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Visualization of Object-Centered Vulnerability to Possible Flood Hazards

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Figure 1: *Understanding the uncertain vulnerability of a selected building to a multitude of flood scenarios. (Left) Vulnerability to floodwall overtopping events, displayed on a water gauge. (Middle) Vulnerability to floodwall breaches, shown along the protection wall. (Right) Adverse impact on the selected building, including cellar flooding. The probability of water reaching a particular level varies around the building and is mapped onto the facades.*

Abstract

As flood events tend to happen more frequently, there is a growing demand for understanding the vulnerability of infrastructure to flood-related hazards. Such demand exists both for flood management personnel and the general public. Modern software tools are capable of generating uncertainty-aware flood predictions. However, the information addressing individual objects is incomplete, scattered, and hard to extract. In this paper, we address vulnerability to flood-related hazards focusing on a specific building. Our approach is based on the automatic extraction of relevant information from a large collection of pre-simulated flooding events, called a scenario pool. From this pool, we generate uncertainty-aware visualizations conveying the vulnerability of the building of interest to different kinds of flooding events. On the one hand, we display the adverse effects of the disaster on a detailed level, ranging from damage inflicted on the building facades or cellars to the accessibility of the important infrastructure in the vicinity. On the other hand, we provide visual indications of the events to which the building of interest is vulnerable in particular. Our visual encodings are displayed in the context of urban 3D renderings to establish an intuitive relation between geospatial and abstract information. We combine all the visualizations in a lightweight interface that enables the user to study the impacts and vulnerabilities of interest and explore the scenarios of choice. We evaluate our solution with experts involved in flood management and public communication.

1. Introduction

Recent climate studies suggest that natural disasters such as floods are likely to happen more often in the future. Measures are taken to make population and infrastructure less vulnerable to these threats. Information technologies are becoming increasingly important for such tasks. For example, computer simulations are widely used for modeling possible catastrophic scenarios and testing various protection options or long-term adaptation strategies. Modern software systems for disaster management produce a vast amount of heterogeneous data addressing multiple aspects of the hazard and its impact on the domain of interest. Visual analytics approaches and tools come to the human's aid mitigating this data complexity. However, it is still a challenging and tedious task even for a technically-skilled domain expert to extract the information relevant for particular objects. Flood managers may need such information to understand the vulnerability of some important infrastructure, e.g., a hospital, to possible flood hazards. On the other hand, for individuals of the general public, the vulnerability of their personal "habitat" may be of interest. This can be the safety of their homes, the ability of their children to attend school, or the accessibility of a hospital or their favorite grocery store.

Even having an integrated decision support tool at hand, a flood manager would need to spend many hours on isolating the required information from the whole lot of data output by the tool. To our knowledge, no solution exists that performs such information extraction, nor do the available tools support the subsequent integration of such information into a convenient representation. For non-expert users, the situation is even more complicated. Unfortunately, the information relevant to them is usually scattered among multiple heterogeneous sources and/or incomplete. Currently, a person would first need to study flood-related brochures, then visit a dedicated web page to consult flood risk maps [hwk]. Such maps are available for river flooding only and offer data for a very coarse sampling of water levels. After finding the relevant buildings and learning which range of water levels might affect them, the person would possibly need to spend even more time checking online maps and routing services for connections and trying to bring all the aspects together in the mind. Yet he or she would not be able to learn any further details about the expected impact on the building of interest, e.g., the exposure of particular facades to the flood water (see Figure 1, right). Moreover, no publicly available services consider heavy rains, sewer overflows, or levee breaches, and convey the uncertainty behind the conclusions drawn.

In this paper, we present a software tool for assessing and visualizing flood-related vulnerability and impacts focusing on a particular object. We call these *object-centered vulnerability* and *object-centered impacts*, respectively. Our approach is based on pre-computing a large pool of possible incident scenarios with ensemble simulations. Using the data from the pool, we, on the one hand, generate uncertainty-aware visualizations conveying the vulnerability of the object of interest to possible flood hazards. We combine 2D visualizations with 3D renderings to display the vulnerability over the incident space. From these, the user can understand, e.g., what water levels affect the building of interest (see Figure 1, left) or which breach locations are particularly dangerous for it (see Figure 1, center). On the other hand, we create object-centered visualizations of aggregated impact using familiar visual metaphors. With the presented approach, instead of manually exploring thousands of flooding scenarios, the user just picks an address and studies the visualizations automatically created by the system.

The presented tool targets two major user groups, namely flood management experts and the general public. For experts, it is important to fully understand the risks of possible incidents to mitigate them by countermeasures. They need to interactively explore the different scenarios and identify vulnerable regions with the inherent uncertainty. Non-experts often have no deep knowledge of flood management and just want clear and simple answers to whether their home and belongings could be in danger. Thus, the two user models in our solution differ in the level of detail employed when presenting the uncertainty.

