FloodVis: Visualization of Climate Ensemble Flood Projections in Virtual Reality

M. T. Oyshi[1,2], V. Maleska[2,3,4], J. Schanze[2,3,4], F. Bormann[1], R. Dachselt[2,5,6,7] and S.Gumhold [1,2,6,7]

[1]Chair for Computer Graphics and Visualization, TU Dresden, Germany
[2]ScaDS.AI, Germany
[3] Leibniz Institute of Ecological Urban and Regional Development (IOER)
[4]Chair of Environmental Development and Risk Management, TU Dresden, Germany
[5]Interactive Media Lab Dresden, Cluster of Excellence Physics of Life, TU Dresden, Germany
[6]Centre for Tactile Internet with Human-in-the-Loop (CeTI), TU Dresden, Germany
[7]Cluster of Excellence Physics of Life, TU Dresden (PoL), Germany

Abstract

Anthropogenic greenhouse gas emissions are leading to accelerating climate change, forcing politicians and administrations to take actions to mitigate climate change and adapt to its impacts, such as changes in flood regimes. For European countries, an increasing frequency and severity of extreme rainfall and flood events is expected. However, studies on future flood risks caused by climate change are associated with various uncertainties. The risk simulations are elaborate as they consider (i) climate data ensembles (temperature, precipitation), (ii) hydrological modeling (flood generation), (iii) hydrodynamic modeling (flood conveyance), and (iv) vulnerability modeling (damage assessment) involving a huge amount of data and their handling with Big Data methods. The results are difficult to understand for decision makers. Therefore, FloodVis *offers a means of visualizing possible future flood risks in Virtual Reality (VR). The presentation of the results in a VR especially supports the user in understanding the complexity of the dynamics of the risk system enabling the feeling of presence. In* FloodVis *the user enters into a virtual surrounding to interact with the data, examine the temporal evolution, and compare alternative development pathways. Critical structures that require improved protection can be identified. The user can follow the inundation process in hourly resolution. We evaluated* FloodVis *through an online and offline user study on the context of whether VR can provide a better visualization of ensemble flood risk data and whether the sense of presence in VR can influence the decision making and help to raise awareness.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Visualization—Virtual Reality, Immersive visualization, natural interaction, sense of presence I.3.3 [Environment]: Climate change—Flood risks

1. Introduction

Climate change causes a shift in worldwide weather conditions in a potentially hazardous and disruptive manner. Anthropogenic greenhouse gas emissions and global warming are playing a vital role in this shift. With the rising temperatures, extreme weather events will become more serious. Flood events occur more frequently and intensely in the future resulting in multi-facetting and long-lasting impacts [IPC21]. The consequences of flooding are particularly disruptive if urban areas are inundated resulting in infrastructural damage, damage to houses including loss of human life. According to the report on financial management of flood risks published by *OECD* in 2016, flood damages exceed $40 billion worldwide annually [OEC16]. In July 2021, Germany experienced the worst flash flood event for decades after Western Germany had been affected by heavy rainfall. At the same time, other European countries, especially Austria, Switzerland, France, Luxembourg, Belgium, the Netherlands, Czech Republic, Croatia, Italy, Romania, and United Kingdom, suffered numerous flood events with an overall damage of $43 billion and more than 190 deaths [DW21], [EGU21]. These major impacts occurred despite the availability of forecasting and warning of extreme rainfall and flooding [Cor21].

Researchers are working on the projections of possible future flood risks under climate change conditions to derive adaptive risk reduction measures. It is assumed that increasing temperature will change future precipitation patterns where additional atmospheric moisture can be held by warmer air with rising potential for heavy rainfall and flood events. Flood damage might cost around €48 billion instead of current €7.8 billion per year on the European continent itself [Cor21]. According to *Huber et al.* [HG11], it might be possible to limit the increasing probability and severity of extreme

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weather events by stopping anthropogenic climate change as it is playing a fundamental role for extreme events. Besides mitigating climate change common measures to reduce flood risks exist. The basis for the derivation of those measures are risk assessments. The spectrum of measures ranges from flood prevention due to dams and dikes to behavioural training of rescue teams and the people at risk.

Flood simulations are crucial for risk reduction. Simulations of alternative flood scenarios support a better understanding of risks with their probabilities of occurrence and the impacts they cause. However, even if there are valuable flood simulations available, they are not always used to their full potential since resulting risk curves with their uncertainty bands are difficult to understand for decision-makers and the people affected.

This paper presents the novel method *FloodVis* for the visualization of ensemble flood events and their impacts in Virtual Reality (VR) to increase the awareness for future change by making flood simulation data accessible in an immersive and playful way. VR is deployed here as it enhances user experience and enables immersive visualization. The ability of creating a sense of presence is considered as the main factor of VR where individuals can have a feeling of being somewhere else even though physically they are not there [Jer15], [BBL*05], [SVS05]. *FloodVis* allows users to understand flood data without prior knowledge. It was evaluated by an online and offline user study.

