wet-Dry cycles*, especially of sodium chloride due to the imbibing of marine water;
    - *Biological growth:* the rising damp in the walls contributes to growth of fungi and mould;
    - *Freeze-thaw cycles, thermoclastism, surface recession and blackening*;

Thus leading even to structural problems.

Regarding the fire effects on limestone, according to Chakrabarti et al. (1996), limestone can show:
- *Colour changing*: In limestones containing hydrated iron oxide, change colour was observed to pink or reddish-brown at 250-300°C, becoming more reddish at 400°C. Between 800 and 1000°C the stone becomes a grey-white powder.
- *Reduction of stone strenght*: even if the intrinsic strength of limestone often remains unchanged in small fires, we have to bear in mind that the calcination of calcium carbonate (the main mineral compound of limestone) begins at 600°C and proceeds rapidly beyond 800°C. The depth of calcination is seldom more than 20 mm and often less and the calcined limestone has a dull, earthy appearance quite different from the original limestone. Once calcination has occurred the strength of the stone is reduced.
- *Spalling and loss of material*
- *Longer-term effects*: patterns of decay may be influenced by a combination of weaknesses inherited from the fire with background environmental factors like salt-weathering/temperature cycling (Gomez-Heras et al., 2009)

Considering the materials that can be present within the castles the repercussion of extreme events can lead to the variation of moisture content, causing:

- Cracks, fractures and fragilities within structures, due to swelling and shrinkage in materials as wood, ivory, textiles and several types of glues.
- Metals corrosion
- Biological attack
- Material discoloration
- Deterioration of specific glass materials (if RH<40%)

Kočevje is a municipality in southern Slovenia, located between the Cherca and Kolpa Rivers. In particular, the town hosts the majority of its historical buildings in the in the city centre along Ljubljanska street (Fig. 14), representing the built heritage of the city.

ure 14. On the top, the municipality of Kočevje highlighted in red, in southern Slovenia. On the bottom highlighted in dotted red line Ljubljanska street.

Building materials affected

Within this project, 14 buildings will be considered as case studies. Two of them are here presented:

- Villa Röthel is one of the most important representatives of Art Nouveau architecture of Kočevje. It was built for doctor Erich Schreyer and then, in 1909 the villa was bought by doctor Georg Röthel. Today the Center for Social Work has its premises in the villa located in Ljubljanska street 9 (Fig.15).

Figure 15. On the left: Villa RÖTHEL before WW2; on the right: Center for Social Work today.

- Marija's home (today Municipality building) is located in Ljubljanska street 26. In the past Marija's home was used as monastery and between the 2nd World war as hospital (Fig.16).

Figure 16. On the left: Marija's home before WW2; on the right: Municipality building today.

Main risks affecting the Kočevje site

All mentioned buildings in Ljubljanska street are regularly affected by urban floods provoked by heavy rain action. Due to the karstic terrain, located on the same depth (around two meters) of the foundations of the buildings, rain water infiltrates into the underground parts of the buildings. For this reason, the basements are exposed to continuous water incursion which leads to the destruction of basement foundations.

In buildings where the basements were not renovated the bases are made of stone blocks and lime mortar, which is muddy. The supporting walls of the ground floors and pavements on the floor were made without suitable horizontal and vertical waterproof barriers.

Thus, another problem that threaten these historical buildings is moisture. It is present in the basements due to absorption of the walls as well as poor insulation (no watertight). Nevertheless, in certain cases, water still penetrates into the renovated buildings.

Focus on Kocevje: extreme events effects on materials and stuctures

Kocevje is cyclically exposed to heavy river floods. The possible effects on the materials present in the historical buildings are listed below:

- *Erosion* due to the action of river water and debris carried by flood;

The prolonged exposure to rain increases the presence of moisture in the masonries, being also a source of cracks, fractures, detachments, changing of colour and loss of materials due to:

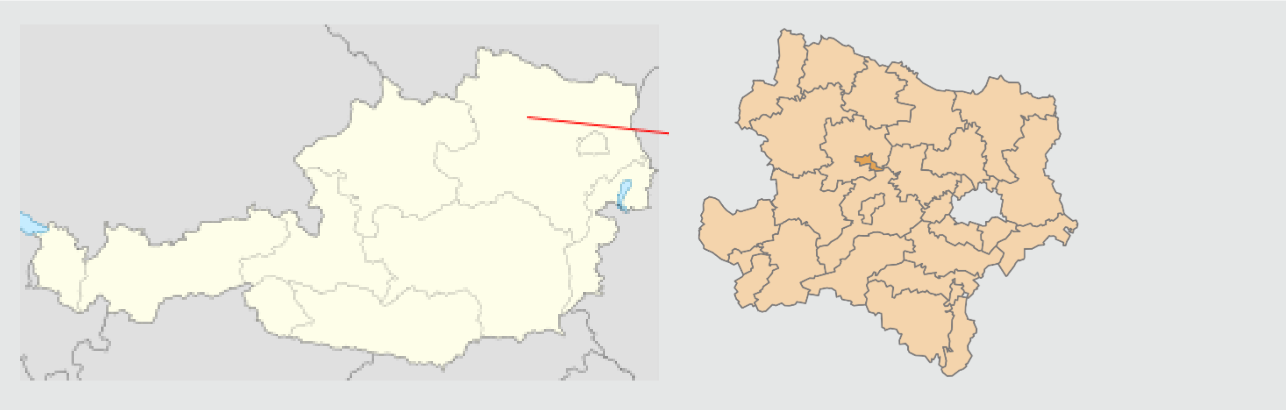
- *Wet-dry cycles*
- *Freeze-thaw cycles*
- *Biological growth*
- *Surface recession and blackening on calcium carbonate based materials*

Furthermore, eventual structural problems can occur.

By reference to the other materials that can be present inside the buildings, the problems due to the variation of relative humidity can be:

- In general it can cause the swelling and shrinkage in materials as wood, ivory, textiles and several types of glue, provoking cracks and fractures (e.g. wood and ivory) and fragility (e.g. paper, parchment and leather).
- Triggering or acceleration of metals corrosion
- Material discoloration (e.g. for paper, fabrics and paintings)
- Deterioration of specific glass materials (RH < 40%)
- Biodeterioration

Krems an der Donau rises on the eastern Wachau, a stretch of the Danube Valley between Melk and Krems in Austria, which is included in the World Heritage List for its importance and high visual quality as cultural landscape[5] (Fig.17).



igure 17. On the left: Krems location within Austria; on the right: Map of the Austrian State Lower Austria highlighting Krems.

Krems and Stein are twin towns on the north bank of the Danube (Fig.18). Both owe their development and historic significance to their location along the main route from East to West along the Danube and their function as a point of reloading from river to land traffic, the cultivation of grapevine and the resulting trade (Bundesdenkmalamt/ REPUBLIC OF AUSTRIA, 1999).

Figure 18. Panoramic view of *Stein an der Donau* (https://de.wikipedia.org/wiki/Datei:Stein_a_d_Donau_Panorama.jpg)

Building materials affected

In particular, the district of Stein, a “long-stretched-out area of the medieval town, rectangular delimitation in the east, acute-angled in the west, which includes vineyard terraces in the north and is traversed on the narrow embankment strip by one single settlement axis.e., the Landstrasse connecting the two town gates” (Fig. 19). Furthermore, it is characterized by medieval and renaissance burghers’ and craftsmen’s houses. In particular, “the smooth facades of the building period prevail, in some places enlivened by late-Gothic window jambs, oriels, or cantilevered upper storeys, and partly with traces of former sgraffito articulation, or, mainly in the squares, adorned with late-Baroque and Josephine facades in accordance with new standards of representation set in the 18th century”(Fig. 20). (Bundesdenkmalamt/ REPUBLIC OF AUSTRIA, 1999).

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[5] https://whc.unesco.org/en/list/970

igure 19. On the left: one of the remaining city gates of Stein – the so called Linzer Tor / Linz Gate; in the middle and on the right, views of Landstrasse in Stein.

Figure 20. Buildings' facades with adornment and *sgraffito* articulation.

Specifically, Krems has in total 303 objects protected by the Austrian monuments protection law, while Stein has in total 98 objects protected. The old towns of Krems and Stein are medieval in their structures (Fig. 21). Bricks, stones and wood are the main building materials. Wood especially in the roof constructions and first floors. In Stein, which is immediately on the shores of the Danube, the ground floors are built slightly sloping towards the Danube, so, when the flood drops the withdrawing water, it transported all the Danube mud and slime out of the buildings automatically.

