Application of the methodology for damage assessment based on interior flood characteristics to field cases studies

Frédéric Grelot, David Nortes Martínez

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Deliverable D2d2 of DEUFI reseach project

Frédéric Grelot (frederic.grelot@inrae.fr)
David Nortes Martinez (david.nortes-martinez@inrae.fr)

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1 Goal and structure of this deliverable

This deliverable showcases the application of the methodologies proposed in deliverable D2d1 to two field cases at district level and 2 archetypical blueprints at building level. The goal is twofold: one, to test the methodologies, and two, to evaluate the contribution of the methodologies to flood damage assessment.

This deliverable is organized in four sections. In section 2, the methodology for damage assessment at a *district* level is applied to two french districts: Richelieu (Nîmes) and the banks of the Yzeron river (Oullins). Section 3 focuses on the application of the methodology for damage assessment at a *building* level. Last, section 4 summarizes the conclusions obtained.

2 *District* level

2.1 Richelieu district, Nîmes

2.1.1 Experimental design

The experimental design uses the 1988 flood event in Nîmes (southeastern France) as reference. This major event was originated by heavy rainfall upstream the city (420mm in 8h), and recorded waters depths up to 3 meters in the streets of the city. Around 45,000 people were impacted and the total damage rose to more than 600 millions of euros [Mignot et al., 2006, Fabre, 1989, 1990]

The simulation perimeter (figure 1) corresponds to the "Richelieu" district, delimited by the streets Vincent Faïta, Sully and Pierre Semard. This perimeter was severely affected during the 1988 flood event. The street layout is rather simple in the perimeter, with mostly 90° intersections. The average slope, oriented north to south, is higher than 1% [Mignot et al., 2006, Choley et al., 2021].

The boundary conditions used in the modeling are as follows: Upstream, the discharge is injected either at the upstream end of streets Sully and Vincent Faïta or at the connection between the Vincent Faïta street and the streets coming from the North. At the peak of the flood, the total injected discharge is $176m^3s^{-1}$ with up to $92m^3s^{-1}$ in the Sully street and $47m^3s^{-1}$ in the Faïta street. At the downstream end, the free surface elevations imposed at the limits corresponding to an outlet street vary in the range [0.46m 1.77m] [Mignot, 2005, Choley et al., 2021].

The perimeter includes 438 buildings; courtyards are not taken into account. The floor level of buildings can be higher, lower or at the same level of the street. The simulation lasts 55,000 seconds. and a uniform Strickler friction coefficient $K = 40m^{1/3}s^{-1}$ is applied [Mignot, 2005, Choley et al., 2021].

With this setup, we simulate two scenarios:

1. The *baseline* scenario, which integrates nonporous buildings as obstacles, not taking into account street-building flow exchanges
2. The *indoor* scenario, which integrates porous buildings as reservoirs, taking into account street-building flow exchanges through fully open openings.

There are two openings per facade adjacent to a street. The width of the openings is variable and related to the width of the facade.. One of the openings is always located at the same level as the building floor, while the other is located at a fixed height above the street level. Thus, since the floor level of each building is located at a variable elevation from the street, the second opening of the pair is located at a variable height from the floor level of each building. Openings are considered fully open, i.e. obstacles to the street-building water flow, such as doors or windows, are not considered. The total number of the openings in a building depends on the number of façades adjacent to streets: a building with one facade adjacent to a street will have 2 openings, a building with 2 facades, 4 openings, etc.

2.1.2 Results

2.1.2.1 Floodwater depth

Figure 1: Simulation perimeter in the richelieu district: buildings considered in the simulations (left) and street mesh (right) for the simulation of the flood event

Figure 2 displays the floodwater depth simulated in the streets when street-building flow exchanges are not considered (*baseline* scenario). The left side of the figure showcases the geographical distribution of floodwater depths in the mesh cells, while the right side of the figure displays a combined density-boxplot graph, summarizing key statistical information. As we can see, the range [0m, 2m] presents the highest density of points, with 87% of the sample. The remaining 13% of the sample falls within the range (2m, 3.45m]). Spatially, this 12% of the sample is mainly concentrated in the northern part of the perimeter, whereas the lowest values of floodwater depth seem distributed from east to west in the medial part of the perimeter.

As described in the deliverable D2d1, section 2 (methodology for damage assessment at a district level), in the case that buildings are considered nonporous, thus disregarding street-building flow exchanges, the water depth inside each building should be estimated using an indirect method. This indirect method consists of i) selecting the maximum floodwater depth around the building and ii) assigning the difference between this value and the building floor level as the floodwater depth inside the building.

The final assignation of water depths following this method is hereafter considered as the *baseline* scenario. The result is shown in figure 3. The left side of the figure 3 shows the geographical distribution of floodwater depths, while the right side of the figure displays a combined density-boxplot graph summarizing key statistical information. In the *baseline* scenario, floodwater depth in buildings is concentrated in the range [0, 1.8m]. Less than 20% of the floodwater depths are higher than 1.8m, and the most extreme simulated floodwater depths reach 3.5m. The spatial distribution of the floodwater depths follows the pattern than the street mesh: the highest depths are concentrated in the north of the simulation perimeter, while the lowest depths (up to 1m) seem to cluster in the eastern and western parts of the perimeter.

2.1.2.1.1 Compared analysis of floodwater depth scenarios

In the *indoor* scenario, the 80% of the observations concentrates in the range [0m, 1.5m] and the most extreme floodwater depth reaches 3.1m. A comparison of floodwater depth values for both the *baseline* and *indoor* scenarios is shown in figure 4-A and table 1. As it can be seen, the *baseline* scenario is systematically higher than the *indoor* scenario.

Table 1: Comparison of main statistics of floodwater depths in buildings for both the baseline and the indoor scenarios. Units: meters

	Minimum	1st quartile	Median	3rd quartile	Maximum	Mean	Standard dev.
baseline	0	0.96	1.38	1.65	3.51	1.40	0.67
indoor	0	0.69	1.09	1.38	3.12	1.12	0.66

When we look at the difference between both scenarios, we observe that the difference of means is statistically significant[1] whereas differences in the dispersion measures are not[2]. Figures 4-B and C show the difference between scenarios by individual building. The *baseline* scenario overestimates the floodwater depth in 95% of the buildings considered in comparison with the *indoor* scenario.
In terms of magnitude, the depth gap between the two scenarios concentrates in the interval [-0.5m, 0.5m] for 92% of the buildings, while the remaining 8% fall in the interval [-1.5m, -0.5m). As for the spatial distribution of those differences, figure 4-C shows that differences do not follow any particular pattern.

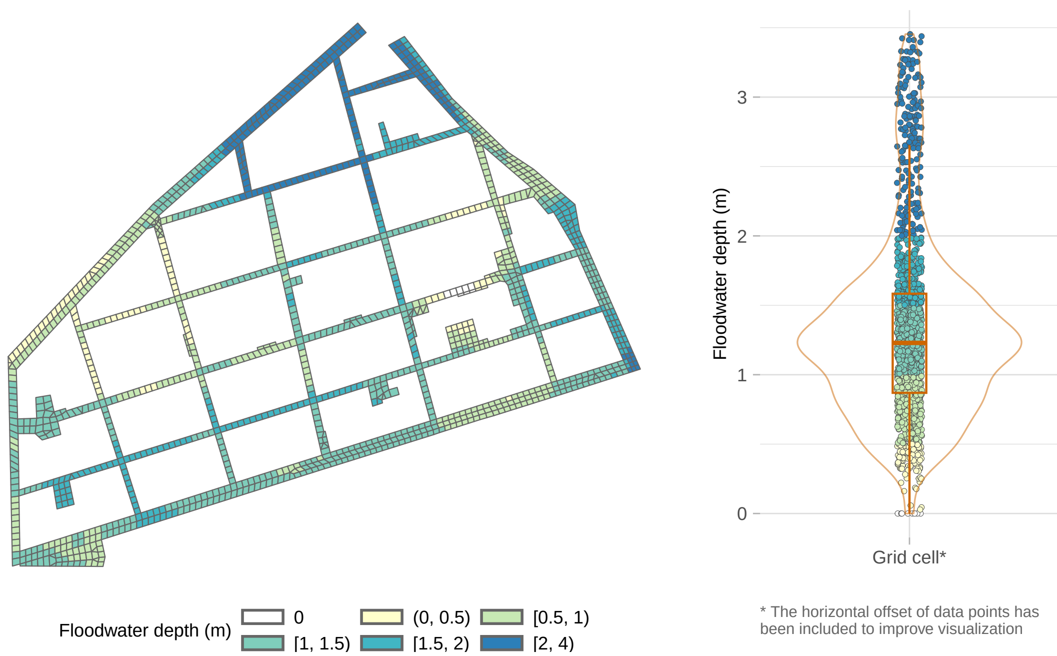

Figure 2: *Baseline* scenario. Simulated floodwater depth in the richelieu street mesh: geographical distribution (left) and density-boxplot graph (right)

2.1.2.2 Economic damage

The flood damage assessment is done using the official average national french damage function for dwellings [Rouchon et al., 2018] in short events (less than 48h). The function links floodwater depth with an estimation of material cost to properties per squared meter for flood durations inferior to 48 hours (figure 5). The function shows a direct relationship between the monetary value of the flood damage and the floodwater depth: as the floodwater depth increases, the monetary value of damage increases. However, the elasticity damage-depth is variable: in the intervals (0m-0.15m] and (2m-2.5m] the sensitivity of the monetary damage to changes in floodwater depth is more pronounced than in the intervals (0.15m-2m] and (2.5m-3m]. Furthermore, in the interval (0m-0.15m] the monetary damage is extremely sensitive to changes in floodwater depth.