2. Related Work

Scientists started focusing on ensemble flood forecasting over the past decade due to the expansion of numerical weather prediction and climate projection and growth of high performance computing for a risk-based decision making advancement [WED*20]. Instead of a single forecast, ensemble forecasting and projection generate a bandwidth of data applying varying initial conditions, parameterizations as well as model approaches. The visualization of flood simulation data has been a topic of research for years to understand the flood risks in a better and easier way. To reduce climate change impacts such as more frequent and intense floods, adaptation occurred to be a key management strategy of decision makers. Hereby, uncertainties play a major role for both climate projections and impact assessment. [JRP01].

At the science-policy interface between the experts of forecastings and projections and decision makers, it has become obvious that decision making does not just follow rational choices but rather additionally involves emotions. The influence of feelings has been researched in the field of virtual hospital experience [GCL*21], stress reduction [GRB21], consumer decision making [ASAD16], stock investments decisions [GNG16], ethical decision making [SSNO22] and many more. *Seo et al.* [SFB07] present an investigation on whether subjective experience of emotions is functional or dysfunctional. They studied 101 stock investors' decisions for 20 consecutive business days and the result shows individuals experiencing more intense feelings accomplish stronger decision making.

There is an ongoing debate on whether VR is important for environmental data visualization or decision making, where studies show that VR allows the sense of presence and guides to a positive attitude towards the surrounding environment [TJD18] [CWT*11]. VR amplifies the human intelligence and establishes the human-machine simulation system which can support decision making in, e.g. emergency management [BWW95]. *Berg et al.* [BV17] present a case study that investigates VR as a decision making tool for early design making. For this research, a group of design and manufacturing engineers was invited to test an immersive environment for a new product development project. According to the results, individuals could identify design flaws and potential solutions which were not identified using non-immersive tools.

VR allows users to view a 3D dataset in a 3D/360 environment instead of a 2D display by connecting dots between data and reality [SS18]. *Mol et al.* [MBB22] examined flood simulation in immersive reality to check whether simulated disasters can influence people for investing in risk reducing measures. According to them, understanding and preparation for low-probability/high-impact risk is often difficult for individuals without experiencing respective events in person. The lack of understanding and preparation usually leads to additional damages. According to their study, individuals, participating in virtual flood visualizations are more likely to invest significantly in flood risk reduction.

Simpson et al. [SPKK22] evaluated storm surge flooding in an immersive environment for risk analysis. According to them, it is challenging to communicate storm surge flood risks using traditional methods like maps. At the same time, virtual flooding visualizations can potentially reduce physical harm as individuals can explore external aid and own behaviour in immersive virtual reality (iVR). Understanding the various impacts of different heights also improves in iVR. The high potential of immersive visualization for user experience is discussed by *Kraus et al.* [KKF*21].

Toshio et al. [TF20] tested public interventions in VR for flash flood to encourage evacuation decision as people blow hot and cold while leaving their home due to natural disasters. In their research they examined whether the social and environmental change in VR caused by flash flood can promote early evacuation decision. 103 students participated in this study from Kumamoto University in Japan and at the end they could effectively take evacuation decisions earlier. *Enes et al.* [EY19] present a web based framework for estimating flood loss using HAZUS. Regions that require assistance to support resource allocation and mitigate planning can be prioritized using their framework. However, this solution does not ensure the sense of presence also they have limitations of the technical requirements, number of inundation scenarios as well as data options.

Several traditional flood risk visualization approaches exist including 2D maps, animations and other methods but none of them can ensure the sense of presence. *Grottel et al.* [GSH*15] presents a real-time flood visualization in 3D targeting non-professionals. The paper discusses the implementation details, data concept and results. But there are no details about the interaction of the users and their feedbacks. The paper does not include VR and the discussion of the sense of presence.

The goal of *FloodVis* is to visualize ensemble flood data in immersive reality to enhance the user's experience referring to the differences between alternative scenarios including uncertainty, iden-

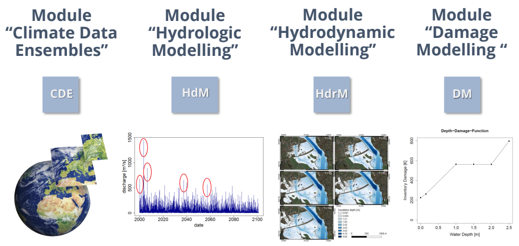

Figure 1: *Representation of the applied model chain comprising the modules (i) climate data ensemble, (ii) hydrologic modeling, (iii) hydrodynamic modeling, and (iv) damage modeling [Mal21]*

tification of houses under water and to see the flood propagation over time. The principal aim of this paper is to determine whether VR supports flood projection data visualization and to know whether the sense of presence influences the decision making regarding the consideration of flood risk reduction measures.

