DEVELOPMENT OF MULTI-HAZARD RISK INDICATORS FOR IMMOVABLE CULTURAL HERITAGE

Flood Vulnerability Assessment

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Introduction

- Methods for the flood vulnerability assessment of cultural heritage **are scarce and/or have significant limitations**.

- A new method combining state-of-the-art knowledge on the topic can support better decision-making for **prioritization and mitigation of vulnerabilities.**

- Among existing conceptual approaches, **indicator-based and vulnerability curve methods appear to be an adequate option, particularly for flood risk assessments at a large scale.**

- To develop a **new indicator-based flood vulnerability assessment, a comprehensive literature review was conducted by analysing semi-quantitative methods** focused on cultural heritage assets.

- Based on this, it was decided that the methodology should be based on an intermediate level of modelling detail, **between large-scale and asset-specific approaches, which are the most commonly available**. In this way, a research gap is addressed.

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Methods that include factors, called ‘indicators’ that will be classified within a range of values to determine a **proxy of the qualitative characteristics that** support the assessment of potential damage through a vulnerability index.

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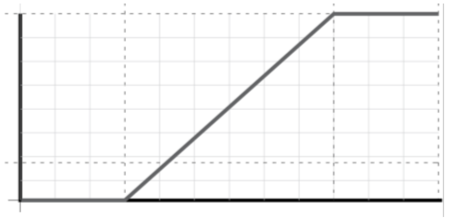
Disadvantages

Aiming for simplicity, they are typically only focused on the characteristics of the exposed elements and **do not take into account the intensity of the natural hazards**, which are crucial for assessing vulnerability and risk.

Introduction

Conceptual idea for an innovative, intermediate-level methodology

Vulnerability curves



Indicators-based method / Vulnerability Index

100	Hgh
50	Moderate
0	Low

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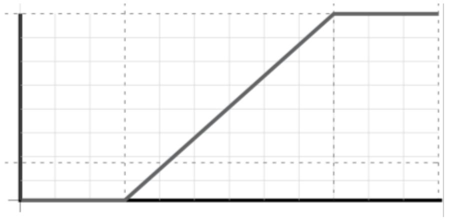

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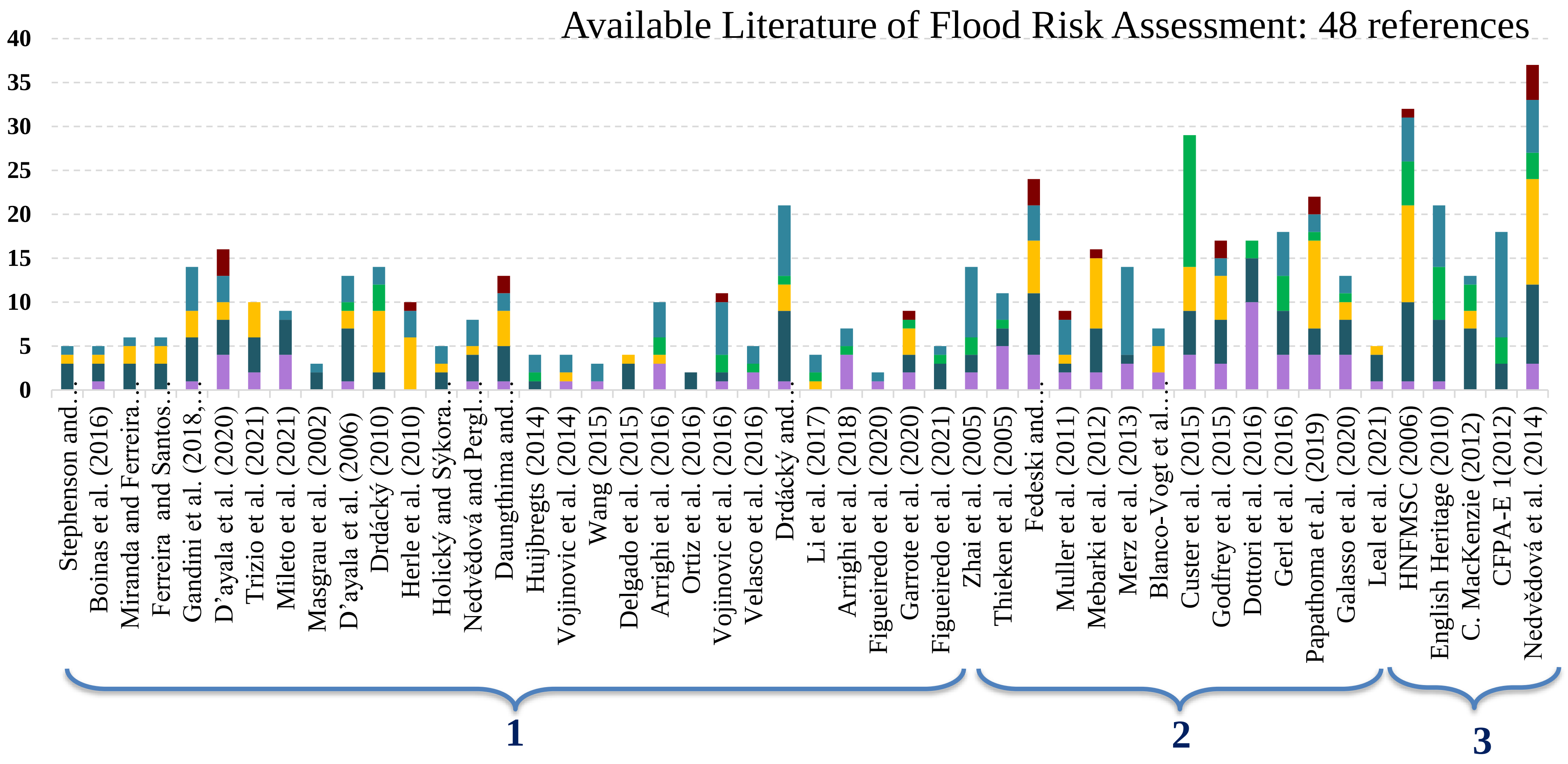
Hybrid Flood Vulnerability Assessment for Historic Buildings and their valuable content

Goal: **to characterise the vulnerability** of large sets of **cultural heritage** assets in a simplified manner, with a **reasonably high level of detail**, **taking into consideration the intensity of the hazard**, in this case, water depth (β)

Review of Methods for the selection of Flood Vulnerability Indicators

Number of aspects, indicators or parameters of the raw data identified



1. Methods tailored for cultural heritage with different levels of 'detail/scale' assessment

2. Literature tailored for ordinary buildings

3. Complementary literature (technical guidelines and reports)

Hybrid Flood Vulnerability Assessment for Historic Buildings and their valuable content

Baseline Vulnerability Curve

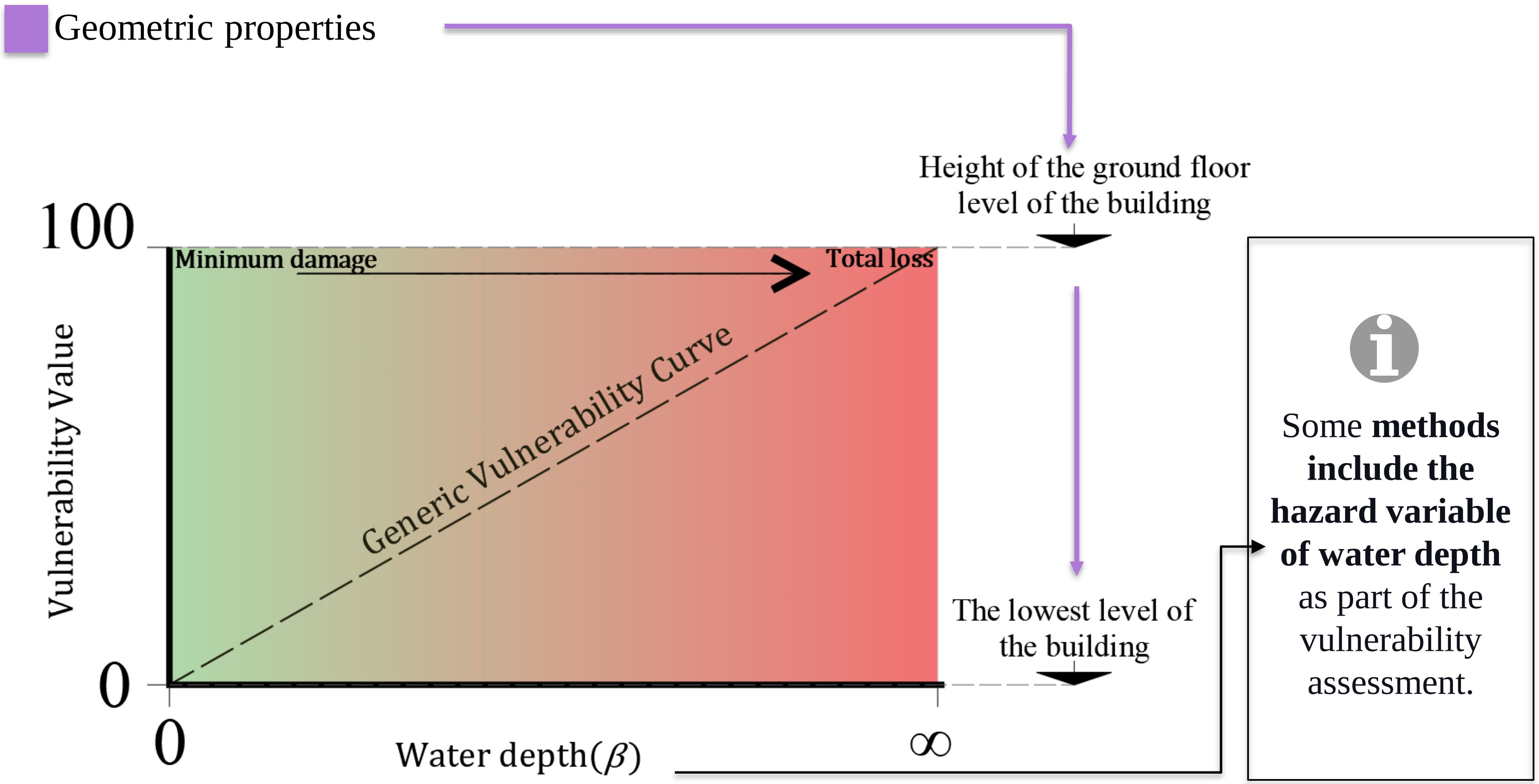
Vulnerability Index

$$FVC(\beta)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{VI_{FL}}{100}\right)_{[0:1]}$$

It functions as the maximum relative flood vulnerability curve that the built cultural heritage asset and its valuable content may have.

