

## Article

# Vulnerability Visualization to Support Adaptation to Heat and Floods: Towards the EXTRA Interactive Tool in Norrköping, Sweden

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**Abstract:** Municipal actors are increasingly expected to consider climate adaptation in operative and strategic work. Here, digital environments can support strategic decisions and planning through visual representations of local climate risks and vulnerabilities. This study targets visualization of vulnerability to heat and floods as a means of supporting adaptation action in preschools, primary schools, caring units, and municipal residential buildings in Norrköping, Sweden. Workshops with sector leaders identified vulnerability indicators used as a basis for collecting, calculating and representing self-assessed vulnerability of individual units and buildings. Informed by user inputs, a map-based interactive visual tool representing resulting vulnerability scores and risk maps was developed to support (1) planners and sector leaders in strategic prioritization and investments, and (2) unit heads in identifying adaptation measures to reduce local flood and heat risks. The tool was tested with adaptation coordinators from targeted sectors. The study finds that the tool made it possible to overview climate risks and adaptation measures, which arguably increases general governance capacity. Allowing yearly updates of set scores, the tool was also found to be useful for monitoring how vulnerability in the municipality evolves over time, and for evaluating how adaptive efforts influence calculated risks.

**Keywords:** climate vulnerability; climate change adaptation; geographic visualization; information visualization

## 1. Introduction

The literature and information on climate change vulnerability and corresponding risks are growing. Yet, local communities face challenges to translate information about abstract vulnerability assessments into tangible local implications, and further, to use it in practice to steer action and find measures at an operational level [1]. As Patiño and Gauthier [2] claim, vulnerability assessments can facilitate the understanding of local risks and impacts to trigger direct interventions and thus generate applied outcomes within pre-existing capacity constraints.

While the literature on vulnerability assessments for various domains and areas is growing (e.g.) [3–6], less attention has been given to the design and evaluation of frameworks and tools that can be used to convey vulnerability in a way that is usable for local actors. For instance, an information delivery and decision support framework called CoastAdapt [7,8] has been developed for Australia's coast, to inform about the risks it faces from climate change and sea-level rise, and what can be done to respond to those risks. In turn, visualization has been recognized as a suitable approach for providing vulnerability scores for municipal officers in Norway who need to know both the location

of vulnerable places and why these places are vulnerable [9]. Moreover, visual interfaces have also proved to be efficient for communicating climate-related information of use for stakeholders [10]. Nevertheless, as Bohman et al. [11] report, users may want to explore data in their own way rather than being provided with the final, “black-boxed” vulnerability rankings. We address this demand for decision-support tools for vulnerability visualization that make climate adaptation relevant and tangible for local administrations.

With this study, we explore the potential of vulnerability visualization to support municipal practitioners in their efforts to adapt to extreme events and climate impacts. Two research questions (RQs) led our investigations:

- (RQ#1) How can climate risks and corresponding indicators of vulnerability to heat and floods be identified and made tangible through dialogues with municipal practitioners?
- (RQ#2) How can the potential of geographic visualization techniques be utilized for making vulnerability scores useful and applicable for local adaptation planning and decision-making?

We examine the relevance of interactive visual interfaces for climate adaptation through an in-depth case study on a vulnerability visualization tool intended to support climate adaptation in selected municipal sectors in Norrköping, Sweden. Specifically, we report on the user-centered design of the EXTRA tool, an interactive geographic visualization (geovisualization) for four sectors: preschools, schools, elderly and social care, and residential buildings administrated by a municipal housing company. Focusing on two user-identified key risks, heat and floods, the tool provides access to vulnerability scores based on an extensive researcher-led vulnerability assessment conducted during 2015–2018. This paper presents a comprehensive study comprising a vulnerability conceptualization, requirements identification, and vulnerability calculation, along with the development and evaluation of a visualization tool. The approach underlying the tool development enables collecting feedback necessary to develop vulnerability scores and alter them, if they are not in line with the users’ observations, or if already implemented adaptation efforts have influenced the vulnerability of the considered object(s).

By providing a dynamic cartographic representation of vulnerability in the targeted sectors, the EXTRA tool aims to support, first, planners and sectoral adaptation managers with an overview of the most vulnerable units/buildings and the generally most needed adaptation measures to facilitate strategic responses and investments, and second, unit heads with hands-on information of measures needed to reduce the unit’s flood and heat risks. Thus, we aim to increase the understanding of how particular objects are vulnerable to heat and floods and provide users with a critical step for their engagement in decreasing vulnerability.

## 2. Background

### 2.1. Climate Change Vulnerability

The future climate in the Nordic countries is expected to become warmer, wetter, and wilder [12,13]. Therefore, studies have examined vulnerability of various sectors towards riverine and pluvial floods, heat, and other extreme events to identify both where the most vulnerable places (objects) are located, as they may be in need for adaptation, and why these places (objects) are vulnerable as such knowledge may indicate how to adapt [6,14].

Vulnerability is a composite concept and many definitions exist [15]. However, in the context of climate change, the definition by the Intergovernmental Panel on Climate Change (IPCC), conceptualizing vulnerability as a function of a system’s exposure, sensitivity, and adaptive capacity [16,17], recently has been frequently used [18].

- Exposure means the climate risks facing a place or a system. Exposure to heat and floods is connected to location. For heat, building density, degree of hardened surfaces and buildings’ surface material are influencing the local temperature. Whereas in low-lying areas, the degree of

hardened surfaces and type of sanitary sewer system and/or storm drain system are influencing the local flood risk.

- Sensitivity captures the degree to which a system responds to a given climate change. For buildings at large, the degree to which indoor temperature responds to higher outdoor temperature is affected by, e.g., ventilation type and indoor and outdoor shading equipment [13]. Regarding floods, the sensitivity of buildings is affected by, e.g., basement entrances, basement floor drains, and whether important equipment and activities are located in a flood-prone part of the building [19]. Studies also acknowledge [20–22] that elderly, young children, sick and functionally impaired are particularly sensitive to extreme heat but also to direct and indirect flood risks.
- In turn, adaptive capacity concerns “the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate” [16:89]. Routines, checklists, organizational readiness, and crisis management affect the ability to handle heat and flood. This also extends to access to equipment to reduce the consequences of floods, such as pumps, and extreme indoor temperatures, such as portable AC-units [23].

From a practical perspective, vulnerability indices are complex and often hard to understand for potential users [11]. Therefore, instead of a top-down approach, based on expert knowledge, a bottom-up approach engaging practitioners seems to be more promising for generating information of applied value to municipal officials. However, regardless of the approach used, adequate methods need to be employed to efficiently communicate on vulnerable places and objects that require adaptation actions.