3. Applied Data

The data used in *FloodVis* were generated in a project that investigates the dynamics and uncertainties of flood risks in the context of climate change [Mal21]. An ensemble-based model chain including the modules (i) climate data ensemble, (ii) hydrologic modeling, (iii) hydrodynamic modeling, and (iv) damage modeling was set up for this purpose. Figure 1 shows the model chain which is applied for the Mulde River catchment with a focus on inundation areas at the community of Bennewitz (a municipality in Saxony, Germany).

The climate data ensemble includes results from global and regional climate modeling of the variables temperature, precipitation, air pressure, humidity, wind, and global radiation. The simulation results visualized in *FloodVis* are based on the global climate models CCCma3 and EC-Earth in combination with COSMO-CLM (KIT, Institute of Meteorology and Climate Research). The data set "CCCma3" employs the climate scenario "A1B" where "EC-EARTH" is based on the scenario "RCP8.5". Scenario A1B represents rapid economic growth and scenario RCP8.5 represents a high-emissions scenario showing the likely outcome if society does not foster the mitigation of greenhouse gas emissions.

The hydrologic model applies climate data as input and provides the discharge generated at a specific location in the river. The simulation data comprise 25 flood events each representing one hydrologic model parametrisation. Parameters relevant for hydrologic modeling are for example properties of the soil as saturated water conductivity to calculate how much water is absorbed by the ground, gets drained, or does evaporate. The resulting flood discharge is used as input for the hydrodynamic modeling input.

The hydrodynamic modeling determines the flow characteristics such as inundation area, water depth, flow velocity and also the flood propagation. 2D models are applied based on a digital elevation model (DEM) of the terrain. The DEM includes buildings due to their impact on the flow of the water as flow obstacles. The output of this module is an elevation value of the water surface for every cell of the simulation grid. If there is no water in one grid cell a no-data value is returned.

In the damage modeling module, the types and footprints of the buildings in Bennewitz are used in combination with the water height around the buildings to estimate the inventory and construction damage at every house.

The spatial and temporal resolution of the simulation, 4 m and 1 h, is extremely high in comparison to other flood simulations. The diversity in climate models, scenarios and the use of different hydrologic model parametrizations allows to get a better understanding for the uncertainties of the simulation results. If there are, for instance, many similar flood events across all the different simulation runs then this suggests that the uncertainties involved in the data are relatively low. On the other hand, if there are major variations in the results of each model run, then this indicates that the uncertainties in the simulation results are much higher [Mal21].

The data set used in this research includes a digital elevation model (DEM) with a resolution of about 1 $pixel/m^2$, aerial images with a resolution about 1 $pixel/0.2m^2$ taken between 20.05.2018 - 01.08.2020, data describing buildings with their footprint, height, and roof type sourced as CityGML (LOD1) files from the Free State of Saxony (Staatsbetrieb Geobasisinformation und Vermessung Sachsen, GeoSN). All of the three geospatial data sets are published as tiles with dimensions of 2x2 km. The input data was given as ascii files in the CRS "EPSG:32633". The simulation data resolution is 1 $pixel/4m^2$ due to hydrodynamic model application. To visualize the development of flood events over time, time-series data was provided for the events $CCCma3\_A1b\_1\_2$ and $EC-EARTH\_rcp85\_1\_4$ with a time interval of 1 hour.

4. Traditional Visualization Techniques in Risk Assessment

Flood hazards are usually visualised by color-graded water depth maps and road maps or aerial photos in the background. The map visualizes the water depth with a blue color gradient. The dark color indicates a high water depth, while a light blue represents a lower water depth. In figure 2, the water depth of a simulated extreme flood event is shown. The background employs aerial pictures as provided by Google or Open Street Map. The 2D visualization approach is sufficient for experts in the field of flood hazard analysis as they are used to analyze flood events by interpreting colored maps.

However, this traditional method cannot ensure the sense of presence and according to published research and also the user study performed in the context of *FloodVis* which is represented in the results and evaluation section. It suggests that, in some cases non-experts better understand the impact of extreme flood events when they can experience them in a 3D environment. Another shortcoming of 2D maps that is resolved by *FloodVis* is that only one time step is displayed on each map, usually the maximum water depth, and the temporal evolution of the floodplain is neglected. This can be relevant for identifying critical locations during the flood event.