It functions as a factorisation to reduce the initial flood baseline vulnerability curve

Flood Vulnerability Assessment in Cultural Heritage

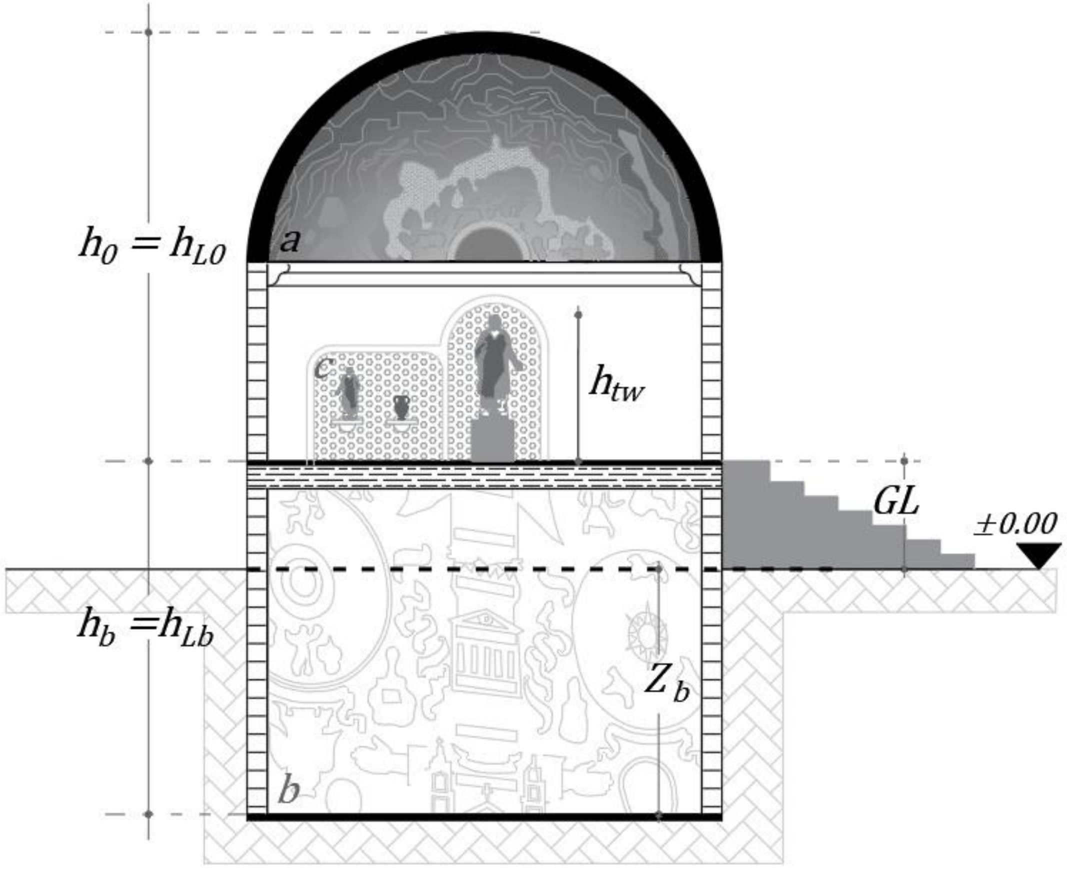


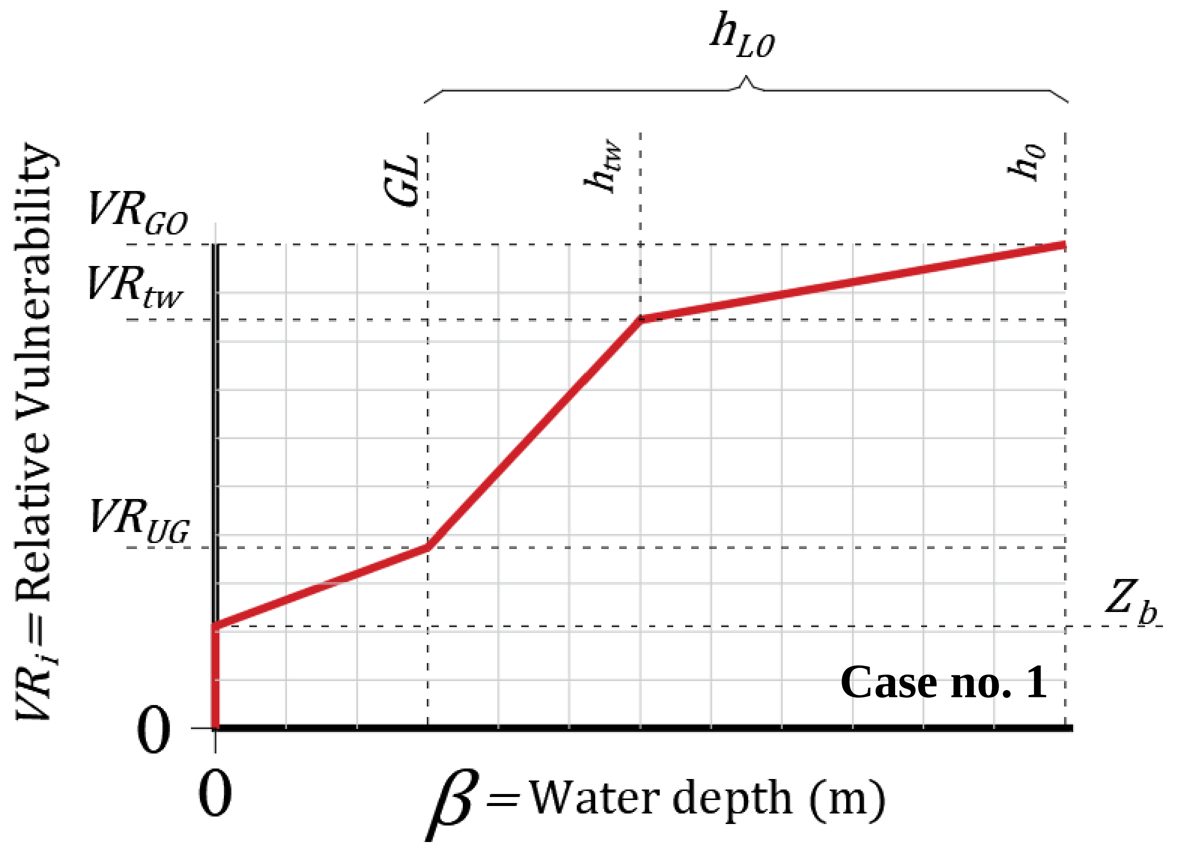
Baseline Vulnerability Curve

Baseline Vulnerability Curve

Case no. 1, *GL ≠ 0 (∴ above ground level),* $h_b = h_{Lb},\ h_b$ *and* $h_{Lb} > Z_b,\ h_0 = h_{L0}$

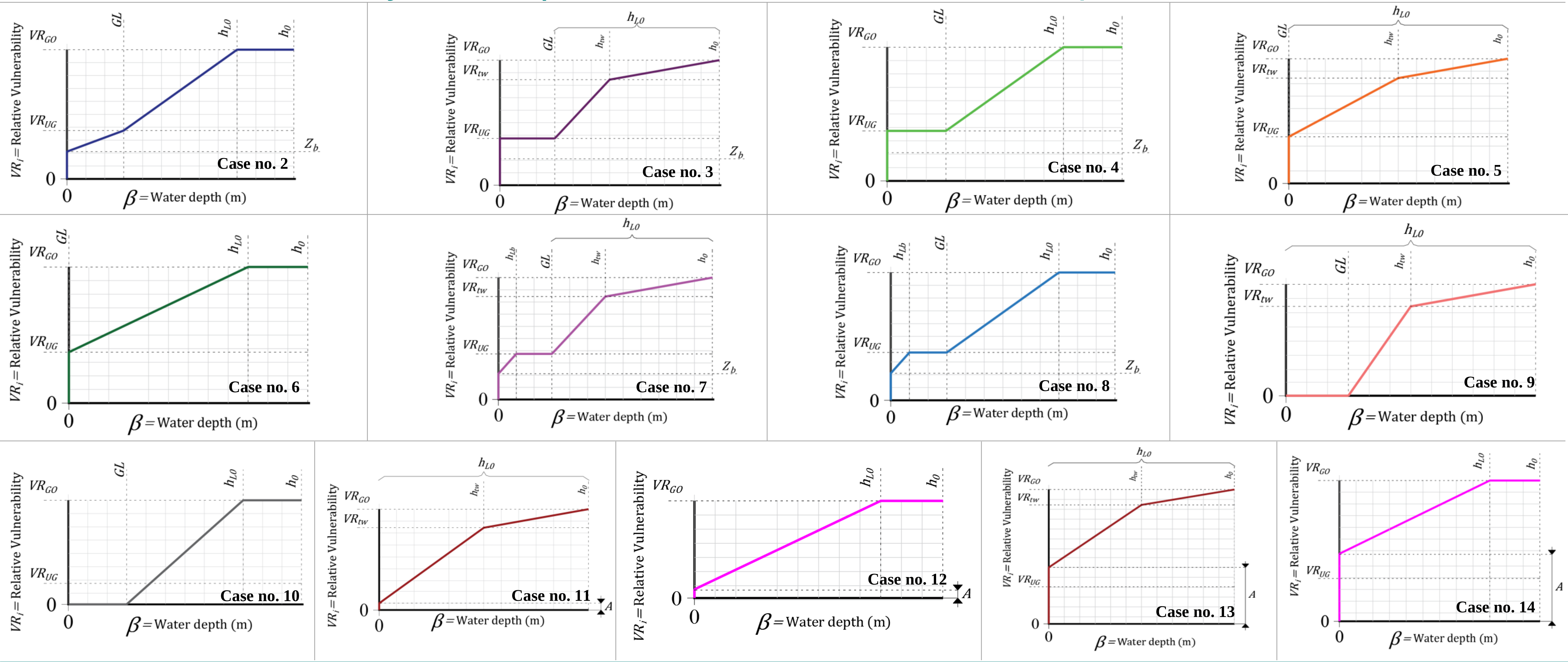
14 baseline vulnerability curves cases were defined considering the geometric properties of historic constructions





Flood Vulnerability Assessment in Cultural Heritage

Baseline Vulnerability Curve (+13 more cases defined cases)



Flood Vulnerability Assessment in Cultural Heritage

C_M – Properties of the built materials and its valuable content

W_M=0.30

- I_{FL1}. Vertical Support Materials
- I_{FL2}. Material of Inter-storeys (β)
- I_{FL3}. Finishings and Linings
- I_{FL4}. Movable heritage content
- I_{FL5}. Attached artwork
- I_{FL6}. Openings (β)
- I_{FL7}. Conservation State

