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Flood Risk Assessment of Urban Critical Infrastructures Using Crowd-Sourced and Open Data on Hazard, Exposure and Vulnerability

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ABSTRACT

Worldwide, cities rely on the proper functioning of critical infrastructures (CIs) such as electricity, telecommunication, water supply and transportation. Failure of those infrastructures can lead to significant and long-lasting impacts, even far beyond the flooded areas due to cascading effects. Local authorities are eager to take action to reduce flood risk and strive to increase the resilience of their communities. However, CI are often not considered in flood risk assessments. One of the reasons is that CI operators do not share their CI data and internal risk assessments. Therefore, an integral view on flood risk is lacking and risks may be unidentified or underestimated. To overcome this limitation, in this paper we propose an integrated framework for flood risk assessment of urban critical infrastructures (UCIs) for local authorities, which is based on publicly available and field-surveyed CI data. The proposed framework supports cities to carry out cross-sectoral risk screenings on urban district level to evaluate the need for in-depth risk assessments and risk dialogues with CI operators.

1 | Introduction

Floods can lead to devastating impacts and losses, causing fatalities, injuries or displacement of people, damage to the environment and severely compromise economic activities and economic development of our society (EU 2007a; FEMA 2020). The increased probability of extreme hydrological events as a consequence of a changing climate (IPCC 2012, 2023), in combination with growth of population and asset values as well as land subsidence is leading to significant compounding effects (Hallegatte et al. 2013; Rentschler et al. 2022) and a rapid increase of flood risk, particularly in urban areas.

On a global scale, Hallegatte et al. (2013) predict an increase of flood risk from 6 billion US$ per year in 2005 to over 60 billion US$ in 2050, even when investing in adaptation to maintain constant flood probabilities. The 2021 Central European Floods in Germany, Belgium and the Netherlands caused damages of more than 46 billion EUR, making it the costliest flood disaster in history (MunichRe 2023). Germany suffered the majority of the losses with 40 billion EUR economic damages and 197 fatalities (EM-DAT 2024).

The 2021 Central European Floods restated the huge importance of critical infrastructure (CI) such as roads, electricity and telecommunication (TC). The flood event led to severe disruption of CIs (Fekete and Sandholz 2021; Koks et al. 2022), which hampered the response before (warning), during (evacuation) and after the flood event (disaster relief and recovery), even far outside the flooded areas as a consequence of cascading effects (Koks et al. 2022; Szymczak et al. 2022).

Though directives (EU 2008, 2022; The White House 2013, 2024) and CI definitions (NCTV 2023; CIPedia 2024), explicitly highlight the importance of CI and despite its huge relevance for the functioning of our society, CI are often not considered in flood risk assessments and risk management plans (Pescaroli and Nones 2016; Fekete 2019; Schotten and Bachmann 2023a, 2023b). Schotten and Bachmann (2023b) emphasise that this is resulting in a decline in the quality of decision making in flood risk management and therefore call for the inclusion of CI in risk assessments.

Research to include CI in flood risk assessments in the past mainly focussed on European Critical Infrastructure (ECI) (EU 2022) and National Critical Infrastructure (NCI), being defined as cross-border or primary national CI with significant consequences for one or several nations in case of disruption (EU 2022; NCTV 2023; CIPedia 2024).

Pant et al. (2018) developed an integrated framework for flood impact assessment of CI on a catchment-level. For the case study of the Thames basin (UK), the authors derived CI assets from NCI datasets in combination with synthetic data. The study highlights that interconnections between CIs lead to failure propagations and disruptions far beyond the extent of the flooded area (Pant et al. 2018). Koks et al. (2019) investigated the consequences of electricity failures due to flooding for business disruption and economic losses, employing a multi-regional NCI model across 37 subnational regions of the United Kingdom. The study shows that total economic losses can be up to three times higher when power outages are included in the risk assessment, compared to when only considering economic impacts of business interruption due to flooded business premises. Moreover, it is found that the number of people and properties affected by power outages can be 10–100 times higher than those directly affected by flooding. Though these studies at the national or regional level do not directly allow for the development of risk management measures on a local level, they highlight the importance of including CI in flood risk assessments.

In contrast, research on the impact of flood risk on CI on an urban scale is scarce. Relevant for this study is the work by Murdock et al. (2018), who carried out an assessment of CI resilience to flooding using a response-curve approach in an urban case study in Toronto (Canada). In their study, the authors emphasise the challenge of CI data collection and use open data as a starting point for the flood risk assessment.

In an urban study in the city of Dordrecht (The Netherlands), De Bruijn et al. (2016) underline the importance of analysing CIs, as their functioning is crucial for efficient flood emergency management and recovery after flooding and stress that data of CI is very difficult to obtain.

Schotten and Bachmann (2023a) present a case study in the city of Accra (Ghana) in which they integrate CI networks in a flood risk assessment by using a combination of different open data sources. The authors demonstrate the added value for flood risk management and conclude that the consideration of CI is leading to more effective flood risk management.

2 | Urban Critical Infrastructures

While ECI and NCI are essential for the security, economy, public health and safety on a national level (EU 2022), UCI are most critical to the proper functioning of our cities and can be seen as a subsystem of the complex urban system (Rome et al. 2015). As illustrated in SWECO (2023), the infrastructure sectors relevant for the functioning of urban areas highly depend on the type of hazard and the local context, thus the delineation of UCI sectors is not as clear as for NCI or ECI. Moreover, UCI have different properties than NCI in terms of smaller scale, high quantity and density, less redundancy and more complexity, as well as more stakeholders involved. Notably, city administrations are CI owners, but are also responsible for permits, while having no authority to coordinate between different CI sectors, as the primary responsibility is with the individual CI operators themselves (Rijksoverheid 2023).

While CI operators do carry out their own risk assessments in due diligence, their risk evaluation may differ between CI sectors due to different priorities, financial considerations, operational aspects as well as limited awareness of potential cascading effects (De Bruijn et al. 2016; Schotten and Bachmann 2023b). Cascading effects occur when a disruption in one infrastructure sector causes the failure of one or more components in a second infrastructure, which subsequently causes disruption in one or more other infrastructure sectors (Burzel et al. 2014; Tsavdaroglou et al. 2018; Schotten and Bachmann 2023b).