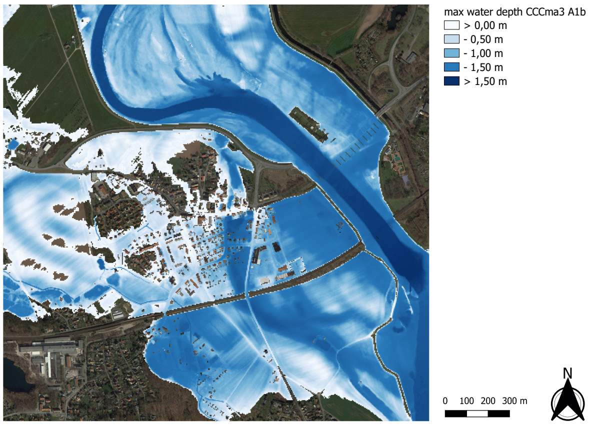

Figure 2: *Color-graded 2D hazard map for water depth; dark blue indicating a relatively high water surface elevation, [Mal21]*

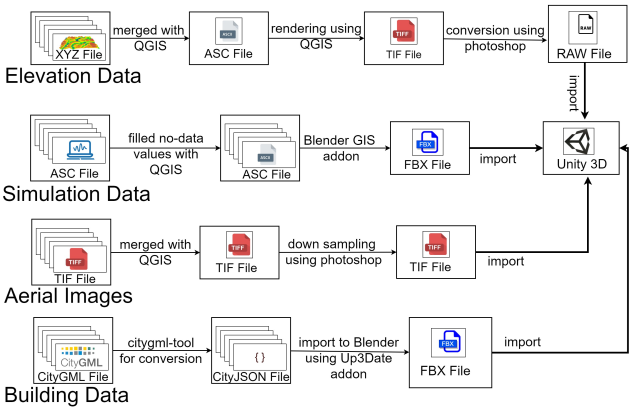

Figure 3: *Data preparation and conversion workflow for creating the 3D model of Bennewitz in Unity 3D*

5. Methods

FloodVis aims to provide users with a digital twin for flood risk assessments tested for the municipality of Bennewitz in 3D and allows for interaction to have a VR experience. The game engine Unity is used as it is known to be one of the most beginner-friendly development platforms. Also the usage of existing resources from the asset store can lead to time savings in the development process.

5.1. Data Preparation and Conversion

To create a 3D model from the supplied data they had to be converted into 3D objects that can be imported in the Unity development platform. The data preparation workflow is summarized in figure 3.

The DEM of the study area is supplied in nine tiles covering the entire study area. Accordingly, the nine tiles in the XYZ file format are merged using QGIS and cropped to the extent of the study area. The resulting DEM is saved into a new ASC file. Afterwards, the DEM is rendered into a grayscale TIF file. The last step is to scale the resulting TIF file to a square format using the software Adobe Photoshop and to export it as 16-bit grayscale RAW (uncompressed and unprocessed image data) file because Unity only accepts this format as heightmaps for terrains. The tiles of the aerial images are merged into a single file and cropped to the study area's extent as already explained for the DEM. The resulting TIF file is downsampled using Adobe Photoshop to reduce the file size of 10 GB.

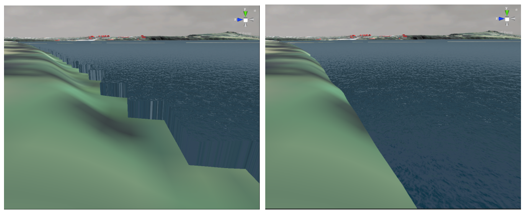

Figure 4: *Artifacts along shoreline before filling of missing values (left) and after filling (right)*

To create meshes from the simulation results the Geographic Information System (GIS) tool QGIS is used to fill the cells that do not contain water height values with the values of the cells next to it. This is necessary to avoid artifacts along the edge of the water surface in the visualization. Figure 4 shows an image of the artifacts that are caused by the lower resolution of the simulation data (4 m). The new copies of the original simulation data are transformed into the CRS "EPSG:25833" to ensure that they properly fit together with all other data sourced from the federal state‘s website. After the filling and transformation process, meshes are created using the addon Blender GIS for Blender. All the meshes are exported into one FBX file (a format to exchange 3D geometry and animation data). Before exporting, 20% of the original mesh face count is reduced using the decimate feature of Blender to reduce the complexity. For time-series data the meshes of one time-series are split into multiple FBX files to reduce the file size of each FBX file as Blender tends to run out of memory when too many meshes are edited and exported at once.

The information about the buildings in the study area is accessible as CityGML files. This data format is an open data model and based on the XML (an extensible markup language file) format. It allows the storage and exchange of virtual 3D city models. CityGML files contain information like the footprints of buildings, along with the buildings' height and their roof type. The CityGML data can be visualized using a 3D view in the QGIS software as shown in Figure 5. To convert the building data into 3D meshes the Blender add-on Up3date is used, which only allows importing CityJSON files - a JSON-based exchange format for the CityGML data model [LAOK*19] that was developed to increase the models' usability for developers, compared to the XML-based version. To convert the given CityGML files to CityJSON files the open-source citygml-tools are used.