Figure 21. View of Krems and main monuments and museums locations.

Main risks affecting Krems-Stein site

ictures taken during the flood in 1991 in Stein, also along the Landstrasse. During the more recent floods the protection was already developed and high enough to prevent flooding in Stein.

The main risks posed to Krems and Stein are floods by the river Danube and rivers and rivulets flowing into the Danube. In fact, in the past Krems and Stein have been affected by floods several times (Fig. 22), as shown in a monumental water gauge (Fig. 23), reporting their dates: 1830, 1776, 2002, 1795, 1799, 1740, 1880, 1899, 1893, 1897, 1991, 1954, 1862, 1883, 1892, 1888, 1730, 1803 and 1890 (listed from the highest to the lowest). Furthermore, a more recent flood event was registered in 1954.

Figure 23. Flood marks of past flood events in Krems-Stein, represented from the highest to the lowest on the marker.

Indeed, both Krems and Stein are included in the hora.gv.at maps that show the risk areas for flood in Austria.

Moreover, fire is recognised as a high risk for the old towns since the roofs of the buildings often are directly connected. The fire brigades of Krems and the whole region are adapting their firefighting plans at the moment and updating the so called “Case Zulu” which is fire in the old towns of Krems and Stein.

xtreme events effects on materials and stuctures

Considering that Krems-Stein is a flood-prone area, the damages due to flood events are connected with the mechanical action of the water and its penetration and infiltration in the masonries.

These phenomena can cause damages through:

- *Erosion* due to the action of river water and debris carried by flood;
- Damage due to horizontal static pressure of raised water: it typically destroys light shutters of building openings, e.g. doors and windows, especially glazing, and it can destroy freestanding walls and fences, in many cases together with dynamic action of streams and flows.
- *Wet-dry cycles*
- *Freeze-thaw cycles*
- Biological growth
- *Thermoclastism*
- *Surface recession and blackening*
- *Deformations, detachments and material loss* of the plastered building façades and of the decorations, due to the moisture presence in the masonries, in addition to the previous deterioration processes (salt weathering, biological growth and freeze-thaw cycles).

Structural problems: hydrostatic pressure can *uplift floors or whole objects*, decreases their stability against overturning and facilitates their damage by horizontal forces;

- *Floated objects move and are displaced*
- *Collapse of historic retaining walls*
- *Destruction of masonry* by washing out joint mortars (the effect can be worsened by the effect of also water pollution)
- *Saturation of materials* with water causes a wide variety of actions and damage related to volumetric changes, chemical action, loss of strength, etc.

According to Gomez-Heras et al. (2009) the most obvious effects (macroscopically noticeable) generated by fire on stones are:
- C*racking of stone* at high temperatures;
- *Coating by soot and colour change* in stones containing iron;
While microscopically, micro-decay features can be hidden within the fabric of the stone, as:
- *Mineralogical and textural changes*: these micro-scale problems can lead to subsequent processes that act at a greater scale, as changes in porosity, mineralogy and micro-cracking.

- *Structural stability of the stone*
- *Spalling and loss of material*
- *Longer-term effects*: patterns of decay may be influenced by a combination of weaknesses inherited from the fire with background environmental factors like salt-weathering/temperature cycling

By reference to the other materials that can be present inside the buildings, the possible damages due to the variation of relative humidity can be:

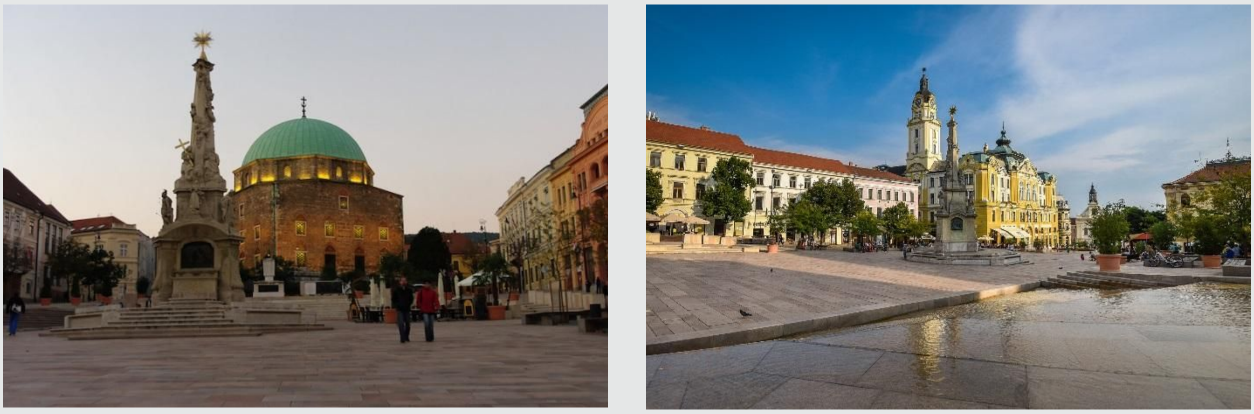
- In general it can cause the swelling and shrinkage in materials as wood, ivory, textiles and several types of glue, provoking cracks and fractures (e.g. wood and ivory) and fragility (e.g. paper, parchment and leather).
- Triggering or acceleration of metals corrosion

- g. for paper, fabrics and paintings)
- Deterioration of specific glass materials (RH < 40%)
- Biodeterioration

The histocal downtown of Pécs lies at the southern hills of the Mecsek, in Hungary (Fig.24).

Figure 24. On the left: location of Pècs respect Hungary; on the right: aerial view of Pècs.

Its history dates back to the Roman period, indeed it was the Roman provincial town of *Sopianae*. Nowadays, we have traces of that period through the presence of 27 decorated tombs of the 4th century, which were built as underground burial chambers with memorial chapels above the ground called *Cella Septichora*. Moreover, these structures show richly mural decors depicting Christian themes. Considered the importance of these monuments, in 2000 they have been inscribed on World Heritage List[6].
Later, in 1000, the "Magyars" settled in the Carpathian Basin and founded the Hungarian kingdom. While from the 16th to the 17th century, Pecs was under the Ottoman Empire domination, thus also its architecture was influenced by the Islam style. For example, the Mosque of Pasha Gázi Kászim, in the main square of Pécs, still preserves the features of Islam architecture (Fig.25).



ure 25. On the left: Mosque of Pasha Qasim © Emmanuel Dyan/Flickr; On the right: Szechenyi square (courtesy of the Hungarian Tourism Agency)

Building materials affected

Regarding the materials forming this built heritage, they are mainly made by wood, bricks and marble.

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[6] https://whc.unesco.org/en/list/853

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While, considering the possible risks to which this site can be exposed to, we have to consider heavy rain and rarely fire. Concerning the first one, heavy rains have caused damages in hilly area, because the drainage system was not able to manage the water amount. Furthermore, the UNESCO site *Cella Septichora* was being flooded with water in case of heavy rain, therefore, in order to avoid these events prevention and renovation works have been performed (Fig. 26).

Figure 26. On the left: Pécs during a flood event; On the right: the underground burial chambers called *Cella Septichora*.

Focus on Pécs: extreme events effects on materials and stuctures

The town of Pécs results affected by heavy rain phenomena and consequently flood events.

In particular, considering the possible effects on the materials belonging to the historical buildings and the archaeological site of *Cella Septichora* the possible damages can be:

- Erosion due to the synergic action of wind-driven rain and heavy rains.
- The prolonged exposure to rain increases the presence of moisture in the masonries, being also a source of cracks, fractures, detachments, changing of colour and loss of materials due to:
    - *Wet-dry cycles*
    - *Freeze-thaw cycles*
    - *Biological growth*
    - *Surface recession and blackening on calcium carbonate based materials*

According to Gomez-Heras et al. (2009) the most obvious effects (macroscopically noticeable) generated by fire on stones are:

- C*racking of stone* at high temperatures;
- *Coating by soot and colour change* in stones containing iron;

While microscopically, micro-decay features can be hidden within the fabric of the stone, as:

- *Mineralogical and textural changes*: these micro-scale problems can lead to subsequent processes that act at a greater scale, as changes in porosity, mineralogy and micro-cracking.

