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W. Aigner, D. Archambault, and R. Bujack
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HORA 3D: Personalized Flood Risk Visualization as an Interactive Web Service

Silvana Rauer-Zechmeister[1], Daniel Cornel[1], Bernhard Sadransky[1], Zsolt Horváth[1], Artem Konev[1],
Andreas Buttinger-Kreuzhuber[1], Raimund Heidrich[2], Günter Blöschl[3], Eduard Gröller[4], and Jürgen Waser[1]

[1]VRVis Zentrum für Virtual Reality und Visualisierung Forschungs-GmbH, Vienna, Austria
[2]RIOCOM Engineering Office for Environmental Engineering and Water Management, Vienna, Austria
[3]Institute of Hydraulic Engineering and Water Resources Management, TU Wien, Vienna, Austria
[4]Institute of Visual Computing and Human-Centered Technology, TU Wien, Vienna, Austria

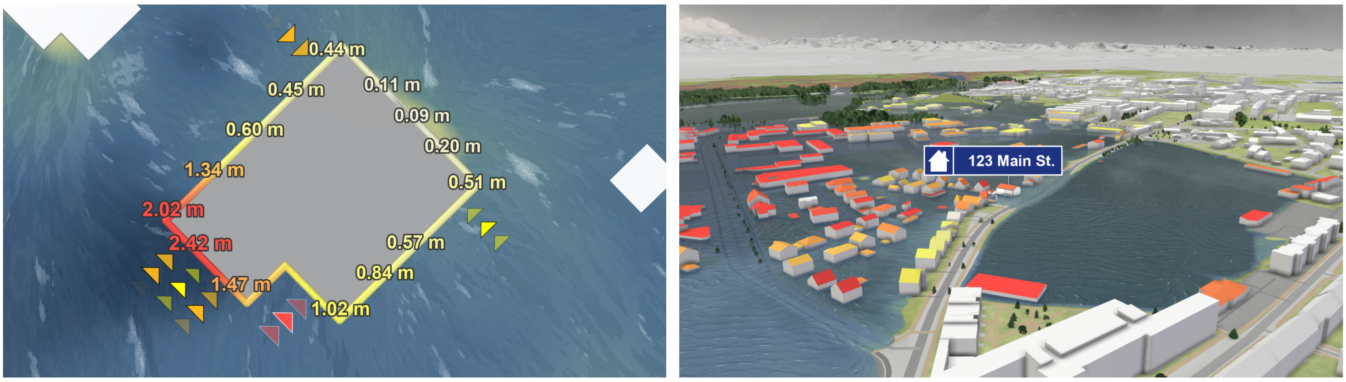

Figure 1: *Flood risk visualization of a selected building of interest, highlighting water depths around the building and high impact velocities on exterior walls via animated arrows in top-down view (left). High water depths at buildings in the vicinity are emphasized via roof coloring in overview (right).*

Abstract

We propose an interactive web-based application to inform the general public about personal flood risks. Flooding is the natural hazard affecting most people worldwide. Protection against flooding is not limited to mitigation measures, but also includes communicating its risks to affected individuals to raise awareness and preparedness for its adverse effects. Until now, this is mostly done with static and indiscriminate 2D maps of the water depth. These flood hazard maps can be difficult to interpret and the user has to derive a personal flood risk based on prior knowledge. In addition to the hazard, the flood risk has to consider the exposure of the own house and premises to high water depths and flow velocities as well as the vulnerability of particular parts. Our application is centered around an interactive personalized visualization to raise awareness of these risk factors for an object of interest. We carefully extract and show only the relevant information from large precomputed flood simulation and geospatial data to keep the visualization simple and comprehensible. To achieve this goal, we extend various existing approaches and combine them with new real-time visualization and interaction techniques in 3D. A new view-dependent focus+context design guides user attention and supports an intuitive interpretation of the visualization to perform predefined exploration tasks. HORA 3D enables users to individually inform themselves about their flood risks. We evaluated the user experience through a broad online survey with 87 participants of different levels of expertise, who rated the helpfulness of the application with 4.7 out of 5 on average.

CCS Concepts

• ***Human-centered computing*** → ***Visualization;*** • ***Information systems*** → *Spatial-temporal systems;*

1. Introduction

Floods have been the natural disaster affecting the most people worldwide [WH] with globally increasing frequency [MBV*21]. It becomes more important to involve the general public and encourage self-protection. To prepare for and protect against future flooding, there must first be an awareness of the personal risk. Traditional 2D flood maps provide a good overview of water depths to communicate the flood hazard, but detailed information about exposure and vulnerability of individual people is missing to convey the risk [LGL*07]. Without the height dimension, these maps can also be difficult to interpret, especially for untrained people.

The proposed HORA 3D application is the first publicly available 3D flood risk communication service covering the entire area of Austria and can be accessed via the link: hora.gv.at. It is a substantial extension to the public information service of the federal government of Austria for risk assessment called *Natural **H**azard **O**verview & **R**isk **A**ssessment **A**ustria* (HORA) [hora], that previously only used 2D maps. HORA 3D enables citizens to virtually explore their flood risk by providing an interactive 3D visualization of their house, premises, and neighborhood. Previous research showed that the display in 3D supports the estimation of water depths and flood impact [LKT*17], which is essential for a proper risk assessment. Our web service provides detailed information about different risk factors for a whole country, involving data larger than 6 TB. The data basis is derived from the HORA 3.0 project [BKWC*22, BWBK*22], where a high-resolution digital twin of the whole of Austria with an area of about 84 000 km^2 and a river network of 33 880 km length was created for hydrodynamic simulations. In this project, four river flood scenarios have been simulated, from which we derive individual risk factors and visualize them via HORA 3D. Figure 1 shows some of these risk factors, such as high impact velocities at exterior walls (left). In addition to the pre-simulated flood scenarios, diverse data are represented in the virtual environment to improve the orientation within the scene, including data about terrain, buildings, transport network, and land use. These large heterogeneous data require pre-processing to avoid long loading times. A cloud-based resource management ensures a fast response to user interactions for 30 concurrent users. For an easily comprehensible visualization, we avoid showing all available information at once. We provide users a selection of visual presets that have evolved from our close collaboration with domain experts and focus only on certain risk factors. For a selected preset, our 3D visualization automatically adapts to the current view to display content that is relevant to the user. It shows risks about the user's premises and house in close-up views and more general information about the neighborhood in overviews. To achieve this behavior, we extended and combined existing visualization techniques of Table 1. The resulting view-dependent focus+context visualization can be interpreted as an extension of the 2D focus+context approach commonly used in information visualization [Hau06].