5.2. Assembling of the model in Unity

After the data preparation and conversion, all data are imported into Unity 3d. The XR Interaction Toolkit is used to develop the

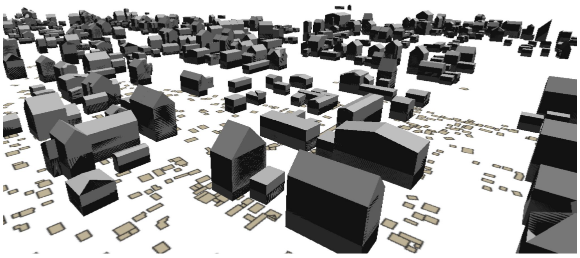

Figure 5: *CityGML data visualized in the 3D view of QGIS*

3D model of Bennewitz, a terrain layer, water surface, teleportation areas, building and skybox. The terrain layer is generated using the previously created heightmap in form of a 16-bit grayscale RAW file. The aerial image is applied as a texture. For the proper dimensions of the terrain layer the width, depth, and height are set to match the values shown in QGIS using the Unity editor. As for terrain height, the difference between the highest and lowest point of the elevation model is used.

For the water surface, a plane is chosen. The scale of the plane is set to the extent of the simulation data. By switching the meshes of the plane, all different flood events can be visualized. To make the water surface appear like water the *basic water shader* from the Unity Standard Assets Version 1.1.6[10] is applied to the plane.

To allow teleportation on the terrain and the water surface, the *teleportation area* component from the SteamVR plugin is applied to each of those game objects. The buildings are imported from the previously created FBX file. They are then placed on the terrain using a script. Some adjustments have to be made by hand to properly align the buildings with the terrain. To add a sky box that fits to the dramatic flood events shown in the flood visualization, a skybox showing a cloudy gray sky from the asset *AllSky Skybox Set* on the unity asset store is applied to enhance immersion and visual appeal.

5.3. Navigation and Interaction

The navigation and interaction of *FloodVis* includes selection, controller input using laser-pointer and teleportation. To interact with the 3D view of Bennewitz in VR, users need to wear the HTC VIVE headset and need controllers for the interaction. The user can sit comfortably or stand while using *FloodVis*. For exploring around users can move their head or use the snap turn feature by pressing the east or west button of the controller. The snap turn feature allows users to turn left and right with an 45° angel without moving head/body. For navigation, the metaphor of teleportation was used to avoid motion sickness as much as possible. Users can use teleportation by pressing the north, south or center button of the right controller and choose a potential teleportation point using a ray of the virtual laser pointer coming out of the right controller. The green color of the ray indicates teleportation possibility and red color indicates teleportation is not possible. Users can increase or decrease elevation by choosing the north and south buttons on the trackpad of the left controller. This action instantly changes the camera position by 10 m along the vertical axis. Users can pop up the menu by selecting the menu button of the right controller and choose anything from the menu by pulling the trigger of the right controller. Turning on the playback mode that cycles through all the flood events is possible by choosing the grip button. The interaction mapping is shown in figure 6.

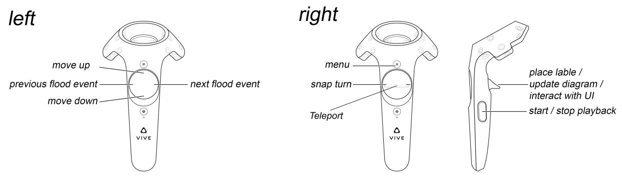

Figure 6: *Navigation concept mapping the actions to the buttons of the HTC VIVE controllers*

5.4. System Requirements

As already mentioned, *FloodVis* is developed using Unity but this is not required to run the program. Users need to have a HTC VIVE base station, headset and controllers for the interaction and SteamVR installed. A minimum OS - Windows 7 SP1, Windows 8.1 or later, Windows 10; processor - Intel Core i5-4590/AMD FX 8350 equivalent or better and memory of at least 4 GB RAM is required. For graphics - NVIDIA GeForce GTX 1060 AMD Radeon RX 480 equivalent is recommended.

6. Results and Evaluation

6.1. Results

Figure 7 represents the non-flooded 3D model of Bennewitz from the birds' eye view (left) and the flooded ground from ground view (right). These views can be achieved by teleporting to the positions or varying the elevation.

Figure 8 illustrates the main menu of *FloodVis*. Choosing *Data Set Selection* brings up a new menu dialog where users can choose between four different datasets including simulation data for 25 hydrologic parametrizations and time-series data with an interval of 1 hour. From the main menu, users can adjust the interval length of every flood event and visualize how each scenario is inundating Bennewitz by enabling the playback mode. It is possible to check the controller mapping by selecting help through the [?]-button from the top-left corner of the main menu. Users can decide whether they want to teleport to the ground or if they want to maintain their current elevation during teleportation by checking the teleport to ground option. Additionally, the user can switch off the visibility of the water level diagram showing the inundation depth of all scenarios of a specific location indicating uncertainty (figure 9) within the selected dataset. Choosing a point of interest and pulling the trigger button on the right controller, updates the diagram to visualize all water levels at this point. Saving and loading allows the opportunity to save specific inundation depths of the point of interest. *Quit Visualization* closes the entire application.