- *Structural stability of the stone*
- *Spalling and loss of material*

atterns of decay may be influenced by a combination of weaknes inherited from the fire with background environmental factors like salt-weathering/temperature cycling

Furthermore, eventual structural problems can occur.

By reference to the other materials that can be present inside the buildings, the possible damages due to the variation of relative humidity can be:

- In general it can cause the swelling and shrinkage in materials as wood, ivory, textiles and several types of glue, provoking cracks and fractures (e.g. wood and ivory) and fragility (e.g. paper, parchment and leather).
- Triggering or acceleration of metals corrosion
- Material discoloration (e.g. for paper, fabrics and paintings)
- Deterioration of specific glass materials (RH < 40%)
- Biodeterioration

The Historic District in Prague Troja rises on the iconic and important river Vltava, in Czech Republic (Fig.27), characterized by shallow banks smoothly continuing in the adjacent urban areas dating back to medieval times. The settlement is featured by natural heritage, hosting the Prague Zoological and Botanical gardens, and protected cultural monuments, namely the Baroque Chateau Troja, Historic Brewery and Troja Mill (Fig.28). Large part of the Troja territory is not protected by the river barriers, which creates specific socio-economic problems in the community.

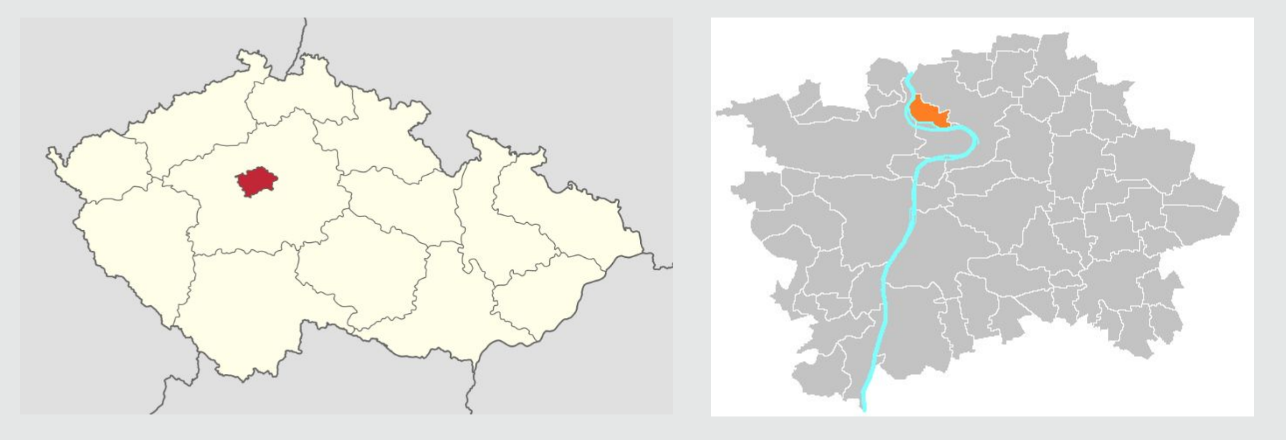

Figure 27. On the left: Prague location within Czech Republic; on the right: Troja location within the city of Prague.

ure 28. Early Baroque Chateau Troja, built in 1679-1691. On the left, aerial view; on the right internal ceiling richly decorated.

Building materials affected

Among the Troja cultural heritage objects, a wide variety of building materials is present – timber, adobe, burnt brick and stone masonries, plasters and renders, terracotta, ceramics, isolation materials, various types of prefabricated boards etc. Further, the building objects exhibit various types of structural elements and compositions – e.g. partition walls, suspended ceilings. The most affected ones were ancient and severely degraded timber elements – through wood deteriorating insects and fungi, which were very susceptible for water and exhibited low mechanical resistance. In addition, masonries with clay based mortars without any stronger binder were easily destroyed. Due to expansion of timber elements secondary damage occurred in masonry walls.

oja District

River flood represents the most important risk in the area, experiencing in recent times a higher frequency of major floods, similar to the medieval period with intervals of about ten years repetitions. The devastating flood in 2002 accelerated the construction of combined permanent- temporary protection barriers, which proved a successful protection of an important part of the territory during the recent flood in 2013 (Fig. 29). However, a substantial part of the urbanized area is still unprotected and under a river flood risk. Minor risk is associated with wind storms which are dangerous namely for large trees in the historic gardens and natural areas of the district.