Since the application is publicly available, the feedback of diverse users is of particular importance. We evaluated the described system with its visualization and interaction opportunities by conducting an online survey and its robustness with stress tests. The main contributions of our application are:

- Personalized high-resolution flood risk communication for the general public at country scale, without loss of local detail.
- View-dependent focus+context visualization of individual flood risks in 3D on real data.
- Easily accessible and interactive web service with a cloud-based architecture dealing with large heterogeneous data.
- Extensive evaluation of the application with stress tests and an online survey with 87 participants.

Visualization of	Contribution	Reference
Impact velocity	new approach for use case	–
Premises inflow	new approach for use case	–
Road accessibility	new approach for use case	–
Water depths	new top-down view/adapted for use case	[CKS*15]
Water flow	extended for large zoom range/animation	[CBKK*19]
Labels	extended for long roads/rivers	[ZCW19]
Transport network, land use	extended by procedural textures	[TBP17, FEP18]
Occlusions	extended for trees	[BF08, CKS*15]
Terrain	unchanged	[CZGW22]

Table 1: *Existing visualization techniques combined and applied to the new use case of risk communication (green), extended to meet our needs (orange), and used unchanged (white).*

2. Related Work

Flood hazard maps indicate the probabilities for the extents and water depths of a flood. These maps contain uncertainties arising, for example, from inaccurate data [Ali18]. Their transparent communication to the general public is a challenge, as uncertainties and probabilities are often confusing and not well understood [SPS11, CMM*16]. There is a trend towards embedding these flood maps into 3D environments [MCCDS19, WHM*19, ZLTW20]. This is because the third dimension provides a natural understanding of flooded scenes and facilitates the interpretation of the hazard [GSH*15, LKT*17]. However, publicly available risk information is still communicated via static 2D maps [JHW*17, MJW18, fem, ris]. Showing the propagation of a flood over time can help to derive flood dynamics and resulting risks [RBHL18]. Available applications are limited, either by restricting the flood visualization to the maximum extent of a flood [MCCDS19] or by displaying animated flow directions and velocities only in 2D [hyd].

The participatory experiment of Rollason et al. [RBHL18] indicates a lack of risk communication systems that provide detailed information at a local scale, where the participants are especially interested in. The system of Zhi et al. [ZLTW20] provides local information with one hazard index per building. The display of individual influences and most vulnerable parts of a building of interest is missing. Amirebrahimi et al. [ARMN16] display diverse influences and the potential damage of individual building parts by using a building information model (BIM). Their system requires extensive information about building components, which is usually not available for large areas. Cornel et al. [CKS*15] use building facades as information surfaces, which does not require information about the interior. This concept is suitable to our use case and we utilize it for side views and extend it by a top-down view. To meet the needs of our application and provide visibility of key risk information over a wide zoom range, we extend and combine other existing visualization techniques listed in Table 1. This includes the rendering of high-resolution water and terrain [CBKK*19, CZGW22]. Visual elements such as labels [ZCW19] and simple geometries such as lines, polygons, and arrows [TBP17, FEP18, KMV*18] are used to emphasize different risk factors and to provide information about the user-selected focus area. Our occlusion handling for objects of interest are advances of adaptive cutaways [BF08, CKS*15].

3. Application and User Interaction

The aim of our application is to provide the general public with an effective tool to assess their flood risk. They can inform themselves about the flooding probability of individual objects of interest, such as their home, neighborhood, and potential new property. An introductory video explains the usage of HORA 3D to novice users, of which an anonymous version is added to the supplemental material of this paper. In this section, we give an overview of the data basis, design, and interaction opportunities of our application.

3.1. Pre-Simulated Flood Scenarios

For HORA 3D we utilize flood simulation results already calculated in the country-wide project HORA 3.0 [BKWC*22] as well as georeferenced data acquired from open data services and authorities. Figure 2 gives an overview of the data used for our visualization. In the HORA 3.0 project, river floods across the country were simulated with an efficient GPU-based simulation [HPW*16, BKHN*19]. Four flood scenarios with three different probabilistic return periods, every 30, 100, and 300 years have been simulated. They are listed as *HQ30*, *HQ100*, *HQ300*, and *Rest Risk* in Figure 3 (bottom). The *Rest Risk* scenario considers the impact of dikes during a 300-year flood by removing them according to an elevation model calculated for the HORA 3.0 project. Return periods are a common concept that expresses the probability of a flood to occur, e.g. a 100-year flood statistically has a 1 % chance to happen in any given year. The simulation data provide us with time-dependent scalar and vector fields defined on a regular grid with 2 m resolution. The fields represent water depths and 2D flow velocities. In addition to water-related data, georeferenced data of premises, buildings, and the surrounding area are integrated to provide a comprehensive view of the flood risk in a familiar context.

3.2. View-Dependent Focus+Context Design

The huge amount of data created within the scope of the HORA 3.0 project cannot be manually explored and interpreted without expert knowledge. To facilitate access for the general public, we developed a concept for information reduction and a visual interface for an easy exploration of the risk information.

Involvement of Domain Experts We conduct applied research in collaboration with partners from the water management field, including water managers and engineers of three large cities, Vienna [rio], Cologne [ste], and Hamburg [ham], and of the German federal state Rheinland-Pfalz [mku]. They work with our decision support system *viscloud* [vis], a desktop application developed for domain experts with out-of-the-box visualizations. Our system has been used by them for over ten years to convey the impacts of flood and heavy rain events to communities and other stakeholders. During regular meetings, our partners give us feedback, make improvement suggestions, and request features. This helped us to identify relevant information and to design a user-friendly visualization for HORA 3D.