C_{AE} — Architectural envelope

W_{AE}=0.30

- I_{FL8}. Vertical structure envelope (β)
- I_{FL9}. Roof
- I_{FL10}. Foundation and soil

C_{FP} — Flood emergency plan

W_{FP}=0.20

- I_{FL11}. Flood preparedness plan
- I_{FL12}. Drainage system
- I_{FL13}. Drying systems
- I_{FL14}. Utilities and appliances (β)

C_{IS} — Immediate surroundings

W_{IS}=0.20

- I_{FL15}. Vegetation
- I_{FL16}. Inclination and type of ground surface
- I_{FL17}. Permeability of the surface
- I_{FL18}. Closeness to a slope

VI_{FL} = **Vulnerability Index**

18 flood vulnerability indicators

$$VI_{FL} = \sum_{i=1}^{4} \bar{C_i} * W_i$$

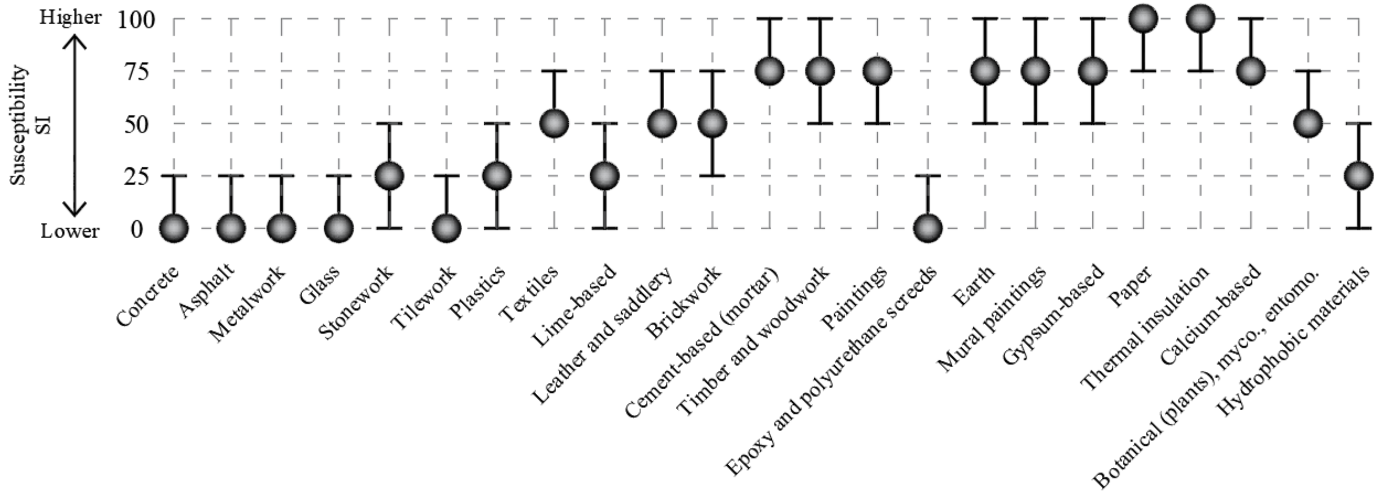
$\bar{C_i}$ = mean value of considering the I_{FLi} for each category

W_i = attributed weight of each category

Note: (β) means that the indicator consider possible water depth measurements

Flood Vulnerability Assessment in Cultural Heritage

How a indicator-based method works?



Description	Susceptibility Indexes (SI)
The occurrence of damage is not expected (i.e. resilient floors, walls or interiors designed to minimise the impact of floodwater). Components may require unspecialized cleaning and/or drying.	0
Some damage is expected in the medium-long term, particularly if components are subjected to continuous exposure to water.	25
Some damage is expected in the short-medium term, although affected components will likely be fully recoverable.	50
Significant damage is expected in the short term. Affected components will likely be only partially recoverable.	75
Extensive damage is expected in the short term. Affected components will likely not be recoverable.	100

(Illustrative example no.1 for $\boldsymbol{I_{FL1}}$)

Indicators associated with the material of the historic construction

For instance a vertical support ($\boldsymbol{I_{FL1}}$) of:

1. three-leaves walls of two leaves of sandstone (*SI=25*)
2. and single-leaf of earth (*SI=75*)
3. using lime mortar joints (*SI=25*),
4. with a coating of lime mortar (*SI=25*)
5. and organic painting (*SI=75*).

$$\boldsymbol{I_{FL1} = \frac{\sum_{i=1}^{n} SI_i}{n}}$$

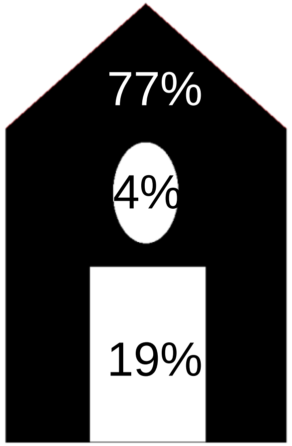
$$\boldsymbol{I_{FL1} = \frac{25 + 25 + 75 + 25 + 75}{5} = 45}$$

Flood Vulnerability Assessment in Cultural Heritage

How a indicator-based method works?

(Illustrative example no.2 for $\boldsymbol{I_{FL6}}$ ($\boldsymbol{\beta}$))

Susceptibility Index	Percentage area of openings with respect to the worst-case façade.			Any type of permanent protection (e.g. locked with fully watertight seal, catches, hinges, double glass)		The hypothetical water depth reaches the bottom of the window	
	<25%	25-50%	>50%	YES	NO	YES	NO
0							X
25				X			
50	X				X	X	
75		X			X	X	
100			X		X	X	

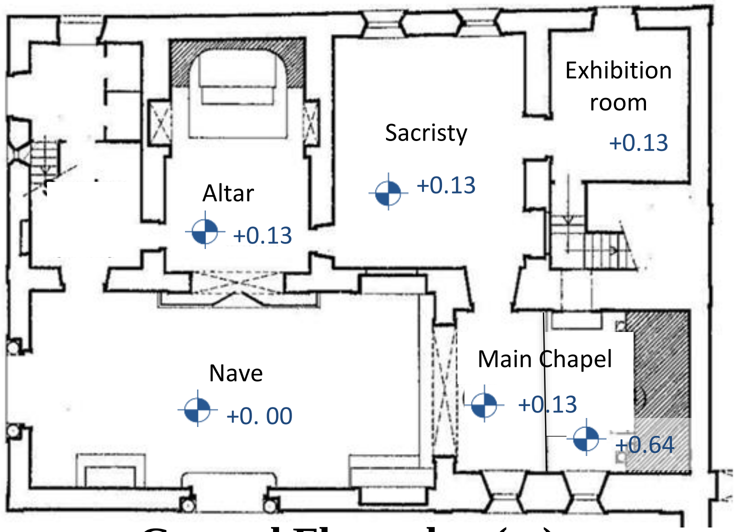


Flood Vulnerability Assessment in Cultural Heritage

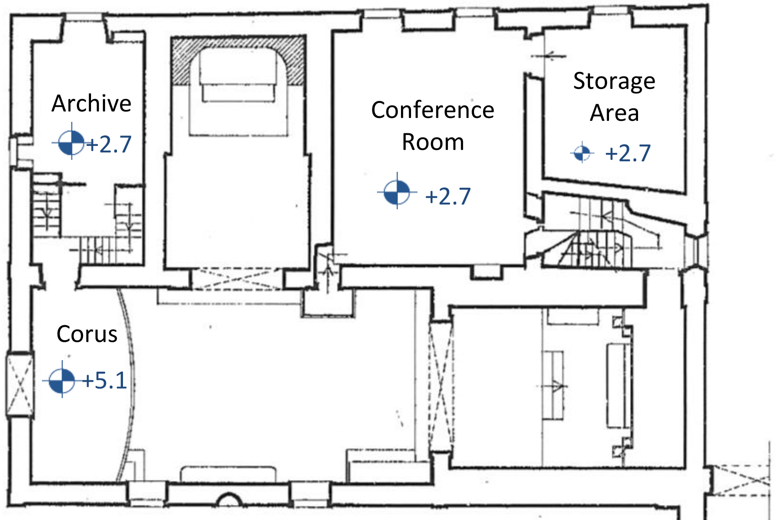
Multi-Attribute Scoring Criteria

Flood Vulnerability Indicators	SI (Susceptibility Indices)							W
I_{FL1}. Vertical Support Materials	Mean values	from	minimum	0	to	maximum	100	
I_{FL2}. Material of Inter-storeys (β)	Mean values	from	minimum	0	to	maximum	100	
I_{FL3}. Finishings and Linings	Mean values	from	minimum	0	to	maximum	100	
I_{FL4}. Movable heritage content	Mean values	from	minimum	0	to	maximum	100	0.3
I_{FL5}. Attached artwork	Mean values	from	minimum	0	to	maximum	100	
I_{FL6}. Openings (β)	0	25		50		75	100	
I_{FL7}. Conservation State	0	25		50		75	100	
I_{FL8}. Vertical structure envelope (β)	0						100	
I_{FL9}. Roof	0	20	40		60	80	100	0.3
I_{FL10}. Foundation and soil	0		35		70		100	
I_{FL11}. Flood preparedness plan	0			50			100	
I_{FL12}. Drainage system	0		35		70		100	0.2
I_{FL13}. Drying systems	0						100	
I_{FL14}. Utilities and appliances (β)	0		35		70		100	
I_{FL15}. Vegetation	0		50				100	
I_{FL16}. Inclination and type of ground surface	0		50				100	0.2
I_{FL17}. Permeability of the surface	0	15	30	45	60	75	100	
I_{FL18}. Closeness to a slope	0						100	
								1

Case Study - *Misericórdia de Esposende* - Church



Ground Floor plan (m)



Plan View First Floor (m)

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Baseline Vulnerability Curve

Parameters considered to model the curve	
GL	0.2 m
h_b	0 (no basement)
h_{Lb}	0 (no basement)
h_0	9.6 m
h_{L0}	9.6 m
Z_b	0 (no basement)
A	Not applicable
h_{tw}	3 m
$h_{tw} + GL$	3.2 m
VR_{UG}	0
VR_{G0}	100
VR_{tw}	80

$$GL \neq 0 \ (\therefore \text{above ground level})$$

$$h_b = h_{Lb} = 0$$

$$Z_b = 0$$

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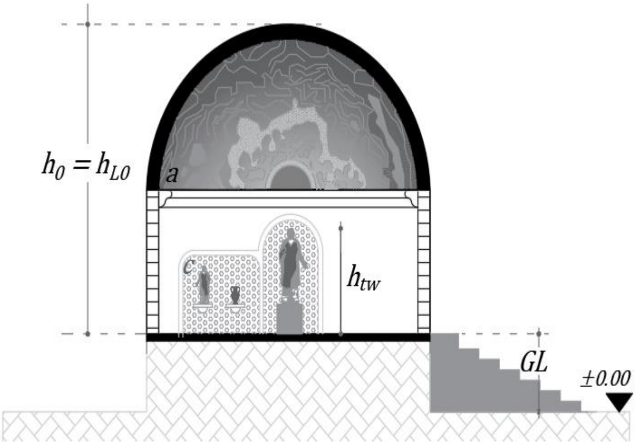