Even if a municipality is taking the initiative, CI operators are often not able to share their CI data and risk assessments. As stated by De Bruijn et al. (2016), the predominant reasons are confidentiality, as well as competitive considerations. Regulations such as NCI protection acts (The White House 2013, 2024) further limit the ability to exchange sensitive data. If CI data is shared, for example under agreement of non-disclosure or in a protected simulation environment, it is often not compliant with open data standards and either requires specialised, licensed software or is so complex that it needs to be generalised to the asset level before it can be processed.

The combination of missing jurisdiction for municipalities, lack of coordination between UCI operators and missing insights in risk evaluations leads to a unique knowledge gap with regard to UCI. To overcome this gap, and to support local authorities in taking actions for reducing flood risks and increasing resilience of their communities, in this paper, we present an integrated framework for flood risk assessment of UCIs. We show in a case study that it is possible to carry out a cross-sectoral risk screening for the identification and prioritisation of risks for UCI on urban district level. The proposed method is using a combination of open data and crowd-sourced data to identify the necessity for further in-depth risk assessments and risk dialogues between local authorities and CI operators.

3 | Research Method and Data Collection

The risk screening method for UCI developed in this paper builds on generally accepted risk assessment practices (UNISDR 2009; ENW 2017; Risk Based Inspection

Framework 2018; IEC 2019) to align with risk assessments carried out by CI operators individually. However, the proposed risk screening method is adapted and further expanded for UCI by case study research in combination with a quantitative data analysis.

To overcome the limitation of data availability mentioned above, the proposed framework is based on crowd-sourced and open data. With this method, data gaps can be filled quickly and at low cost through field work by technical staff, scholars or citizens.

While there is limited research on open data for risk analysis of CI (e.g., Nirandjan et al. 2022; Schotten et al. 2024), open data is becoming increasingly popular in other fields of application. In 2003, the European Union adopted Directive 2003/98/EC, known as the Open Data Directive (EU 2019), formulates minimum requirements for EU member states regarding making public sector information, hereafter termed as Official Open Data, available for re-use. As a result, open data policies and standards like INSPIRE (EU 2007b) have been adopted in member states. International institutions such as United Nations and the World Bank advocate the use of open data for supporting critical management decisions and providing key statistical information (GFDRR 2018; World Bank 2024; UN Data 2025).

As a worldwide database for open spatial data, OpenStreetMap (OSM) is mostly built from data collected by individual contributors (OSM 2025a). In some countries, OSM does also contain map features derived from Official Open Data, as for example nation-wide building footprints or land-use types (OpenStreetMap Community 2023). With regard to CI data, OSM does contain above-ground assets such as electricity substations (OSM 2025b), hospitals or roads, but is usually lacking underground infrastructure such as water distribution or electricity distribution networks. However, the global coverage of OSM and collaborative data collection and mapping initiatives such as Map Your Grid (2025) make OSM a valuable data source and enable the application of the method proposed in this paper for local authorities in other countries.

Due to the nature of the data, OSM often has unknown quality and completeness ratings (Nirandjan et al. 2022; Schotten et al. 2024). It is therefore required to complete and ground-truth OSM data with field-surveyed data, hereafter jointly termed as crowd-sourced data or using data validation techniques such as pattern, density or gap analysis or comparison against subsets of other datasets. Table 1 provides a comparison of data properties between CI operator data, official open data and crowd-sourced data.

In conclusion, official open data and crowd-sourced data have the advantage to not require licensed or specialised software for analysis and the need for non-disclosure agreements with UCI operators. Furthermore, open data standards ensure the repeatability and transferability of the approach to other countries. However, with regard to UCI, open data have a lower level of

TABLE 1 | Comparison of data properties between critical infrastructure operator data, official open data and crowd-sourced data.

Data properties	Critical infrastructure operator data	Official open data	Crowd-sourced data
Data quality	High: operator needs to keep data updated to comply with quality and asset management standards.	Medium to high: Open data from official organisations tends to have high quality, but data is often aggregated to lower level of detail.	Medium: depending on source. Crowd-sourced databases such as OpenStreetMap are checked by administrators. Training and supervision are required. Data may be limited to visible and accessible assets.
Data formats	Mainly proprietary formats. Data is often not compliant with open data standards, requires specialised and licenced software.	Open data formats (gdal, geojson and other open data standards) are present, following the requirements of open source licences.	Availability depends on type and goals of project, preferably use of open data standards.
Data accuracy	High: operators are expected to have the most actual infrastructure asset data.	Medium to high: official open data is updated frequently.	Medium to high: Actuality on OpenStreetMap is dependent on attendance and performance of its community. Crowd-sourcing by technical staff or citizens can be used to quickly collect actual data.
Data scope	Technical characteristics are available, as part of asset inventory, e.g., load thresholds or critical water depth for safe operations.	Technical characteristics are unavailable. Open datasets are often limited to location of assets and only contain limited technical characteristics such as asset type.	Technical characteristics are partially available when performing field work: thresholds can be measured or estimated per (type of) asset, nevertheless subject to uncertainties and assumptions. Not available from crowd-sourced databases such as OSM.