[1] Paired samples t-test, t = 28.411, p-value < 2.2e-16
[2] F-test, F = 1.0393, p-value = 0.6874

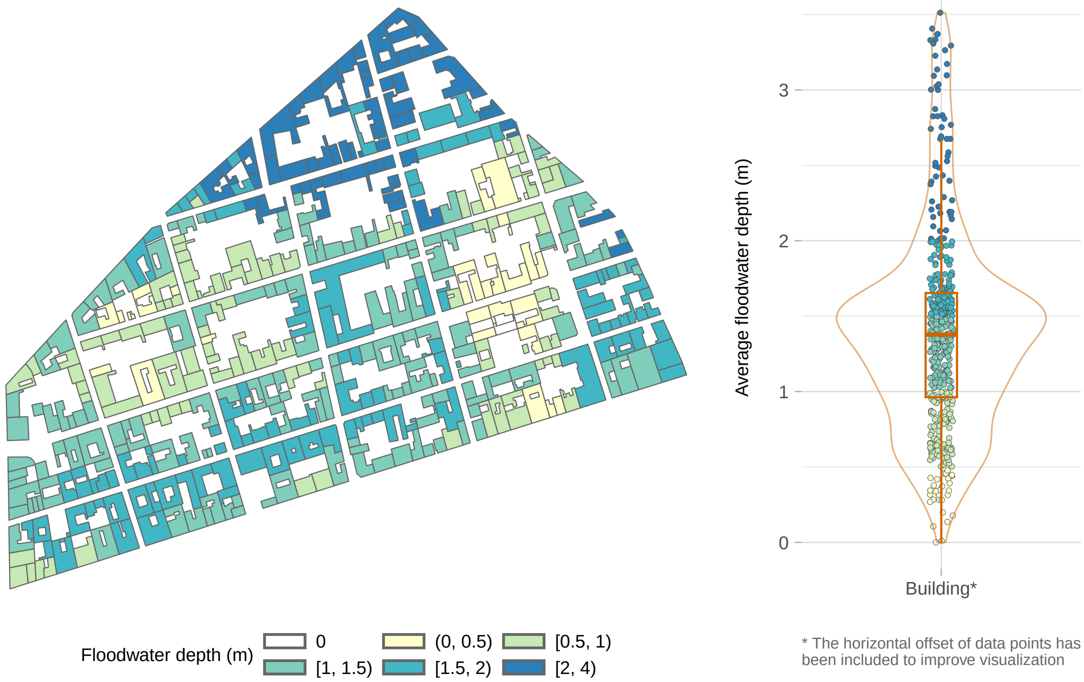

Figure 3: *Baseline* scenario. Floodwater depth associated to each building in the richelieu district: geographical distribution (left) and density-boxplot graph (right)

Table 2: Estimated monetary damage in the simulation perimeter using the simulated floodwater depths

	Baseline	Indoor
Aggregated monetary damage (Millions of EUR)	15.3	13.7
Average damage per squared meter (EUR/m^2)	309.0	277.0

Table 2 shows the monetary estimation of flood damage for the ensemble of the simulation perimeter, calculated according our two scenarios, *baseline* and *indoor*. The estimated flood damage in the *baseline* and in the *indoor* scenarios are 15.3 and 13.7 millions of euros, respectively. In other words, not considering street-building exchanges leads to a 10% overestimation of the damage caused by the flood event.

Figure 6-A and table 3 present a comparison of key measures for the monetary damage per squared meter estimated for the *baseline* and *indoor* scenarios. Both scenarios present the same range of monetary damage (between 0 and 439 euros/m^2), although the *indoor* scenario consistently present smaller estimations of monetary damage than the *baseline* scenario and somewhat more scattered.

Focusing on the difference between the two scenarios, we observe that both the difference of means[3] and the difference in the dispersion measures[4] are statistically significant. Figures 6-B and 6-C show the difference between scenarios by individual building. The *baseline* scenario overestimates the monetary damage in 86% of the buildings, underestimates the monetary damage in 4% of the buildings and remains the same as the *indoor* scenario in the other 10%. The interval [-50, 50] euros/m^2 groups 84% of the buildings. The spatial distribution of the differences, although not systematic, follows a similar pattern as the differences in floodwater depth.

[3] Paired samples t-test, t = -19.143, p-value < 2.2e-16
[4] F-test, F = 1.4564, p-value = 9.004e-05

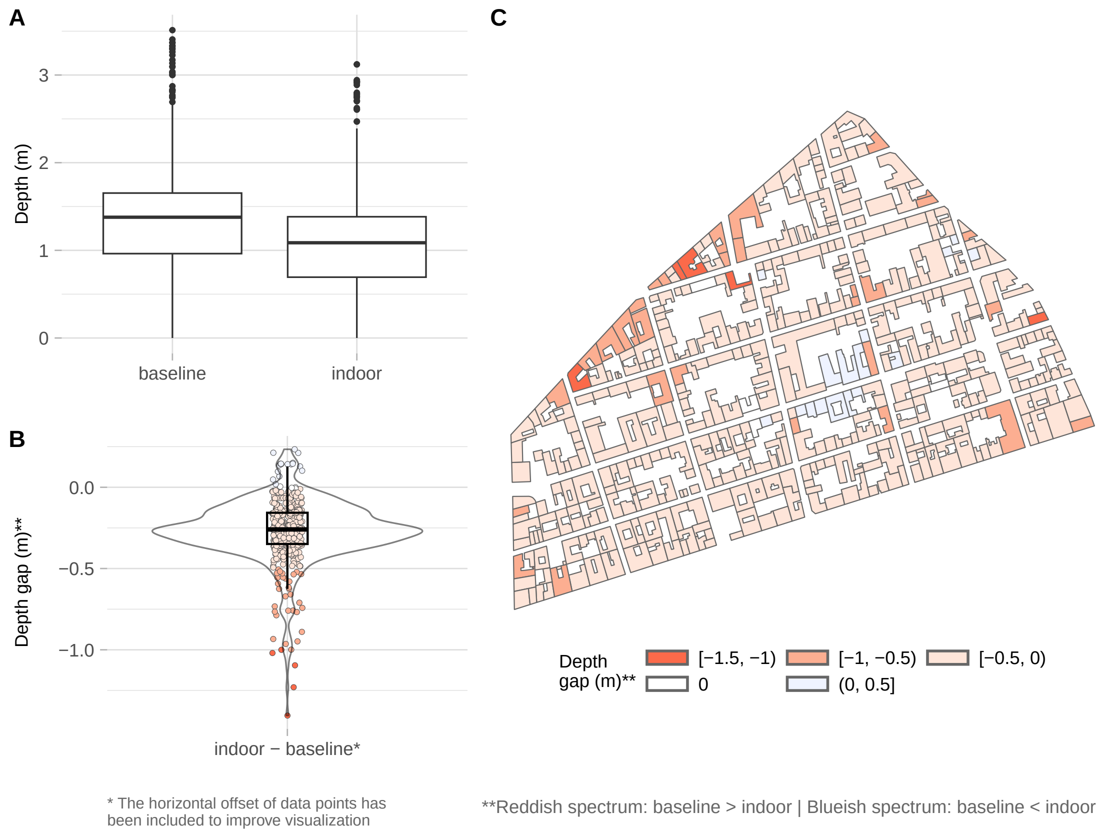

Figure 4: Differences in the estimated floodwater depth from the baseline scenario versus the indoor scenario: (A) comparison side by side of both scenarios; (B) density-boxplot of the differences between both scenarios; and (C) geographical distribution of the differences

2.1.2.3 Sensitivity analysis of economic damage

To determine the influence of the state of the openings we set two alternative scenarios:

1. The *indoor-cl* scenario, which includes the same elements as the *indoor* scenario but with closed openings although not waterproof (so water can still enter the building).
2. The *indoor-cds* scenario, which adds cofferdams to each opening that is considered a door in the *indoor-cl* scenario. The cofferdams are 1m high and are assumed to block the water from entering the building in the range [0m, 1m]

The results at the district level are shown in the table 4. As can be seen, the fact that the openings remain closed (in other words, the openings hold up throughout the whole flood event) reduces the estimated monetary damage and increases the difference with respect to the *baseline* scenario. The addition of cofferdams to all the doors in the district reduces the flow of water into the buildings, further reducing the estimated monetary damage.