## 2.2. Geovisualization Tools to Support the Implementation of Adaptation

Successful adaptation to heat and floods can be executed through actions that increase adaptive capacity and decrease vulnerability [6,8]. These might be alterations of policies regarding working hours during extreme heat [24], physical interventions to local infrastructures, such as roads or water drainage system [25], and managing and regulating water resources [5]. However, adequate knowledge of factors that make objects vulnerable is necessary to strengthen local authorities’ capacities regarding strategic climate adaptation. Such knowledge can be retrieved through various strategies. Nevertheless, each strategy requires efficient support. Stakeholder engagement to gather reliable information accompanied by geovisualization to support analysis, learning and implementation of climate adaptation are discussed as effective means [26].

Recently, numerous initiatives have led to the development of geovisualizations supporting climate adaptation. For instance, the European Research Area for Climate Services (ERA4CS) supports research for developing tools and methods to cope with climate variability. Further, the California Energy Commission has provided advisory oversight of visualization tools such as Cal-Adapt [27]. Hence, both researchers and practitioners have already suggested areas where visualization can facilitate climate adaptation. Such tools come in multiple forms, varying by the amount of data input, supported user tasks, provided functionality, and proficiency required to use them. Neset et al. [10] reviewed map-based web tools and concluded that linking climate information directly to relevant adaptation measures would improve such tools, as they provide relevant adaptation information on their separate parts. In turn, Camarillo-Naranjo with colleagues [28] concluded that climate information can be considered common information that should be distributed, used by and benefit all. Finally, a tool that provides integrated vulnerability scores has been designed by Opach and Rød [9], concluding that complex visual interfaces might look “too scientific” for inexperienced users.

Advances in climate research and progress in information and communication technology constantly open new opportunities. One of those opportunities concerns citizen interaction, drawing from the literature on GeoParticipation and citizen science and is exemplified in the CityPlanner application in use in several Swedish cities (e.g., Norrköping), and in emotional mapping [29]. CityPlanner lets users suggest future city planning and evoke discussions regarding the cities’ civic

potential [30]. In turn, emotional mapping enables expressing reactions to specific issues such as routes and places for bicycle infrastructure. Accordingly, previously passive citizens become active and demanding “customers” [31].

Literature outcomes directly advocate equipping interactive tools with reliable vulnerability assessments [9] and functions that let the tools’ users access local knowledge on how to cope with extreme natural events [11]. In contrast to the tools developed with a top-down approach (by experts, for experts), tools that are based on content generated through citizen interaction are more likely to provide understandable information [26].

### *2.3. Case Study: Vulnerability Visualization to Support Adaptation in Norrköping*

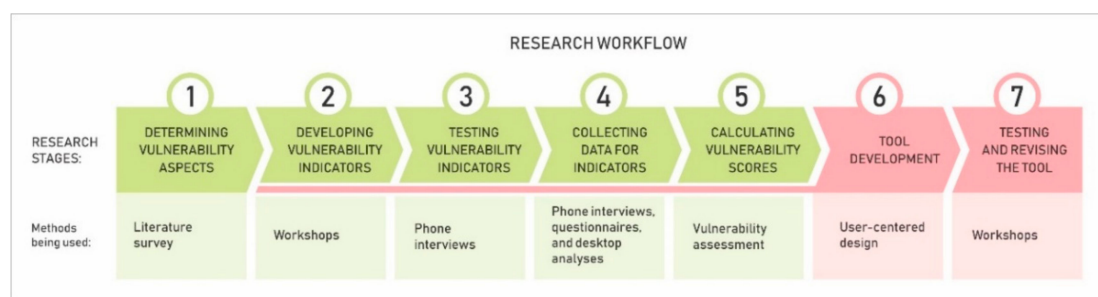
This study targets climate vulnerability and adaptation of selected municipal sectors in Norrköping, a mid-sized municipality (population 140 000) in eastern Sweden. The city center of Norrköping is located by a river mouth in a bay of the Baltic Sea, has an old wastewater infrastructure, and has been increasingly densified over the last decade. Norrköping’s exposure and sensitivity in combination with anticipated climate change make the municipality vulnerable to floods and heat [32], which recent weather impacts have showcased. For example, in 2011 Norrköping was hit by a cloudburst that flooded some 850 basements and affected road and railroad infrastructure [33]. Regarding heat impacts, July 2018 was reported as the hottest month in the last 260 years in Sweden. In Norrköping, that exceptionally hot summer put high pressure on municipal caring and preschool services, where most units reported that heat had severely affected their activities, staff, and caretakers [23].

To increase the capacity to manage climate-related risks in Norrköping, a decision was taken in 2014 to develop an adaptation plan covering all administrations and municipal utilities. A cross-sectoral group, consisting of municipal officials with a mandate to coordinate climate adaptation in their respective sectors, and researchers (including authors of this paper), was mandated to develop this plan based on a comprehensive vulnerability assessment. The group has met regularly over the past five years and is expected to deliver the plan by the end of 2019. The vulnerability assessment is used to inform discussions not only about practical adaptation needs and measures but also about strategic responses and principles to be included in the plan.

The vulnerability assessment has been led by the involved researchers and focused on risks related to heat and floods. These risks were considered relevant for all municipal activities, yet hard to comprehend due to their complex effects and impacts. Vulnerability along with its aspects and detailed indicators were especially seen as hard to overview within such municipal sectors as preschools, primary schools, caring units, and residential buildings. It was caused by the fact that those sectors’ individual units are dispersed spatially and that their personnel were relatively unfamiliar with climate adaptation. To be able to grasp vulnerability in these sectors a map-based tool was deemed necessary by the involved sectoral adaptation coordinators. The tool presented and tested in this study answers to this demand.

## **3. Study Design and Methods**

We address the needs outlined above by designing a decision-support web tool that provides local strategists with an easy access to geographies of climate vulnerability to heat and flood to guide and support climate adaptation. To assess and visualize flood and heat vulnerability in preschools, primary schools, caring units, and residential buildings in Norrköping, a stepwise workflow was applied, consisting of seven stages (Figure 1). The methods used at the various stages differed significantly. Furthermore, as presented in Figure 1, Stages #2–5 are all part of the tool development at Stage #6 since they provided insight into the decision-making processes that the tool aims to support, and thus what role(s) the tool could have in supporting adaptation. The methods are outlined below, whereas the outcomes of each stage are described in the Section 4.



**Figure 1.** A stepwise workflow used in the study along with the methods being used at the workflow's specific stages.

### 3.1. Stage #1: Determining Vulnerability Aspects

To determine general features (aspects) that potentially constitute vulnerability, studies addressing climate vulnerability and risks were reviewed by applying “constant comparison analysis” [34]. Using the Google Scholar database with combinations of the following search terms: “climate change”, “impacts”, “vulnerability”, “heat”, “flooding”, “preschool”, “primary school”, “vulnerable groups”, “elderly”, “infant”, “child”, “disabled”, and “building,” a set of studies were collected. Abstracts of these studies were scanned to isolate the most relevant articles, which were read in full (in a total of 31 papers). Drivers of vulnerability in the four targeted sectors were identified from the resulting list of papers and lastly grouped under either of the three vulnerability dimensions, i.e., exposure, sensitivity, and adaptive capacity (Section 2.1). Lists of the flood (Table S1) and heat indicators (Table S2) used and the full list of references are presented in the Supplementary Materials.