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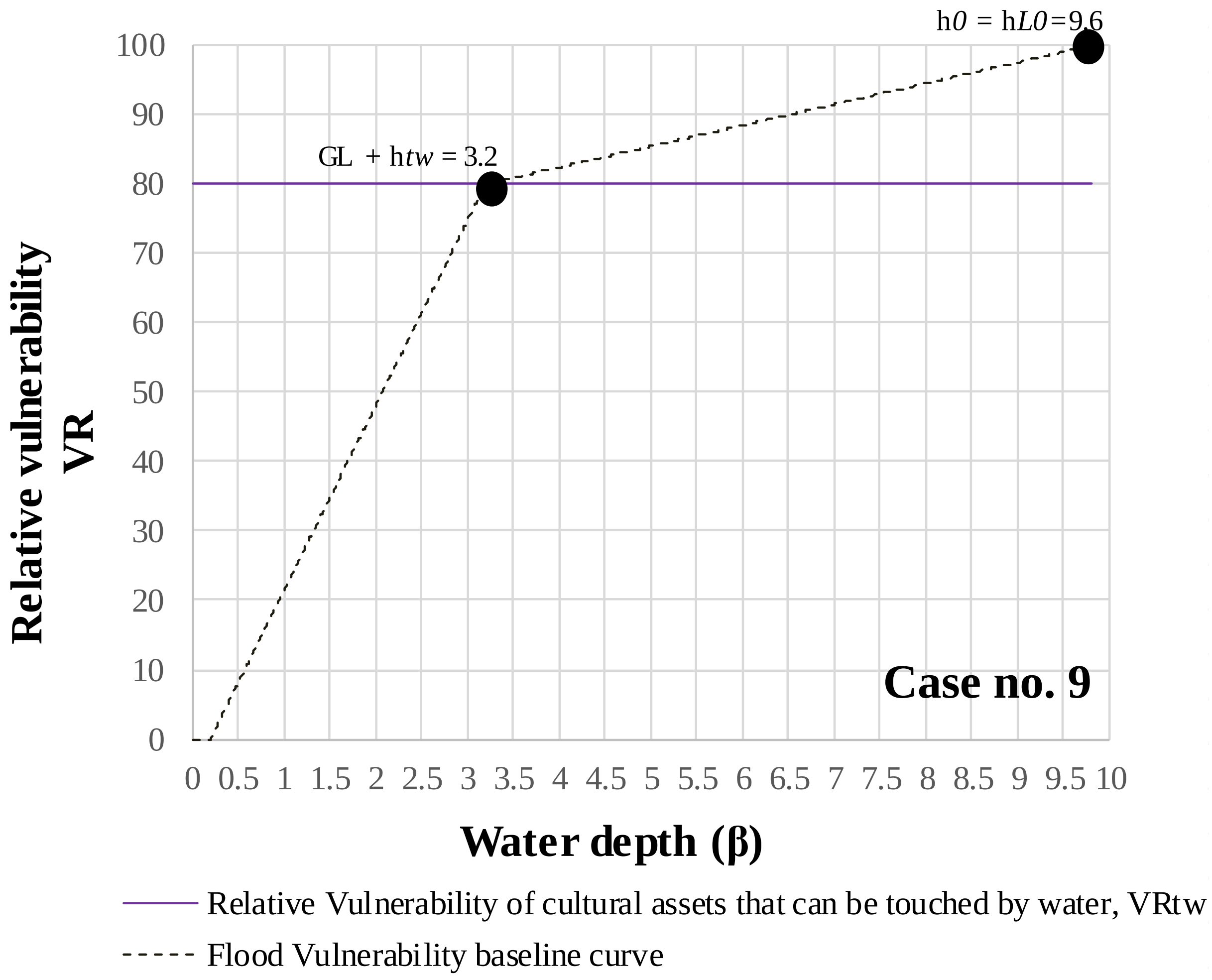

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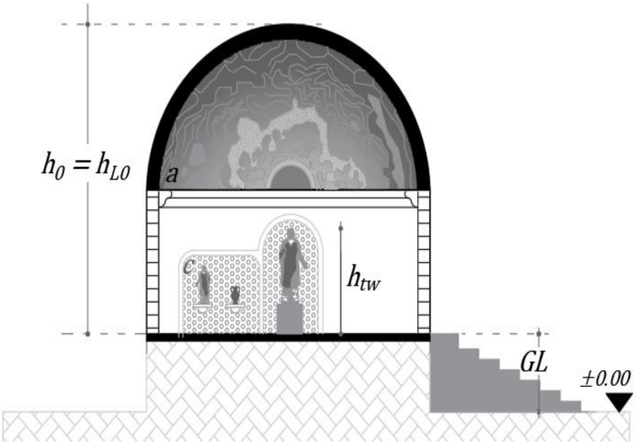

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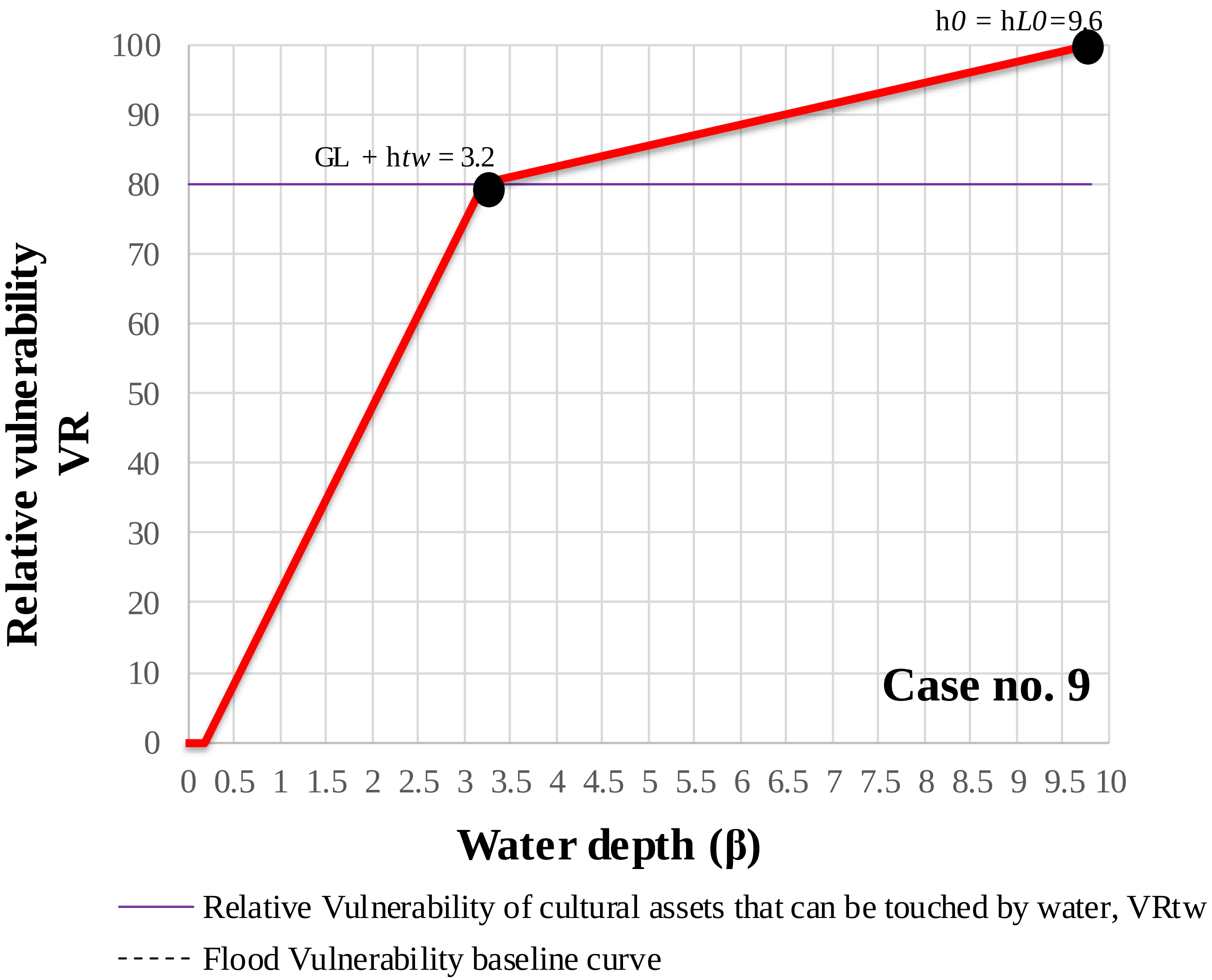

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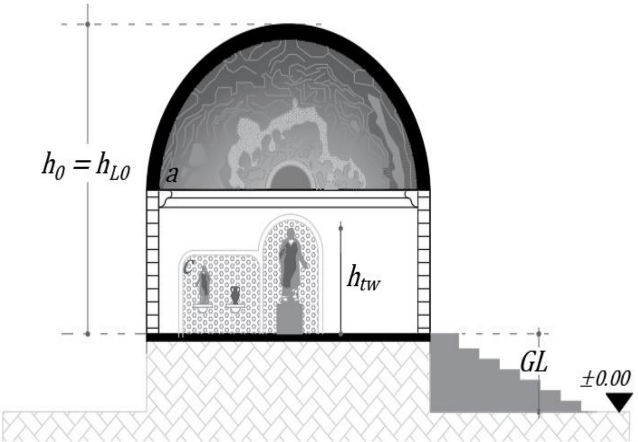

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Flood Vulnerability Index (e.g. of three different water depths - β)