Figure 9 also shows two different views from above the study area. In the top most image, users placed labels in the virtual world

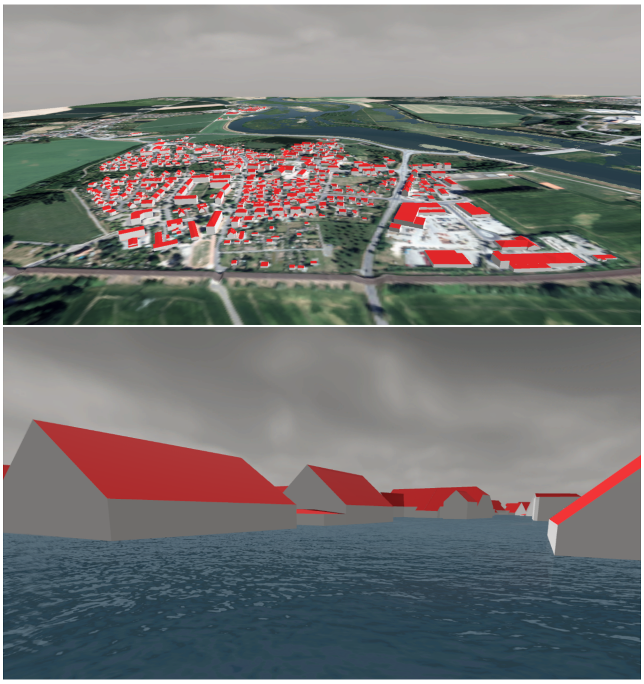

Figure 7: *3D model of Bennewitz from different perspectives; (top) view without flood, (bottom) submerged ground view*

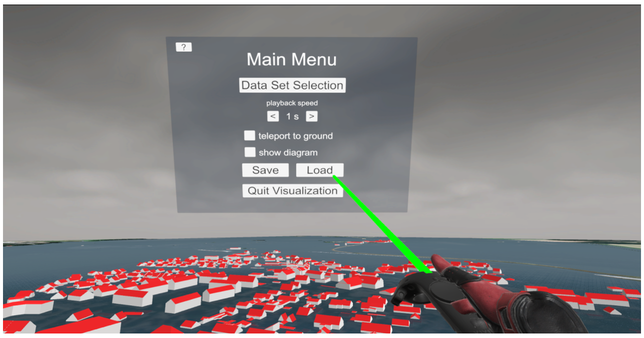

Figure 8: *Main menu of the FloodVis User Interface; the selection tool using laser ray pointer from right controller supports to choose anything from the menu*

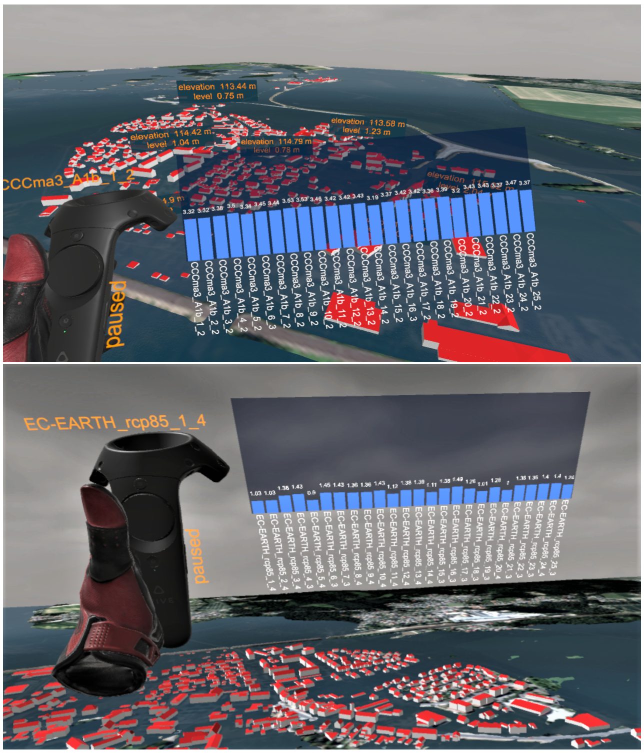

Figure 9: *A scenario is attached to the left controller. The diagram shows water depths of 25 flood events with low uncertainty for different data sets (please check applied data for more details about different data set). Labels indicate elevation and water level (top).*

to measure elevations and water levels. All labels are updated when the flood event is switched by the left and right buttons on the left controller or by enabling the playback mode using the grip button on the left controller. To make sure that the user can read the values shown in the labels, they always face towards the user and scale depending on the distance to the user. User can have an idea about the current scenario using the label attached to the left controller. It is also possible to identify fully or partially flooded houses easily.