### 3.2. Stage #2: Developing Vulnerability Indicators

To develop precise and exact vulnerability indicators, workshops with municipal practitioners were organized in 2016 and 2017. The workshops (Table 1) were arranged separately for the targeted sectors, except education units—preschools and primary schools—for which one combined workshop was held since they are led by the same municipal steering group. All workshops were audio-recorded and transcribed.

**Table 1.** Workshops arranged to develop vulnerability indicators.

Sector	Date	No. Participants	Work Responsibilities of Participants
Education (preschools and primary schools)	2016.11.21	6	Facilities responsible, adaptation coordinator, heads of preschools and primary schools.
Caring units (elder centers, caring homes and home care units)	2017.01.23	3	Continuity analyst, adaptation coordinator, unit head
Residential buildings	2017.09.27	6	Facilities and safety responsible, maintenance staff, area heads, adaptation coordinator
Residential buildings (follow-up workshop)	2017.10.11	3	Facilities and safety responsible, adaptation coordinator, maintenance

The workshops lasted 1.5–2 hours and were arranged in the “stakeholder dialogue” format [35]. In each, first, the concept of vulnerability was introduced and its general aspects were identified to capture the respondents’ view of overall drivers of vulnerability in their sector. Second, vulnerability aspects considered at Stage #1 were revisited to jointly develop indicators that could serve as proxies of the highlighted risks. Third, respondents were asked to determine weights for the indicators by elucidating what risks would have the most drastic impacts on their activities and thus should be



avoided as well as what indicators they viewed to have the most influence in those risks in order to establish weights. For the residential buildings sector, the respondents provided weights of the identified indicators, as well as questions posed to provide data for each indicator, were discussed at a follow-up workshop (Table 1).

### 3.3. Stage #3: Testing Vulnerability Indicators

Once indicators and weights were developed for each sector, a reporting system in the form of a questionnaire was created. Each indicator was translated into a question with 2–3 response options. For example, the indicator “impervious surfaces” was translated into the question “How big proportion of impervious area does the surface surrounding your building feature?” with three response options: “mainly green/permeable,” “around 50%”, and “mainly impervious.” For some indicators, “yes/no” questions were created, for example, “Do you have a checklist or a routine for managing heat?” The reporting system covered risks related to both flood and heat and was divided into questions covering exposure, sensitivity, and adaptive capacity.

To pilot test the indicators and the reporting system for the education and caring sectors, phone interviews (n = 10) were held in January 2017 with selected unit heads: two primary school heads, two preschool heads, two elder center heads, two caring home heads, and two heads of home care units. During the interviews, a facilitator read questions with response options and asked if they were seen to make sense for the unit and were easy to answer. When all questions were presented, the respondent was asked to reflect on the questionnaire, and if he/she agreed with the weightings set for the indicators.

Based on inputs from the pilot test, a few questions and response options were reformulated to become easier to answer for unit heads and to better capture the everyday activities in the different sector units. A few indicators that were perceived as saying more about overall vulnerability in the municipality rather than within each unit were consequently removed. Finally, a few weights were adjusted. Through constant updates of the questionnaire during the phone interviews, the response time decreased considerably. A list of questionnaire items, i.e. the vulnerability indicators, and response options for preschools, primary schools, elderly and social care as well as residential buildings are presented in Tables S3–S8 in the online Supplementary Materials.

### 3.4. Stage #4: Collecting Data for Indicators

To collect data for indicators, we used different approaches for residential buildings and the remaining sectors’ objects (education and caring units). For education and caring units, phone interviews using the final set of questionnaires were performed with heads of units in January–May 2017. They were held with:

- 57 heads of elderly centers, caring homes, and home care units, covering a total number of 82 units,
- 43 preschool managers, covering 114 units,
- 28 interviews with school principals, covering 28 units.

Some heads within the care sector, and all preschool heads, were responsible for more than one unit. This meant that more units were covered than the number of interviews held. If heads of several units were interviewed, they provided answers for all their units separately. Interviews covering only one unit lasted about 20 minutes each, whereas interviews covering up to three units lasted about 35 minutes.

The decision to use phone interviews rather than a web form was taken to increase the response rate and consequently provide better data coverage. Considering the coverage of responses including 69% of the caring units, 93% of preschools and 56% of schools, it appears to have been a good decision.

In turn, a research assistant was hired by the municipal housing company to compile data matching the indicators for residential buildings through a desktop study. For most indicators, data were found in company databases, drawings, and documents. However, to cover indicators that lacked data

(e.g., flooding history), internal interviews were held with maintenance personnel and area heads. Some indicators further demanded data from the municipal water utility (e.g., buildings located in areas with combined sewage and stormwater system), for which maps were reviewed together with a utility representative. In total, data matching the indicators were collected for 574 buildings during January–April 2018.

### 3.5. Stage #5: Calculating Vulnerability Scores

The data from Stage #4 were then summarized in an MS Excel spreadsheet. Using the pre-defined vulnerability scores for each response option (see Stage #2), overall vulnerability scores were calculated for all units and buildings by a linear combination of all collected scores. It is important to acknowledge that the overall vulnerability scores, using the proposed procedure, result in that bad performance of one indicator can be compensated by the good performance of another [36]. Therefore, through the separation of indicators underexposure, sensitivity, and adaptive capacity, combined scores for the three vulnerability dimensions were calculated separately to ensure that users would get insight into overall vulnerability scores but also, would get a good understanding which dimension(s) influences the overall vulnerability of the individual object the most. Such a procedure was accomplished separately for vulnerability to floods and heat. Nevertheless, it is important to note that the proposed procedure is limited by the researchers' and staff's incomplete understanding of the complex issues of vulnerability to flood and heat [36] and thus, that the results should not be treated as a final result, rather as a systematic basis for discussions on how to adapt education and caring units and residential buildings.

### 3.6. Stage #6: Tool Development

The tool development was led by a user-centered design approach [37], which is an iterative process where designers involve users throughout the tool development using various methods such as workshops or interviews. The tool was developed from scratch using various open-source web technologies. Although the second prototype was done with the Angular web framework, mostly at Stage #6, the tool's initial prototypes were being designed iteratively and collaboratively with end-users over the period 2016–2019 (Table 2) by means of various JavaScript libraries (e.g., OpenLayers, jQuery) with no web frameworks being used, based on the input from workshop participants and respondents in the preceding stages (see Figure 1). The workshops conducted at Stage #2 helped us to recognize requirements guiding the EXTRA tool design. Adaptation coordinators and municipal practitioners also suggested functional requirements for the tool. Furthermore, the phone interviews at Stage #3 allowed us to test the reporting system to be implemented in the EXTRA tool. Although the system's software was not ready yet, the interviews were done in a way that resembled web questionnaires. After revisions and corrections, the questionnaires were to form part of the tool's data collection module.