Indicator	Susceptibility Indices (SI) at different water depths (β) in m. β=0.23	β=0.73	β=1.43	$(\frac{\sum SI_i}{n})*W_i$ β=0.23	β=0.73	β=1.43
I_{FL1} – Vertical support materials	25	25	25	9.29	9.29	13.57
$I_{FL2}(\beta)$ –Material of inter-storey floors (4.5)*	0	0	0			
I_{FL3} – Finishings and linings	43.75	43.75	43.75			
I_{FL4} – Movable heritage content	66.67	66.67	66.67			
I_{FL5} – Attached artwork	31.25	31.25	31.25			
$I_{FL6}(\beta)$ – Openings (1.1)*	0	0	100			
I_{FL7} – Conservation state	50	50	50			
$I_{FL8}(\beta)$ – Vertical structure envelope(0.61)*	0	100	100	0.00	10.00	10.00
I_{FL9} – Roof	0	0	0			
I_{FL10} – Foundation and soil	0	0	0			
I_{FL11} – Flood preparedness plan	70	70	70	13.50	18.50	18.50
I_{FL12} – Drainage system	100	100	100			
I_{FL13} – Drying systems	100	100	100			
$I_{FL14}(\beta)$ – Utilities and appliances(0.7)*	0	100	100			
I_{FL15} – Vegetation	100	100	100	9.00	9.00	9.00
I_{FL16} – Inclination and type of ground surface	50	50	50			
I_{FL17}– Permeability of the surface	30	30	30			
I_{FL18}– Closeness to a slope	0	0	0			
TOTAL (VI_{FL})				31.79	46.79	51.07

***These indicators considers the water depth (β) for the flood vulnerability assessment. The value of β considered in this evaluation that follows the instructions of Section 4 and may influence the damage impact is referred in "()", in metres.**

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Flood Vulnerability Index (e.g. of three different water depths - β)

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I_{FL5} – Attached artwork	31.25	31.25	31.25			
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I_{FL10} – Foundation and soil	0	0	0			
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I_{FL13} – Drying systems	100	100	100			
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Based on hazard maps developed in the scope of the Portuguese implementation of the European Floods Directive

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I_{FL3} – Finishings and linings	[illegible]	[illegible]	[illegible]			
I_{FL4} – Movable heritage content	[illegible]	[illegible]	[illegible]			
I_{FL5} – Attached artwork	[illegible]	[illegible]	[illegible]			
$I_{FL6}(\beta)$ – Openings (1.1)*	0	0	100			
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Indicators that have an influence in the vulnerability assessment throughout the linear distribution of the curve.

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Case Study - *Misericórdia de Esposende* - Church

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I_{FL5} – Attached artwork	31.25	31.25	31.25			
I_{FL6}(β) – Openings (1.1)*	**0**	**0**	**100**			
	50	50	50			
	0	**100**	**100**			
	0	0	0	0.00	10.00	10.00
	0	0	0			
	70	70	70			
I_{FL12} – Drainage system	100	100	100	13.50	18.50	18.50
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I_{FL15} – Vegetation	100	100	100			
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TOTAL (VI_{FL})				31.79	46.79	51.07

Susceptibility Index outcomes for each flood vulnerability indicator at associated heights/water depths

***These indicators considers the water depth (β) for the flood vulnerability assessment. The value of β considered in this evaluation that follows the instructions of Section 4 and may influence the damage impact is referred in "()", in metres.**

Case Study - *Misericórdia de Esposende* - Church

Flood Vulnerability Index (e.g. of three different water depths - β)

	Susceptibility Indices (SI) at different water depths (β) in m.			$(\frac{\sum SI_i}{n})*W_i$		
Indicator	β=0.23	β=0.73	β=1.43	**β=0.23**	**β=0.73**	**β=1.43**
I_{FL1} – Vertical support materials	25	25	25	9.29	9.29	13.57
I_{FL2}(β) –Material of inter-storey floors (4.5)*	0	0	0			
I_{FL3} – Finishings and linings	43.75	43.75	43.75			
I_{FL4} – Movable heritage content	66.67	66.67	66.67			
I_{FL5} – Attached artwork	31.25	31.25	31.25			
I_{FL6}(β) – Openings (1.1)*	0	0	100			
I_{FL7} – Conservation state	50	50	50			
I_{FL8}(β) – Vertical structure envelope(0.61)*	[illegible]	[illegible]	100	0.00	10.00	10.00
I_{FL9} – Roof	0	0	0			
I_{FL10} – Foundation and soil	0	0	0			
I_{FL11} – Flood preparedness plan	70	70	70	13.50	18.50	18.50
I_{FL12} – Drainage system	100	100	100			
I_{FL13} – Drying systems	100	100	100			
I_{FL14}(β) – Utilities and appliances(0.7)*	0	100	100			
I_{FL15} – Vegetation	100	100	100	9.00	9.00	9.00
I_{FL16} – Inclination and type of ground surface	50	50	50			
I_{FL17}– Permeability of the surface	30	30	30			
I_{FL18}– Closeness to a slope	0	0	0			
TOTAL (VI_{FL})				31.79	46.79	51.07

Final weights for each category

***These indicators considers the water depth (β) for the flood vulnerability assessment. The value of β considered in this evaluation that follows the instructions of Section 4 and may influence the damage impact is referred in "()", in metres.**

Case Study - *Misericórdia de Esposende* - Church

Flood Vulnerability Index (e.g. of three different water depths - β)

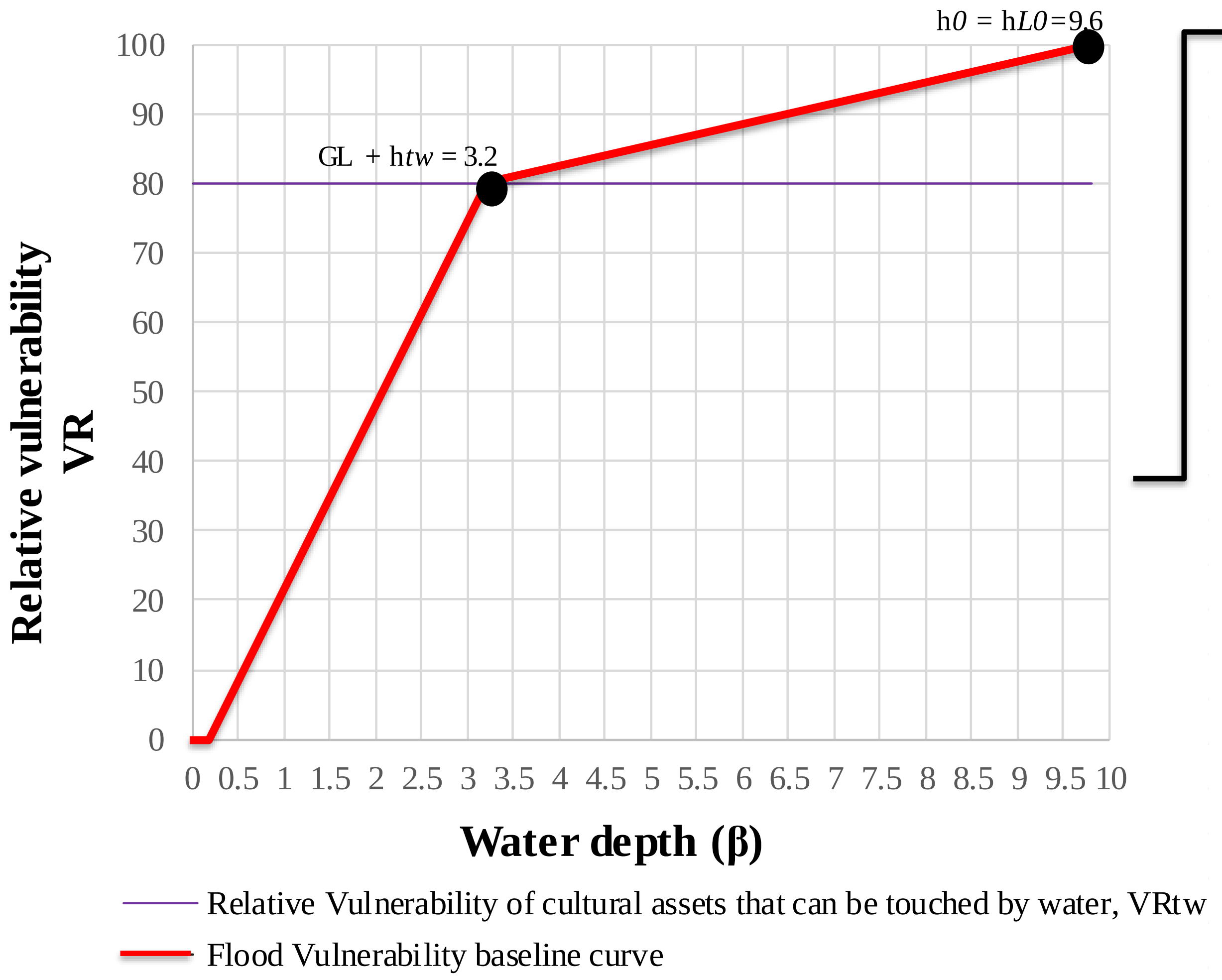
Indicator	Susceptibility Indices (SI) at different water depths (β) in m. β=0.23	β=0.73	β=1.43	$(\frac{\sum SI_i}{n})*W_i$ β=0.23	β=0.73	β=1.43
I_{FL1} – Vertical support materials	25	25	25			
$I_{FL2}(\beta)$ –Material of inter-storey floors (4.5)*	0	0	0			
I_{FL3} – Finishings and linings	43.75	43.75	43.75			
I_{FL4} – Movable heritage content	66.67	66.67	66.67	9.29	9.29	13.57
I_{FL5} – Attached artwork	31.25	31.25	31.25			
$I_{FL6}(\beta)$ – Openings (1.1)*	0	0	100			
I_{FL7} – Conservation state	50	50	50			
$I_{FL8}(\beta)$ – Vertical structure envelope(0.61)*	0	100	100			
I_{FL9} – Roof	0	0	0	0.00	10.00	10.00
I_{FL10} – Foundation and soil	0	0	0			
I_{FL11} – Flood preparedness plan	70	70	70			
I_{FL12} – Drainage system	100	100	100	13.50	18.50	18.50
I_{FL13} – Drying systems	100	100	100			
$I_{FL14}(\beta)$ – Utilities and appliances(0.7)*	0	100	100			
I_{FL15} – Vegetation	[illegible]	[illegible]	100			
I_{FL16} – Inclination and type of ground surface	[illegible]	[illegible]	50	9.00	9.00	9.00
I_{FL17}– Permeability of the surface	[illegible]	[illegible]	30			
I_{FL18}– Closeness to a slope	0	0	0			
TOTAL (VI_{FL})				31.79	46.79	51.07

Final Flood Vulnerability Index(VI_{FL}) at different height/water depth

***These indicators considers the water depth (β) for the flood vulnerability assessment. The value of β considered in this evaluation that follows the instructions of Section 4 and may influence the damage impact is referred in "()", in metres.**