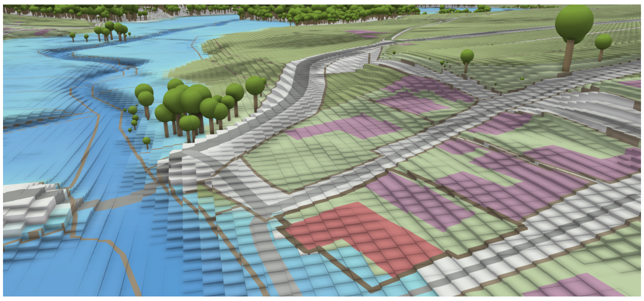

Figure 2: *Input data: Grid-based terrain and water (blue), focus building footprint (red), premises borders (brown), other building footprints (purple), roads (gray), land use (green), and vegetation.*

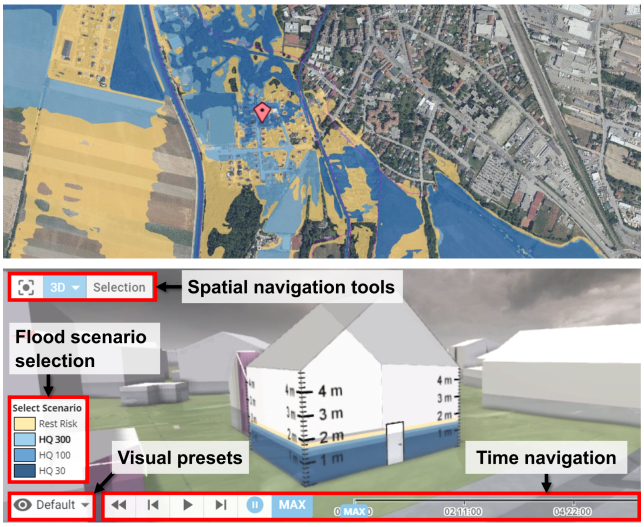

Figure 3: *Top: 2D map for POI selection (red pin) with differently colored areas corresponding to flood scenarios. Bottom: User interface of HORA 3D, which provides visual presets and tools for spatial and temporal navigation to explore these scenarios.*

Application Access An easy access to HORA 3D is important to reach a broad audience. Server-side processing allows users to simply visit our application through a web browser without any specific hardware requirements. The entry point of the application is the HORA website [hora], where users can select an arbitrary point of interest (POI) in Austria by entering an address or by picking a point on a 2D map, as depicted in Figure 3 (top). The map shows areas affected by flooding of different magnitudes corresponding to the return periods of the pre-simulated flood scenarios. After the selection of a POI, the 3D view is loaded with a simple user interface centered around it as in Figure 3 (bottom).

Information Selection To help users focus only on the essentials, we hide the complexities of the system, data, and algorithms. We developed a strategy to deal with only a subset of the data by re-

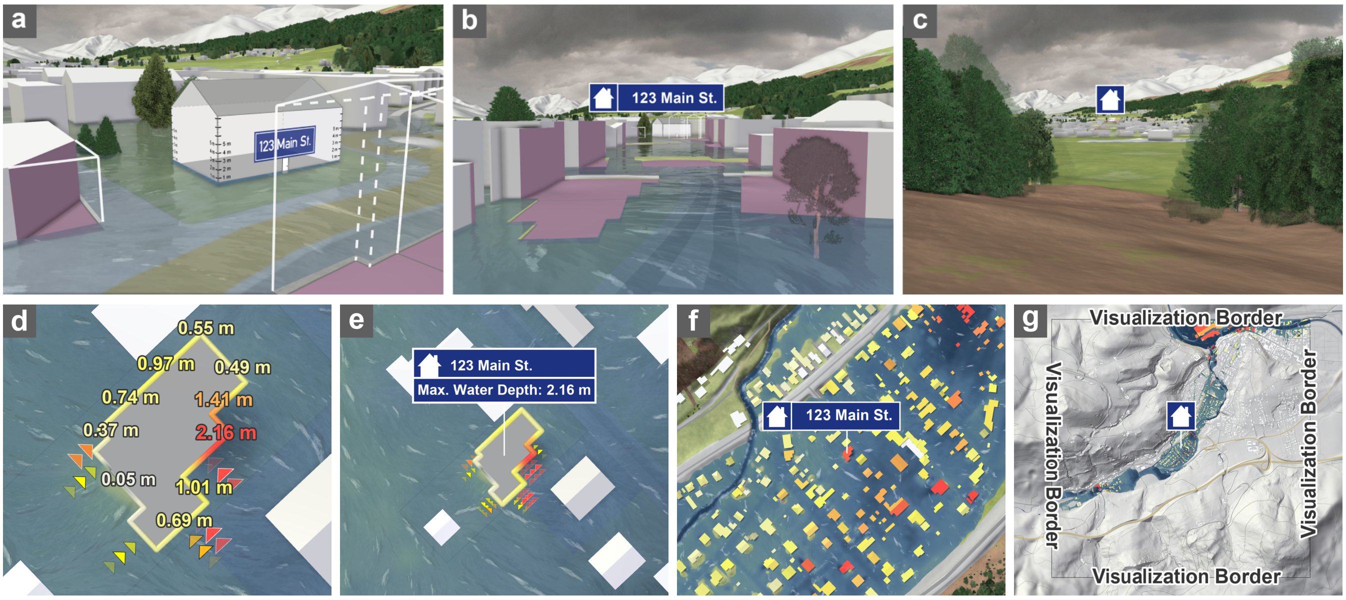

Figure 4: *Zoom-outs with occlusion handling on a side view (a–c) and view-dependent behavior on a top-down view (d–g). (a) Neighboring buildings occluding the focus object are cut away and closed by purple cut surfaces, their white contour lines remain visible. (b) Trees fade out before they occlude the focus object. (c) The focus object remains visible even in forests. (d) Animated arrows highlight high impact velocities on facades. A roof outline shows maximum water depths by colors and labels. (e) Water depth labels fade out, waves are scaled to show the water flow in the vicinity. (f) Roofs of neighborhood buildings are colored according to the surrounding maximum water depth. (g) Water becomes opaque and the land use visualization fades out for a high-contrast shore line within the visualization borders.*

ducing the data at two stages: on startup and on user interaction. On startup, only data related to a user-selected POI and its close surroundings are extracted and visualized. The second stage of data filtering relies on a view-dependent focus+context visualization. It guides the user's attention towards important risk information without occlusions or distractions by context objects. Figure 4 shows this view-dependent behavior on a side view with occlusion prevention and on a top-down view with a wide zoom range. Detailed information about an object of interest is shown in close-up views, whereas information about the vicinity is shown in overviews. For more structured risk information and a better distribution of the information load, the information is linked to individual tasks that can be performed by users. They are described in more detail in Subsection 3.3. The resulting view-dependent focus+context design provides guidance through predefined tasks and improves performance, which benefits the interactivity of the application.