### 3.7. Stage #7: Testing and Revising the Tool

A workshop was held with representatives from the cross-sectoral adaptation group in Norrköping in September 2019 to evaluate the tool, discuss its use in municipal adaptation work, and gather suggestions for improvements. A total of 10 coordinators participated, including representatives from all targeted sectors. The workshop was divided into three phases. First, a demonstration of the tool and its main components was held. Second, participants commented on the various components and the tool design. Third, a general discussion on the potential use of the tool was conducted.

During the workshop, the following broad questions were asked to the participants:

- (Q#1) What is your impression of the tool and its main components/functions?
- (Q#2) How could the tool be used by planners/decision-makers/sector leaders? For what decisions is it suitable?
- (Q#3) How could it be used by heads/staff at the targeted units?

- (Q#4) How could it be improved to better support decision-making and practical work within the targeted sector units?
- (Q#5) How could it be used in other sectors?

The opinions and suggestions from workshop participants will serve as the basis for revisions to be performed as a follow-up step of this study.

**Table 2.** The EXTRA tool development process.

Step	Prototype	Period	Description
1	Handmade drawings and black-board sketches	2016–2017	Requirement identification, testing the reporting system to be implemented in the tool
2	First prototype of a web application	Winter 2017/2018 to late fall 2018	Software developed in JavaScript with no web frameworks being used; the prototype consisted of a map component and a table; a placeholder was used for the questionnaire
3	Second prototype	Winter 2018/2019	We used Angular web framework to develop the second prototype; the questionnaire component was developed but not linked with a database
4	Prototype revision	Spring and summer 2019	Layout and functionality improvements were done; a number of changes concerned the way how information is visualized in the tool

## 4. Results

### 4.1. Vulnerability Aspects and Indicators (Stages #1–3)

The literature review performed at Stage #1 let us compile a set of vulnerability aspects that we found to be of primary importance to the targeted sectors. While a detailed description of the review results is outside the scope of this study, a majority of studies reviewed addressed how vulnerable groups such as elderly, disabled, and young children are vulnerable to heat, and—to some extent—to flood (e.g.) [20,21]. Moreover, the rich literature on anticipated climate vulnerability in buildings emphasized both flood and heat impacts in different building types and for various building materials [13,19].

Generally formulated aspects identified as important in influencing vulnerability within each of the targeted sectors were categorized as: (a) exposure, (b) sensitivity, and (c) adaptive capacity. Consequently: (a) aspects related to the location of buildings, outdoor spaces and associated infrastructure in relation to flood-prone areas and heat islands were categorized as exposure components, (b) aspects related to building type, its materials, placement of critical equipment, and share of residents in risks groups were categorized as sensitivity components, and (c) aspects related to preparedness to respond to flood or heat impacts such as availability of checklists, warning systems, and pumping equipment were categorized as adaptive capacity components.

In Stage #2, the vulnerability aspects from the literature were presented at the workshops. Most aspects were acknowledged by the participants, who however emphasized that they should be presented in an understandable way for the staff and thereby avoid technical language, such as in the impervious surface case described above, and by changing from “Building elevation” to “Is the building located lower than surrounding buildings, similar, or higher/on a hill?”. They also found it important that indicators explicitly relate to effective adaptation measures (when applicable) to facilitate unit heads being able to see how the unit’s vulnerability could be decreased. The workshops’ discussions enabled unit heads to remove some aspects, deemed irrelevant for their unit, and, on the other hand, to formulate indicators that say something about feasible adaptation actions, answering to research question one. Figure 2 exemplifies the most common vulnerability indicators developed for floods



resulting from the workshop discussions. Interestingly, many of the indicators were seen as applicable to most of the targeted sectors, which facilitates cross-sector comparisons of individual indicators.

Vulnerability component	Indicator	Preschools	Primary schools	Caring units	Residential buildings
<b>EXPOSURE</b> building & surroundings	Location (proximity to flood areas)	×	×	×	×
	Impervious surfaces	×	×	×	×
	Combined water systems	×	×	×	×
	Flooding history	×	×	×	×
<b>SENSITIVITY</b> equipment & materials	Basement	×	×	×	×
	Outdoor basement stairs/entrance	×	×	×	×
	Low lying electric equipment	×	×	×	×
	Low lying heat equipment	×	×	×	×
	Low elevator shaft	×	×	×	×
	Share of residents in risk groups	×	×	×	×
<b>ADAPTIVE CAPACITY</b> staff & knowledge	Checklist or routine	×	×	×	×
	Information on preventive measures	×	×	×	×
	Flood warning system	×	×	×	×
	Emergency management group	×	×	×	×
	Pumping equipment	×	×	×	×
	Access to food and water	×	×	×	—
	Access for emergency vehicles	×	×	×	×
	Ability to contact parents/relatives	×	×	×	—

**Figure 2.** Examples of indicators developed for flood vulnerability.

After identifying key risks and vulnerability indicators, the workshop participants were asked to determine the rankings (weights). Here, workshop participants from the building and caring sectors agreed that power outage was the most severe impact, clarifying what climate risks are most relevant for their sector (RQ1). As argued, if the main electric switch is placed close to a basement floor in a flood-prone location, this severely affects the building's vulnerability. Without electricity, as several argued, it would be, for example, harder to evacuate, elevators would stop, and electric pumps could not be used. To avoid this, the installation of backflow valves and water-proofing of doors to electricity rooms were suggested as effective adaptation measures to reduce flood risk. Sewage water intrusion was also identified as a key risk, especially for preschools, indicating the importance of combined water systems (sewage and rainwater) for the overall vulnerability of a unit. Moreover, caring unit heads considered district cooling or air condition as severely affecting vulnerability to heat, highlighting the importance of indoor cooling. Weighing discussions further targeted adaptive capacity indicators including, e.g., warning systems, routines, access to food and water for 24 hours and information about preventive responses. Though deemed relevant in affecting local vulnerability, generally adaptive capacity indicators were seen less influential than, e.g., flood history, location, and building design.

Once the list of indicators and their relative weighing had been set for flooding and heat vulnerability, each indicator was translated into a concrete question to be answered by unit heads. These questions were formulated so that they (1) follow the parlance within each sector, (2) are connected to potential adaptation measures, and (3) are understood by non-experts in climate vulnerability. Such formulations were discussed already at the workshops, providing the foundation for the sector-specific questionnaires, which consequently were developed.