Figure 29. Flood in Troja in 2013.

Focus on Troja: extreme events effects on materials and stuctures

As aforementioned, the Troja District, in Prague, is cyclically exposed to heavy river floods. Furthermore, a minor risk is associated with wind storms which are dangerous particularly for large trees in the historic gardens and natural areas of the district.

The possible effects on the materials present in Troja historical buildings are listed below:

- *Erosion* due to the action of river water and debris carried by flood;
- *Damage due to horizontal static pressure of raised water*: it typically destroys light shutters of building openings, e.g. doors and windows, especially glazing, and it can destroy freestanding walls and fences, in many cases together with dynamic action of streams and flows.

The prolonged exposure to rain increases the presence of moisture in the masonries, being also a source of cracks, fractures, detachments, changing of interior climate (high humidity), changing of colour and loss of materials due to:

  - *Wet-dry cycles*
  - *Freeze-thaw cycles*
  - *Biological growth*
  - *Surface recession and blackening on calcium carbonate based materials*

Furthermore, eventual structural problems can occur:

- Hydrostatic pressure can *uplift floors or whole objects*, decreasing their stability against overturning and facilitating their damage by horizontal forces;
- Dynamic low velocity stream action is typically observed inside closed buildings where *floated objects move and are displaced*;
- *Collapse of historic retaining walls*: long lasted action can even *wash out subsoil or clay mortar from masonry;*
- Dynamic high velocity stream action represents one of the most dangerous actions on structures and it is responsible for the majority of severe damage on bridges, on earth structures, (e.g. dams), *destruction of masonry* by washing out joint mortars (the effect can be worsened by the effect of also water pollution)
- Saturation of materials with water causes a wide variety of actions and damage related to volumetric changes, chemical action, loss of strength, etc.

Alfieri L., Dottori F., Betts R., Salamon P. and Feyen L., 2018. Multi-Model Projections of River Flood Risk in Europe under Global Warming, Climate, MDPI, 6, 16; doi: 10.3390/cli6010016.

Arnold A., Zehnder K. 1989. Salt weathering on monuments, proceedings, I Simposio Internazionale Bari 7-10 giugno La conservazione dei monumenti nel bacino del Mediterraneo, pp.31-58.

Barbosa Ferreira P., Camia A., Kucera J., Libertà G., Palumbo I., San-Miguel-Ayanz J., Schmuck G., 2008. Assessment of forest fire impacts and emissions in the European Union based on the European Forest Fire Information System. Dev Environ Sci 8:197-208. doi: 10.1016/S1474-8177(08)00008-9

Berti S., Fanelli C., Palanti S., Pinzari F., 2009. Wood, within "Plant Biology for Cultural Heritage: Biodeterioration and Conservation", edited by Caneva G., Nugari M. P., Salvadori O., ISBN 978-0-89236-939-3, Getty Conservation Institute.

Bonazza A., Maxwell I., Drdácky M., Vintzileou E,. Hanus C, Ciantelli C., De Nuntiis P., Oikonomopoulou E., Nikolopoulou V., Pospíšil S., Sabbioni C., Strasser P. 2018. Safeguarding Cultural Heritage from Natural and Man-Made Disasters A comparative analysis of risk management in the EU, © European Union, 2018, ISBN 978-92-79-73945-3, DOI:10.2766/224310, (catalogue) NC-05-17-059-EN-N, 207 pp.

Bonazza A., Messina P., Sabbioni C., Grossi C. M., Brimblecombe P. 2009a. Mapping the impact of climate change on surface recession of carbonate buildings in Europe. Science of the Total Environment 407, pp. 2039-2050.

Bonazza A., Sabbioni C., Messina P., Guaraldi C., De Nuntiis P., 2009b. Climate change impact: Mapping thermal stress on Carrara marble in Europe. Science of the Total Environment 407, pp.4506–4512.