In summary, this paper contributes the following:

- Automatic extraction of object-centered impact and vulnerability from a large pool of pre-simulated scenarios
- Uncertainty-aware visualizations of fine-grained impacts on a building and the accessibility of important infrastructure with respect to it
- Visualizations of uncertain vulnerability to flood-related hazards, mapped onto the geospatial representation of hazard parameters
- Selection of scenarios by means of direct interaction with the presented visualizations, avoiding the need for abstract navigation tools

2. Related Work

Simulations, where a process development is modeled over time, have long been a standard tool for studying real-world phenomena [COJT*11]. However, such modeling is plagued with uncertainty originating from imperfect initial conditions, model incompleteness, or intrinsic stochasticity of the modeled processes [ODR*02]. One way to handle such uncertainty is to use simulation ensembles. In these, multiple simulations are conducted using slightly different initial conditions or even different models [PSH*05]. For example, Booshehrian et al. [BMPM12] utilize ensemble simulations to support decision makers in fisheries management.

One of the largest applications for ensemble simulations is in climate modeling and weather predictions [GR05, Col07, SSB*09]. Tailor and Buizza [TB03] use weather ensemble predictions to forecast electricity demand. Cloke and Pappenberger [CP09] review the trends and challenges in flood forecasting. Blöschl et al. [BRK08] present a model for flash flood prediction. Demeritt et al. [DNCP10] discuss the issues of communication and use of ensemble flood forecasts.

Ribičić et al. [RWF*13] simulate ensembles of flooding scenarios for protection planning in urban areas. Waser et al. [WKS*14] provide an extension of this approach to multiple ensemble dimensions to create response plans. VASA [KZX*14] is a tool for interactive computational steering that combines multiple simulations in a single

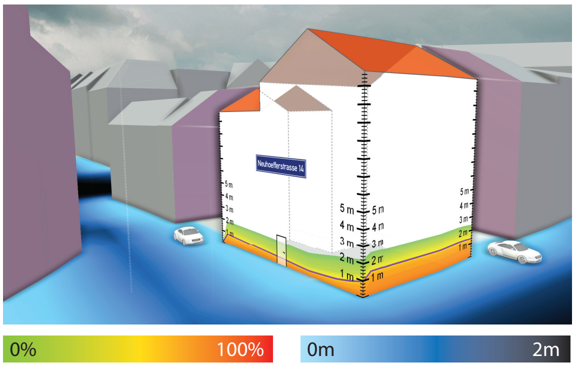

Figure 2: *Impact visualization with facade area plots. The color indicates the probability of that particular part of the facade to be exposed to the water.*

pipeline. Further works on disaster management include the FLIWAS [GWL07] flood information and management system and the SECOM [Sec] serious game. To our knowledge, no system computes and visualizes natural catastrophe-related data focused on a particular object or set of objects.

Creating visualizations of flood-related data suitable for a wider audience requires a careful selection of techniques. In this regard, dedicated online resources and brochures can be of interest [ste]. A cutaway technique can be used to indicate indoor flooding [lun]. Current evacuation status, evacuation zones and accessible shelters can be conveniently shown together in an online application [pin]. In visualization literature, Maas and Döllner present object-integrated annotations and labels [MD06,MD08]. Lorenz and Döllner [LD10] provide techniques to map surface property data on 3D objects. Cutaway techniques are described for geological modeling [LHV13], medical data [VKG04], or generic polygonal scenes [BF08]. A proper indication of uncertainty is required for the derived data [BOL12]. MacEachren et al. [MRH*05] review the uncertainty visualization agenda for geospatial data. Mirzargar et al. [MWK14] suggest a method for summarizing ensembles of 2D and 3D curves. Correll and Gleicher [CG14] vote for a cautious use of error bars for the 2D-visualization of uncertain data and suggest different approaches, including gradient-based ones.

3. Scenario Pool and Uncertainty Treatment

In this work, we focus on visualizing object-centered impacts and vulnerability with respect to flood-related hazards. We call an *impact* the damage inflicted by the flood water upon the buildings of interest, or the inaccessibility of important locations, e.g., hospitals or schools, due to inundation. By *vulnerability* we mean the degree of being exposed to flood-related hazards.

The cornerstone of the approach is the so-called scenario pool. This is essentially a large database of pre-simulated flooding scenarios [WKS*14], which we created by using a shallow water 2D flood simulation engine [HWPa*14]. In our case study, the pool maintained scenarios for four basic types of flood-related incidents in Cologne, Germany. These are floodwall breaches (dam breaks), sewer overflows, heavy rains, and floodwall overtoppings (water spilling over the wall). For each incident type, we varied some of its fundamental characteristics, thus obtaining four multidimensional ensembles of flooding events. For breach events, we simulated 30 possible breach positions and 5 possible breach widths against 4 different water levels and 4 breach event durations. For floodwall overtoppings, we picked 10 possible water levels and 10 overtopping durations. Regarding heavy rains, 10 different precipitation rates were simulated for 10 possible event durations. Finally, 15 alternative locations were picked to model sewer overflow events of 5 possible durations. Summing all up, the scenario pool created for this paper contained 2675 different flooding scenarios.