#### 4.2. Data for Indicators and Final Vulnerability Scores (Stages #4–5)

For most indicators, the interviewed unit heads/school principals provided answers to the questions asked. However, they lacked knowledge of three indicators: proximity to flood areas and heat islands, and combined water systems. The researchers, therefore, collected data for these indicators afterward. Proximity was retrieved from flood maps (modeling of 100-year rain and modeling of 100-year flow in Motåla ström) and a heat island map (modeling of, e.g., building heights, materials, and street width) previously developed by the municipality. All considered units were overlaid with these maps providing data for the indicators. Similarly, all units were overlaid with the map of the municipal sewage and stormwater system providing data for that indicator.

For residential buildings, participants at both workshops helped identifying key staff that possessed data about the vulnerability indicators, such as flood experience, to facilitate data collection. For the proximity and combined water system indicators, a similar approach as above was taken. The desktop analyses and interviews provided data for all indicators for all 574 buildings.

The compiled data for all sectors gave a first impression of the main drivers of vulnerability. Some general patterns could thus be observed before developing the visual data representation. For example, the study showed that:

- Buildings with basements are more vulnerable to floods, but can provide cool indoor environments during heat waves,
- A surprisingly high share of primary schools have been flooded (approximately 75%),
- Many caring units are located in flood-prone areas and/or within the urban heat island,
- Few caring units and almost none of the preschools and primary schools have some form of indoor cooling, and
- Adaptive capacity is generally higher for caring units than for education units and within municipal housing companies.

During the interviews, most unit heads stated that they have not thought of vulnerability to floods and heat, despite acknowledging that it was part of their day-to-day activities and should have been handled strategically. Several also stated that they would benefit significantly by better descriptions of how their unit is vulnerable and how adaptation measures would be effective.

#### 4.3. The EXTRA Tool: Design and Functionality (Stages #2–6)

##### 4.3.1. Identifying Conceptual and Functional Requirements

First, a user-friendly visual representation of vulnerability scores was deemed fundamental by representatives from the cross-sectoral adaptation group to be able to grasp vulnerability in these sectors. Therefore, the first conceptual requirement—CR#1 (see Table 3) concerned designing a geovisualization to provide a quick and comprehensive representation of the geographies of vulnerable objects. Next, the workshop discussions at Stage #2 and phone interviews at Stage #3 clarified the benefits of including a module for data collection (CR#2), following the questionnaire outline to allow for adjustments in vulnerability scores once adaptation measures had been taken. The phone interviews at Stage #4 clarified the need to include risk maps in the tool (CR#3). Moreover, the interviews also clarified the need to overview vulnerability components that were most influential for each unit (CR#4).

**Table 3.** Conceptual requirements (CRs) identified for the EXTRA tool.

ID	Requirement	Description
CR#1	Design a user-friendly visual representation of vulnerability scores	Employ interactive geovisualization to convey vulnerability scores to intended users.
CR#2	Add a module for data collection	Let users modify unrepresentative scores through an interactive web questionnaire embedded into a visual interface.
CR#3	Include risk maps	A set of auxiliary thematic overlays with risk maps is seen as of value to stakeholders who might need to know whether their units are situated in a risk area for floods or urban heat.
CR#4	Show the structure of vulnerability scores	Provide an overview of which components of vulnerability have the most impact on each individual unit.

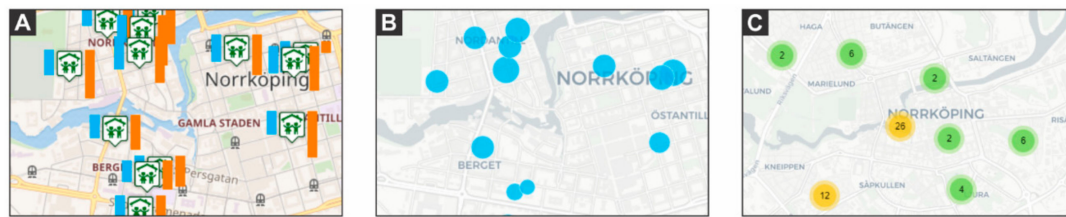
Although the target audience for the EXTRA tool includes municipal officials and urban managers with a more or less explicit task to adapt to climate risks, the group is diverse and differently experienced in interpreting geographic information. Considering this and CRs above, we identified functional requirements (FRs) guiding its design in relation to research question two, to support the user experience with the EXTRA tool. For example, CR#1 (Table 3) about the need for geovisualization was accompanied by FR#2 (Table 4) to show vulnerability scores as proportional map symbols.

**Table 4.** Functional requirements (FRs) of the EXTRA tool.

ID	Requirement	Description
FR#1	Organize navigation throughout the tool by sectors and hazards	The tool's content is grouped by sectors (preschools, primary schools, caring units, and residential buildings administrated by a municipal housing company) and by hazards, i.e., heatwaves and floods.
FR#2	Vulnerability scores shown as map symbols	Proportional map symbols are used to visually encode vulnerability scores.
FR#3	Basic visualization and interaction techniques	To avoid user reluctance, only well-known visualization and interaction techniques are used.
FR#4	Different base maps	Different background maps are used to facilitate the interpretation of vulnerability scores.

#### 4.3.2. Addressing CR#1 and CR#4: Showing Vulnerability Scores on an Interactive Map Display

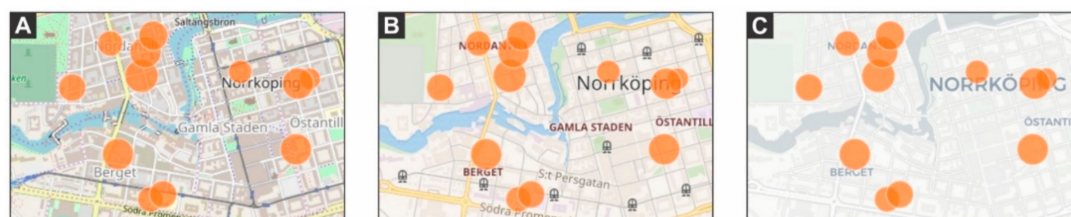
As determined in FR#2, although we employed proportional point symbols for objects of any kind, we have also experimented with glyph-based mapping [38] to show the structure of vulnerability scores as suggested in the workshops (CR#4). However, we decided to use proportional point symbols to fulfill FR#3, i.e., to use well-known visualization techniques and thus avoid user reluctance. In one attempt, we used vertical bars for objects from the education and caring sectors (Figure 3A) and proportional circles for residential buildings. Moreover, each object from the education and caring sectors was given three symbols at once, i.e., a map marker to show the geographic location and two sidebars to encode vulnerability scores separately for heat and flood. However, due to visual clutter and an unclear geographical location of the symbols, this setting evolved towards the simplest possible solution, in which only proportional circles are used consistently, no matter what sector and what vulnerability is being displayed (Figure 3B). Moreover, to fulfill FR#1, we decided to show only one vulnerability type at once since the juxtaposing of vulnerabilities to heat and flood could lead to misleading interpretations.