6.2. Evaluation

In general people are under-prepared for floods [MK18] due to less frequent flood experiences. But the sense of presence can influence the preparation for rare frequent floods. To evaluate *FloodVis*, we performed an extensive user study with 28 participants both online (15) and offline (13) by (i) comparing the traditional flood maps, animations, *FloodVis* as a desktop application and (ii) *FloodVis* including VR experience.
Along with traditional flood maps and animations, *FloodVis* as desktop app without VR interaction was presented to the participants to determine whether the desktop app can provide a sense of presence and influence the decision making. Participants were asked to identify critical locations and submerged houses. At the end all offline participants were surveyed concerning the sense of presence and whether this sense of presence can influence decision making (directly - verbal, indirectly - questions that indicate influence). Additionally, this solution was presented in the inauguration of a ScaDS.AI's "Living Lab" as a demonstrator where politicians and decision makers were present and the feedback was extremely positive.

To evaluate the sense of presence in the survey, our questionnaire shown in table 1 was inspired from the *WS Presence Questionnaire* [WS94]. For system evaluation, we used the *System Usability Scale (SUS)* [JTWM96] combining positive and negative questions where the user needs to think more before answering. To measure whether users felt simulation sickness, we applied the *Simulation Sickness Questionnaires* [KLBL93]. The evaluation of

FloodVis resulted from concrete project based questions. A choice of the project focused questions are shown in table 2 and simulation sickness questions depicts table 3. In total there are 49 questions including 24 project focused questions, 10 system usability questions, 14 simulation sickness questions and 11 sense of presence questions. Except the questions, users were also open to give feedback or highlight if they liked/disliked something significantly.

All the questions used for the user study as well as the results can be found in the supplementary materials as Q1 (general, comparison with non-VR, *FloodVis*, system usability and simulation sickness) and Q2 (sense of presence).

As introduction of the user study, users were given an overview of the data, VR experience and risks of motion sickness were also described to the participants as 90% of the participants did not have prior experience with VR. Most of the participants have a civil engineering background with at least a Bachelor's degree. Some participants come from directions of BigData, Renewable Electricity Production, Spatial Analysis, Geoinformation Systems and Remote Sensing, Political Science, and Scientific Visualization. Participants were from the age group of 25-42 years, most of them were students from Technische Universität Dresden, researchers from ScaDS.AI and countries from Bangladesh, Ethiopia, France, Germany, India, Italy, Mozambique and Pakistan.

Due to the restrictions of the Covid pandemic regarding personal meetings, an online user study was implemented for the participants who really wanted to experience the system but could not attend personally. Although it is difficult to ensure the sense of presence online, videos of *FloodVis* with and without VR interaction were used to provide a general understanding of *FloodVis*.
15 users participated in the online user study and most of them expressed their interest to test the system in person and almost all of them agreed to have a better visualization in VR comparing to non-VR mode shown in figure 10. One participant actually participated the user study in person (BigData researcher) later and agreed that the sense of presence influences the decision making in a positive manner.

Another survey was performed to understand the sense of presence including 13 participants in a scale from 1 to 7 where the scaling is different for each question, in general with 1=not at all and 7=very important except Q9. The average results are shown in table 1. Users were asked whether this immersive inspection is important for the people living in flood prone areas and majority of this group highly agreed that it is important (Q1[sense of presence]: Mean=6.85, SD=0.38).
For most of the users, being able to identify submerged houses was interesting and according to them if the residents of Bennewitz as well as policy makers could experience this application and identify their own submerged houses, they would be much more concerned about the flood risks. None of the participants complained to have long delays between their actions and expected outcomes (Q9[sense of presence]: Mean=2.08, SD=0.64) scaled as 1 (no delays) to 7 (very long delays).

To understand the usability and in-general idea about *FloodVis*, another user study was performed with 10 participants in a scale from 1 (strongly disagree) to 5 (strongly agree). In general, *FloodVis* received a positive feedback. Most of the users liked the overall experience (Q1: Mean=4.6; SD=0.70), and most of the participants agreed or strongly agreed to have navigation efficiency for teleportation (Q9: Mean=4.50; SD=0.53). Almost all of the users agreed or strongly agreed that presenting complex data in VR is possible (Q18: Mean=4.8; SD=0.42), whereas the majority of them agreed or strongly agreed that VR supports information presentation for policy and public (Q21: Mean=4.7; SD=0.48) and almost all of them agreed or strongly agreed to have a smooth navigation in VR, with a significance of the elevation labels (Q7: Mean=4.3; SD=0.48, Q23: Mean=4.6; SD=0.70). The average SUS score achieved 79.0 with a rank B, meaning a good system with room for improvement.