The ensemble dimensions listed above can be divided into two groups. The dimensions of the first group (breach positions, overtopping water levels, precipitation rates, sewer locations) are used to visually map object-centered vulnerability. For example, in our visualizations, the vulnerability to a breach occurring at a particular position is shown exactly at that position along the actual floodwall (see Figure 1, middle). The other ensemble dimensions (second group) are used to treat uncertainty. For instance, for sewer overflows, modeling multiple overflow durations per sewer position increases the fidelity of the computed (uncertain) vulnerability. In addition, some of the dimensions of the second group are used to give more details on the presented vulnerability (e.g., breach widths in Figure 1, middle).

Our tool provides the user with several basic exploration options. First, the user can select the incident type to be considered. From the scenario pool perspective, this means switching between the available multidimensional ensembles. Second, the user can select what he or she wants to see in the auto-generated visualizations. The two alternatives are vulnerability and impact. For each of them the user has to further specify what exactly he or she is interested in, e.g., vulnerability with respect to the inaccessibility of hospitals. This defines what kind of information has to be extracted from the ensemble of interest and how exactly this information has to be presented. Finally, the user can pick any scenario for manual exploration. This can be done directly from the generated visualizations. For further details on the user interface we refer to the accompanying video.

4. Object-centered Impacts

To visualize the impact of flood-related hazards on a building of interest, we map the water levels aggregated over all relevant scenarios onto the building in the 3D city model. More specifically, we accumulate the facade areas exposed to the

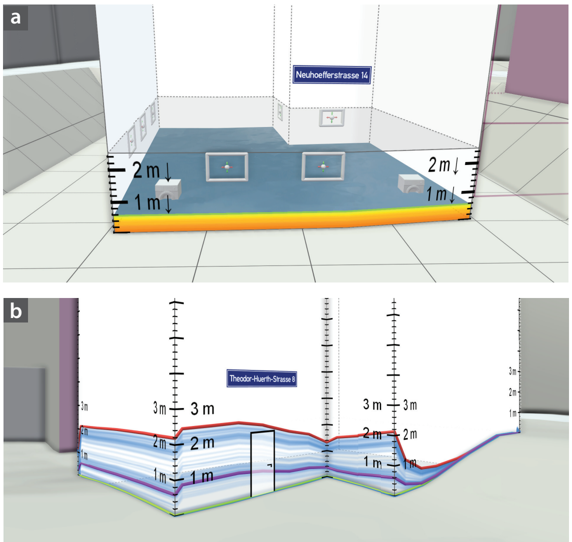

Figure 3: *Internal and external flooding impact. (a) Estimated cellar flooding through user-sketched windows. Water levels are visualized with a facade area plot. (b) Facade line plot showing the water level probabilities for the external flooding.*

water in each scenario in a density plot. The density then indicates the probability distribution for such an exposure. After applying a color transfer function, the resulting plots are displayed on the corresponding facades of the building of interest. We call them facade area plots. Example screenshots are shown in Figure 1, right and Figure 2. This continuous visualization along the facades of the building allows for an easy perception of the detailed possible damages and conveys the underlying uncertainty. Additionally, the user can select a scenario by picking a water level directly on a building facade. The water level corresponding to the selected scenario is then indicated with a purple line along the facades, and the respective water depths map is shown on the terrain using shades of blue.

To improve the readability of the water levels, zoom-dependent gauges are provided on the facade canvas (Figure 2). Additionally, reference objects of well-known size are given for better size comparison. A (fictitious) door is shown on the camera-facing facade so that it is always visible. At the contour edges of the building, a car is displayed such that occlusions of the facade area plots are avoided. The building of interest itself is visually emphasized by using facade and roof colors different from the neighboring buildings, and by accentuating the outlines of the facades. The address of the building is displayed in a billboard of a fixed screen-space size. This billboard is either displayed as a floating label above the building or, if it does not occlude the building too much, on the most prominent facade [MD08].

To avoid occlusions from neighboring buildings, adaptive cutaways [BF08] are used. We found that using a proxy cuboid as the cutaway volume rather than the building itself results in simpler and more comprehensible cut surfaces. Instead of calculating the view-dependent cutaway surfaces based on a Chamfer distance of the depth buffer, we generate them in the geometry shader from the contours extracted from the cutaway volume. In Figure 1, right and Figure 2, the cut surfaces are colored in purple. Ghost lines are displayed in light gray to indicate the former shape of the cut buildings. Note that, in Figure 2, the viewpoint is located inside a neighboring building, which is cut away completely to allow the user a clear view on the building of interest from this angle.

Beside the exterior water levels, it is possible to visualize the water levels inside a building. For estimating this interior flooding, we consider the water inflow through leaky windows, which the user can sketch [RWG*12] directly on the facades, as illustrated in Figure 3a. From the sketched windows, user-specified inflow rate and the exterior water levels, the development of the interior water levels over time is estimated. For visualization, the camera-facing facades are made transparent to show the cellar. As the cellar is usually occluded by terrain, a cutaway volume is used to virtually excavate the building. Inside the building, the maximum water level is displayed as a surface. Washing machines are used as reference objects for a better perception of water levels. Interior and exterior water levels can be displayed on the facades at the same time, as in Figure 1 to the right.