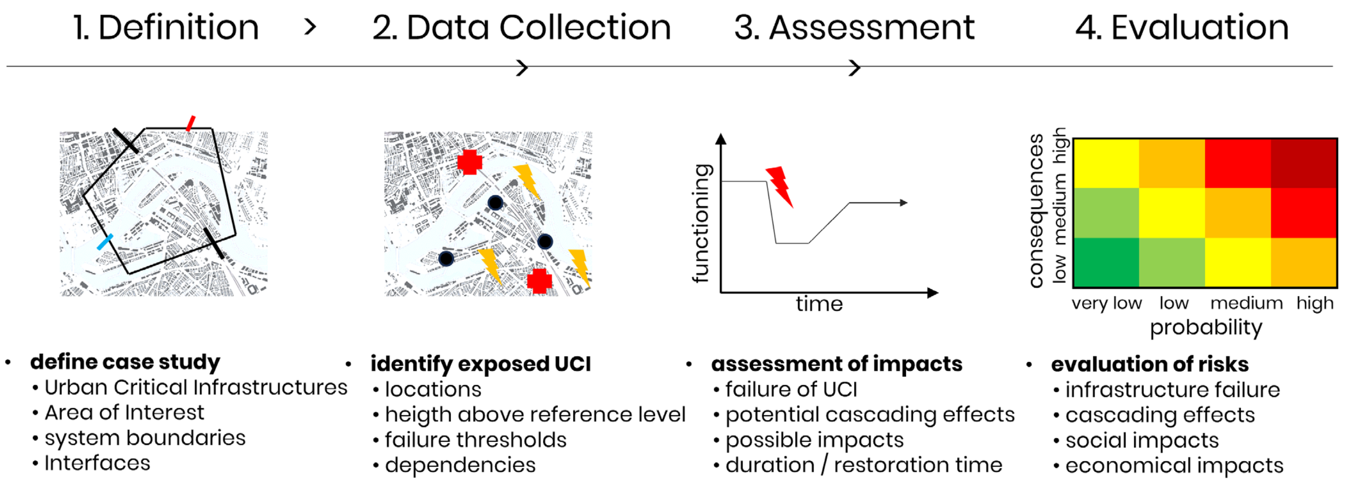


FIGURE 1 | Four steps of the proposed risk screening method for urban critical infrastructures.

detail and are mostly limited to above-ground infrastructure assets. Data collection through crowd-sourcing is subject to limitations such as the size of the study area, as well as potential errors in interpretation, mapping and labelling of data. Nevertheless, as the goal is a risk screening by local authorities on an urban district level, crowd-sourced and official open data are identified as the most preferable data sources for the proposed methodology in this paper.

4 | Risk Screening Method for UCIs

The main goal of the proposed method is to enable local authorities to perform a cross-sectoral risk screening of UCI for districts in their city. Based on open and crowd-sourced data, the risk screening enables the identification of UCI prone to flooding as defined in IEC 31010 (2019) and a straightforward assessment of risks arising from UCI failure for its communities. The results can inform the necessity for further in-depth risk assessments and the need for risk dialogues with CI operators.

The method is based on the risk definition where the flood risk R is expressed as a combination of likelihood or probability of flooding p and related adverse consequences or damages, D (ISO 2009; UNISDR 2009; IPCC 2012; ENW 2017). The proposed risk screening method consists of four main steps, as illustrated in Figure 1, which will be described in more detail below:

1. *Definition* of the area of interest (AoI), relevant urban UCIs, system boundaries and Interfaces (I) with UCI assets outside the AoI
2. *Data collection*: socio-economic and UCI data, that is, location, height, critical thresholds for failure and dependencies with other UCI sectors and assets, quality control
3. *Assessment* of failure of UCI assets, potential cascading effects, failure duration, restoration times and resulting consequences
4. *Evaluation* of risk combining probability of occurrence and consequences using a risk matrix

4.1 | Step 1: Definition

The first step covers a pre-screening of the area to define the AoI, which is the area where flood risks for communities and their resilience are assessed. For the AoI, the definition of UCI is based on the disruptive potential for society. Following EU (2022) and Rome et al. (2015), this considers 'assets, systems or parts thereof which are essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people and the disruption or destruction of which would have a significant impact on the urban area'.

Next, infrastructure sectors critical for the functioning of the AoI need to be defined. We propose a sectoral classification for UCI expanded from existing NCI sectors (EU 2022) as presented in Table 2.

The AoI can be defined either by administrative boundaries (e.g., one or more urban districts), by the boundaries of flood hazards (e.g., a flood-prone area outside an embankment or flooded area after a dike breach) or, from a system perspective, as the service areas of the UCI sectors. The following aspects are considered:

- hazard extent for low-probability pluvial or fluvial flood events, for current and/or future climate scenarios,
- vulnerabilities of UCI assets from previous flood events or records of UCI failures
- identified exposure of critical, non-redundant UCIs.

Due to the networked character of CI, and the large spatial extent of several UCI sectors, as for example drinking water, it is likely that critical assets are located outside of the AoI. As it is not favourable to define the boundaries of the risk study as the maximum extent of all UCI systems, we propose the utilisation of interfaces (I). An interface I is defined as the critical connection between the AoI and UCI assets outside its boundaries. For example, if health care is defined as being a critical UCI sector, but the next hospital is located outside of the AoI, the access road is defined as an interface for health care (I_{HC}).

TABLE 2 | Proposed sectoral classification for UCI, including sector abbreviations used in this paper.

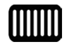
UCI sector	Abbreviation	Symbol	UCI sector	Abbreviation	Symbol
Electricity	EL		Public administration	PA	
Drinking water	DW		Production	PR	
Education	ED		Public safety	PS	
Flood defence	FD		Storm water	SW	
Finance	FI		Telecommunication	TC	
Food supply	FS		Transport	TR	
health care	HC		Waste water	WW	

TABLE 3 | Overview of data collected for the risk screening.

Category	Description	Preferred source
Base data	Concerns the fundamental characteristics of the AoI and comprises administrative boundaries, number of inhabitants and census data with demographic indicators like age and income distribution. Base data provides insight about the general structure and vulnerability of the population within the case study area.	Official open data
Hazard data	Focussing on potential flood events that may disrupt UCI within the AoI, i.e., fluvial and pluvial flood hazard maps with water depths, characterised by their return periods or probability (p). Hazard data can be complemented with photos or measurements from previous flood events.	Official open data Modelling results
Exposure data	Provides insight into the extent that UCI are exposed to flooding. Data like asset type, location of asset and height above reference level is collected, resulting in a comprehensive UCI inventory for the AoI.	Crowd sourced data OpenStreetMap
Vulnerability data	Deals with the vulnerability of the UCI. This incorporates the critical threshold for failure, tf, per asset relative to street level, redundancy and dependencies with other UCI assets, resulting in insight into the vulnerability of UCI assets. For underground infrastructure susceptible to flooding, such as metro networks and tunnels, critical values can be collected for openings, ventilation inlets, entrances and other critical above-ground assets. This can be also done for underground cables and pipeline networks, such as gas, electricity and drinking water. While cables and pipes are usually not susceptible to flooding, control units, measurement points and electrical cabinets located above ground are susceptible and flooding can lead to failure of these infrastructures.	Crowd sourced data

4.2 | Step 2: Data Collection

After setting the scope of the AoI and defining the UCI sectors, data needs to be collected. These data is divided into base data, hazard data, exposure data and vulnerability data (Table 3).