**Figure 3.** The evolution of the cartographic representation of vulnerability scores. ((A)—vertical bars are used to show vulnerability scores for each object, (B)—proportional circles are used to show one vulnerability score for each object, (C)—the attempt to aggregate overlapping symbols).

Visual clutter [39] may occur if hundreds of objects are displayed at once on a limited map space or/and if users zoom out map content. We experienced this when symbolizing vulnerability scores of the 574 residential buildings in the resulting tool. Since the experiments with dynamic symbol aggregation (Figure 3C) made the map interpretation unintuitive and confusing, we have let the symbols overlap in the zoomed out map. When zooming in, the symbols are easy to differentiate, and since they are drawn transparent, they could be identified even if they partially overlap.

Our experiments with the tool's design have also included the use of various map backgrounds (FR#4). Although a detailed map (Figure 4A) facilitates locating objects in a geographic context, a too detailed background may impede object recognition. Conversely, a simplified base map (Figure 4B,C) enables a quick overview of presented objects. However, it provides users with sometimes insufficient geographic context. Therefore, to avoid user confusion, we have equipped the EXTRA tool with a layer switcher that enables users to alter the background.



**Figure 4.** Three map backgrounds available in the EXTRA tool. ((A)—detailed map, (B)—simplified base map, (C)—simplified base map with faded colors).

In parallel to the cartographic symbolization of vulnerability scores, we have also worked on a graphical user interface. Here, we took on the role of user experience (UX) designers on the tool. In addition to the development (coding) of this application in the Angular web framework, we were incrementally improving the usability of the application by adding commonly known interactive functions such as map panning and zooming or centering the map display around a map symbol dynamically linked to a data record selected in the table view. Usability means ease-of-use, and together with a utility that concerns the usefulness of proposed interactive functionality, are typically known under the term of usability engineering [37]. This concept is of growing importance to geographical information science. In the user-centered design process, we followed the suggestion by Roth [40] and considered representation and interaction solutions. Of primary importance to us was to directly address the recognized conceptual (Table 3) and functional requirements (Table 4). Apart from an interactive map, we also had to accompany it with other components and equip them with adequate interactive functions.

Two functional requirements led our efforts: (FR#1) the navigation throughout the tool should be arranged by sectors and hazards, (FR#3) only basic visualization and interaction techniques were to be used. To fulfill these requirements, we designed the graphical user interface to be intuitive and to follow Shneiderman's [41] visual information seeking mantra "overview first, zoom and filter, then details-on-demand". The tool's opening window guides the users through the sector and

vulnerability selection. Next, users see an overview of the data displayed as proportional point symbols (Figure 5), whereas at its top part, users can alter sector and vulnerability type. Additionally, the table provides object names along with their vulnerability scores. Finally, filtering can be applied by setting a minimum vulnerability threshold.

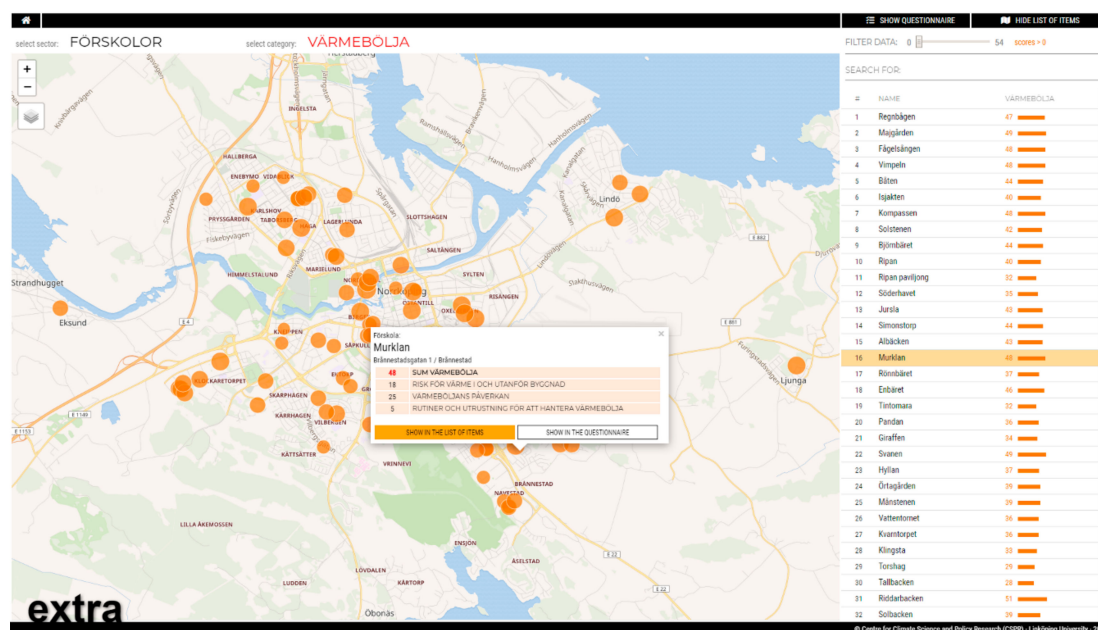


Figure 5. The graphical user interface of the EXTRA tool.

The interface provides users with only well-known interactive functions. When a map symbol is selected, details about the structure of the vulnerability score (CR#4) are displayed in a pop-up window as shown in Figure 5. The left button in the pop-up window allows users to toggle the list of items (the aside panel) and inspect the total score of the selected object compared to all other objects. The list is dynamically linked with the map. Whereas clicking on the right button of the pop-up window allows users to toggle the questionnaire panel being propagated with the scores on separate vulnerability indicators of the object.

#### 4.3.3. Addressing CR#2: Adding Module for Data Collection

As argued by workshop participants (Stage #2), overviews of vulnerability at each unit should be up to date to provide the best conditions for adaptation decisions. If answers to the questions could be dynamically updated, several argued, it would enable decision-makers and leaders to track the progress of adaptation actions and would facilitate prioritization of units and adaptation measures. These results have been instrumental in guiding the design of the questionnaire (the rightmost panel in Figure 6).

The questionnaire panel can be enabled either from the main window or from the pop-up window that shows up if an object is selected. It allows altering scores if they are not in line with user observations, or if already implemented adaptation measures have decreased the unit's vulnerability. By default, the questionnaire is propagated with the scores collected at Stage #4. If the user selects an object, e.g., Servicebostad in Figure 6, the questionnaire shows its scores. Then, the user can alter the scores and submit them to the database.