One more representation of uncertain flood impacts is shown in Figure 3b. A density plot displays the distribution of water levels. More opaque regions (darker blue in Figure 3b) indicate a higher probability of water reaching this level.

5. Uncertainty Mapping

In this section, we describe a basic pattern for visualizing uncertain values ranging between 0 and 1 (or, equivalently, between 0% and 100%). This pattern is primarily used to display an object's vulnerability to user-selected hazards. Additionally, we utilize it for impact visualization if considering inaccessibility of important infrastructure with respect to the building of interest.

The pattern is shown in Figure 4. We color-code the percentage according to the user-defined transfer function (bottom right). Uncertainty can be presented at two different levels of detail, thus targeting expert users or the general public (or both). For non-expert users (left column), the simplified visualization uses solid colors to present, according to the user's choice, the minimal ("at least"), average ("expected"), or maximal ("worst case") value across all scenarios under consideration. For expert users, we provide a more informative representation (middle column). The actual color en-

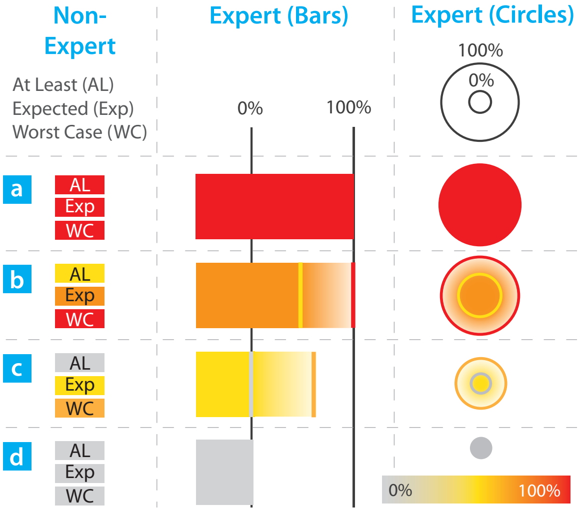

Figure 4: *Pattern for the uncertainty-aware visualization of vulnerability. For non-experts, only one of the three choices (at least, expected, worst case) is shown at a time. For experts, this uncertainty information is combined. (a) 100% vulnerable in all cases. (b) Vulnerable up to 100% in some cases, at least 50%, average 75%. (c) Safe in some cases, but in some other cases up to 60% vulnerable. Average vulnerability is 50%. (d) Always safe.*

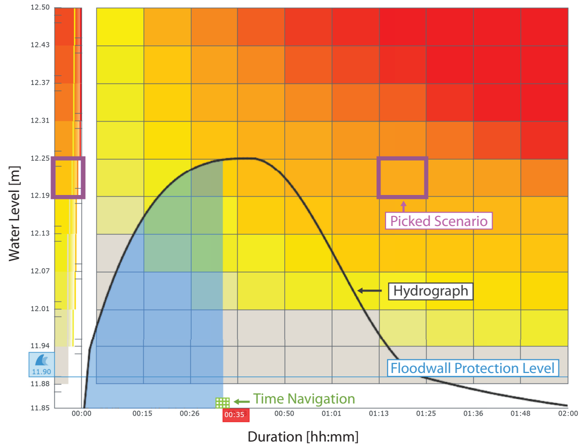

Figure 5: *Interactive 2D chart for the vulnerability to floodwall overtoppings. The gauge shows the water levels and the corresponding uncertain vulnerability values for experts. Each cell in the chart shows the vulnerability for the corresponding scenario (water level + duration).*

codes the average value. A context legend is provided, indicating the 0% and 100% reference levels with black lines. The two thick lines, colored according to the same transfer function, denote the minimal and maximal values across the considered scenarios. Between these two lines, a transparency gradient indicates the uncertainty range. The right column in Figure 4 shows the same pattern in a circular layout. Here, the vulnerability is proportional to the radius of the circle in order to establish the same linear scale between 0% and 100% as for the bars.

Our design follows the well-known box plot visualization to present the uncertainty of the results in a compact and familiar way that contains the minimum, average, and maximum values. When mapped onto the spatial domain, the final visualization adopts the shape of its spatial reference object to emphasize the correspondence of abstract and geospatial data. Vulnerability to sewer overflows is displayed with a circular plot to resemble the shape of a manhole. The accessibility of a building is visualized along its ground plan and the outlines of the routes leading to it. The vulnerability to breaches is visualized along the floodwall. In all cases, the visualization is displayed to be large enough to allow for picking of a concrete scenario. The transfer functions employed for the visualization can be changed by the user via presets or by manual editing through standard techniques.

6. Floodwall Overtoppings and Heavy Rains

We visualize the object-centered vulnerability to floodwall overtoppings in an interactive 2D chart. Such a chart is presented in Figure 5, where the vulnerability is shown with respect to the damage inflicted on the building of interest. In the left part of the chart, a vertical gauge shows different water levels and the corresponding vulnerability values. The value encoding follows the convention described in Section 5. Note that the visualization shown in the figure is the expert version with a more detailed uncertainty indication.