In order to determine spatial relationships between UCI assets, a number of substitute techniques are commonly employed, for example, the estimation of service areas using geometric methods such as Voronoi decompositions or shortest-path algorithms in GIS (Pant et al. 2018; Schotten et al. 2024). This means that if failure is calculated for an electricity asset i_n,

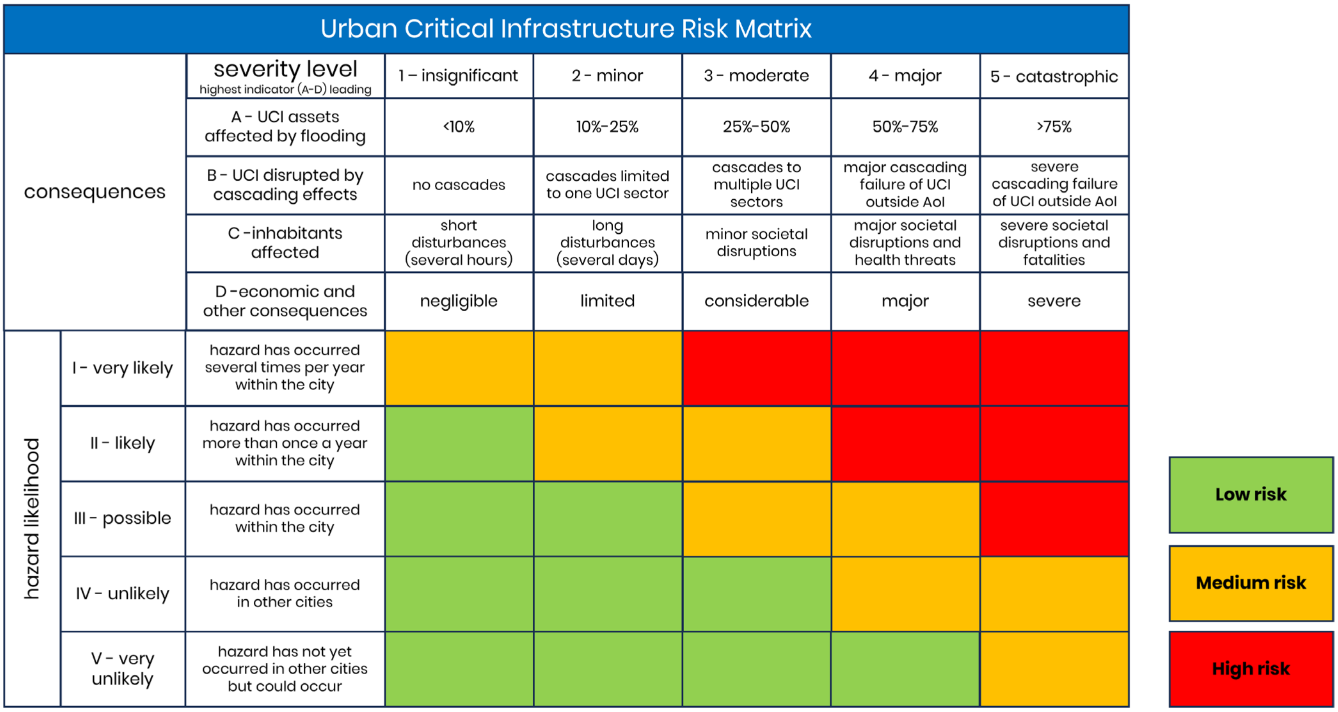


FIGURE 2 | Proposed risk matrix for different types of consequences due to UCI failure including indication of risk levels (extended from BBK 2010; Risktec 2016, IEC 31010, 2019 and LGB 2022).

UCI assets depending on electricity within the service area of the failed asset i_n are also assumed to fail and population n_p and businesses n_b within the respective service area are affected by the disruption.

To describe the dependencies between different assets and sectors, in the UCI asset inventory dependencies can be expressed through indexes in tables (with asset *i* for a given sector being dependent on one or several asset *j, e, …* of another sector), a GIS database or a graph model. Likewise, the number of people n_p affected, the number of businesses n_b affected and other indicators can be connected to one or several UCI assets. The sector with the highest level of dependencies (usually EL) is used as a starting point for assessment of cascading effects in Step 3.

4.3 | Step 3: Assessment

The third step covers the assessment of failure of UCI assets, potential cascading effects, failure duration, restoration times and resulting consequences for different flood scenarios. The assessment is done on asset level by comparing critical threshold for failure t_f per asset i in the UCI inventory with water depths d_w from the hazard dataset:

$$d_i = t_{f,i} - d_{w,i} \qquad \text{with failure of UCI asset } i\text{, if } d_i > 0$$

Starting from the sector with the highest level of dependencies, the failure of UCI assets is then further translated into possible cascades to depending UCI sectors and their assets, which are stored in the UCI inventory as dependent on the failed asset i_n and have no redundancy through other functioning assets.

Furthermore, for all failed assets i_n, consequences for population n_p, businesses n_b and other indicators are calculated. This can be done for both directly and indirectly affected people and businesses if the data is available and linked to the UCI assets accordingly.

4.4 | Step 4: Evaluation

The final step is the evaluation of risks by bringing together both parameters, hazard probability *P* and potential consequences *D*. For this, we propose a qualitative risk matrix (Figure 2), as it allows for a straightforward and consistent classification of risk levels and supports the discussion and understanding of different hazard scenarios (BBK 2010; Risktec 2016; IEC 2019). To account for the variety of potential consequences, the risk matrix includes the following assessment criteria:

A. *UCI assets disrupted by flooding*: classification of the proportion of UCI assets directly affected by flooding—reflecting potential redundancies and resilience of the UCI.