Case Study - Misericórdia de Esposende - Church

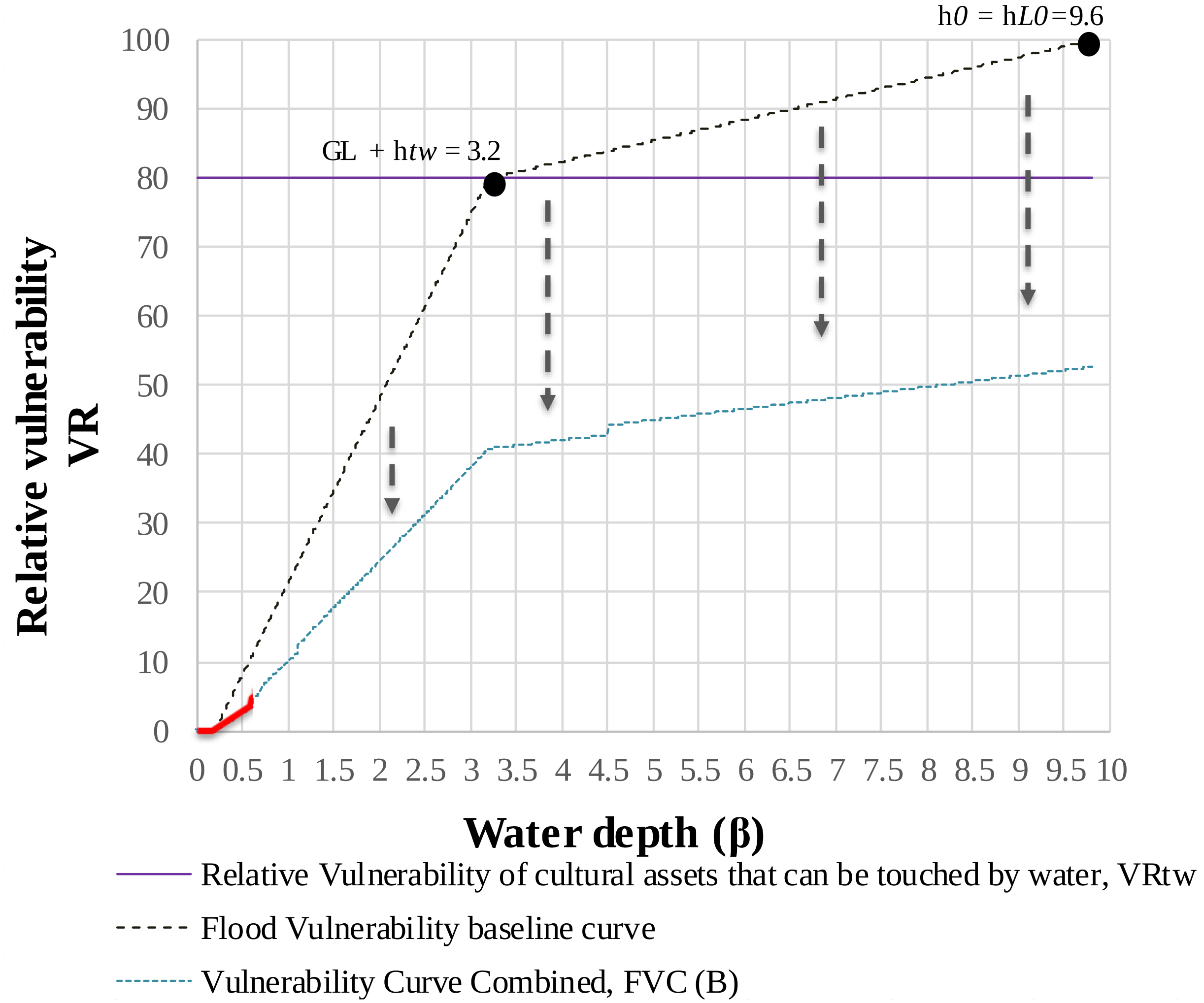
Combined Flood Vulnerability Curve – Hybrid Method



$V_C(\beta)_{[0:100]}$

Case Study - Misericórdia de Esposende - Church

Combined Flood Vulnerability Curve – Hybrid Method

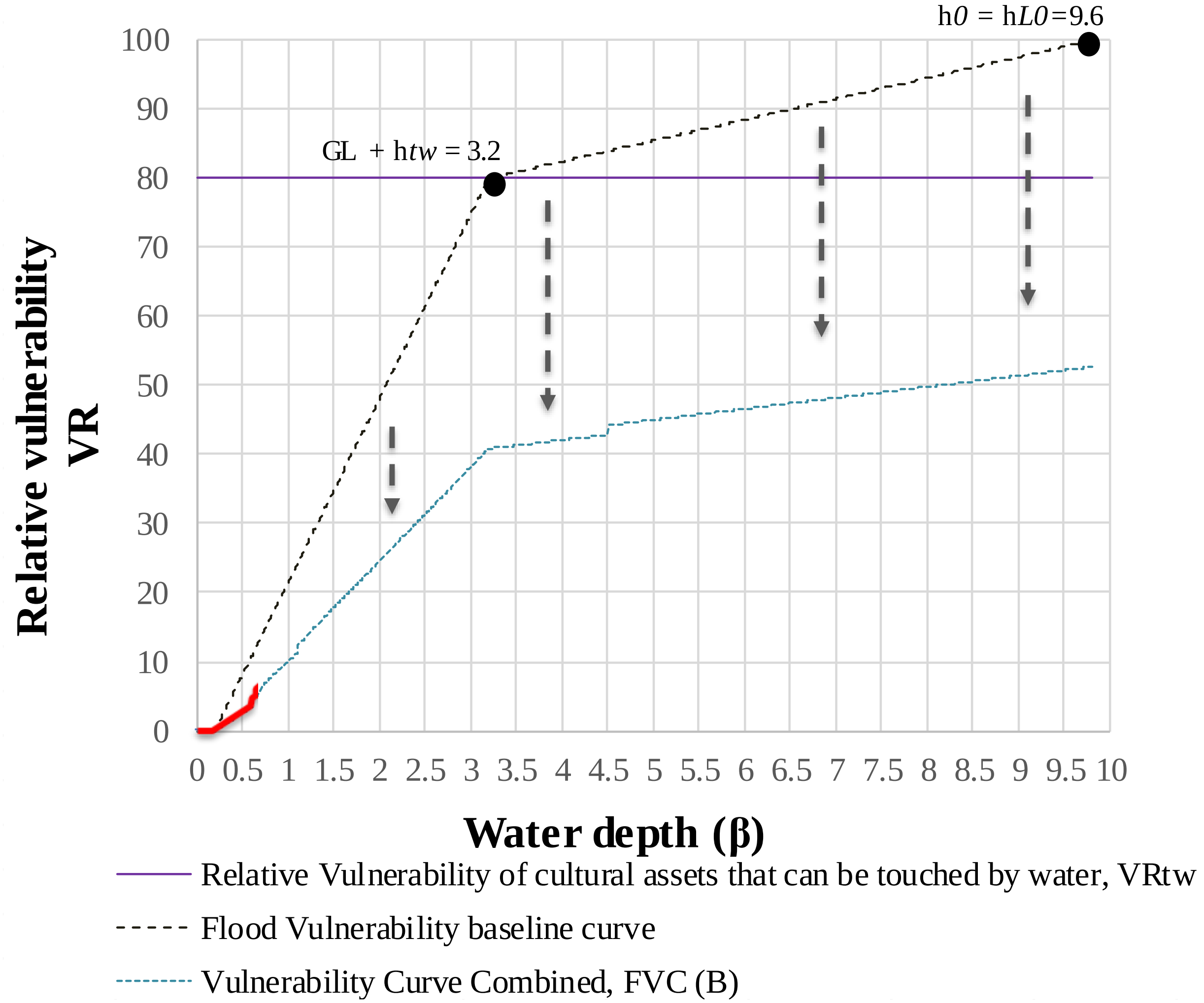


$$FVC(\beta)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{VI_{FL}}{100}\right)_{[0:1]}$$

$$FVC(\beta < 0.61)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{31.79}{100}\right)_{[0:1]}$$

Case Study - Misericórdia de Esposende - Church

Combined Flood Vulnerability Curve – Hybrid Method

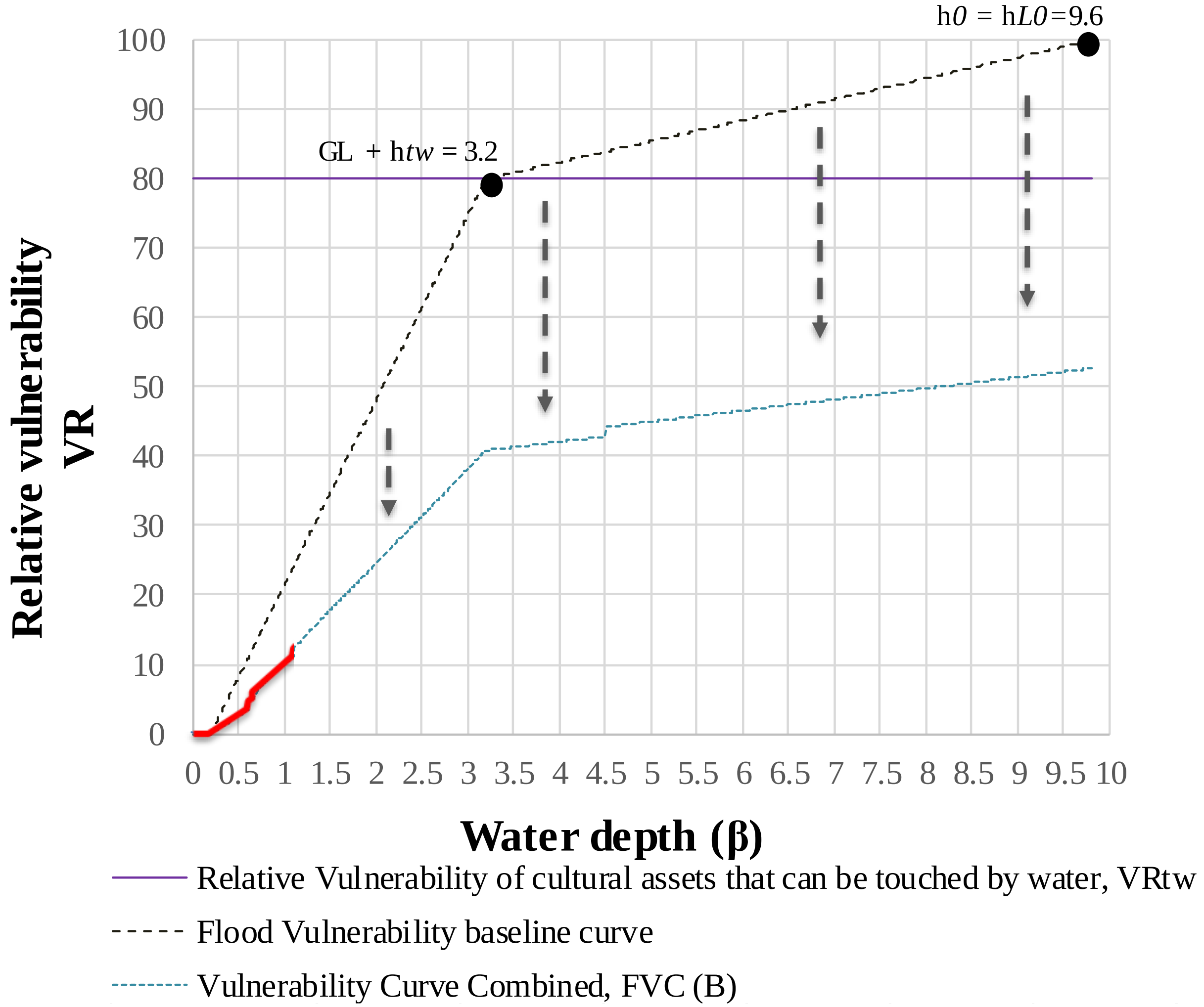


$$FVC(\beta)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{VI_{FL}}{100}\right)_{[0:1]}$$

$$FVC(\beta < 0.61)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{31.79}{100}\right)_{[0:1]}$$

$$FVC(0.61 \leq \beta < 0.70)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{41.79}{100}\right)_{[0:1]}$$