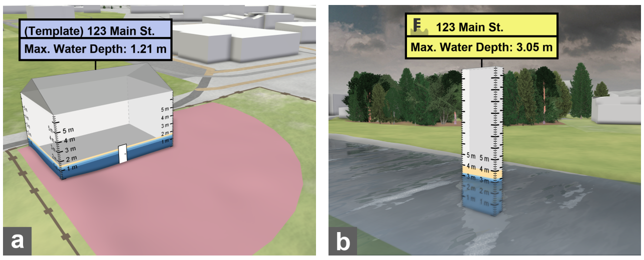

Figure 5: *Default focus objects for premises with no actual building found within* 50 m *of the POI (red area). For premises marked as building site, a template building is placed in alignment with the premises borders (a), otherwise a water gauge is used (b).*

Focus Objects The user-selected POI defines a premises and a focus object. If there is a building on the premises, it becomes the focus object. Otherwise, a fictional focus object is created as a visual aid to help display the associated flood risk. Depending on whether or not the premises is a building site, a template building Figure 5(a) or a water gauge (b) is used as fictional object. Water gauges are a common concept in hydrological applications to indicate water depths. Users can place them at different locations to retrieve information on water depth and other risk factors. A template building allows people to asses risks before building a house there. It is placed on the premises by searching for an optimal position within a 50 m radius from the POI (red area in Figure 5 (a)). Flood impacts are shown at fictional objects, but their effects on floods are not considered. It would cause a time-consuming re-simulation and the effects on the overall flood event are rather small. An initial perspective is determined that centers the focus object and avoids occlusions by the terrain. Initially, the zoom and rotation are also centered on the focus object, which the user can change by panning the scene. In case the user gets lost in the 3D scene, a dedicated button resets the view to the focus object. All types of focus objects (existing building, template building, water gauge) are highlighted by the same distinctive visual features. In addition, their facades and outlines are used as canvas for the visualization of flood risks.

Context Objects To gain a comprehensive understanding of personal flood exposure, it is important to consider not only the object of interest, but also the surrounding area. Visualizing the context around a focus object provides important reference points and supports the user's orientation in the 3D environment. We provide a variety of context objects including buildings, labeled streets and places, land use surfaces, and vegetation. A low-resolution terrain model covering the entire area of Austria is available for users to zoom out and locate the scene at the country scale if needed. To keep the user attention on the focus object, the terrain and all other context objects are available at high resolution in its immediate vicinity only. While context information is important, focus elements take precedence in visualization, and occlusions are avoided by applying adaptive cutaways to buildings [BF08, CKS*15] and a new approach of fade-outs to trees, as shown in Figure 4 (a–c).

3.3. Task-Specific Visualization

For years, domain experts have requested the visualization of diverse flood risk aspects from us. Based on their input, we selected aspects that are particularly important for personal risk assessment. To avoid information overload, we group the information relevant for predefined tasks meant to inform about certain risk factors, while our visualization assists users in performing them. Switching between tasks is realized through view-dependency and user interactions with interface elements for temporal navigation and the selection of visual presets depicted in Figure 3 (bottom).

Identify Most Vulnerable Building Parts To better protect a building, it is necessary to know where its vulnerability is high and action needs to be taken. Local water depths around a building often correlate with possible damage. By rotating around the focus building, the user can see the maximum local water depths for each flood scenario, displayed on the facades, as shown in Figure 5. The colors correspond to the scenarios of the original 2D map in Figure 3 (top). The technique resembles the known concept of marking water levels of past floods on facades of real buildings and provides an easy comparison between different flood events. In addition to the colored areas on the facades, a semi-transparent water surface is displayed around the building. In top-down views, users can only see the roof and the water depths on the facades are hidden. To make them accessible in top-down views as well, we indicate water depths of the currently selected flood scenario by a colored and labeled roof outline (Figure 4 (d)). High water pressure, which correlates with water depth and impact velocity, poses a particular threat to doors and basement windows. High impact velocities are emphasized by animated arrows moving perpendicular to the facade, as in Figure 4 (d). When the user zooms out further, detailed information is no longer discernible. With our novel focus+context visualization, maximum water depths are automatically aggregated per building and indicated by roof colors, as depicted in Figure 4 (f).

Identify Most Vulnerable Parts of the Premises While the water surface display within a premises provides hints of what the flooding would look like, we also offer insights into where most water enters the premises. An inflow representation requested by our partners from Cologne [ste] can help identify particularly vulnerable parts of the premises in order to focus preventive action. The water inflow volume aggregated over the current flood scenario is visualized by arrows placed along the premises border, as in Figure 6 (a).

Evaluate Personal Protection Measures With HORA 3D, we want to increase awareness for flood protection on private grounds. Besides the exploration of flood impact factors, two different kinds of protection measures, shown in Figure 6 (b-c), can be tested to see how high a barrier has to be to hold the water back. Sandbags, which are a cost-effective, short-term flood protection measure, and concrete walls, which constitute a more durable flood protection, can be automatically placed along the premises borders. Their required height is derived from the simulation data. Despite being rather coarse, this individual protection design shows the barrier heights necessary to protect a property during a selected flood scenario. It is not meant to be a fully featured planning tool for personal flood protection, but rather a platform to raise awareness and encourage people to take protection into their own hands.

Explore Causes of Risk To help users understand the causes of their flood risk and how they and their neighborhood are exposed to flooding, we do not limit our visual representations to a specific focus object. The display of the water surface in the vicinity supports the perception of water depths in relation to the known environment. Knowing dominant directions and velocities of water flows is important to identify bottlenecks where the pressure becomes high and water can inflict damage. By default, animated waves based on flow direction and velocity are displayed on the water surface, depicted in Figure 4 (d–f). Previous work has shown that this is a descriptive way to present these attributes [CBKK*19]. As an alternative representation of the water flow, dense velocity arrows can be displayed on the water surface, which point in the flow direction and color-code the velocity magnitude, as shown in Figure 6 (d). Flooding can be explored through space and time navigation. Spatial navigation with zoom, pan, and rotation allows users to identify spatial relationships. For temporal navigation, a playback widget is employed, which allows users to play back the simulated flood scenario or navigate to particular time steps. The maximum water expansion of a scenario is particularly interesting and therefore available through a dedicated button.

Explore Road Accessibility Constraints During flooding, the road network can be disrupted and personal movement may be restricted. In particular, connections to hospitals, pharmacies, or grocery stores may become inaccessible. We highlight inaccessible roads by coloring them according to their maximum water depth (see Figure 6 (e)). This is intended to encourage users to early consider possible evacuation routes.

4. Web Service

The application is provided as a web service queried from the HORA website [hora], where the user selects a POI. The selection starts a personal user instance on the server that loads all required data and renders the requested image. The image is streamed to the web client via video stream with GPU-accelerated H.264 encoding and provides the user a real-time visualization. In the following, we describe the implementation of the application from data preprocessing to our focus+context visualization.