B. *UCI disrupted by cascading effects*: classification of cascading effects to one or several sectors—indicating the importance of assets for other UCI sectors

C. *Inhabitants affected*: consequences for population based on calculated or estimated duration of outages, reflecting the societal effects and potential for social disruption

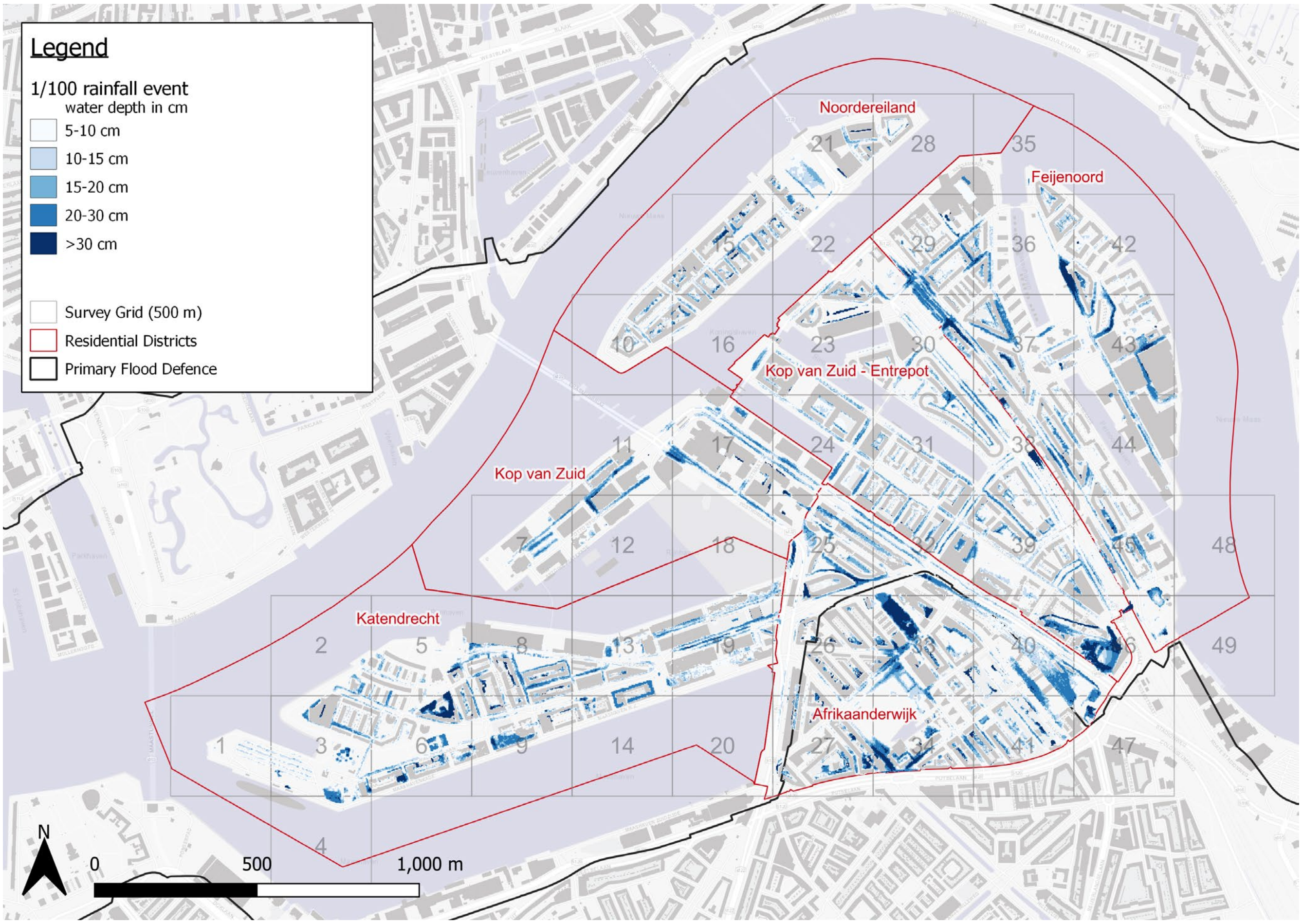


FIGURE 3 | Case study area Rotterdam-Zuid with water depths as a result of intense rainfall with a probability of 1/100 years, boundaries of the six residential districts and survey grid for crowd-sourced data collection.

D. *Economic and other consequences*: classification of the severity of other short and long-term consequences inside and outside of the AoI

The goal of the risk matrix is the identification and prioritisation of risks according to IEC (2019), to ensure that the largest risks are prioritised. This classification is carried out for each UCI sector and its assets, with the highest level of consequences (A–D) being considered as significant. For example, if telecommunication (TC) failure for a hazard rated as 'II—likely' leads to short disturbances for the population (1—insignificant), but causes cascades to multiple UCI sectors (3—moderate), then TC failure is classified as 'medium risk'. Within the group of TC assets, it is then possible to identify the assets causing the largest risks.

It is important to stress that at this stage of the risk screening process, there is possibly limited information about potential cascading effects between different UCI sectors and assets due to restricted insights about operational procedures and (inter)dependencies. Nevertheless, the screening process provides valuable insights across all UCI sectors about potential risks due to UCI failure and allows for the identification and prioritisation of risks. The insights can be used by local authorities to initiate in-depth risk assessments and cross-sectoral risk dialogues.

5 | Case Study: Rotterdam Feijenoord

The city of Rotterdam is the second-largest city of the Netherlands with more than 650,000 inhabitants and home to the largest seaport of Europe. It is located at the river New Meuse close to the North Sea coast. As part of the city's objective to become more resilient, Rotterdam acknowledges the importance of CI and emphasises associated knowledge gaps (Resilient Rotterdam 2022; Municipality of Rotterdam 2023).

The case study is situated in the township Rotterdam Feijenoord, south of the river New Meuse (Figure 3). The case study area consists of six residential districts: Kop van Zuid, Katendrecht, Kop van Zuid Entrepot, Afrikanderwijk, Feijenoord and Noordereiland and is home to about 37,000 inhabitants (CBS 2023). The case study area has a total area of 478 ha, from which 290 ha are land and 188 ha water (CBS 2023).

Rotterdam Feijenoord is partly located outside of the embankments, where shallow fluvial flooding can occur at a low probability, with water depths less than 0.5 m for the 1 in 1000 year flood scenario (Basisinformatie Overstromingen 2024). More likely is pluvial flooding due to intense rainfall (Figure 3), which has led to damages at public and private assets in the past and is expected to increase in the future (Resilient

TABLE 4 | Identified UCI sectors in the case study area and main characteristics.