Combined Flood Vulnerability Curve – Hybrid Method



$$FVC(\beta)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{VI_{FL}}{100}\right)_{[0:1]}$$

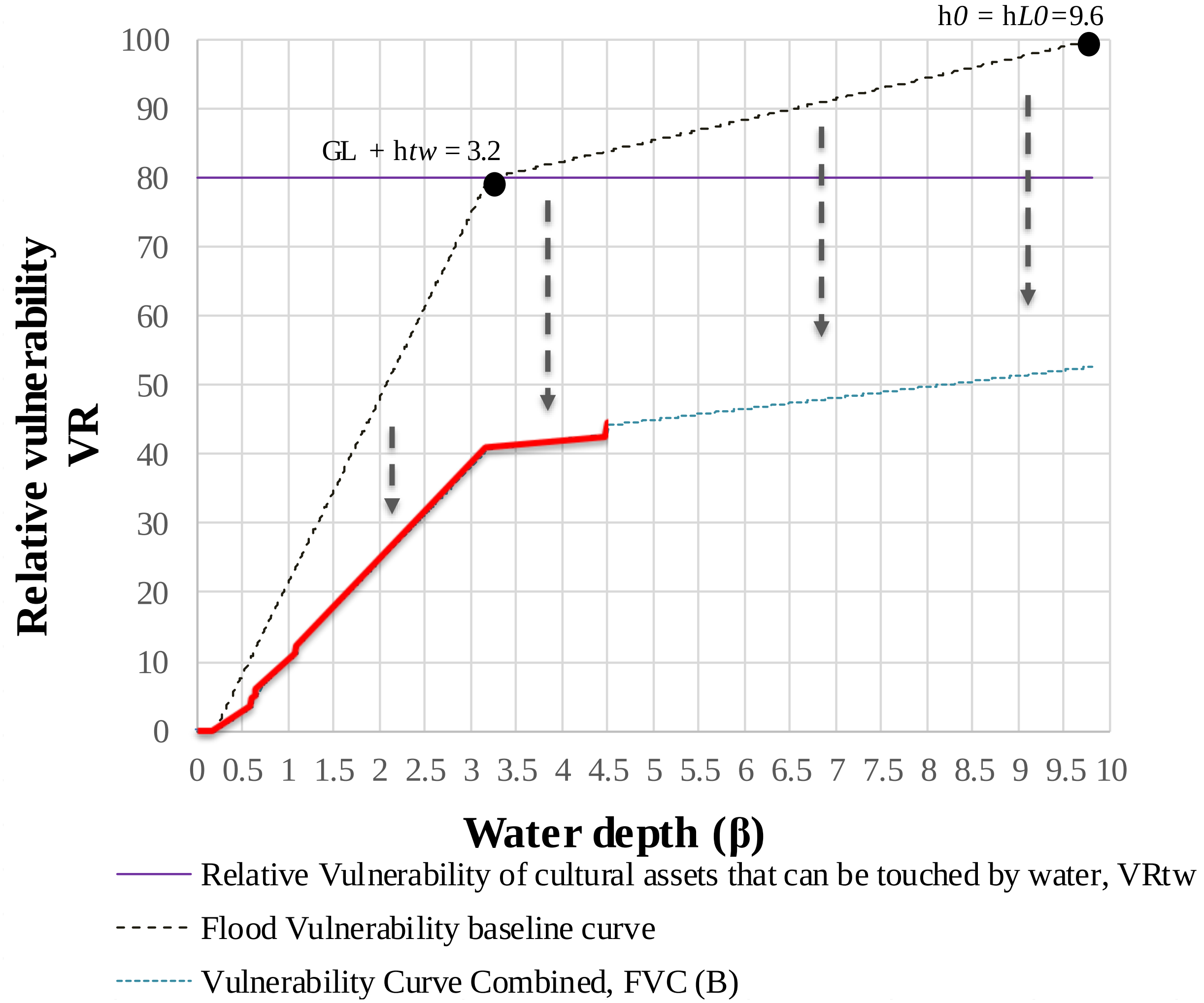
$$FVC(\beta < 0.61)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{31.79}{100}\right)_{[0:1]}$$

$$FVC(0.61 \leq \beta < 0.70)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{41.79}{100}\right)_{[0:1]}$$

$$FVC(0.70 \leq \beta < 1.10)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{46.79}{100}\right)_{[0:1]}$$

Case Study - Misericórdia de Esposende - Church

Combined Flood Vulnerability Curve – Hybrid Method



$$FVC(\beta)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{VI_{FL}}{100}\right)_{[0:1]}$$

$$FVC(\beta < 0.61)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{31.79}{100}\right)_{[0:1]}$$

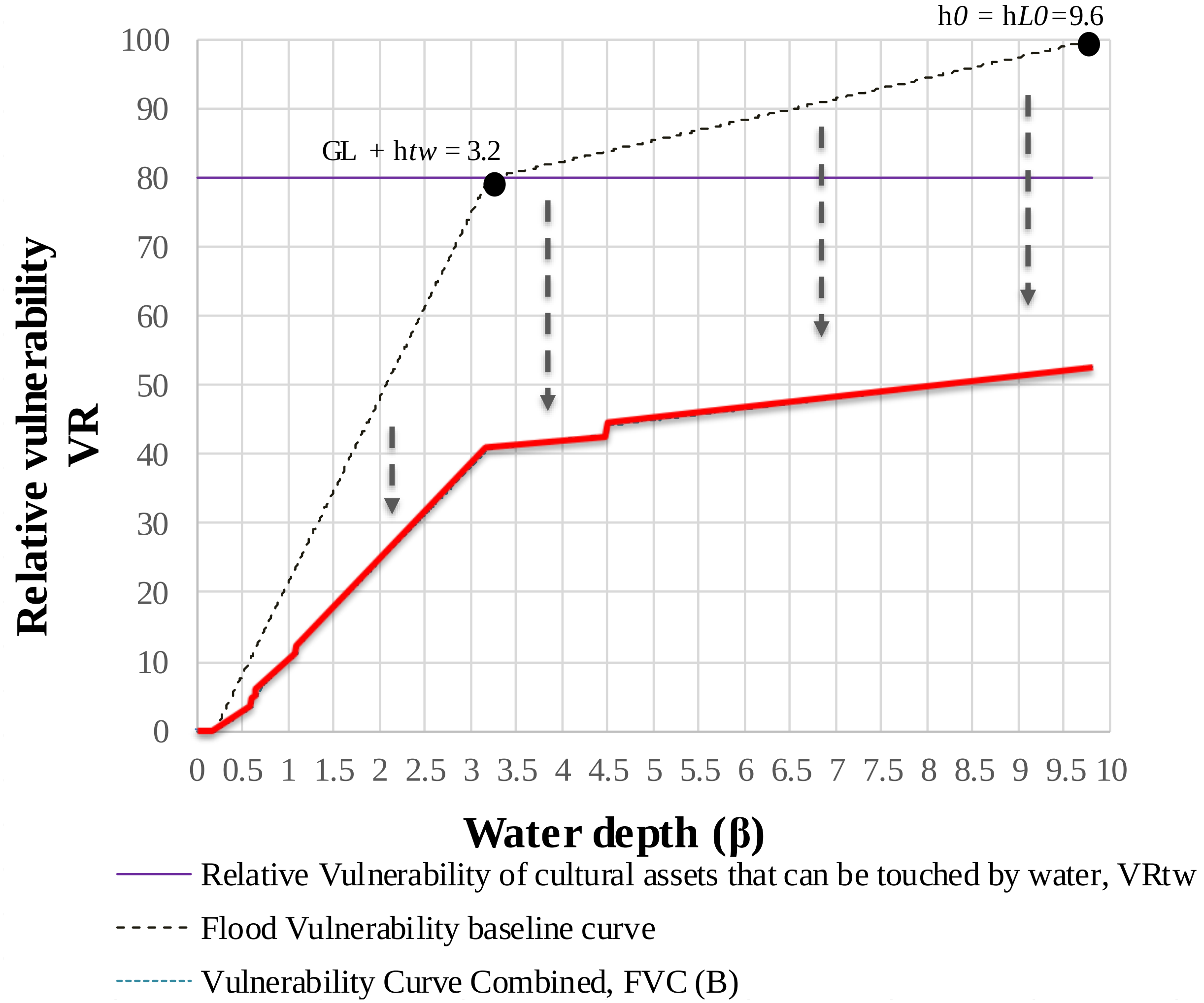
$$FVC(0.61 \leq \beta < 0.70)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{41.79}{100}\right)_{[0:1]}$$

$$FVC(0.70 \leq \beta < 1.10)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{46.79}{100}\right)_{[0:1]}$$

$$FVC(1.1 \leq \beta < 4.5)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{51.07}{100}\right)_{[0:1]}$$

Case Study - Misericórdia de Esposende - Church

Combined Flood Vulnerability Curve – Hybrid Method



$$FVC(\beta)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{VI_{FL}}{100}\right)_{[0:1]}$$

$$FVC(\beta < 0.61)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{31.79}{100}\right)_{[0:1]}$$

$$FVC(0.61 \leq \beta < 0.70)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{41.79}{100}\right)_{[0:1]}$$