Table 3: Main statistics of monetary damage. Units: EUR/m^2

	Minimum	1st quartile	Median	3rd quartile	Maximum	Mean	Standard dev.
baseline	0	283.04	320.27	339.19	439.61	307.81	66.13
indoor	0	229.44	292.35	320.27	439.60	277.64	79.81

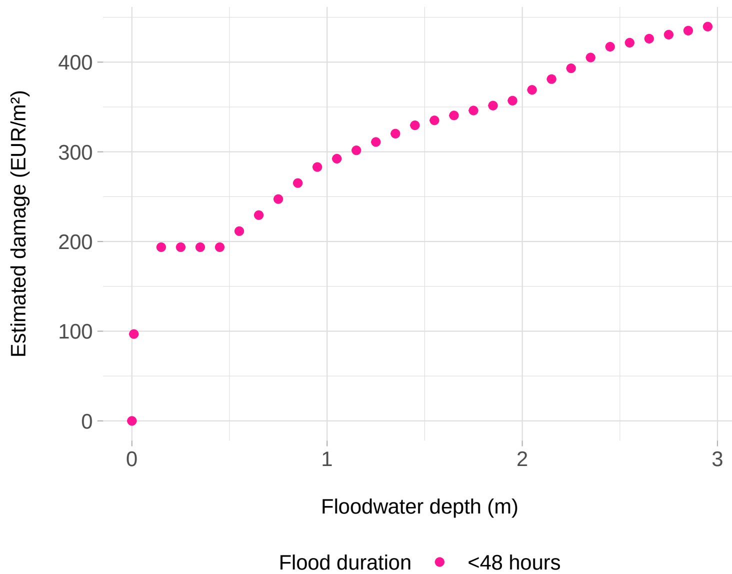

Figure 5: Official average national french damage function for dwellings in short events. Used for flood damage estimation in the field cases of the Richelieu district (Nîmes) and the banks of the Yzeron river (Oullins)

Table 4: Estimated monetary damage in the simulation perimeter using alternative opening scenarios

Simulation	Damage	Δ baseline (%)
baseline	15.3 M€	0
indoor (open openings)	13.7 M€	-10
indoor-cl (closed openings)	13 M€	-15
indoor-cds (closed openings + cofferdams)	9.3 M€	-39

Note, however, that the difference in the estimated monetary damage between the *indoor* (open openings) and the *indoor-cl* (closed openings) scenarios is small. A plausible explanation can be found in the duration of the flood event: since closed openings are not waterproof, the simulated 15-hour flood event appears to be long enough for the buildings to fill with water due to the infiltration rate of the closed openings. Indeed, installing cofferdams (*indoor-cds*), since they completely prevent water from entering the building in the range [0m, 1m], significantly reduces the estimated monetary damage.

Figure 6: Differences in the estimated damage per squared meter using the floodwater depth from the *baseline* scenario versus the *indoor* scenario: (A) comparison side by side of both scenarios; (B) density-boxplot of the differences between both scenarios; and (C) geographical distribution of the differences

2.2 Banks of the Yzeron river, Oullins

2.2.1 Experimental design

The experimental design considers two different flood return periods (i.e. magnitude of flood event): 50 years and 100 years. The simulation perimeter considers 609 buildings located in the banks of the Yzeron river on its way through the Oullins county (Lyon's Metropolis, France). The simulation perimeter is limited by two bridges: Pont Blanc and Pont d'Oullins. This extent corresponds to the Bussière district (around the Boulevard de l'Yzeron and Boulevard d'Emile Zola) and the Impasse des Célestins.

Buildings blueprints have been simplified. The presence of fences around houses has not been considered in the simulations included in this design plan. The estimated floor level of buildings can be higher, lower or at the same level of the street. For each flood return period, 2 different simulations have been considered:

- *baseline* considers neither fences nor building openings
- *indoor* considers building openings but not fences

When openings are considered, they are located as follows: doors, at floor level, and windows, 1 meter above the floor. They are assumed to have the following widths: doors, 1m, and windows, 1.5m. It is also assumed that they are completely open.

The number of openings per building varies from a minimum of one door and one window, to a maximum of three doors and eight windows. The number of openings and their location depends on the number of segments describing the geometry of the building. For instance, if a building is defined by 4 segments (e.g. rectangular building), there is a door on the 2nd segment and a window on the 4th segment (thus opposite to each other). Two openings will not be on the same segment.

2.2.2 Results

2.2.2.1 50-year flood event

The extent of a 50-year flood event over our simulation perimeter is shown in figure 7. The number of buildings impacted depends on the scenario: in the baseline scenario, the number of buildings impacted (i.e. floodwater depth strictly higher than zero) reaches 97 out 609 (~16%), whereas in the indoor scenario, the number of impacted buildings descends to 76 buildings out of 609 (13%).

Figure 7: Area covered by a 50-year flood event (blue) over the simulation perimeter

2.2.2.1.1 Floodwater depth

As in the case of Richelieu, applying the method described in section 2 of the deliverable D2d1, we can estimate the floodwater depth for each building in absence of street-building flow exchanges (*baseline* scenario). The results are shown in figure 8. The left side of the figure showcases the geographical distribution of floodwater depths attributed to the buildings in the perimeter, while the right side of the figure displays a combined density-boxplot graph, summarizing key statistical information.

As we have said, only the 16% of the buildings register floodwater depths higher than zero. Floodwater depths range from zero to 1.59m. Of those with a floodwater depth higher than zero, 75% are located in the range (0m, 0.8m] and up to 91% in the interval (0m, 1m).

Figure 9 displays the differences between the baseline and the indoor scenarios. As it can be appreciated, the large number of non-impacted buildings penalizes data visualization. Hereafter, all comparative figures will showcase only impacted buildings. The result is displayed in figure 10. The information in this figure is completed with table 5.

As we can see in figure 10-A and table 5, the *indoor* scenario is systematically lower than the *baseline* scenario. Furthermore, a few buildings that present floodwater depths values higher than zero in the *baseline* scenario present null floodwater depths in the *indoor* scenario.

Table 5: Comparison of main statistics of floodwater depths in buildings for both the baseline and the indoor scenarios in the 50-year return period flood event. Units: meters

	Minimum	1st quartile	Median	3rd quartile	Maximum	Mean	Standard dev.
baseline	0.12	0.31	0.6	0.80	1.6	0.60	0.34
indoor	0.00	0.10	0.4	0.69	1.6	0.44	0.38

When we look at the difference between both scenarios (figure 10-B), we observe that, in comparison with the *indoor* scenario, the *baseline* scenario overestimates the floodwater depth of around the 91% of the buildings considered. In contrast, the *baseline* scenario underestimates the floodwater depth in the remaining 8% of the buildings. The depth gap between the two scenarios concentrates in the interval [-0.5m, 0.1m] for the 90% of the buildings. As for the spatial distribution of those differences, figure 10-C shows that differences do not follow any particular pattern.

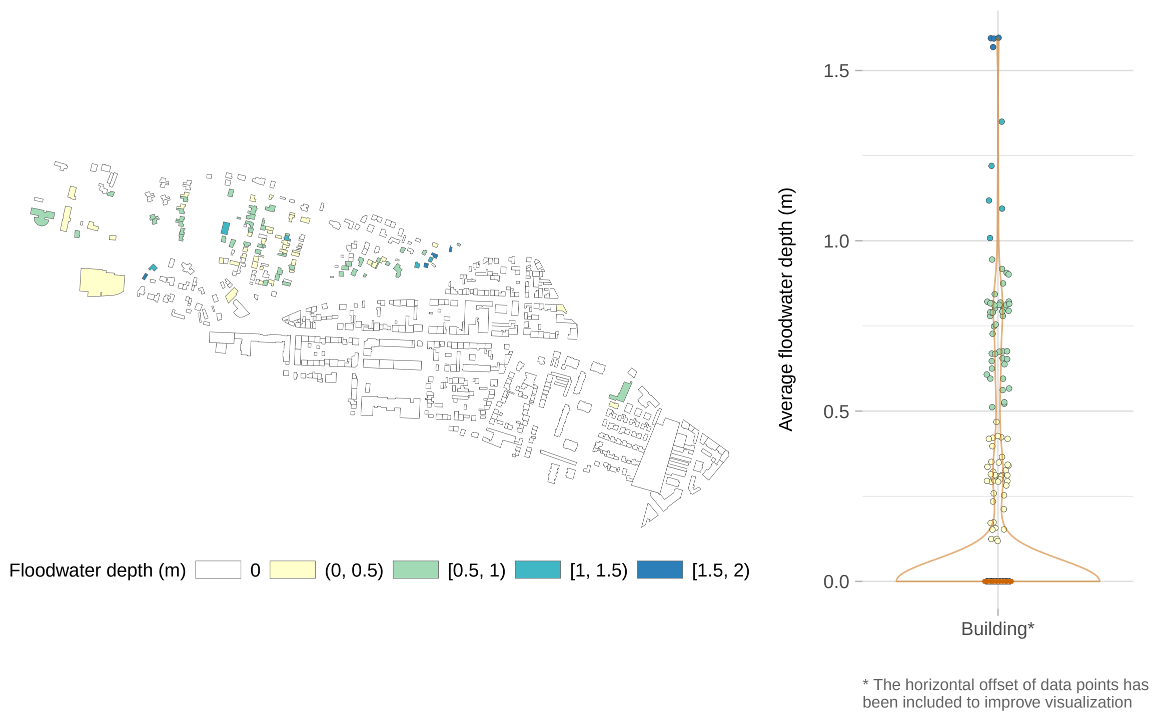

Figure 8: *Baseline* scenario. Floodwater depth associated to each building in the oullins perimetrer when neither fences nor exchanges street-building are considered in a 50-year return period flood event: geographical distribution (left) and density-boxplot graph(right)

2.2.2.1.2 Economic damage

As the case of the Richelieu district, the flood damage assessment in the Banks of the Yzeron river is done using the official average national french damage function for dwellings [Rouchon et al., 2018] in short events (see figure 5).