UCI sector	System description	Potential vulnerabilities and cascades
Electricity (EL)	Mid- and low-voltage underground electricity distribution network, with above-ground transformers, on street level and within buildings	Failure of transformers due to flooding, direct effects and potential cascades to all other UCI sectors
Drinking water (DW)	Distributed through underground drinking water pipes	Pressure boosters (hydrophore) for buildings larger than five floors, dependent on electricity
Education (ED)	Primary and secondary schools, colleges and two universities of applied sciences	Direct impacts from flooding
Food supply (FS)	Several small and medium-sized grocery stores and bakeries for daily food supply	Direct impacts from flooding and loss of electricity due to frozen and cooled foodstuff
Health care (HC)	Several providers of health care and geriatric care	Direct impacts from flooding, inaccessibility of clients in case of flooded roads
Public administration (PA)	Court of Justice, Municipality of Rotterdam headquarters	Direct impacts from flooding, high rise building elevators susceptible to electricity failure
Public safety (PS)	Local police station, sports hall, community centre	Direct impacts from flooding, accessibility may be limited
Storm water (SW)	Storm water system, draining rainfall into river New Meuse, mostly gravitational system, partially mixed system with WW, relies on pumps	Pumps dependent of electricity (see WW)
Telecommunication (TC)	Telephone network and glass fibre internet network, below ground cables with above-ground street cabinets Mobile telecommunication network with control equipment located on street level and in basements	Direct impacts from flooding, dependent of electricity with limited duration of backup batteries
Transport (TR)	Several main roads connecting parts of Rotterdam, access roads to residential areas, traffic lights and street lights	Accessibility for emergency services, repair teams and citizens, road safety
Waste water (WW)	Partially pressurized waste water network with several pumping stations	Dependent on electricity, potential health risks in case of contamination of surface water and flood water due to sanitary sewer overflow (SSO)

Rotterdam 2022). Moreover, intense rainfall is difficult to predict and occurs on a relatively small scale, but can significantly disrupt CIs in an urban environment (Resilient Rotterdam 2022). Therefore, we demonstrate the proposed method in this case study utilising two intense rainfall events which were used before for the preliminary flood risk assessment for the EU Floods Directive and other flood risk assessments (De Bruijn et al. 2022).

Important characteristics of the study area are unemployment rates three times higher than on average in Rotterdam and a relatively large proportion of households living on social welfare (CBS 2024). To strengthen the resilience of its communities, the city of Rotterdam is striving to map out potential risks of UCI disruptions in order to develop adaptation measures for the area (Resilient Rotterdam 2022).

5.1 | Step 1: Definition

In the first step, the AoI for the risk assessment is defined. In our case study, we followed the official administrative boundaries from CBS (2023) for the six districts.

In consultation with experts from the Municipality of Rotterdam, and based on the UCI definition presented in Section 2, the sectors listed in Table 4 were identified as UCI in the first step.

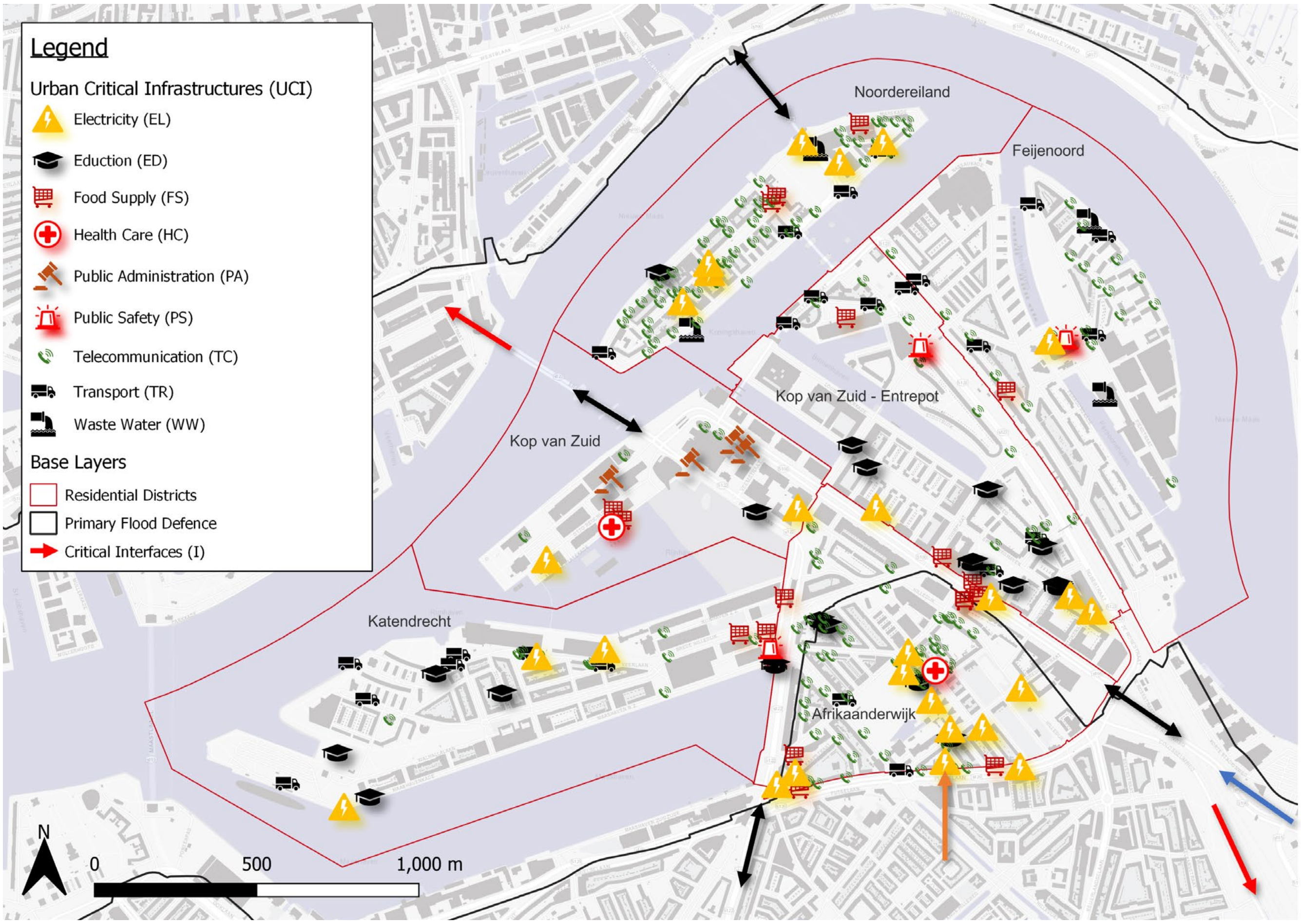


FIGURE 4 | Identified UCI assets and critical interfaces in the case study area.