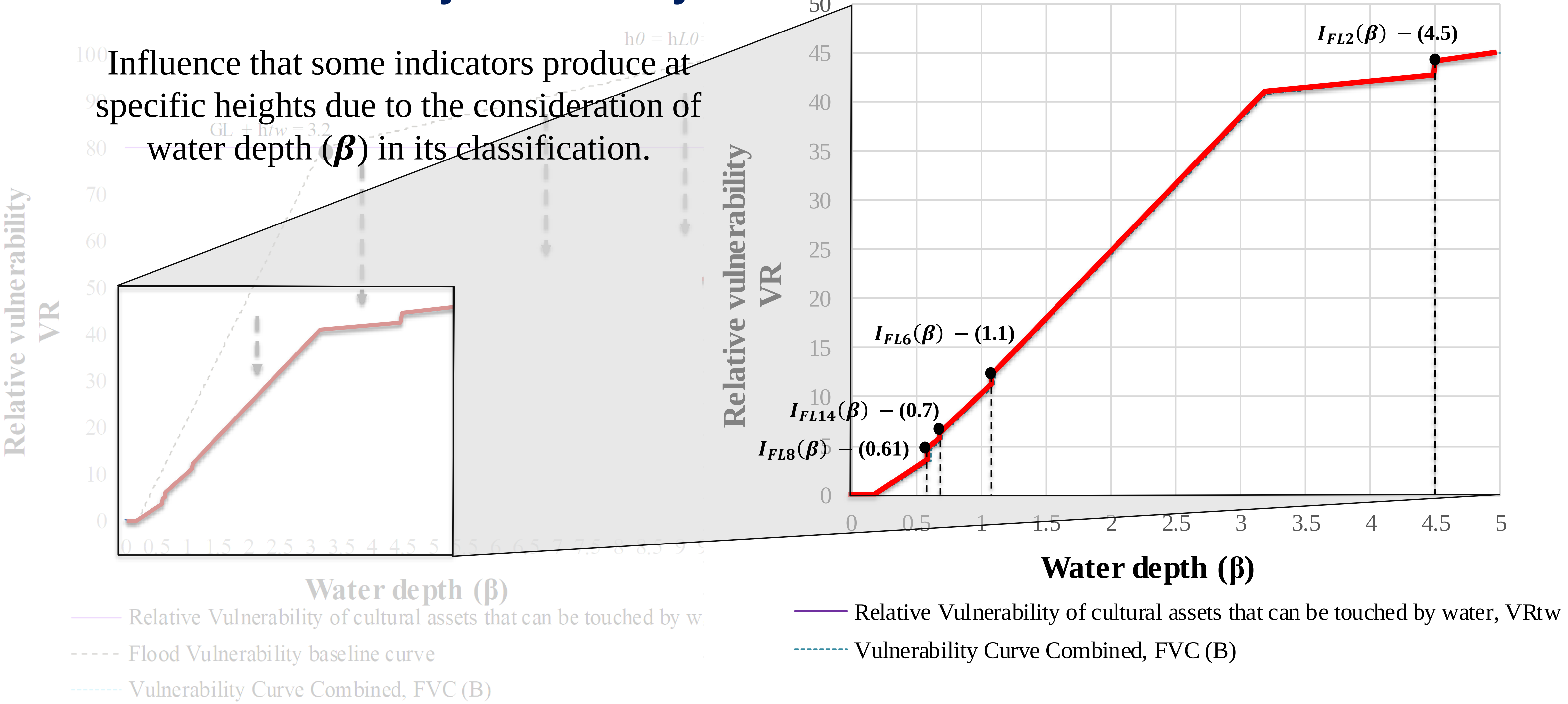
$$FVC(0.70 \leq \beta < 1.10)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{46.79}{100}\right)_{[0:1]}$$

$$FVC(1.1 \leq \beta < 4.5)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{51.07}{100}\right)_{[0:1]}$$

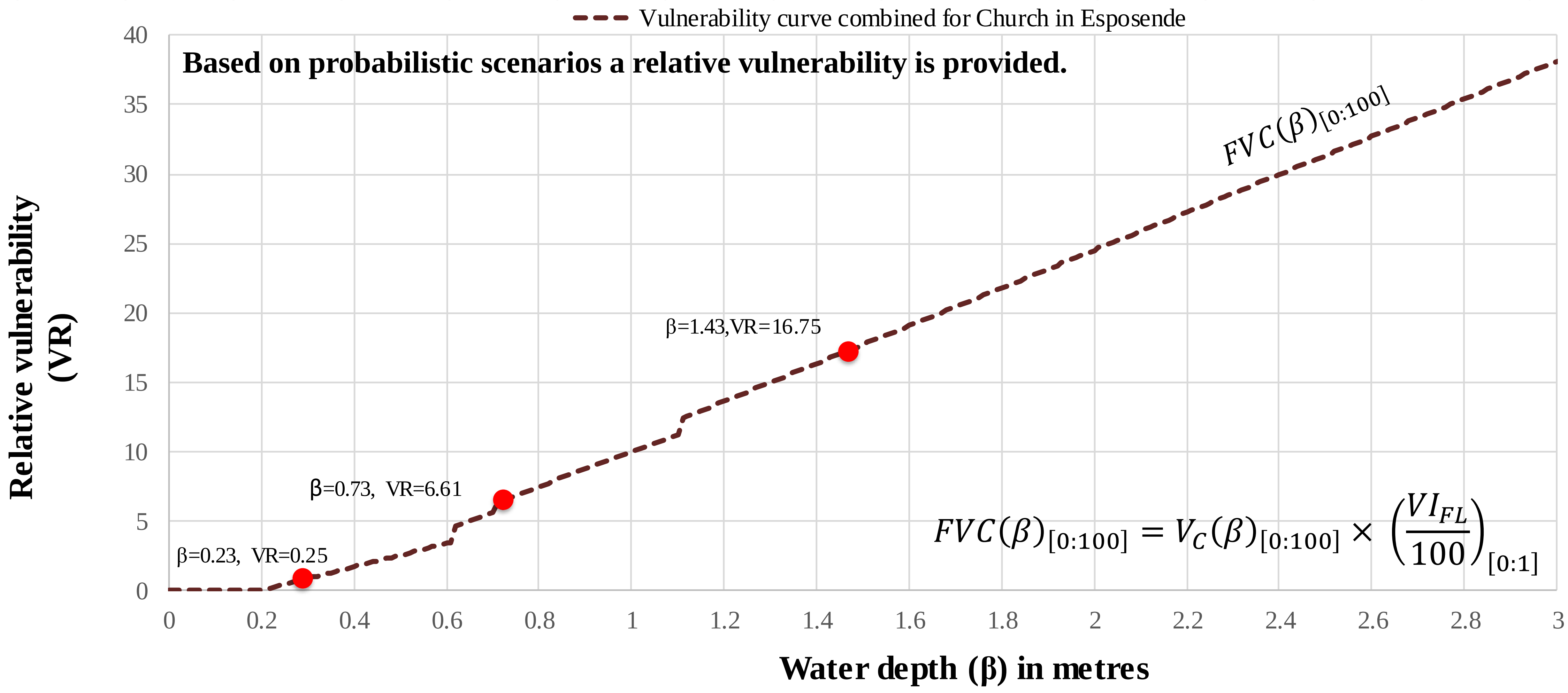
$$FVC(\beta \geq 4.5)_{[0:100]} = V_C(\beta)_{[0:100]} \times \left(\frac{52.68}{100}\right)_{[0:1]}$$

Combined Vulnerability Curve – Hybrid Method

Influence that some indicators produce at specific heights due to the consideration of water depth (β) in its classification.



Case Study - Misericórdia de Esposende - Church



Ongoing Work- Development of Seismic Vulnerability Assessment in Cultural Heritage

Seismic Vulnerability Indicators (SVIs)

Structural Building System

- **SVI-1** Type of resisting system
- **SVI-2** Quality of the resisting system
- **SVI-3** Number of floors / height
- **SVI-4** Foundations and soil
- **SVI-5** Inter-storey systems
- **SVI-6** Interaction between the roof and vertical systems

Irregularities and Global Interaction

- **SVI-7** Construction position in an aggregate and interaction with surrounding constructions
- **SVI-8** Regularity in height
- **SVI-9** Façade consideration and alignments
- **SVI-10** Plan configuration

Conservation status, structural alterations and non structural elements

- **SVI-11** Fragilities and conservation state
- **SVI-12** Structural alterations
- **SVI-13** Non-structural elements

Preventive Measures

- **SVI-14** Cultural Value: social, economic, political or institutional
- **SVI-15** Protection of artwork (movable or immovable) cultural heritage
- **SVI-16** Emergency Preparedness

Research Products and Future Tasks

Conference papers (21/22)

- **F. Salazar, L. G., Romão, X., Paupério, E. Survey of Vulnerability Indicators for Fire Risk Assessment in Cultural Heritage. 2nd International Conference on Urban Risks ICUR 2022, Lisbon, Portugal.**

- **F. Salazar, L. G., Figueiredo, R., Romão, X. Survey of Vulnerability Indicators for Flood Risk Assessment in Cultural Heritage. 2nd International Conference on Urban Risks ICUR 2022, Lisbon, Portugal.**

- **F. Salazar, L. G., Romão, X., Paupério, E. Development of a Fire Damage Index for Immovable Cultural Heritage. 12th International Conference on Structural Analysis of Historical Constructions SAHC 2021, Barcelona, Spain. DOI: 10.23967/sahc.2021.077**

- **Tikhonova, O., Romão, X., & Salazar, G. The use of GIS tools for data collection and processing in the context of fire risk assessment in urban cultural heritage. International Conference of Young Professionals «GeoTerrace-2021» (Vol. 2021, No. 1, pp. 1-5). European Association of Geoscientists & Engineers, Lviv, Ukraine. https://doi.org/10.3997/2214-4609.20215K3048**

Research Products and Future Tasks

Ongoing Research Articles (22/23)

- **Fire Damage Index for Vulnerability Assessment in Cultural Heritage**
- **Performance of Fire Vulnerability Assessment Method in Historic Centre of Guimarães**
- **Review of Vulnerability Indicators for Flood Risk Assessment in Cultural Heritage**
- **Hybrid Flood Vulnerability Assessment for Historic Buildings and their valuable content**

Future Tasks (22/23)

- **Development of a Simplified Seismic Vulnerability Assessment in Cultural Heritage using different data sources (e.g. Remote Sensing)**
- **Brief discussion of multi-risk/multi-hazard/multi-vulnerability assessment in cultural heritage**

THANK YOU FOR YOUR ATTENTION

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