The second part of the chart, displayed on the right, is organized in a table layout. The horizontal dimension of the table represents the possible overtopping durations. Each cell visualizes the vulnerability of the scenario defined by the corresponding water level and duration. The user can pick scenarios for exploration by clicking on the cells or on the water level gauge. If a scenario is picked, the view displays a hydrograph [HWPa*14] representing the evolution of the water level in the river over time. The hydrograph is an inflow boundary condition for the simulation. It is defined by a synthetic function with the two parameters peak water level and duration of overtopping, which are varied in the ensemble. A dedicated cursor can be used for time-navigating the scenario of interest. The critical water level, after which the overtopping starts (11.9 m for Cologne), is shown with a blue horizontal line. The vulnerability to heavy rains is visualized in a similar fashion. In this case, the vertical gauge indicates different precipitation rates, and the hydrograph displayed on picking a scenario shows the rain development over time.

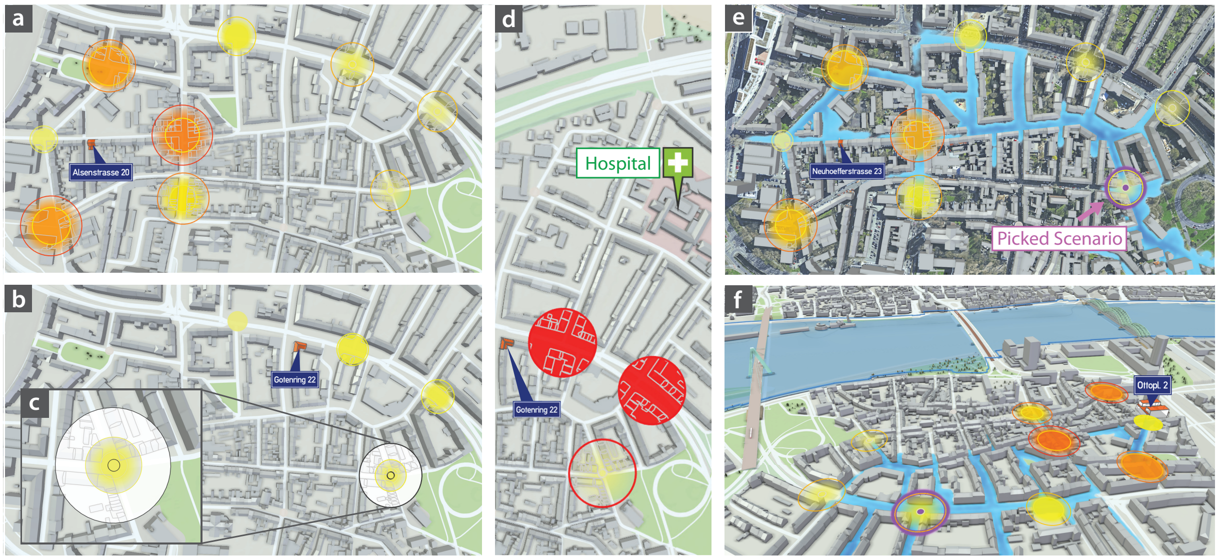

Figure 6: *Vulnerability to sewer overflows, presented for experts. (a) Sewer locations potentially dangerous for the selected building. (b) For another building, different locations are dangerous. (c) On mouse-over, a context legend is displayed, showing the 0% and 100% bounds. The building contours preserve the spatial context. (d) Vulnerability with respect to the hospital accessibility. (e) One sewer location is picked, the shades of blue show the expected water depths associated with an overflow at that location. A satellite image is used as a texture. (f) A different perspective is chosen, and a different building is selected.*

7. Sewer Overflows

We visualize the vulnerability to sewer overflow events on a 3D city model, as shown in Figure 6. The vulnerability values are shown at the corresponding sewer locations by using the circular pattern described in Section 5 and Figure 4. Note that, for non-expert users, these are circles of different radii and solid colors. In this case, both the color and the radius of each circle reflect the same (user-selected) minimal, average, or maximal vulnerability across the relevant scenarios. For expert users, the gradient-based representation is employed.

The user can clearly see the sewer locations potentially dangerous for the building of interest (see Figure 6a). For a different building selected, other sewer locations are more dangerous (see Figure 6b). A context legend, showing the 0% and 100% vulnerability bounds, is displayed on mouse-over (see Figure 6c). In Figure 6d, the vulnerability of the same building is presented with respect to the accessibility of the hospital. Two sewer locations are potentially very dangerous, and one is dangerous in the worst case only. Notice that, if some of the buildings are overlaid with the vulnerability visualization, their contours are shown to keep the context. In Figure 6e, the user has picked a sewer location to study the expected inundation associated with the overflow of that particular sewer. It is also possible to apply a satellite image (e.g., from Google Maps) as a texture. Such textures can be fetched automatically. Different perspectives can be used for the visualizations (see Figure 6f).

8. Floodwall Breaches

The object-centered vulnerability to floodwall breach incidents is presented with a plot along the actual floodwall in the 3D city model, as shown in Figure 7. For each position on the floodwall, the plot displays the vulnerability to a breach occurring at that particular position. The visualization uses the pattern described in Section 5 varying along the floodwall. Namely, for expert users, the representation includes the minimum and maximum within the uncertainty range, and the expected value is encoded in the color. For non-experts, the plot shows (with both color and magnitude) only minimal, average, or maximal vulnerability across the relevant scenarios. As for the sewer-overflow vulnerability visualization, the context legend is displayed on mouse-over.