The monetary estimation of flood damage in the simulation perimeter is displayed in table 6 for both scenarios: *baseline* and *indoor*.
The estimated flood damage for each scenario is, respectively, 2.5 and 1.5 millions of euros; that is, the absence of openings overestimates flood damage by 41%

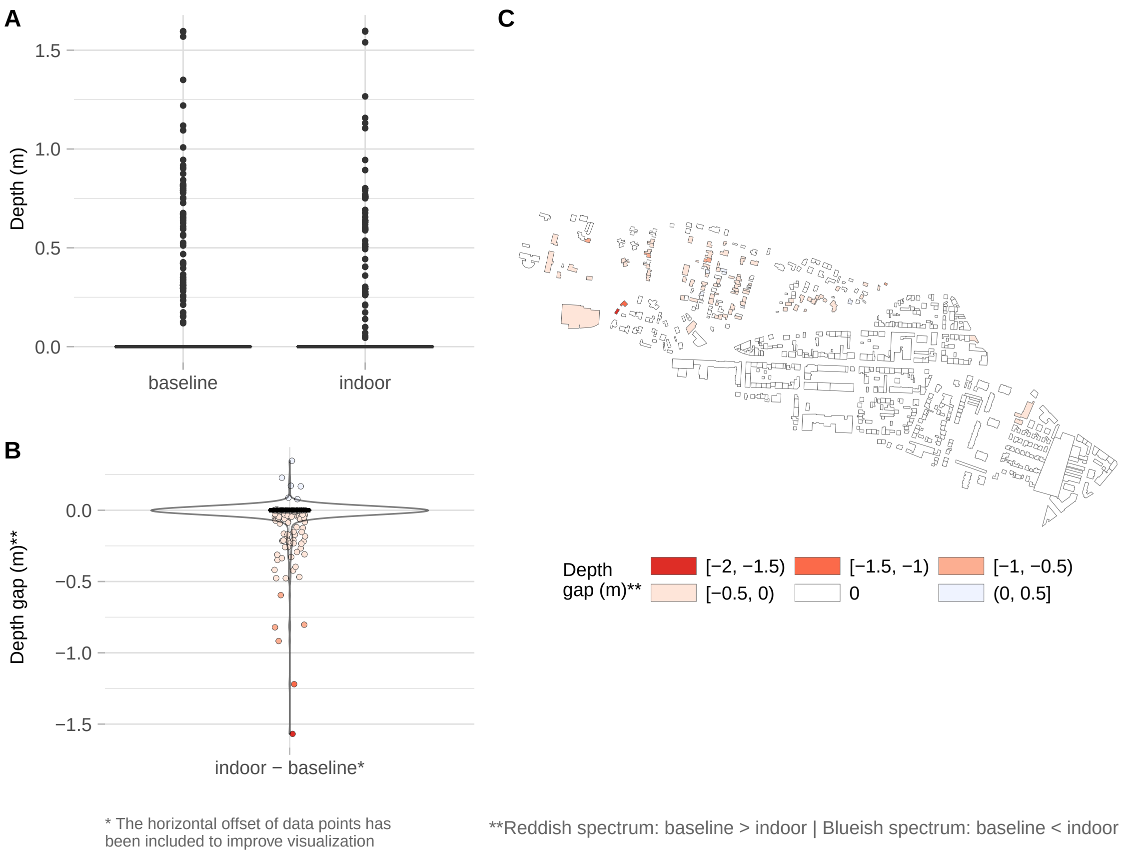

Figure 9: Differences in the estimated floodwater depth from the *baseline* scenario versus the *indoor* scenario in a 50-year return period flood event: (A) comparison side by side of both scenarios; (B) density-boxplot of the differences between both scenarios; and (C) geographical distribution of the differences

Figure 11-A and table 7 present a comparison of key measures for the monetary damage per squared meter estimated for the *baseline* and *indoor* scenarios. Both scenarios present the same range of monetary damage (between 0 and 335 euros/m^2), though the *indoor* scenario displays smaller estimations of monetary damage than the *baseline* scenario with higher dispersion of values (double).

Focusing on the difference between the two scenarios (figure 11-B), the *baseline* scenario overestimates the monetary damage in 45% of the buildings, underestimates the monetary damage in 2% of the buildings and remains the same than the *indoor* scenario in the remaining 53%. As for the magnitude of the gap, the interval [-100, 60] groups 80% of the buildings.

2.2.2.2 100-year flood event

The extent of a 100-year flood event over our simulation perimeter is shown in figure 12. As it also ocurred

Table 6: Estimated monetary damage in the simulation perimeter using the simulated floodwater depths in the 50-year return period flood event

	Baseline	Indoor
Aggregated monetary damage (Millions of EUR)	2.5	1.5
Average damage per squared meter (EUR/m^2)	212.8	125.5

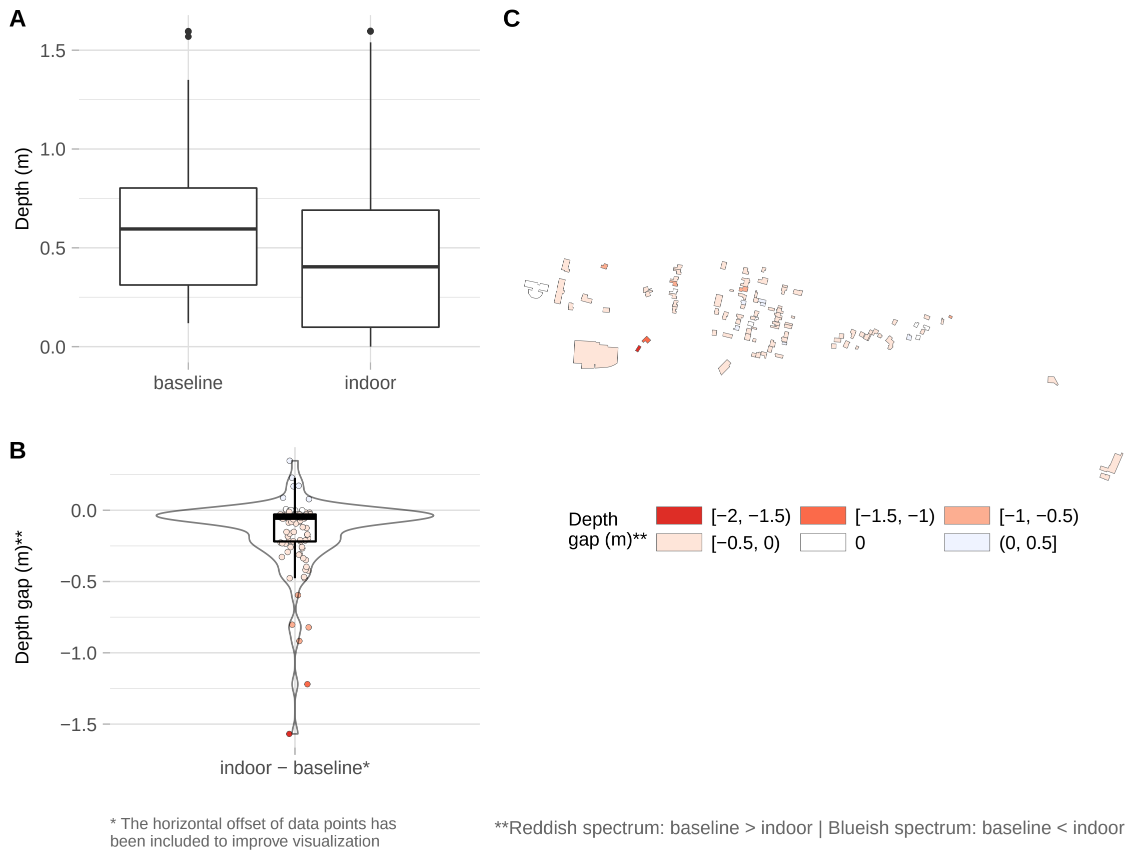

Figure 10: Differences in the estimated floodwater depth from the baseline scenario versus the indoor scenario in a 50-year return period flood event: (A) comparison side by side of both scenarios; (B) density-boxplot of the differences between both scenarios; and (C) geographical distribution of the differences

in the prior case, the number of buildings impacted depends on the simulation. In the baseline scenario, the number of buildings impacted reaches 228 out 609 (~37%), whereas in the indoor scenario the number of buildings affected is 195. In comparison with the 50-year flood event, the 100-year flood event more than doubles the amount of buildings that can be considered impacted by the flood.

2.2.2.2.1 Floodwater depth

The results of floodwater depth for the *baseline* scenario in the case of a 100-year return period flood event are shown in figure 13. As stated, the 37% of the buildings register floodwater depths higher than zero. Floodwater depths go up to 1.75m. 76% of buildings fall in the range [0, 0.4m] and 88% in the range [0m, 1m].