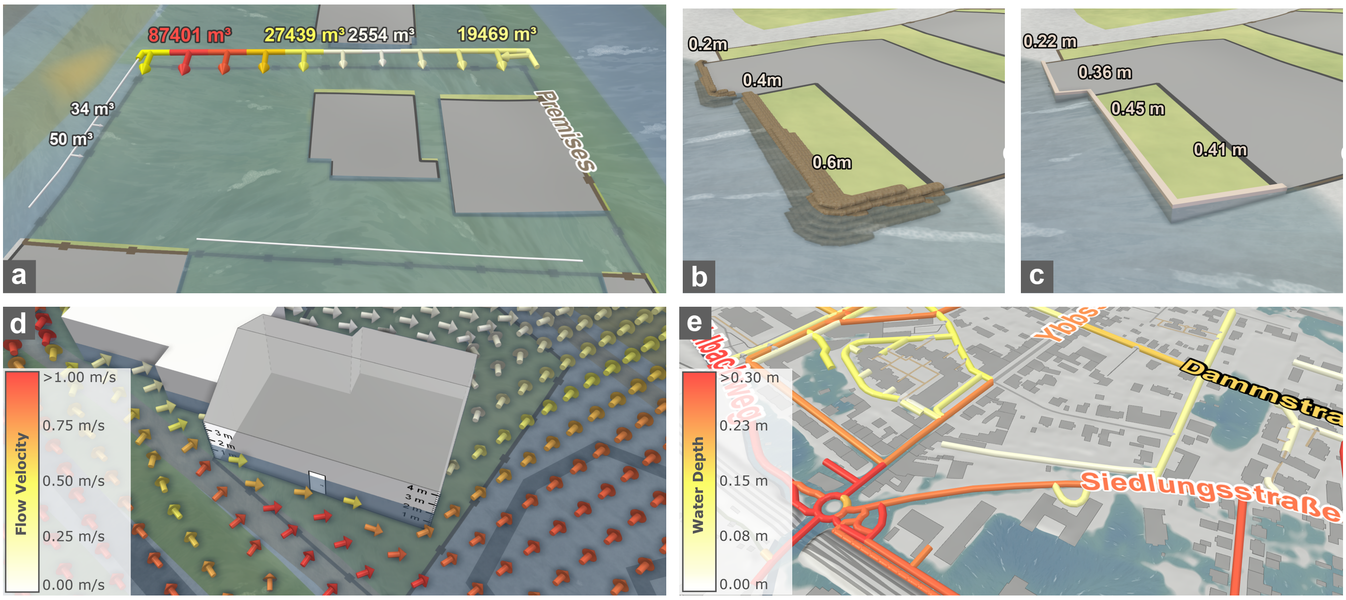

Figure 6: *(a) A line with colored, labeled, and scaled arrows around the premises shows inflow volumes accumulated over the flood scenario. (b-c) Flood protection by sandbags and concrete wall with required heights around the premises. (d) Arrows indicate flow directions and highlight high velocities with color. (e) Flooded road segments are colored according to the maximum water depth along the segment.*

4.1. Data Pre-Processing

Data have to be prepared to provide an efficient web service with short startup times and a real-time visualization with fast response to user interactions. Besides water depths and flow velocities from pre-simulated flood scenarios, we process additional geospatial data to visualize the 3D environment (see Figure 2). The terrain consists of four nested digital elevation models (DEM) with increasing cell sizes of 2 m, 20 m, 50 m, and 250 m originating from the POI. To increase the recognition of buildings, we use detailed 3D building models where available and reconstructed ones otherwise. 2D building footprints in combination with the high-resolution DEM and a digital surface model (DSM) with a resolution of 0.5 m are used for the reconstruction [vcs]. 2D vector data in the form of points, lines, and polygons provide points of reference to users, such as important places, roads, rails, and premises. Information about the location and types of vegetation is obtained from land use polygons and a tree cadastre from OpenStreetMap [osm]. All data used by HORA 3D covering the area of Austria amount to more than 6 TB. To make the data quickly available upon user request, they have been split into smaller parts during a data tiling process in advance. The tile size depends on the data complexity. Water depths and flow velocities are divided into areas of 4 km^2, terrain DEMs into areas between 4 km^2 and 16 km^2. The tiled data are stored in a binary data format and enable fast access to the relevant subset of data by loading only tiles in the vicinity of the POI.

4.2. Instance Management

HORA 3D must handle many concurrent users and peaks in requests that are organized via cloud-based instance management. For a fast response to user requests, the instance manager distributes resources over two high-performance servers with two CPUs (AMD EPYC 74F3, 512 GB RAM) and three GPUs (NVIDIA A40, 48 GB memory) each. To ensure interactivity while delivering full HD images, we limit our web service to 30 concurrent users. In case all server resources are occupied, users have to wait in a virtual waiting room until resources are released again.

4.3. Progressive Startup

For each new instance, the entire flooded scene has to be initially built up, which takes some time. To reduce the perceived waiting time, this is done progressively [HKC*16]. The basis for this progressive startup is a hierarchical settings management [SWR*13]. The loading process is split into several steps and for each step, a new image is generated and sent to the client. The scene is updated and extended by further elements according to the settings of the current step. This way, users can follow the loading process by watching a scene that is built up step by step until fully loaded.

4.4. View-Dependent Focus+Context Visualization

The application requires a visualization that is very responsive and can handle dynamic changes by users quickly. Since the visualization is customized based on each user's object of interest, the possibilities for pre-computation are limited. We extend and combine existing real-time visualization techniques listed in Table 1 to display focus and context elements efficiently. The visibility of focus objects and associated flood risk factors is supported by adapting the 3D visualization view-dependently and preventing occlusions.

View-Dependent Adaption Users define the focus of the visualization explicitly by selecting a POI and a visual preset in the user interface and implicitly by changing the view. We differ between three main views: a close-up view of the focus object from the side, from top-down, and an overview of the scene. Different scaling approaches are used for important content to remain visible for users over a large zoom range. For a smooth transition of displayed information in different views, zoom- and perspective-dependent fading is applied to appearing and disappearing visual components.

Close-Up Side View Near a user-selected object, the object and associated risk factors have to be in focus. This requires a visualization that is centered around the object and makes it stand out. Our visualization of focus objects is based on the work of Cornel et al. [CKS*15], who use building facades as a canvas to show flooding probabilities. Their proposed density plots can be hard to interpret without statistical knowledge. For our use case, we reduce the display to water depths of four flood scenarios. They are represented by a simple area plot with a single color per scenario. The visibility through water is varied depending on the zoom level. In close-up views, as in Figure 4 (a), users can see the premises border and roads that pass by through water. With decreasing zoom level, the water becomes opaque and land use polygons are faded out (see Figure 4 (g)). This results in a shoreline with a high contrast to the terrain, which facilitates the identification of the water extent.