To convey further vulnerability details, the possible breach widths for every considered breach position are visualized on the other side of the floodwall by means of a centered bar plot. The extent of each bar corresponds to the width of a breach the bar represents. The shapes of the bars follow the outline of the floodwall at the corresponding positions. The color of each bar encodes the average vulnerability across all scenarios sharing that particular breach position and width. In other words, such aggregations are done over the two remaining ensemble dimensions, i.e., water levels and durations. The user can click on any bar to explore the expected inundation, aggregated over the relevant breach scenarios.

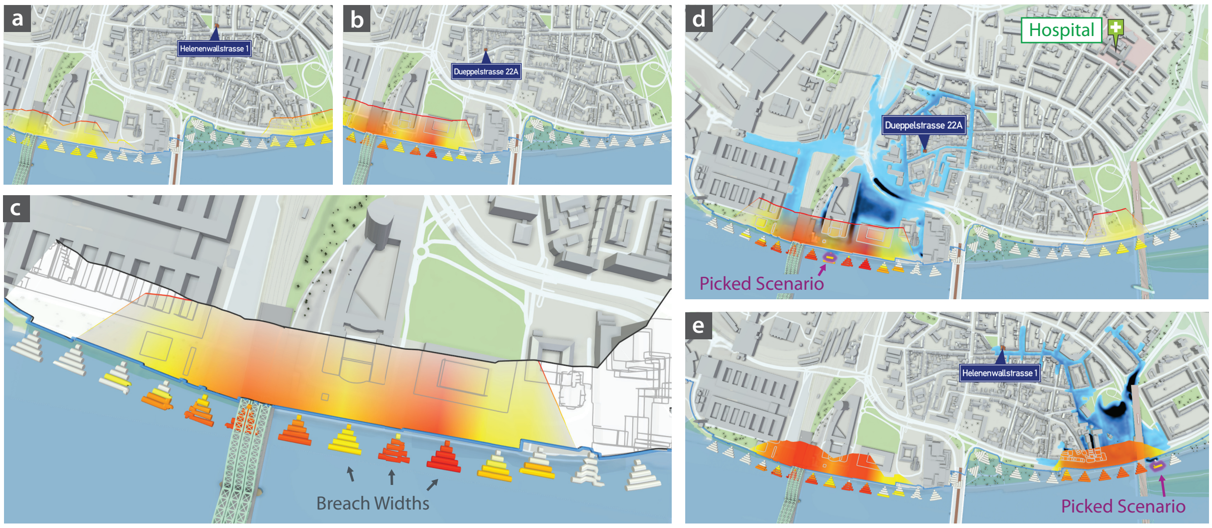

Figure 7: *Vulnerability to floodwall breaches. (a) For the selected building, dangerous breach positions are indicated by the plot. (b) Another building has a different vulnerability profile. (c) A close-up view of (b) with the context legend displayed. The vulnerability per width is shown for each position in centered bar plots. (d) Vulnerability with respect to the hospital accessibility. A scenario is picked by clicking on a width bar, showing the aggregated water depths on the terrain. (e) Vulnerability with respect to the damage of the building from (a), non-expert view.*

Figure 7a illustrates the design described above. For the building of interest, the dangerous breach positions are clearly visible from the vulnerability plot. For another building selected (see Figure 7b), the vulnerability profile changes. Figure 7c shows the close-up of the same case with the context legend displayed. At some positions, a breach of any size is very dangerous, but there are also positions where only some or none of the breach sizes are dangerous for the building of interest. In Figure 7d, the vulnerability of the same building with respect to the accessibility of the hospital is visualized. There is a larger set of potentially dangerous breach positions (right-hand side of the view). A scenario is picked (purple), for which the aggregated water depths map is shown. Figure 7e shows the non-expert visualization for the case of Figure 7a. The worst-case vulnerability is displayed with respect to the building damage. A scenario is picked, and the worst-case water depth map is shown.

9. Accessibility of Important Infrastructure

In this section, we describe our visualizations for the impact of flood-related hazards on the accessibility of important infrastructure with respect to the building of interest. By important infrastructure we mean buildings such as hospitals, pharmacies, or schools (see Figure 8), as well as the routes (see Figure 9) by which these buildings can be reached from the selected building. Since there are usually multiple ways to reach a location, we evaluate ten distinct routes to each of the important buildings. We automatically request these routes from the Google Directions service. To create a diversity, we make ten routing requests through ten different way points for each important building. It is likely that, within the whole set of routes obtained, many route parts overlap. Since our visualization does not support overlapping routes, we split the routes into segments to isolate the overlapping parts and then remove the duplicate segments. As a result, we obtain a set of unique route segments from which any of the routes can be reconstructed. Given a scenario, we consider a building accessible if there exists a connected sequence of route segments leading to this building such that each segment in this sequence is accessible. A segment is considered accessible if the water depth along it does not exceed 0.3 m.