As a number of relevant UCI assets are located outside the AoI, three types of critical interfaces (*I*) are identified (see Figure 4):

- I_{TR}: main access roads S106/S120 and S122, Erasmus bridge and Willems bridge.
- I_{HC}: two hospitals are located outside the AoI, to the north: Erasmus MC, accessible via $I_{TR,1}$, Erasmus bridge and to the south: Maasstad hospital, accessible via $I_{TR,2}$, S106
- I_{EL}: electricity for the area is provided from high voltage station Waalhaven 1 underground via trajectory Putselaan to 25 kV-station Retiefstraat south of the case study area

5.2 | Step 2: Data Collection

For the case study, base data (population distribution, demographic characteristics and official boundaries) is extracted from the national Open Data portal PDOK (PDOK 2024). For the UCI inventory, data collection was performed using a combination of crowd-sourced data from OpenStreetMap and fieldwork with groups of students.

For the field work, a two-tiered approach was applied. First, data was collected from OpenStreetMap into a GIS-database to get an overall understanding of UCI exposure in the area. Then, the identified UCI assets were visited during field work to complete the vulnerability data. Next, the area was systematically surveyed to complete the inventory. To ensure a thorough data collection, the AoI was divided into a rectangular survey grid of 500 by 500 m (see Figure 3). Groups of students were assigned to adjacent survey grid cells with 10% overlap to verify the quality of the field work (triangulation). The following exposure and vulnerability parameters were registered:

- UCI sector
- Type of asset
- Short description
- Geolocation
- Critical threshold for failure t_f, relative to street level

Mobile TC antennas, located well-above street level on facades or roofs of buildings, were exclusively queried from OpenStreetMap, as they cannot be easily identified during field work. Similarly, underground utility mains are difficult to assess through field work. However, utility location signage is present in the area for the drinking water and natural gas mains, which can be used to create an asset or network dataset for the risk analysis. However, due to the low susceptibility of these underground infrastructures to intense rainfall, with rather limited water depths and flow velocities, this was not necessary in this case study.

The storm water and sewage system in the case study area partially consists of a combined storm and sanitary sewer line, but is mostly separated. Storm water is released into the river by gravitation, while sewage water is pumped to the waste water (WW) treatment plant in a pressurized system. Failure of electricity for pumps will cause sewage system overflow (SSO) to the surface water, which is not favourable due to ecological and health considerations.

For a number of locations, Google StreetView was used for additional verification of UCI inventory records. In this step it was found that some street cabinets, during field work assigned to the electricity (EL) sector, appeared to be glass fibre distribution panels for TC. In a few occasions, those were street light cabinets or traffic lights, which belong to the sector transport (TR), hence needed to be corrected in the UCI inventory.

Furthermore, spatial pattern analysis showed a lower density of transformer stations in two areas. Additional field work showed that in these recently built areas, transformers are not situated on the street. Instead, they are installed in the buildings, accessible from the street through doors and therefore were not recognised initially. Finally, a number of transformers were attributed to be high voltage, while they appeared to belong to the medium voltage network as stated on the asset signage.

The abovementioned aspects were corrected in this verification step to ensure a reliable basis for the risk assessment. The collected UCI data is shown in Figure 4. Table 5 lists the UCI sectors and number of assets identified in the case study area.

TABLE 5 | UCI assets identified in the case study area.

Type of critical asset	UCI sector	Number of assets
Street cabinets	Telecommunication (TC)	148
Telecommunication towers	Telecommunication (TC)	22
Medium voltage station/transformers	Electricity (EL)	21
Schools and daycare	Education (ED)	20
Supermarkets	Food supply (FS)	19
Street cabinets (traffic light and street lights)	Transport (TR)	17
Access roads	Transport (TR)	7
Municipality headquarters, court, tax office, public works	Public administration (PA)	4
Waste water pumping stations	Waste water (WW)	4
Police, shelters	Public safety (PS)	3
Healthcare providers	Healthcare (HC)	2

5.3 | Step 3: Assessment

In our case study, we analysed two intense rainfall events from klimaateffectatlas (2024):

- 70 mm precipitation within 2 h, with a probability of occurrence of 1 in 100 years
- 140 mm within 2 h, with a probability of occurrence of 1 in 1.000 years

The rainfall probabilities were determined by STOWA (2018) using a Generalised Logistic Distribution (GLO) and translated into rainfall-duration curves. In the current climate, such precipitation can occur with the given average probability of 1/100 and 1/1.000 years, respectively, at a particular location. klimaateffectatlas (2024) emphasises that the probability of those events can be twice as high by the end of this century due to climate change.

Both events are seen as suitable representations of a scenario with a possible likelihood under current climate conditions, and a less likely but still reasonably likely scenario to be considered for climate adaptation planning. Both events are used for a wider range of assessments related to climate risks and climate adaptation in the Netherlands, and are available as Official Open Data from the climate data portal (klimaateffectatlas 2024).

In the open dataset, water depths are expressed as five discrete classes. To allow for the comparison with critical thresholds for failure t_f, the classes are first translated into water depths using a linear approximation between mean values for each class. Furthermore, we resampled the original dataset to a resolution of 25 m to allow for identification of assets adjacent to buildings, where water depth was clipped in the original dataset. In Figure 5 we show a box plot of the water depths for all UCI assets, grouped by UCI sector, for both rainfall scenarios.

Next, to assess potential UCI failure through pluvial flooding, the critical threshold for failure t_f as recorded for each critical asset during field work is subtracted from the water depth d_w. This allows for accounting for location specific situations, as for example UCI assets which are situated slightly below street level due to recently increased street levels. For this reason, the critical threshold takes the elevation of the asset relative to street level into account.

Figure 6 shows the resulting flood depth d, that is, critical threshold t_f minus water depth d_w, as box plots for all UCI assets, grouped by UCI sector, for both intense rainfall scenarios.

It can be seen that several UCI sectors are not (directly) affected by flooding: healthcare (HC), WW and TC. On the other hand, thresholds are exceeded for all other UCI sectors for the 1/100 or 1/1.000 years intense rainfall scenario, respectively. Table 6 lists the number of UCI assets affected.