Close-Up Top-Down View To be able to retrieve the water depth information around a focus building in top-down views as well, we extended the approach of Cornel et al. [CKS*15]. When the user switches to a top-down view, as in Figure 4 (d), we fade in a labeled 3D line around the roof outline. The water depths are encoded by colors along that line. We apply the common concept of impostor rendering [KMV*18] for an efficient display of the roof outline and other 3D lines and arrows representing the premises inflow and road accessibility. High impact velocities at focus objects are displayed by animated arrows (triangles) projected on the water surface. To emphasize high velocities, the speed of the arrows corresponds to the impact velocity and the arrows are scaled and colored according to threshold values of a risk analysis guide [CGR*].

Overview In case the user zooms out, space is limited and detailed information shown by labels, impact velocity arrows, and inflow arrows are faded out. By zooming out, the user shows interest in the flood extent and impact in the vicinity. Besides the focus building, other buildings in the surrounding area are shown. The detected roof surfaces of all buildings affected by flooding are colored according to the surrounding maximum water depth. For more visual context, vector data of the transport network and land use are projected on the terrain with screen-space visualization techniques for lines [TBP17] and polygons [FEP18]. Color and structure variations are introduced by textures to increase the recognizability of the virtual scene and for a better distinction between different land use, shown in Figure 7. These variations are noise-based and procedurally generated with visual properties according to the represented data, such as forest, grass, asphalt, and rock. To get a more realistic appearance with similar but distinct fields, we add an additional color variation per field with a coarse-resolution noise. The participants of our survey preferred this semi-realistic representation over orthophotos from satellite images because of its high resolution and higher contrast to inundation areas. To provide additional visual context about the land use, we render simple and transparent 3D models of trees and vines to indicate forests and vineyards.

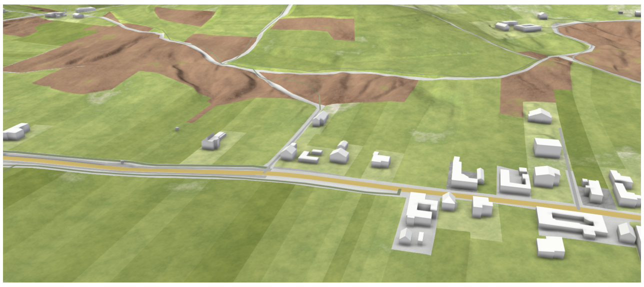

Figure 7: *Procedural textures to highlight different land use types and color variations to distinguish individual fields.*

Dynamic Scaling Important visual elements, such as 3D arrows and lines, waves, and labels should remain visible over a large zoom range. They are dynamically scaled with different approaches to achieve a roughly constant size on the screen. We apply continuous scaling to the geometry of 3D lines and arrows. For the rendering of water with its flow directions and velocities, we use a technique with animated waves and foam [CBKK*19]. It was proposed with static wave sizes and is only suitable for a small zoom range. We extend this approach by a step-wise scaling such that waves are scaled over predefined zoom ranges in which they remain constant. Domain experts highly appreciate the water animation and requested a permanent activation. It requires frequent image updates, which had a negative effect on the performance of the application. For interactive frame rates, we implement framebuffer caching for static scene elements during water animation. Labels are used to display concrete values of risk factors and to label landmarks such as roads, places, and water bodies for a better orientation. Their visualization is based on the work of Zechmeister et al. [ZCW19] by providing zoom-dependent labels embedded in the 3D scene. We extend their approach by a hierarchical subdivision of road and river lines for labels with a level of detail that corresponds to the zoom level.

Occlusion Prevention The focus object should always be visible and not occluded by other less relevant objects, such as neighbouring buildings and trees. Cutting off buildings with adaptive cutaways [BF08] has already been shown to be effective [CKS*15]. Figure 4 (a–c) shows cut surfaces of context buildings indicated in purple. Using the same approach for trees produces irregular cut surfaces, which are difficult to interpret. Therefore, we hide trees completely if they are within a predefined pixel distance to the focus object. Since a conical cutout provides a better view, visibility tests based on the angle between a tree, the focus building, and the viewer are applied. To avoid trees popping in and out, we increase their transparency nearby the predefined disappearing volume for a gradual fade-out, as depicted in Figure 4 (b–c).

5. Evaluation

The aim of our application is to raise public awareness of flood risks and possible ways to mitigate them. Awareness is difficult to quantify, but the impact of HORA 3D in practice has to be evaluated after its public availability for a longer period of time. To offer a reliable and user-friendly public service, we evaluated the application from two different perspectives. First, we carried out stress tests to quantify its robustness and its performance with many concurrent users. Second, we collected user feedback regarding comprehensibility and usefulness of the application.

5.1. Stress Tests

The provider of the HORA website [hora] experienced high access numbers of their risk communication service during flood events and media releases, which is also expected for HORA 3D. We conducted two extensive stress tests to assess the performance of our application during such peak events with many concurrent users.

Basic Setup Two test sessions with 39 114 virtual users were performed on both servers used to deploy the application. Initial loading times of POIs corresponding to premises in flood hazard areas and the visual output for different screen sizes and ratios were tracked. Per test, 1000 virtual users were permanently requesting the service, while only 30 of them were allowed to use it in parallel and all others are redirected to a virtual waiting room. After they finished the predefined tasks, their slot was released to the waiting users. With the first test session, we examine whether the loading times of HORA 3D are acceptable, even with high access numbers. It lasted 18 h 42 min and during that time, 37 396 virtual users requested a POI, waited for the startup, and left the application. For every user, an image was exported to manually check a subset for correct visual output. Many edge cases in the application have been identified this way and remedied, such as initial perspectives in which the focus building was obscured by the terrain. In the second test session, lasting 3 h 30 min, 1718 virtual users performed predefined user interactions. We generated seven tasks with different workloads: spatial and temporal navigation, wave animation, switching between flood scenarios or visual presets, and image or video download. All interaction sequences were captured as MP4 videos to examine the visual quality and interactivity of HORA 3D based on visual inspection of random samples.