The accessibility is displayed by using the pattern described in Section 5. Figure 8a shows the impact of sewer overflows on the accessibility of multiple important buildings (marked with labels) with respect to the building of interest (marked with an address plate). In this visualization for expert users, the 0% vulnerability bound is given by the building contour, whereas the 100% bound is shown on mouse-over. One can see that each building is accessible in most scenarios, yet inaccessible in some worst-case scenarios. In addition to the impact, the average water depths across all relevant scenarios are shown. In Figure 8b, the impact of heavy rains on the accessibility of the same buildings is shown along with the maximum water levels across the relevant scenarios. Here, the worst-case accessibility and the worst-case water depths are displayed for non-expert users. Apparently, the green buildings are always accessible, whereas the red buildings are inaccessible in some scenarios.

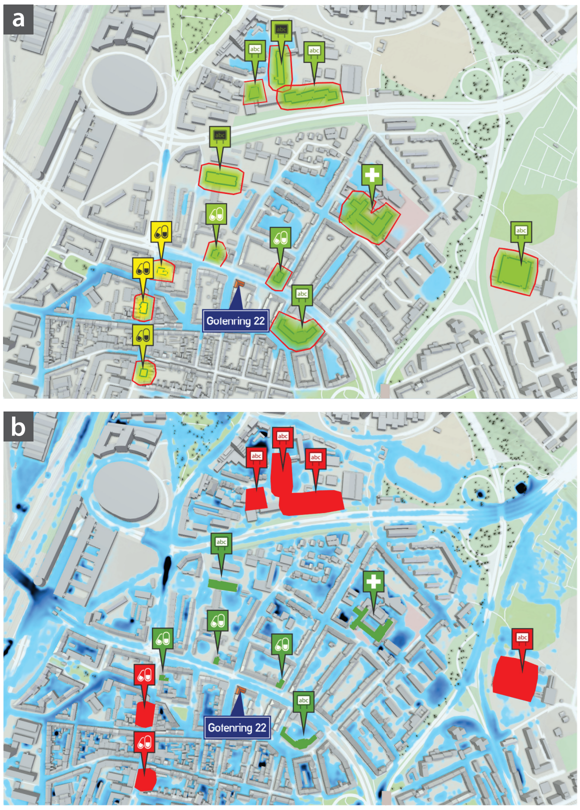

Figure 8: *Building accessibility. (a) Expert view showing the accessibility of hospitals, schools, and pharmacies with respect to sewer overflows. (b) Non-expert view showing the worst-case accessibility with respect to heavy rains.*

In Figure 9a, a visualization for expert users is presented, showing the impact of heavy rains on the accessibility of routes to the hospital. In this case, the hospital is unreachable over the red routes in every scenario, certainly reachable over the gray routes, and mostly reachable over other routes in the vicinity. Figure 9b shows the average impact of sewer overflows on the accessibility of routes to pharmacies in the vicinity. The presented visualization targets non-expert users. Route segments display solid colors according to their accessibility. The average accessibility of the buildings is indicated by the label colors only. The full accessibility visualization on top of the buildings is omitted to avoid visual clutter when showing the routes.

10. Evaluation

The overall idea of the presented work developed from a long-lasting and well-established collaboration with the Flood Protection Center of Cologne, Germany. Two experts, a flood manager and a logistics expert, were then evaluating our solution in two separate sessions. Both experts were partially involved in public communication activities. After the introduction into the basic concepts, the experts were asked to interpret different visualization results and evaluate their usefulness and readability. During this evaluation, valuable feedback was provided, and suggestions were made on how to refine our solution.

Both experts required a learning phase of about 15 minutes, and multiple different examples for comparison, to correctly interpret our uncertainty visualization pattern. The facade area plot and interactive 2D chart were found to be more comprehensible than mapping uncertainty onto 3D visualizations. Initially, both experts assumed that the size of the mapped vulnerability visualizations (e.g., for sewer overflows) had a spatial relation, and interpreted them as areas of influence. After the main idea of these visualizations was internalized, the domain experts were able to correctly interpret the visualizations and found them useful for their needs in flood management. However, they stated that the proposed uncertainty-aware visualizations contained information unnecessary for the general public and were hard to interpret without knowledge of statistics. According to our experts, for the general public, a binary information on whether or not the object of interest is vulnerable would have been sufficient. Therefore, they suggested to simplify the visualizations, which led us to implement two different user models, i.e., one for flood managers and one for the general public.

The facade area plots were found helpful and comprehensible for both targeted user groups. The experts agreed that the mapping of water levels onto the building facades is very descriptive and immediately tells the general public how vulnerable the object of interest is. It was also pointed out by the flood manager that this allows affected people to focus protection measures on facades where the highest damage is expected. Estimation and visualization of cellar flooding was also well-received by both experts. According to them, the combination with interior reference objects gives a vivid image of the possible damage. The exterior reference objects were rather perceived as decoration that is too far away from the actual building to be helpful. This led us to displaying a door on the facade. The facade line plot was seen as useful for experts, but too complex for the general public. Both experts were very positive about the cutaway visualizations of terrain and surrounding buildings, since it helped to avoid occlusion of the building in focus.