In figure 14 and table 8 we display the comparison of floodwater depth values for the *baseline* and the *indoor* scenarios. Again, both scenarios differ from one another, with the *indoor* scenario showing lower values than

Table 7: Main statistics of monetary damage for 50-year return period event. Units: EUR/m^2

	Minimum	1st quartile	Median	3rd quartile	Maximum	Mean	Standard dev.
baseline	96.85	193.70	211.57	247.30	335.08	221.89	43.75
indoor	0.00	96.85	193.70	229.43	335.07	167.34	98.93

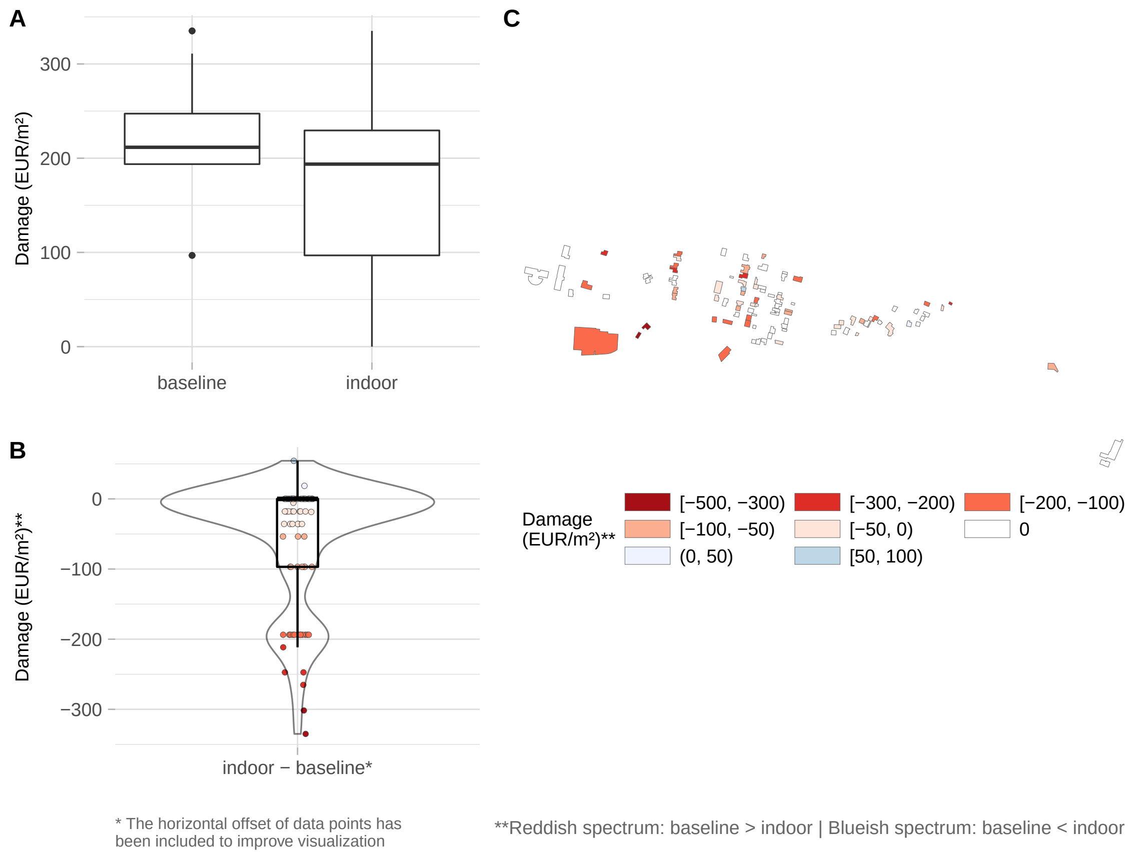

Figure 11: Differences in the monetary flood damage estimated from the baseline scenario versus the indoor scenario in a 50-year return period flood event: (A) comparison side by side of both scenarios; (B) density-boxplot of the differences between both scenarios; and (C) geographical distribution of the differences

the *baseline* scenario. In addition, as is the case for the 50-year return period flood, a number of buildings assumed to be inundated in the *base* scenario ("attributed water depth > 0") cannot be considered as such in the *indoor* scenario. They are still surrounded by floodwaters but the water does not enter the building in a significant way.

Comparing both scenarios, (figure 14-B) the *baseline* scenario overestimates the floodwater depth in around 79% of the buildings considered. On the other hand, the *baseline* scenario underestimates the floodwater depth for the remaining 21% of the buildings. The depth gap between the two scenarios is concentrated in the interval [-0.35m, 0.1m], with 86% of the cases. The spatial distribution of differences does not follow any particular pattern.

2.2.2.2.2 Economic damage

Table 8: Comparison of main statistics of floodwater depths in buildings for both the baseline and the indoor scenarios in the 100-year return period flood event. Units: meters

	Minimum	1st quartile	Median	3rd quartile	Maximum	Mean	Standard dev.
baseline	0.01	0.25	0.66	1.04	1.76	0.67	0.45
indoor	0.00	0.16	0.50	1.02	1.92	0.57	0.48

Figure 12: Area covered by a 100-year flood event (blue) over the simulation perimeter

Table 9: Estimated monetary damage in the simulation perimeter using the simulated floodwater depths in the 100-year return period flood event

	Baseline	Indoor
Aggregated monetary damage (Millions of EUR)	7	5.6
Average damage per squared meter (EUR/m^2)	234	188.1

The monetary estimation of flood damage for the *baseline* and *indoor* scenarios for the 100-year return period simulation is in table 9. The *baseline* scenario overestimates flood damage by 19.5% compared to the *indoor* scenario.

A comparison of key measures of the monetary damage per squared meter estimated for the scenarios *baseline* and *indoor* in case of a 100-year return period flood event is available at figures 15-A and table 10. Both scenarios present the same range of monetary damage (between 0 and around 350 euros/m^2) though. The *indoor* scenario presents higher dispersion of values and lower average and median than the *baseline* scenario.

Looking at the difference between the two scenarios (figure 15-B) for a 100-year return period flood event, the *baseline* scenario overestimates the monetary damage in 34% of the buildings; it remains the same for 60% of the buildings and underestimates the monetary damage in 5% of the buildings.

Table 10: Main statistics of monetary damage for 100-year return period event. Units: EUR/m^2

	Minimum	1st quartile	Median	3rd quartile	Maximum	Mean	Standard dev.
baseline	0	193.70	229.43	283.04	346.07	222.55	71.11
indoor	0	193.69	193.70	283.04	351.56	193.59	101.11

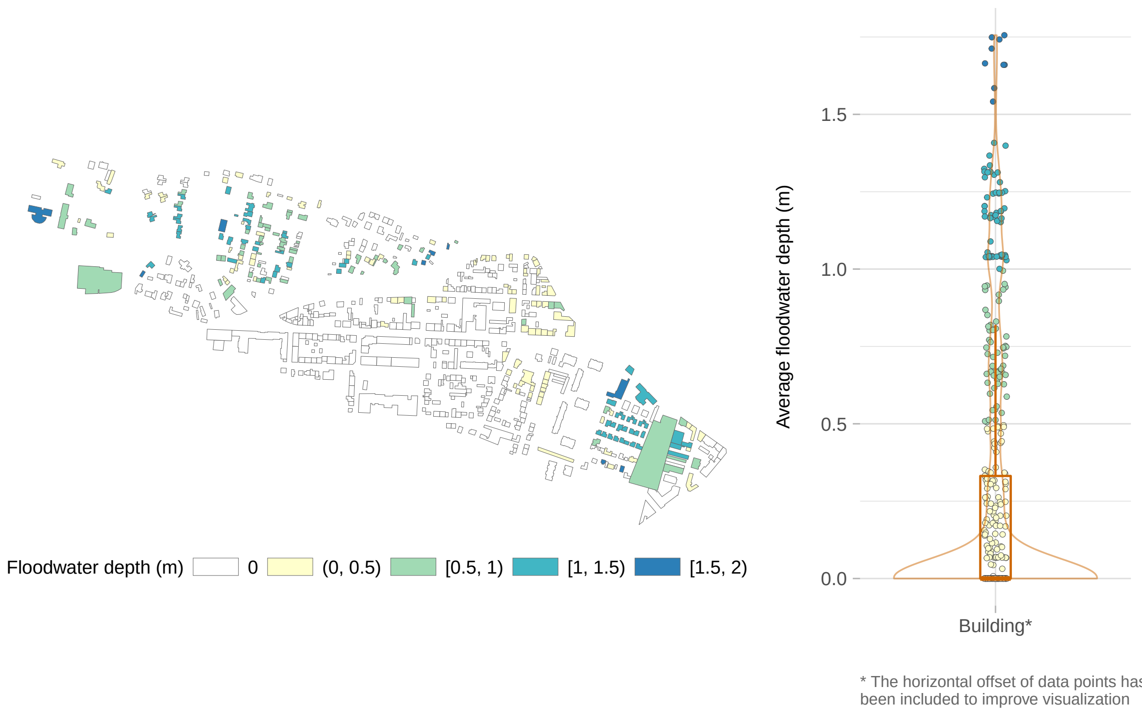

Figure 13: *Baseline* scnario. Floodwater depth associated to each building in the oullins perimetrer when neither fences nor exchanges street-building are considered in a 100-year return period flood event: geographical distribution (left) and density-boxplot graph(right)