Brimblecombe P., 2014. Refining climate change threats to heritage, Journal of the Institute of Conservation, 37:2, 85-93, DOI: 10.1080/19455224.2014.916226

Brimblecombe P., Grossi C.M., 2005. Aesthetic Threshold and blackening of stone buildings. Science of Total Environment 349:175-189.

Buljan M., Zore Armanda M., 1976. Oceanographical properties of the Adriatic Sea, Oceanography and Marine Biology Annual Review, 14, pp. 11-98.

Bundesdenkmalamt/ REPUBLIC OF AUSTRIA, 1999. THE WORLD HERITAGE, Documentation for the nomination of WACHAU CULTURAL LANDSCAPE.

Caneva G., Nugari M. P., Salvadori O., 2009. Plant Biology for Cultural Heritage: Biodeterioration and Conservation, ISBN 978-0-89236-939-3, Getty Conservation Institute.

Chakrabarti B., Yates T., Lewryet A., 1996. Effect of fire damage on natural stonework in buildings, Construcrion and Building Materials, 10: 539-544.

Fatorić S., Seekamp E., 2017. Are cultural heritage and resources threatened by climate change? A systematic literature review. Climatic Change, 142: 227. doi:10.1007/s10584-017-1929-9

Forzieri G., Bianchi A., Filipe e Silva B., Marin Herrera M. A., Leblois A., Lavalle C., Aerts J. C.J.H., Feyen L., 2018. Escalating impacts of climate extremes on critical infrastructures in Europe, Global Environmental Change, 48, 97-107, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2017.11.007.

R., Flörke M., Wimmer F., Bianchi A., 2014. Ensemble projections of in Europe. Hydrol. Earth Syst. Sci. 18, 85– http://dx.doi.org/10.5194/hess-18-85-2014.

Gomez-Bolea A., Llop E., Arino X., Saiz-Jimenez C., Bonazza A., Messina P., Sabbioni C., 2012. Mapping the impact of climate change on biomass accumulation on stone. J. Cult. Herit. 13 (3), 254–258.

Gomez-Heras M., McCabe S., Smith B. J. Fort R., 2009. Impacts of Fire on Stone-Built Heritage An Overview, Journal of Architectural Conservation, DOI: 10.1080/13556207.2009.10785047

Grillini G.C., 2006. Due singolari pietre nelle architetture estensi e malatestiane: il calcare grigio di Noriglio e il marmo di Candoglia, in "Antichi mestieri della Tradizione Edilizia Ferrarese-Terrecotte e Dipinti Murali", a cura di Maurizio Zerbini, Rita Fabbri, Fabio Bevilacqua, SATE S.r.l. Ferrara, pp.87-93.

Grossi C.M., Brimblecombe P., Menéndez B., Benavente D., Harris I., Déqué M. 2011. Climatology of salt transitions and implications for stone weathering. Science of the Total Environment 409, 2577–2585.

Guerreiro S. B., Dawson R. J., Kilsby C., Lewis E. and Ford A., 2018. Future heat-waves, droughts and floods in 571 European cities, IOP, Environmental Research Letters, 13, 3.

ICOMOS-ISCS, 2008. Illustrated glossary on stone deterioration patterns/ Glossaire illustré sur les formes d'altération de la pierre, MONUMENTS AND SITES/MONUMENTS ET SITES XV.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Istituto per i beni artistici, culturali e naturali della regione Emilia-Romagna, CNR-ISAC, 2007. Oggetti nel tempo: principi e tecniche di conservazione preventiva, Clueb, c2007. - XV, 258 p., Collana ER Musei e Territorio - Materiali e ricerche - n.7 ISBN 9788849128666.

Krawchuk M. A., Moritz M. A., Parisien M.-A., Van Dorn J., Hayhoe K., 2009. Global Pyrogeography: the Current and Future Distribution of Wildfire, PLoS ONE 4(4): e5102. doi:10.1371/journal.pone.0005102.

La Russa M. F., Belfiore C. M., Comite V., Barca D., Bonazza A., Ruffolo S. A., Crisci G. M., Pezzino A., 2013. Geochemical study of black crusts as a diagnostic tool in cultural heritage, Applied Physics, 113, pp 1151–1162.