Generally, the visualizations including our uncertainty pattern were considered useful. The interactive 2D chart was seen as intuitive and well-suited for exploring the scenario pool even for the general public. The spatially mapped vulnerability visualizations were found useful mostly for domain experts. The logistics expert welcomed that the shape of the visualization resembles the shape of the object it is mapped onto. He also stated that displaying the contours of the underlying buildings on top of the vulnerability plot helps in the perception of the locality. The other expert, how-

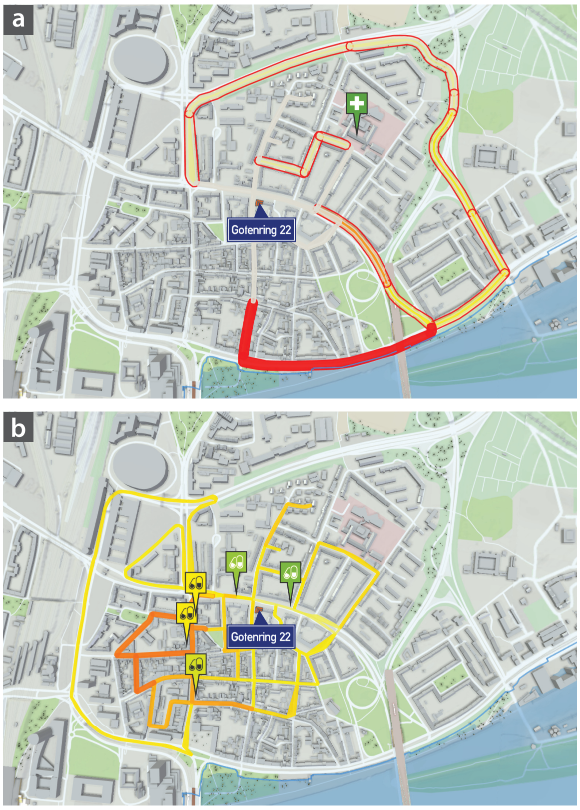

Figure 9: *Routes accessibility with respect to the shown buildings. (a) Expert view showing the hospital accessibility with respect to heavy rain incidents. (b) Non-expert view showing the expected accessibility of pharmacies with respect to sewer overflow scenarios.*

ever, found the contours distracting. It was well-received by both experts that the breach- and sewer-related visualizations allow flood managers to focus on particularly dangerous regions. The display of breach widths was seen as a helpful addition. The interactive scenario picking from these visualizations was found intuitive. Both domain experts appreciated the indication of the picked scenario and the display of the corresponding water depths map. Visualizations mapping accessibility onto streets and important objects were highly rated. According to the experts, this is an intuitive way to convey the accessibility of important infrastructure.

To summarize, the domain experts considered our solution useful both for their tasks in flood management and for the general public. The visualization of uncertainty was found reasonable for domain experts, but challenging for non-technical users. The experts concurred that, for the general public, simplified visualizations were needed to conceal the uncertainty, and suggested to consider two different user models. This major suggestion was implemented and made our application more versatile.

11. Conclusions and Future Work

In this paper we address the problem of isolating geospatial information for a particular object scattered in GIS data and a large pool of pre-simulated flooding scenarios. The automatic combination of these heterogeneous data in a conclusive way is hidden from the user and relieves him or her from dealing with multiple and often incomplete data sources. As a consequence, users of our application require no knowledge about the underlying data and data sources. The object-centered approach enables the user to obtain expressive visualizations of flood-related vulnerabilities and impacts with respect to a particular building. This allows both the general public and domain experts to investigate, whether, why, and how much this building is in danger, without manually exploring different flooding scenarios. Although our solution was tailored to the needs of flood management, the proposed concepts and visualizations also work for any other hazard to infrastructure, for example wildfires or landslides.

For the visualization of vulnerabilities and impacts, we rely on visual metaphors people are used to, like city maps or temperature ensemble figures in weather forecasts, and extend them. Whenever possible, information is mapped onto the spatial domain to establish visible relations between geospatial and abstract information. Through different user models, the uncertainty can be visualized to satisfy the different demands of experts and non-experts. Yet a meaningful, compact visualization of uncertainty remains a challenging task in the visualization for the masses.

A next step for future work is to give users the ability to adapt to the vulnerability by means of interactive sketching of protection measures such as barriers, local terrain modification, and curb elevation. The coverage of the adaption can then be visualized on top of the vulnerability to see which incidents can be addressed with the protective measures. Since such protective measures require a re-simulation of the scenario pool, strategies for an efficient re-computation are needed, such as considering only dangerous scenarios. Right now, our solution only focuses on direct impacts of flood-related hazards. For a more thorough investigation, long-term impacts of erosion and frequent flooding incidents to the infrastructure should be considered as well. In this context, financial considerations could also play a role when estimating the cost for maintenance and repair of said infrastructure compared to the cost of adaption. To know whether proper protective measures are worth their investment again concerns both domain experts and the general public.

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