Time Measurements We divided the progressive startup of the application into seven loading steps. The startup timings of the four main steps (Step 1 to Final) presented in Figure 8 are most important from user's perspective. They give us information on how long users have to wait until they get access to the application (Step 1), see the first rendered image (Step 2), can navigate around the focus object (Step 3), and have full access to HORA 3D (Final Step). For each virtual user, we measured the startup time during the two stress tests T1 and T2, which are given in Figure 8. The individual timings and corresponding geographic coordinates are included in the supplemental material. Our service was able to serve all virtual users after an average startup time of 15.9 s (Final Step). Our resource management has proven to be very robust by completing its work after 0.5 s on average, while handling permanent user requests (Step 1). There are only six outliers with timings longer than 25 s to finish the whole startup. The POIs of these outliers belong to large building complexes or to their neighbors. A high complexity of focus buildings requires more time to process the information

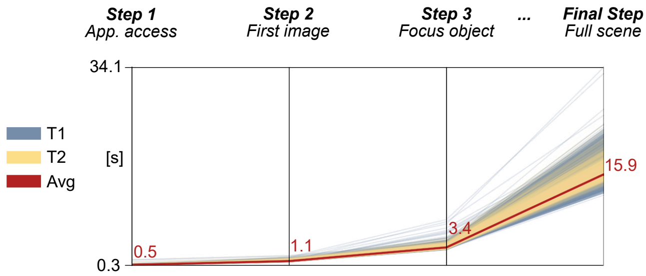

Figure 8: *Startup timings of the application with four main loading steps. Durations in seconds are shown per virtual user of two test sessions (T1, T2), and averaged over all (Avg).*

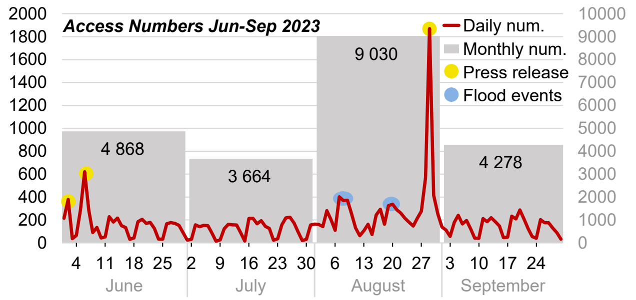

Figure 9: *Daily and monthly accesses to our web service from June to September 2023. All Sundays are labeled. Peaks related to press releases and flood events are highlighted in yellow and blue, resp.*

for the facade and the top-down visualization. The complexity of adjacent buildings has a negative impact on the pre-computation of contour lines for the occlusion handling. The user interaction enabled for the second stress test (T2) after Step 3 increased the timing by 1.2 s on average, but shortens the user's waiting time for the first interaction opportunity. The stress tests were successful in demonstrating that the system can serve 30 highly active users in parallel while delivering interactive frame rates at 1080p resolution for all of them.

Real Users HORA 3D has already handled 21 840 real users in four months. Daily and monthly access numbers are given in Figure 9. There are fewer accesses on weekends, so we assume that more people from expert circles are aware of our service and use it during work. Peak access numbers correlate with press releases and flood events that took place shortly before. There are higher access numbers in August, when several severe weather events with heavy rain and flooding occurred in Austria and two news articles referring to our application were published. These events led to the peak access count of 1870 users on the 29th of August 2023.

5.2. Online Survey

To collect user feedback on our application, we conducted an online survey with 87 participants. The main goal of the survey was to find out how user-friendly the application is and how effective the tool and its components are for personal flood risk communication.

Participants As the application is targeted to the general public, we invited people with different background knowledge to provide their feedback. On the one hand, we reached out to our collaboration partners from multiple current and past projects who distributed the questionnaire in their network. These are experts working in the water management domain: engineers, hydrologists, architects, scientists, and students. On the other hand, we invited people generally interested in flood risk communication: geography and economics teachers, specialists of the insurance sector, GIS analysts, and a few members from the general public. As a result, 50.6 % of the participants work in the field of water management and the majority of them deal with data and models similar to those used for our application. Due to their significant background knowledge, they are referred to as domain experts.

Questionnaire The participants received a link to the application, which they were supposed to study on their own, like users accessing the service via the website. They were asked to accomplish different tasks and then fill out an online questionnaire, which is still available online [horb]. A complete list of all questions with their intentions and participants' answers is part of the supplemental material. There are three types of questions: binary and multiple choice questions, and questions with a numerical rating scale between 1 and 5 for very negative to very positive feedback. Binary choice questions collect personal background information of the participants, while multiple-choice questions are used to check participants' understanding of the shown content. Two multiple-choice questions tested the correctness in interpreting two visualized risk factors: water depth around a focus building and impact velocity on building facades. For both factors, the magnitude is color-coded according to a provided legend. It was clear for 95.4 % of the participants that the coloring of the building roofs indicated the water depth around buildings. The meaning of the colored, animated arrows pointing towards building facades was clear to all participants. Numerical rating questions about the application in general, the view-dependent visualizations, and the display of individual risks give us comparable values of various aspects.

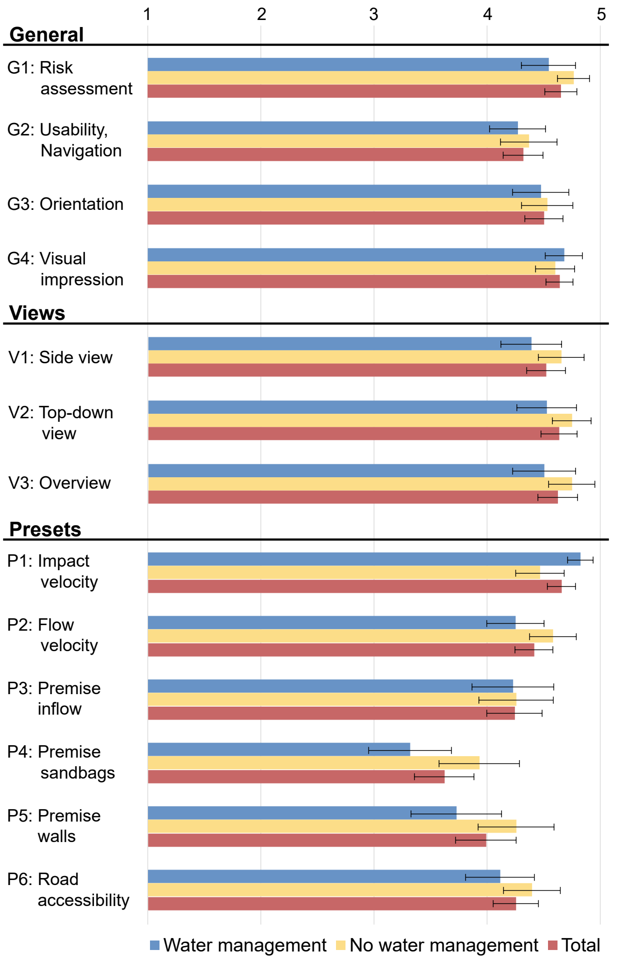

Figure 10: *Numerical ratings (1 to 5) of the application features averaged over three user groups with 95 % confidence intervals.*