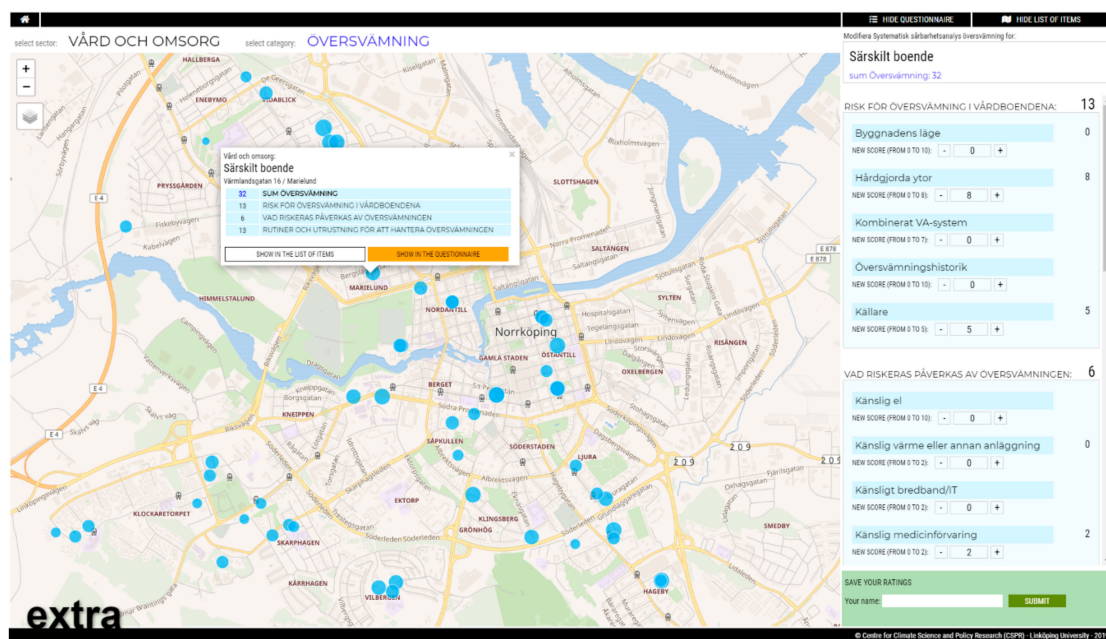


Figure 6. The interface of the EXTRA tool with the questionnaire being visible.

#### 4.3.4. Addressing CR#3: Adding Risk Maps

The interviewees also expressed (Stage #4) that auxiliary map overlays accompanying the vulnerability scores would be appreciated by users since they can improve their understanding of potential risks (e.g., proximity to risk areas). We, therefore, added the following overlays to the map display:

- Water extent after a 2-meter sea-level rise,
- Water extent in a 100-year flood of Motala ström,
- The map of low-lying areas,
- Water extent in fluvial flooding, and
- The heat island map of Norrköping.

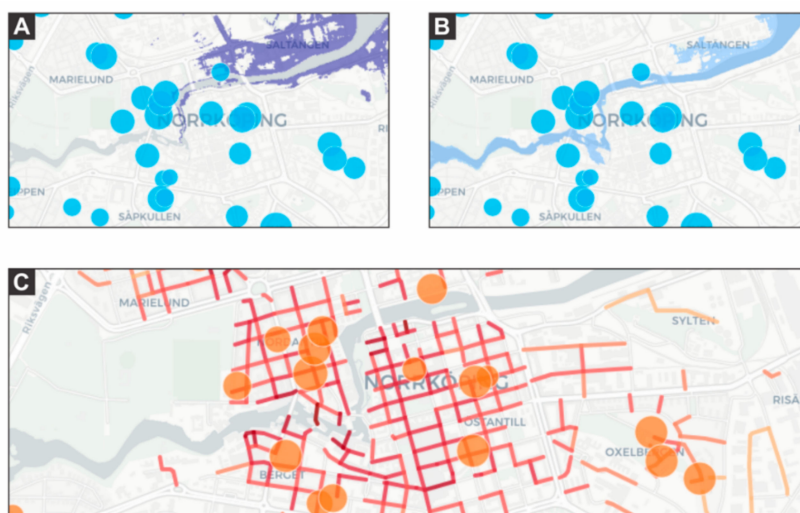
Most of the auxiliary layers concern vulnerability to floods. For example, the layer showing potentially flooded areas after a +2m sea level rise (Figure 7A) was calculated based on a digital elevation model. In turn, the water range of the 100-year flood of Motala ström (Figure 7B) was obtained from the municipality of Norrköping [42].

One auxiliary layer only concerns heat vulnerability, it displays urban heat islands (UHI) in downtown Norrköping (Figure 7C) and was compiled by combining Oke's model with a wind flow analysis [43]. This layer displays the UHI intensity of different areas, i.e., streets in Norrköping, by coloring street segments accordingly.

#### 4.4. Tool Evaluation (Stage #7)

The workshop in September 2019 provided an evaluation of the geographic visualization in the tool for supporting local adaptation planning (RQ2). When it comes to the general impression (see Q#1 at Stage #7), the comments were generally positive. Apart from remarks concerning the vulnerability assessment in itself, it was stated that visualizing vulnerability scores in relation to potential risks can facilitate the dialogue with politicians about strategic investments, especially if the tool shows vulnerability changes over time. The discussion also concerned the handling of sensitive information and ensuring that only publicly open data are available for external users. The discussions pointed out that there are routines to ensure that sensitive information is not presented externally. It was thus

concluded that the data compiled in the tool must be kept within the municipal firewall to be accessible only for staff with a municipal login.



**Figure 7.** The preschools sector’s scores (circles) on flood (A and B) and heat vulnerability (C) shown with auxiliary thematic layers: (A) water range after a +2m sea level rise, (B) water range if 100-year flood of Motala ström occurs, and (C) the heat island in central Norrköping.

Inputs on Q#1 also provided detailed remarks. For instance, it was suggested to show the heat island extent to ensure whether a certain unit or building is exposed or not. Arguably, this would make it easier to know if there is no heat island at a specific point, or if the point is not within the modeled area. Moreover, one participant asked whether there was an automatic connection between the flood layers and the vulnerability scores presented, which is not the case. This points to the need for an explanation in the tool about data generation. Finally, a recommendation concerned using color instead of circle size as a visual variable [44] to encode vulnerability scores. As the person said: “often you use green to signal that here the vulnerability is low.”

For the question of how the tool could be used by stakeholders (Q#2), the participants enthusiastically answered that the tool can definitely be used in practice. As claimed, the tool was seen to provide an overview of the most vulnerable units and buildings in the municipality, and—especially its questionnaire panel—can serve as a good basis in annual stakeholder meetings with, for example, heads of care units and preschools. As argued, by supporting a dialogue on how stakeholders can reduce the vulnerability at their unit, the tool can help to (a) have an updated description on how the vulnerability is composed at a given unit, (b) develop common learning and provide information about needed adaptive actions, and (c) create a continuous routine for reporting on climate vulnerability and adaptation.

When it comes to the question of how the EXTRA tool could be used by heads of units (Q#3), one participant stated that the tool could be used to supervise operations. Furthermore, as argued, the tool can facilitate detailed inspections on how units should adapt to climate change through, e.g., installing backflow valves in buildings or ensuring that drains are cleaned properly.