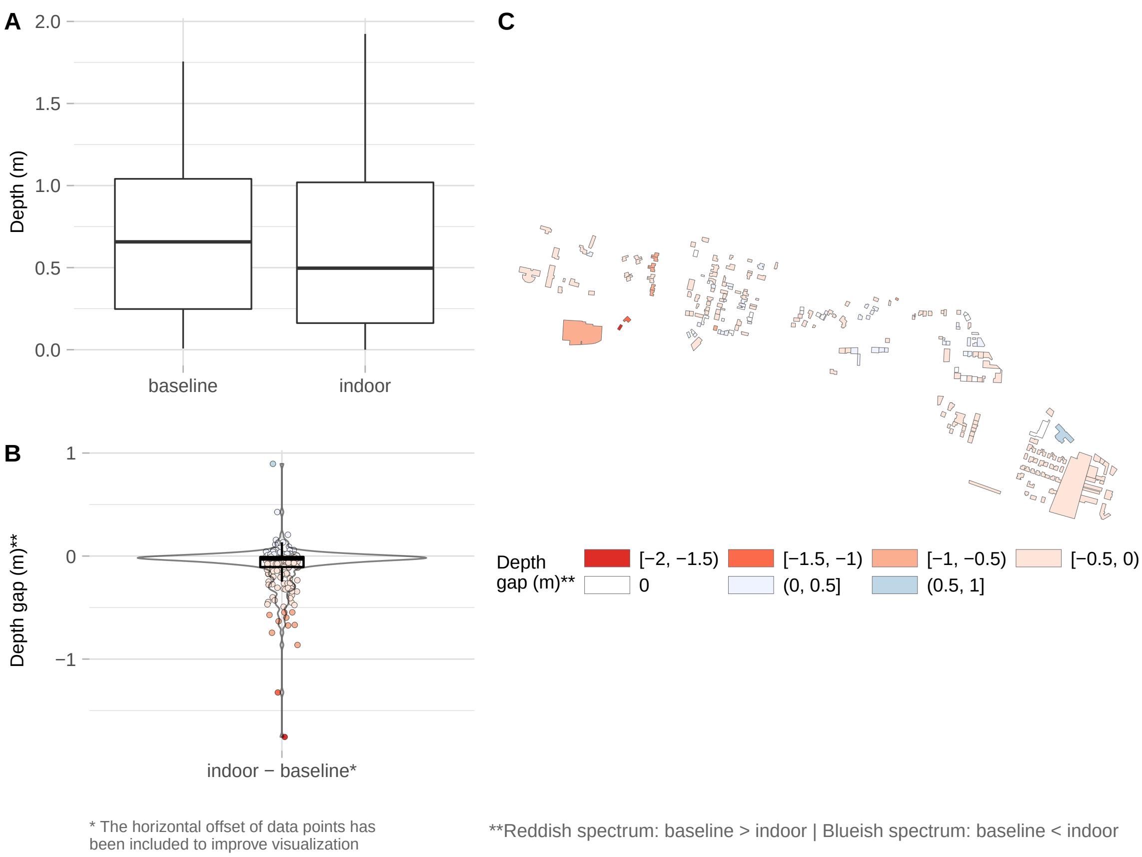

Figure 14: Differences in the estimated floodwater depth from the baseline scenario versus the indoor scenario in a 100-year return period flood event: (A) comparison side by side of both scenarios; (B) density-boxplot of the differences between both scenarios; and (C) geographical distribution of the differences

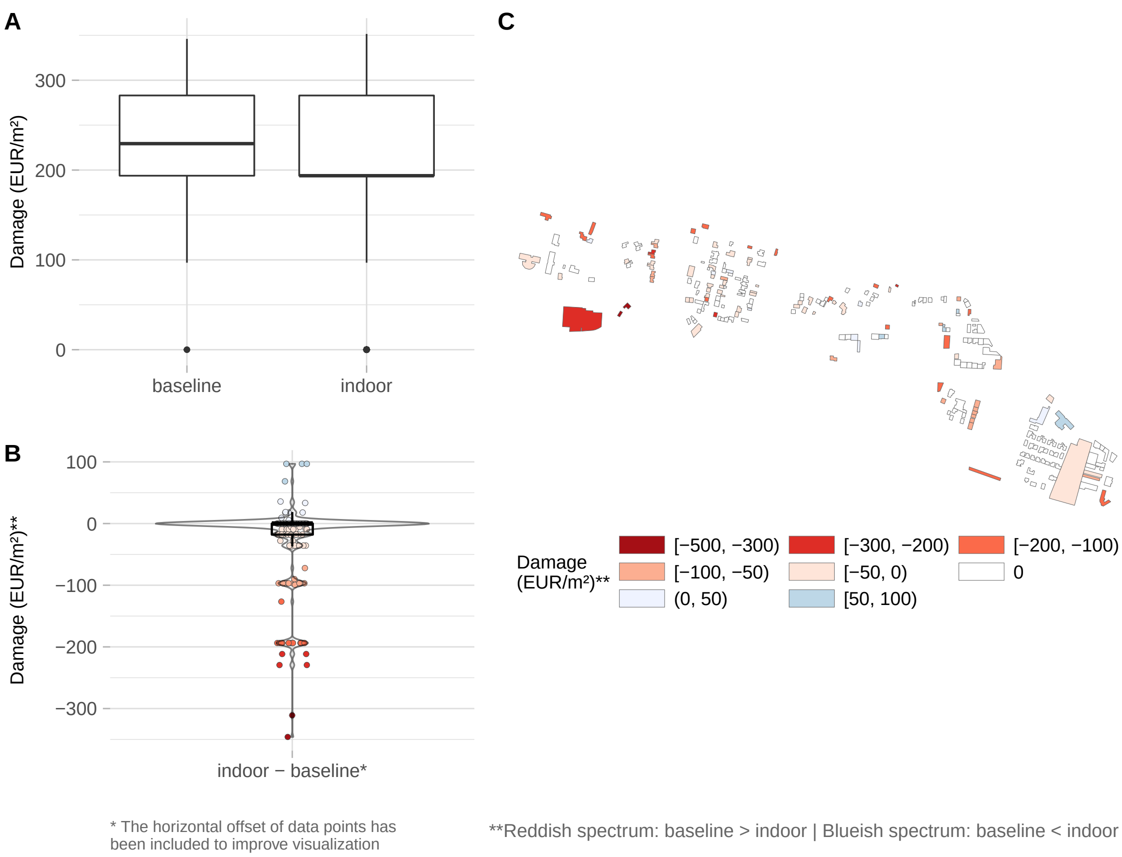

Figure 15: Differences in the monetary flood damage estimated from the baseline scenario versus the indoor scenario in a 100-year return period flood event: (A) comparison side by side of both scenarios; (B) density-boxplot of the differences between both scenarios; and (C) geographical distribution of the differences

3 *Building* level

3.1 Synthetic analysis of building

This section focuses on the fine-scale analysis of porous dwellings. It employs the methodology presented in the section 3 of the deliverable d2d1 to produce damage functions for the monetary assessment of flood damages that consider the hydraulic behavior of the building at high resolution levels. Specifically, we present a comparative study using two archetypical buildings to test the effect of changes in the opening state, building layout, flood exposure, flood duration and flood depth peak on the damage functions produced.

3.1.1 Experimental design

The experimental design for this comparative study focuses on three parameters. For each of them, we provide two alternative values (figure 16):

1. Building layout. We consider a so-called T-shaped and a l-shaped buildings.
2. Flood exposure. We consider that either the front facade is flooded or that the back facade is flooded.
3. Opening states: all openings fully open or all openings fully closed though not waterproof.

In addition, we simulate flood events whose duration ranges from 1h to 12h, with increments of 1h. Flood depth peaks outside the building range from 10cm to 3m, with increments of 10cm.

Flood duration and flood depth peak outside the building are provided through limnigraphs. In all cases, the limnigraph is symmetrical: the water takes as much to rise as it takes to decrease, i.e. in a 1h event, the water rises reaching the highest depth in half an hour; then it decreases until zero for the remaining half an hour. The model needs as many limnigraphs as openings exist in the building

T-shaped and l-shaped buildings are identical, except for their layout. Both have the same floor level (equal to the street level), surface and dimensions per room. Both use the same construction materials and type and number of openings. They also count on the same distribution of openings over their facades: 1 window on the back facade and 2 windows and a door on the front facade. Windows are located 0.9m above the street level while doors are located at the street level.

Therefore, when the back facade is exposed to floods, there is only one opening –a window– located 0.9m above the street level. Conversely, when the front facade is exposed, we find three openings –two windows located 0.9m above the street level and a door at the street level.

Fully open openings refer to real-life cases in which the the openings are either open or they brake due to the hydrostatic/hydrodynamic pressure, letting floodwater pass freely. Inversely, *fully closed* openings corresponds to the case in which the openings hold up throughout the duration of the flood event, but certain level of infiltration cannot be prevented.

The experimental design considers 2,880 simulations. Each simulation provides a estimation of monetary damage per 2-tuple of flood duration and floodwater depth peak outside the building. Combining these estimations we are able to build damage functions tat we can then compare to each other.

3.1.2 Results

To analyze the results obtained, we will use as reference the damage function obtained using a more standard approach, i.e. disregarding hydraulic behavior in the interior of the building and facades exposed. This damage function is represented using a grey dotted line in figures 17 to 19 and the black line in figure 20.

Since the T-shaped and the l-shaped buildings only differ in their layout, the damages functions of reference overlap. In other words, when the hydraulic behavior in the interior of the building is not considered, the T-shaped and l-shaped building would share the same damage function.

Damage functions obtained considering the hydraulic behavior in the interior of the building are represented with blue lines in the case of the T-shaped building and with pink lines for the l-shaped building.