Leissner J., Kilian R., Kotova L., Jacob D., Mikolajewicz U., Broström T., Ashley-Smith J., Schellen H. L., Martens M., van Schijndel J., Antretter F., Winkler M., Bertolin C., Camuffo D., Simeunovic G., Vyhlídal T. (2015). Climate for culture: Assessing the impact of climate change on the future indoor climate in historic buildings using simulations. Heritage Science, 3: 38, DOI 10.1186/s40494-015-0067-9.

Masala F., Bacciu V., Sirca C., Spano D., 2012. Fire-weather relationship in the Italian peninsula, Climate and Fires.

Mazzeo R., 2005. Genesi, Patine su Manufatti Metallici, within "Le patine. Genesi, significato, conservazione", Edited by: Tiano P., Pardini C., Nardini Press.

del Perseo di Benvenuto Cellini, within “Meteo e Metalli, Conservaz perto. Dal Perseo all’arte contemporanea.”, edited by Salvi A., Nardini Press.

Ozga I., Bonazza A., Bernardi E., Tittarelli F., Favoni O., Ghedini N., Morselli L., Sabbioni C., 2011. Diagnosis of surface damage induced by air pollution on 20th-century concrete buildings, PERGAMON-ELSEVIER SCIENCE LTD 2011, doi:10.1016/j.atmosenv.2011.05.072.

Ozga I., Bonazza A., Lyazidi S.A., Haddad M., Ben-Ncer A., Ghedini, N., Sabbioni C., 2013. Pollution impact on the ancient ramparts of the Moroccan city Sale, ELSEVIER FRANCE-EDITIONS SCIENTIFIQUES MEDICALES ELSEVIER 2013, doi:10.1016/j.culher.2012.10.018

Ruffolo S. A., Comite V., La Russa M. F., Belfiore C. M., Barca D., Bonazza A., Crisci G. M., Pezzino A., Sabbioni C., 2015. An analysis of the black crusts from the Seville Cathedral: A challenge to deepen the understanding of the relationships among microstructure, microchemical features and pollution sources, Science of The Total Environment, 502, pp. 157-166.

Sabbioni C., Brimblecombe P., Cassar M., 2012. The Atlas of Climate Change Impact on European Cultural Heritage Scientific Analysis and Management Strategies, Anthem Press.

San-Miguel-Ayanz, J., Schulte, E., Schmuck, G., Camia, A., Strobl, P., Libertà, G., Giovando, C., Boca, R., Sedano, F., Kempeneers, P., McInerney, D., Withmore, C., Santos de Oliveira, S., Rodrigues, M., Durrant, T., Corti, P., Oehler, F., Vilar L., Amatulli, G., 2012. Comprehensive monitoring of wildfires in Europe: the European Forest Fire Information System (EFFIS) in: Tiefenbacher, J. (Ed.), Approaches to Managing Disaster - Assessing Hazards, Emergencies and Disaster Impacts, pp. 87-105, InTech, ISBN 978-953-51-0294-6.

San-Miguel-Ayanz J., Durrant T., Boca R., Libertà G., Branco A., de Rigo D., Ferrari D., Maianti P., Artés Vivancos T., Schulte E., Loffler P., 2017. Forest Fires in Europe, Middle East and North Africa 2016. EUR 28707 EN, Publications Office, Luxembourg, ISBN 978-92-79-71292-0, doi: 10.2760/17690.

Terrier A., Girardin M. P., Périé C., Legendre P., Bergeron Y., 2013. Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. Ecol. Appl., 23, 21–35.

Török Á., 2003. Surface strength and mineralogy of weathering crusts on limestone buildings in Budapest., Building and Environment 38,1185 – 1192.

UNI EN 335-1, 1992 – Durability of wood and wood-based products – Definition of hazard classes of biological attack.

Weyer A., Roig Picazo P., Pop D., Cassar J., Özköse A., Vallet J.M., Srša I., 2016. EwaGlos EUROPEAN ILLUSTRATED GLOSSARY OF CONSERVATION TERMS FOR WALL PAINTINGS AND ARCHITECTURAL SURFACES. English definitions with translations into Bulgarian, Croatian, French, German, Hungarian, Italian, Polish, Romanian, Spanish and Turkish, Series of Publications by the Hornemann Institute, Edited By Angela Weyer, Vol. 17.