Participants also provided feedback on (Q#4), how the tool can be improved to better support actions within the targeted sector units, and (Q#5), how the tool could be used in other sectors. As discussed for Q#4, it would be valuable to display scores only on selected vulnerability indicators (filtering by vulnerability indicator), and that one should be able to display the most vulnerable units in each sector. Such filtering would arguably facilitate visual examination of vulnerable areas and finding synergies in the adaptation work. On Q#5, a workshop participant suggested adding extra thematic overlays with industries and socially critical objects, as well as qualitative descriptions of vulnerable points previously identified for other municipal sectors, including traffic, water and

sanitation infrastructure, rescue services, parks, public buildings, and the electricity grid. For these sectors, however, a different approach to add vulnerability scores was suggested since the questionnaire approach was not seen operational for vulnerable points in, e.g., the road network or the stormwater system. It was thus pointed out that the tool could be equipped with a possibility to add points for other sectors enabling qualitative descriptions of vulnerability and, possibly, an overall vulnerability score.

## 5. Discussion and Conclusions

Returning to our research questions, first (RQ#1), we asked how climate risks and corresponding indicators of vulnerability to heat and floods can be identified and made tangible through dialogues with municipal practitioners. Our study finds that unit heads were well aware of how their building(s), outdoor spaces and local practices can contribute to vulnerability, deepening the knowledge of detailed climate risks facing the targeted sectors, once tangible indicators had been identified and vulnerability weights been assigned. Before investigating such detailed risk factors, interviewees often referred to climate vulnerability as an abstract and remote process. Many unit heads in the caring and education sectors thus appeared surprised, yet empowered by the easily understandable risks and related adaptation measures for which they were either directly responsible for or had an ongoing dialogue with the municipal housing company that owns their premises. Likewise, the officials at the municipal housing company initially stated that they would never work with climate adaptation unless specifically required by the municipality. However, the risks identified by their own staff made it clear that adaptation has already—to some extent—been part of their maintenance and renovation, for which they invest approximately 30 million euros annually. These funds, as they stated, could be invested more wisely if also considering flood and heat risk more explicitly. This became especially evident when zooming in on buildings that were given high vulnerability scores and that also had previously experienced flooding, which was often the case. This high congruence seems to have increased their confidence in the approach, linking their experienced hazards to indicators of risks. Both the municipal housing company and several caring units have also implemented measures in the last two years, often based on the results from the self-assessed vulnerability assessment and risk maps, such as focusing on residential buildings with caring units and improving access to portable AC in preschools with high vulnerability to heat.

Altogether our above findings correspond with findings in previous literature. As showcased, making climate vulnerability tangible and personally relevant for local practitioners (e.g.) [45] and involving them in exploring local risks (e.g.) [46] are key aspects for creating engagement and empowerment. Such engagement can be furthered through user-friendly visual interfaces that serve as a means to convey vulnerability scores to municipal strategists. The results also support previous studies stating the importance of establishing that local climate risks and impacts resonate with previous experiences and local practices (e.g.) [47]. The approach taken to jointly—with sector leaders—develop vulnerability indicators, which unit heads later provided with meaningful content, seems to have provided a valid bottom-up representation of local risks, making outcomes more understandable and governable by municipal actors [13,26].

We also wanted to explore how the potential of geovisualization can be utilized for making vulnerability scores useful and applicable in local planning and decision-making (RQ#2). Through the collaborations with and feedback from municipal participants, our study finds that a map-based visual interface facilitates the visual overview of vulnerability scores if the interface is not overloaded with data content and interactive functions. As reported in previous literature [e.g. 9,11], too much data and too many functions may hinder data interpretation and thus make users confused. Our study has also confirmed the findings described in previous literature [37] that the primary success factor of how geovisualization tools should be designed and developed is to prioritize their pragmatic aspects, i.e., prepare such tools for and together with the intended users. A user-oriented approach was found to enable continuous dialogue between developers and users and thus facilitates meaningful feedback.

Although the EXTRA tool's last version had been found to fulfill user expectations, there are still suggestions, such as grouping overlapping map symbols into clusters that require follow-up studies with detailed investigations. Moreover, users prefer color-coding instead of symbol size to visually encode vulnerability scores. However, such modification would demand setting thresholds for when a given object is at low, medium, or high risk. Finally, a follow-up study needs to address the research question on how interactive geovisualization of vulnerability to extreme climate events can influence what actions are taken "on the ground."

The EXTRA tool was designed to fulfill two specific aims, to support (1) planners and sector leaders in strategic priorities and investments, and (2) unit heads in identifying measures to adapt to local flood and heat risks. Regarding the first, we conclude that adaptation coordinators see the tool as useful, not only to identify vulnerable buildings and units (as expected), but also as a means to: lift strategic issues and investments with politicians, identify the most common adaptation measures needed, and track the effects of implemented actions. Involving intended users throughout the tool development was here instrumental to identify and incorporate additional elements in the tool to support these extended roles in municipal adaptation governance. Nevertheless, whether the tool will be used as proposed by the adaptation coordinators depends on political priorities over the next years.

What is clearer, however, is that the second aim has been fulfilled, at least to some extent. We can see that adaptation measures already have been implemented by caring and education units and the municipal housing company. Though it is hard to determine the linkages between such measures and joint risk identification and tool development, the relationship can be elucidated through some examples. One example concerns the implementation of several adaptation measures by the housing company to decrease vulnerability in a building used partly for caring for the functionally impaired. In the vulnerability assessment, this vulnerable group and the building was deemed sensitive to flooding. By implementing backflow blockers, pumps and securing electricity installations in the basement, and thus, following the indirectly suggested measures in the tool, this selected building will be less sensitive, and its vulnerability score can be reduced. A further positive side effect in this example is a new cooperation between the municipal housing company and the head of this caring unit—illuminating another value of the joint vulnerability assessment and tool development process.

Finally, we conclude that the tool development process in itself is, at least, as important as the resulting tool in increasing municipal governance capacity. The potential role(s) of an interactive visualization tool is hard to predict beforehand and should be open for continuous scrutiny. However, by using the methodology and local developments of our proposed indicators and questionnaires presented in this study, other municipalities could likely reduce the starting distance and time required. The tool presented here will be made freely available on the internet for others to use but without the data from this case.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2071-1050/12/3/1179/s1>, Table S1: Indicators of vulnerability to floods; Table S2: Indicators of vulnerability to heat; Table S3: Preschools and primary schools: vulnerability to floods; Table S4: Preschools and primary schools: vulnerability to heat; Table S5: Elderly and social care: vulnerability to floods; Table S6: Elderly and social care: vulnerability to heat; Table S7: Residential buildings: vulnerability to floods; Table S8: Residential buildings: vulnerability to heat; References to the studies investigated to identify indicators of the vulnerability to floods and heat.

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