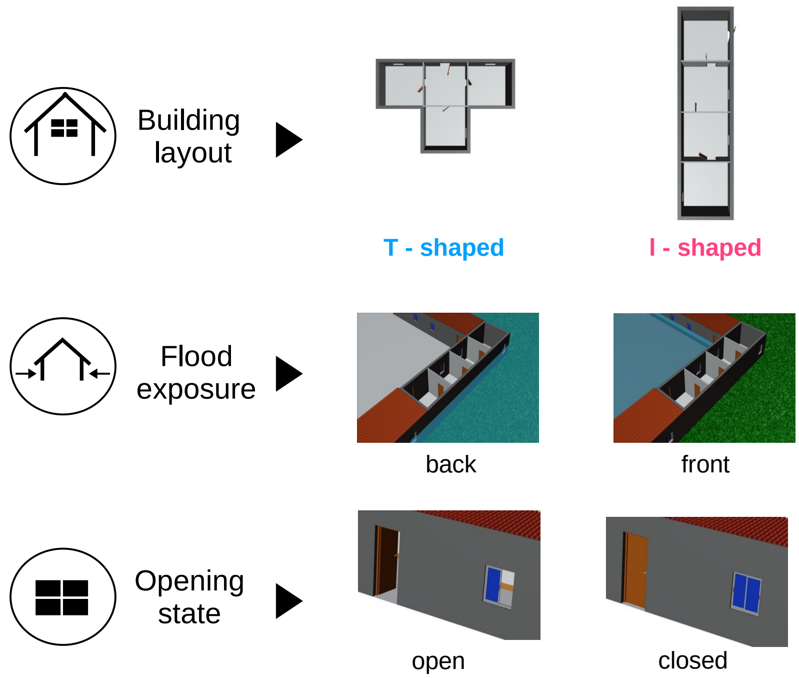

Figure 16: Main parameters and values tested in our experimental design

3.1.2.1 Influence of the layout of buildings and the exposure

The effect of the layout of the building and the exposure to floods is showcased in figure 17. The damage functions displayed for the T-shaped and l-shaped buildings correspond to the case of a 12 hours flood event whose peak depth varies between 0 and 3m, when openings are *fully open*

Comparing the left and right sides of the figure 17, we can appreciate how the facade exposed plays a role in the level of damages. The front facade (right) not only has a higher number of openings than the back facade. It also has an opening located at street level, which enables floodwaters to penetrate inside the building from the very beginning of the flood. Consequently, flood damage affects both the exterior and the interior of the building When the back facade is exposed, water cannot penetrate the building below 0.9m. Thus up until that threshold, the damage corresponds to the damage to the exterior wall. Once the threshold is trespassed, the damage increases exponentially as the water gets inside the building.

These results indicate that the number and nature of openings over a facade do influence the damage suffered by the building.

Contrarily, the damage functions of both the T-shaped building and l-shaped building practically overlap, pointing to a negligible influence of the building layout in the hydraulic behavior of the building, thus in the estimation of damages.

3.1.2.2 Influence of the opening state and the duration of the event

Figure 18 builds over figure 17 and showcases the effect of a change in the state of the openings. The top of the figure corresponds to the case in which openings are considered *fully open*, whereas the bottom of the figure displays the *fully closed* case. As in figure 17, the right side of the figure corresponds to the front facade exposed, and the left side of the figure to the bak facade.

As it can be observed in the figure, the state of the openings do influence the level of damage for a given flood event. When openings remain closed during the flood event, the amount of damage registered in the building is somewhat smaller than in the case of *fully open* openings.

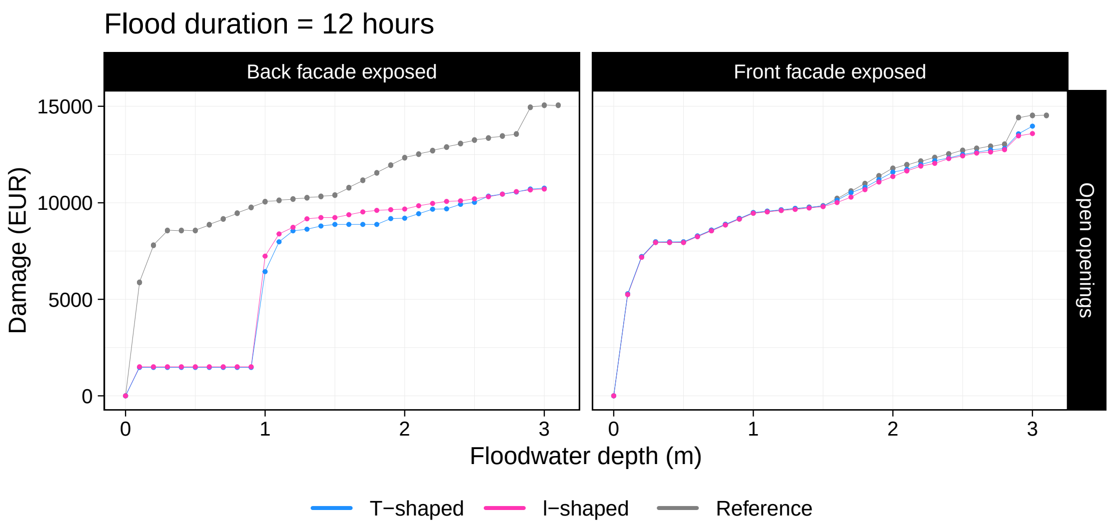

Figure 17: Comparison of damage functions for the l- and t-shaped buildings, when either the front or the back facades are exposed and openings are fully open. Flood duration: 12 hours

If we compare the 12 hours event with a 1 hour event, as in figure 19, we can appreciate that, when openings hold up closed during the whole flood event, shorter events imply smaller flood damage for a given floodwater depth. Contrarily, if windows and doors do not holp up –*fully open scenario*–, flood duration becomes irrelevant.

In consequence, the relevancy of the duration of the flood event in the determination of damage functions considering the interior hydraulic behavior is subject to the state of the openings along the duration of the event. When windows and doors do hold up, the observable differences between the damage function of reference and the damage functions produced come explained by the effet caused by the number and nature of openings over the facade, and the duration of the flood event. If windows and doors do not hold up, the observable differences with the damage function of reference are due to the number and nature of openings over the facade.

Since flood duration is relevant for the determination of damage functions when openings hold up closed, we are interested in comparing the different flood durations simulated. This comparison is displayed in figure 20.

As we can see, there is a high variability of damage level for a given floodwater depth depending on the duration of the flood event. The shorter the flood event is, the bigger the difference between the reference function and the function considering hydraulic behavior.

Furthermore, if the facades exposed to the flood do not have doors (hence the water needs to trespass certain depth threshold before being able to infiltrate the building), the difference between the damage function of reference and the damage function with hydraulic behavior increases significantly.

3.1.2.3 Concluding remarks

According to our results, considering openings has implications for the use of generic functions for short duration events. When openings remain close throughout the flood event, the damage functions of reference (standard practice) overestimate the damage. the magnitude of the overestimation depends on whether there are opening at street level (a door) on the façade exposed to the floods, and on the duration of the flood.

When openings do not hold up, observable differences between damage functions of reference and damage functions considering hydraulic behavior come explained by the number and nature of openings over the facade. If openings are numerous and include, at least, one opening at street level, all damage curves overlap regardless of flood duration or building layout. Thus the level of damage could be estimated using the damage

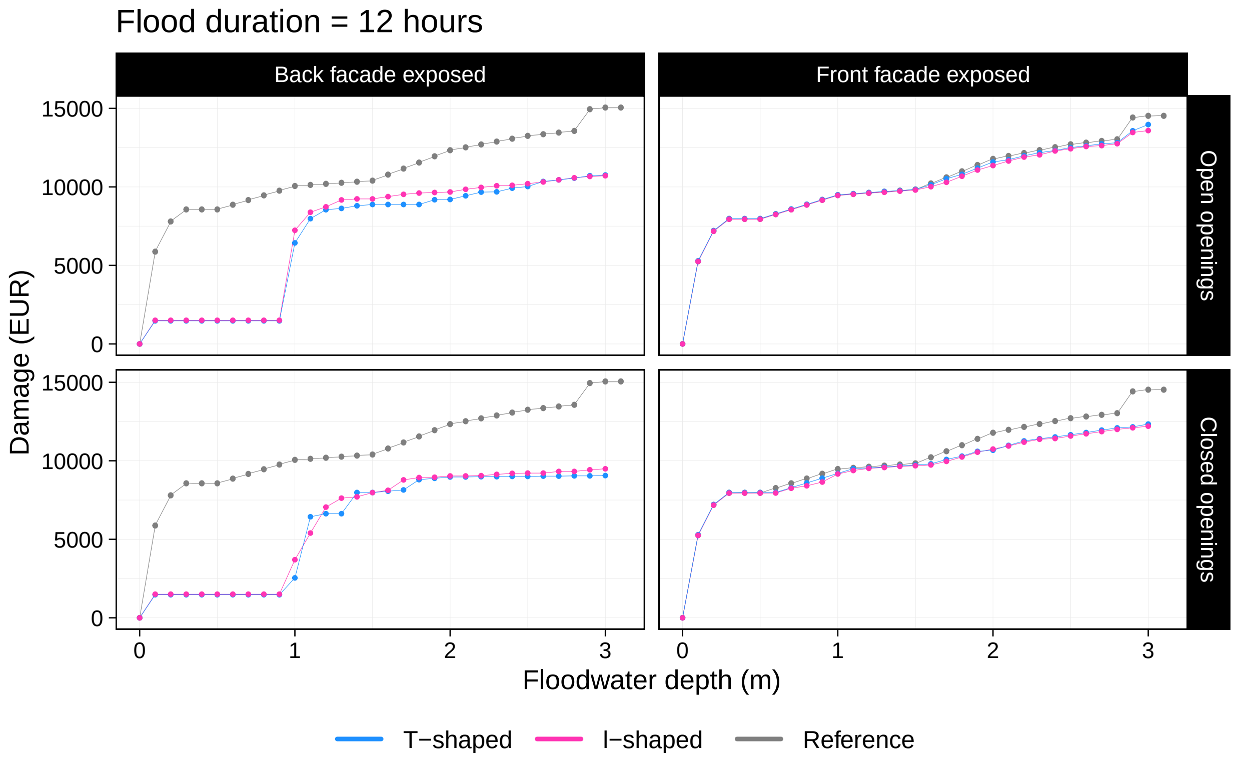

Figure 18: Comparison of damage functions for the l- and t-shaped buildings, when either the front or the back facades are exposed and openings are either fully open or closed. Flood duration: 12 hours

functions of reference without significant biases. If the number of openings is reduced and they are above the street level, all damage curves considering the hydraulic behavior of the building overlap, but they do not overlap with the function of reference. Hence, to use the latter to estimate the flood damage endured by the building would provoke a significant bias in the monetary estimation.