Table 1: *Questions and users' input in a scale of 1 to 7 to understand the sense of presence*

	Mean	SD
Please state your opinion on how important the immersive inspection is for people owning a building in a flood affected area?	6.8	0.4
Please state your opinion on how important the immersive inspection is for people that want to buy or build a building in a flood affected area?	6.9	0.3
How much did the visual aspects of the environment involve you?	6.1	0.8
How involved were you in the virtual environment experience?	6.4	0.8
How well could you examine objects (houses/flood events) from multiple viewpoints?	6.2	0.7
How closely were you able to examine objects (houses/flood events)?	6.5	0.5
How well could you place lables (elevation & water depth) in the virtual environment?	6.5	0.7
How helpful were the labels while playback (both in ground view and bird eyes view)?	6.5	0.5
How much delay did you experience between your actions and expected outcomes?	2.1	0.6
How natural did your interactions with the environment seem?	5.5	0.5
How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	6.5	0.5

An overview of the user study results are shown in figure 11. The same group was questioned regarding simulation sickness in a scale of 1 (not at all) to 5 (very strong) and none of them complained to have any mild to major simulation sickness like general discomfort, fatigue, headache, difficulty concentrating (Q35; Mean=1.2; SD=0.4, Q36: Mean=1.0; SD=0.0, Q37: Mean=1.2; SD=0.4, Q43: Mean=1.0; SD=0.0) except one who stated to have difficulty on focusing (Q39: Mean=1.6; SD=1.1).

The applied non-VR materials for this user study, e.g. flood risk maps and simulations, as well as the video demonstration of *FloodVis* can be found in supplementary material.

Table 2: *Sample of project-based questions and users' input in a scale of 1 (strongly disagree) to 5 (strongly agree)*

	Mean	SD
I like the overall experience	4.6	0.7
Possibility of smooth navigation inside the VR scene of Bennewitz	4.3	0.5
The teleportation feature allowed efficient navigation in VR	4.5	0.5
Presenting complex data in a Virtual Reality environment is possible	4.8	0.4
The temporal evolution of the flood event supports to detect critical locations	4.6	0.5
VR supports information presentation for policy and public	4.8	0.4

Table 3: *Sample of simulation sickness questions and users' input in a scale of 1 (not at all) to 5 (very strong)*

	Mean	SD
General Discomfort	1.2	0.4
Fatigue (an overall feeling of tiredness or lack of energy)	1	0.0
Headache	1.2	0.4
Difficulty Focusing	1.6	1.1
Difficulty Concentrating	1.0	0.0

7. Current Limitations and Future work

Although *FloodVis* received a positive feedback from most of the users, the user study identified some limitations. Currently, it is not possible to see any map to have a proper understanding of the area which misleads the user initially. Although after applying *FloodVis* for a while, the user gets familiar with the environment. Our next step is to add some 2D map to guide users as well as a guided tour to make this visualization more exciting and easy. Later, we wish to extend this solution to ScaDS.AI's "Living Lab" to make it accessible to public users.

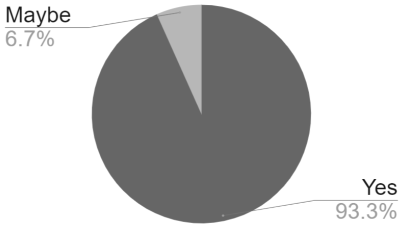

Figure 10: *Pie chart from the online survey with 15 participants showing the majority agreeing on better visualization of* FloodVis *comparing to non-VR visualization*

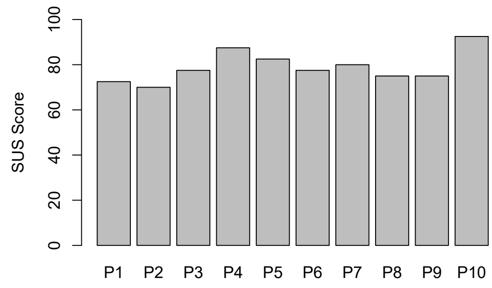

Figure 11: *SUS results of 10 individual participants*

The approach of *FloodVis* is based on open source data from Germany and software tools which makes the generalization of FloodVis to other areas possible. A limitation arises from the lack of high temporal and spatial resolution modeling results for flood events. Scalability cannot be assessed at this time, but will result from the future application of *FloodVis* in other areas. We will additionally extend the project to the visualization of constructions damages at single houses. In future, we plan to extend this VR visualization to other climate impacts like heavy rainfall, heatwaves and drought events.

8. Conclusions

The goal of this research was to visualize ensemble flood risk for climate change in a way that is easier, exciting and significant for everyone and to know whether VR visualization justifies flood ensemble visualization and to know whether the sense of presence can influence decision making. This paper can argue about the positive feedback received from different groups of participants attending the evaluation virtually as well as physically. According to one user, "we have been watching weather related disaster news and videos for years but we do not feel the outcome as we are not being effected personally. But this type of visualization can actually enable the sense of presence and this might be an asset helping us to prepare for the worst." None of the participant disagrees with this statement. This paper can also argue about smooth navigation, fast response, techniques to avoid simulation sickness and the overall experience. With further development, *FloodVis* can be an asset to visualize weather and climate-related hazard and risk data and prepare for the worst. We, therefore, plan to continue this research by working on the limitations and extensions.

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