Numerical Ratings and Remarks Figure 10 summarizes the results of questions with numerical ratings. The ratings are averaged per participant group: domain experts in the water management field (blue), participants not working in the field (orange), and all together (red). For a better estimate of the distribution, we provide the 95 % confidence interval per question and group. We also collected comments from participants to find out the motivation behind their ratings. Participants gave positive feedback about HORA 3D, especially for the overall risk assessment (G1). They rated its helpfulness for assessing their flood risk with 4.7 out of 5 on average. We initially showed participants an example image of a premises with and without risk. It avoided the potential challenge of recognizing a risk situation in the first place, but it ensured that they can see and evaluate our risk visualization. Some participants reported navigation problems in the 3D environment, which they included in the usability evaluation (G2). Besides technical problems with unsupported browser versions, the unfamiliar zooming in 3D was listed as a reason. To evaluate our focus+context design, participants were asked to rotate around the focus object as well as to zoom in and out. The high ratings of different views (side, top-down, and overview), presented as V1–V3 in Figure 10, indicate that the concept worked very well. In general, domain experts rated our features slightly lower than the other participant group. The only exception here is the visualization of high impact velocities (P1), which seems to be particularly suitable for domain experts. All participants had concerns regarding the design of protection measures (P4–P5). They agreed that it does not seem reasonable to place sandbags along the premised borders, especially for very large premises. In reality, this would be very time- and resource-consuming. Domain experts indicated that the erection of protection walls would probably not be allowed around private premises because important retention space would be lost. Participants welcomed the display of flooded roads (P6). However, some of them remarked that too many road segments are highlighted, making it hard to see which ones were passable. A generally positive rating of the premises inflow visualization (P3) was affected by the accidental display of decimal places in the labels. This led to visually overloaded scenes and an apparent pretense of false accuracy. The decimal places were removed right after the evaluation.

6. Discussion

Many participants from experts to non-experts mentioned that HORA 3D is a useful tool and that they like our focused visualization. Despite being generally very positive, the feedback highlighted several potential areas for improvements and future work.

Feature Improvements Participants of the survey suggested a sandbag placement at building openings, such as doors and windows. Data on building openings are not generally available, but we consider a sandbag placement around the building rather than along the premises border. This would constitute a more cost-effective approach to protect a building. The display of protection walls turned out to be a misleading feature. Our intention was not to motivate people to build walls around their premises, but rather to make them aware that there are personal measures that can be taken to reduce flood risk. Indicating a wall height necessary to protect a premises from flooding is also a way to convey the water depth around the premises. A change from walls to a more abstract representation could help users to correctly interpret our message.

Fine-Tuning Risk Representations Visually overloaded scenes were reported by survey participants. This concerned the visualizations of flooded roads and premises inflows. Highlighting entire flooded road segments seems to produce visual clutter. We have to investigate whether highlighting can be restricted to the actually flooded parts. Currently, our visualizations present exact values, for example for water depths and inflow quantities. This can be misleading, as it does not communicate the inherent uncertainty of the used approach. According to previous work [CKS*15], worst-case scenarios are the most relevant ones. With the *Rest Risk* scenario, we integrate uncertainty for a 300-year flood by considering dike breaches. Moreover, all four statistically derived flood scenarios already consider the occurrence probability of a flooding event. Nevertheless, probabilistic flood risk information is not widely understood [SNWP17,CMS*18]. A more abstract representation, such as using risk categories ("low", "medium", "high") instead of providing exact numbers, might avoid giving false impressions of conclusiveness [CDP*23]. To communicate the reliability of the shown risk to the users, we have to examine how additional uncertainty information about the simulation model and the underlying data quality can be effectively conveyed without being overwhelming.

Extensibility Our application has sparked interest among survey participants to further explore their personal flood risk and to change parameters interactively. One mentioned example of such an exploration is the ability to place protection measures at different locations and test their effectiveness. Barriers can also have negative impacts on other premises, which could be simulated and shown in a new scenario to be considered by users. Such interactive changes introduced into the model require a recalculation of the entire flood scenario. Even though our simulation can perform such tasks with low latency already [HBKK*20], we consider the further reduction of its intrinsic complexity important future work. Moreover, additional interactive tasks require new user interface elements, which in turn can make the application overly difficult to use, especially for the general public. An option to switch to an expert mode with an extended toolset could solve this problem. Besides the individual visualization per user, HORA 3D could be further personalized through user input, e.g., on the preferred means of transport for evacuation routes. More complete and detailed data about building openings, cellars, garages, access routes, and fences could be used for a more accurate flood simulation leading to a better evaluation of flood risk. However, availability of such data remains an issue, which might be alleviated by photogrammetry and point cloud-based technique in the future. Currently, 30 users can access our service simultaneously. To increase this number, more server resources with greater GPU capacity are required due to our server-side architecture.

Generalizability The promising 3D focus+context design can also be applied to communicate the risk of other natural hazards such as heavy rain, avalanches, landslides, storms, and wildfires effectively. The presented techniques seem very well suited for the presentation of risk factors such as snow pressure on building roofs or heat on facades. The HORA website [hora] already provides information about some of the aforementioned hazards in the form of static 2D maps. To communicate the risk of such hazards with our application, it suffices to provide geo-referenced data defined on regular grids from which we can derive the risk. With the availability of live data from spatially-distributed gauges, the presented visualization could support flood forecasting by communicating expected flood levels and wave arrival times. Besides user benefits, HORA 3D can also have a positive effect on land development by preventing the construction of buildings near rivers and their renaturation areas.

7. Conclusion

In this application paper, we presented a web service already available to the general public. It communicates country-wide information about flood risks at an individual scale through an interactive 3D visualization. Our application is a lens that allows a user to look inside vast and complex time-dependent data of pre-simulated flood scenarios without being overwhelmed. The extraction of information relevant for a user-selected building and its premises facilitates the assessment of a personal risk. This risk is shown by means of our new focus+context visualizations with automatic view-dependent adjustments that allow users to explore different risk factors without expert knowledge. This is confirmed by the participants of an online survey who only partially come from the water management sector. Although our application offers interactive navigation, the option for interactive changes is limited. Users are interested in the interactive testing of protection measures, which is a feature for future consideration. Improving performance and image quality can possibly be achieved with AI-based supersampling, which we consider future work. The effective representation of uncertainty in a visualization comprehensible to laypeople is still an open issue for public risk communication.

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