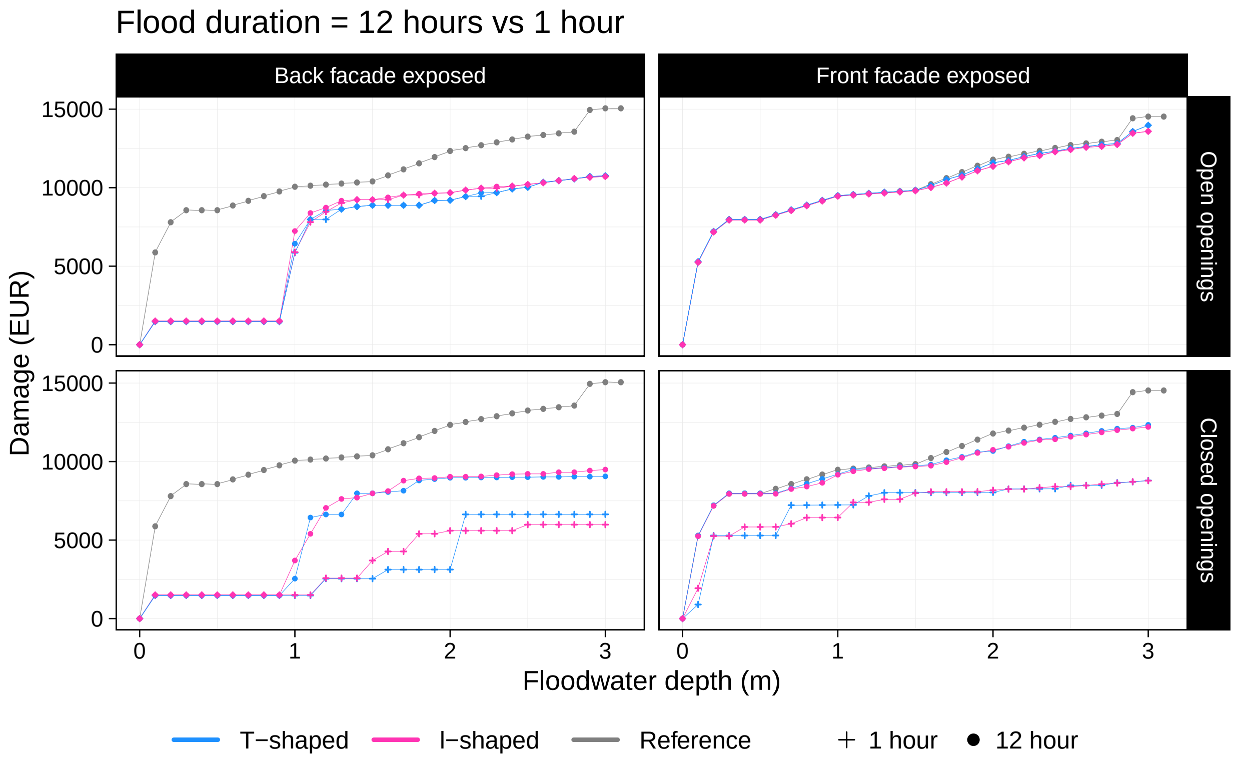

Figure 19: Comparison of damage functions for the l- and t-shaped buildings, when either the front or the back facades are exposed and openings are either fully open or closed. Flood duration: 12 hours vs. 1 hour

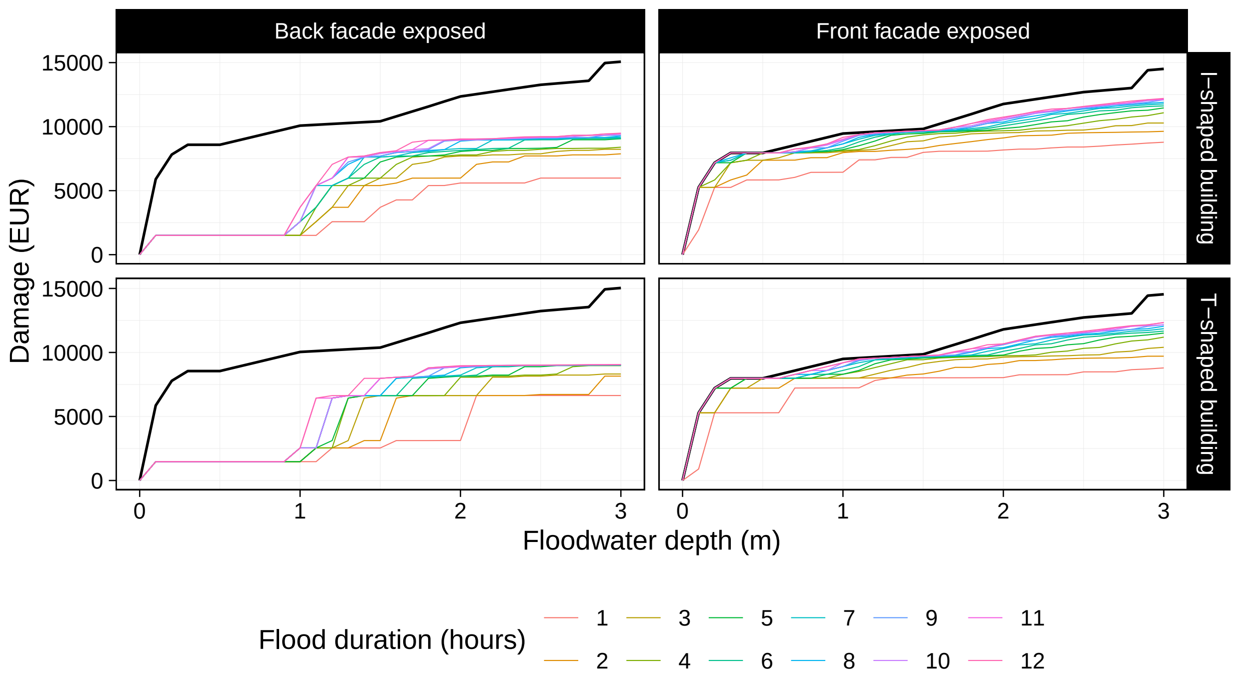

Figure 20: Comparison of damage functions for the l- and t-shaped buildings, when either the front or the back facades are exposed and openings are fully closed. Flood duration: 1 hour to 12 hours with increments of 1 hour

4 Conclusions

The analyses conducted at district level in Nîmes and Oullins reveal that there exist significant differences between scenarios with nonporous (*baseline*) and porous (*indoor**[5]) buildings. The number of buildings presenting differences between the *baseline* and the *indoor** scenarios in terms of floodwater depth, flood damage or both is noteworthy. For instance, in the Richelieu district, 95% of the buildings present differences in floodwater depth between the *baseline* and the *indoor* scenario. In the case of the estimated monetary damage, 90% of the buildings differ from one scenario to another.

Thus, not considering street-building exchanges through openings lead to the overestimation of flood damage at the district level. However, the magnitude of this overestimation seems to depend on the case study : in the case of the Yzeron river, the magnitude of the overestimation varies from 40% to 20% depending on the return period of the flood, while in the case of the Richelieu district, the magnitude of the overestimation is 12%.

The results obtained at district level are coherent with the type of *indoor* scenario simulated. When considered, openings are set as fully open, thus water does not found any obstacle to fill the building. In these conditions minimal differences between the *baseline* scenario and the *indoor* scenario are to be expected.

As the more in-depth analyses conducted at building level reveal, significant differences in the level of damage exist when openings are close though not waterproof. The results obtained show that, at a building level, flood duration becomes a relevant parameter when combined with openings (closed) and the hydraulic behavior of the water flows inside the building layout.

These results also show that there exist implications for the use of data from post-event field surveys when floodwater depth measurements come either from the exterior of buildings or from one unique measure in the interior of the building. Same conclusion applies to standard post-event hydrologic simulations.

Adapting the model district models to consider alternative opening states, as well as carrying out complementary analyses at both building and district levels, is part of the ongoing and future research works. Furthermore, the influence of the hydraulic behavior inside buildings could be considered not only in the estimation of monetary damages but also in terms of dangerousness of the building for its inhabitants.

[5] *indoor** refers to all the alternative *indoor* scenarios presented: *indoor*, *indoor-cl* and *indoor-cds*

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