Due to the large number of dependencies on the UCI sector Electricity (Table 2), the effect of possible cascades and disruptions is assessed in more detail. For this, outage areas are estimated using a Voronoi decomposition, dividing the AoI into smaller areas around each substation as indicated in Figure 7. The population distribution is resampled from

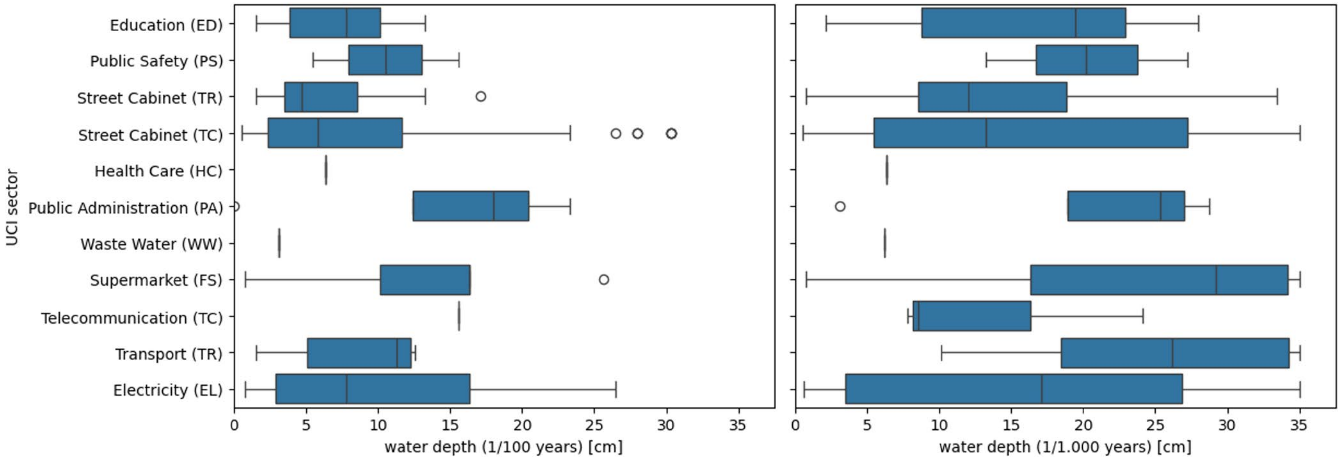


FIGURE 5 | Water depths in the case study area grouped by UCI sector for the 1/100 (left) and 1/1.000 (right) 2-h intense rainfall scenarios.

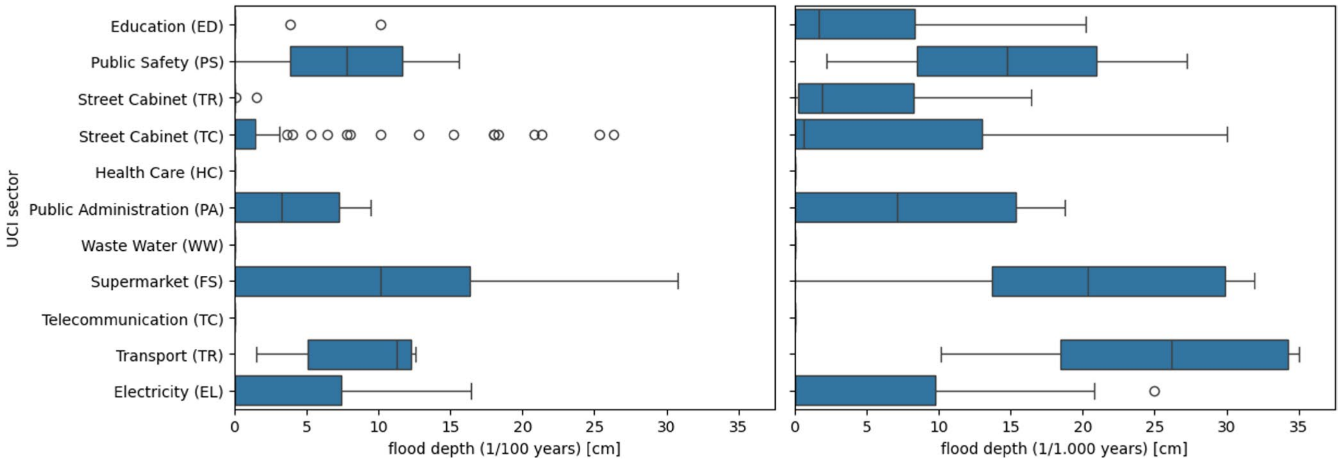


FIGURE 6 | Flood depths *d* in the case study area for UCI assets, grouped by UCI sector, for the 1/100 (left) and 1/1.000 (right) 2 h intense rainfall event.

TABLE 6 | Number of UCI assets directly affected by intense rainfall, by UCI sector.

UCI sector	Types of critical assets	1/100 rainfall	1/1.000 rainfall
ED	Schools and daycare	2	6
EL	Medium voltage transformers	3	4
FS	Supermarkets	5	9
PA	Municipality headquarters, court, tax office, public works office	2	2
PS	Police, shelters	1	2
TC	Glass fibre street cabinets	23	52
TR	Access roads	6	6
TR	Street cabinets (traffic lights and street lights)	2	7

CBS district data collected in Step 2 (CBS 2023) to 100 m resolution. Population density is distributed by combining the footprints for residential buildings from OpenStreetMap with building height. The latter is derived for each building from the high resolution (5 m) national digital surface model AHN4 (ArcGIS 2021). The population for each urban district is then equally distributed to the calculated floor space and transferred into a 100 m grid.

The assessment shows that the failure of electricity directly affects about 5.200 inhabitants for the 1/100 scenario and 6.800 inhabitants for the 1/1.000 rainfall scenario (Figure 7). Moreover, people are affected indirectly, as for example, people who are living outside the AoI but their workplace in the AoI is affected or people from outside the AoI who use affected supermarket or school within the AoI. The number of indirectly affected people is however not quantified due to a lack of data.

In the next step, the following cascading effects are identified:

- *EL to DW*: For buildings above five floors, water is pressured through hydrophores; thus, drinking water is unavailable as soon as electricity fails (VHM 2024).

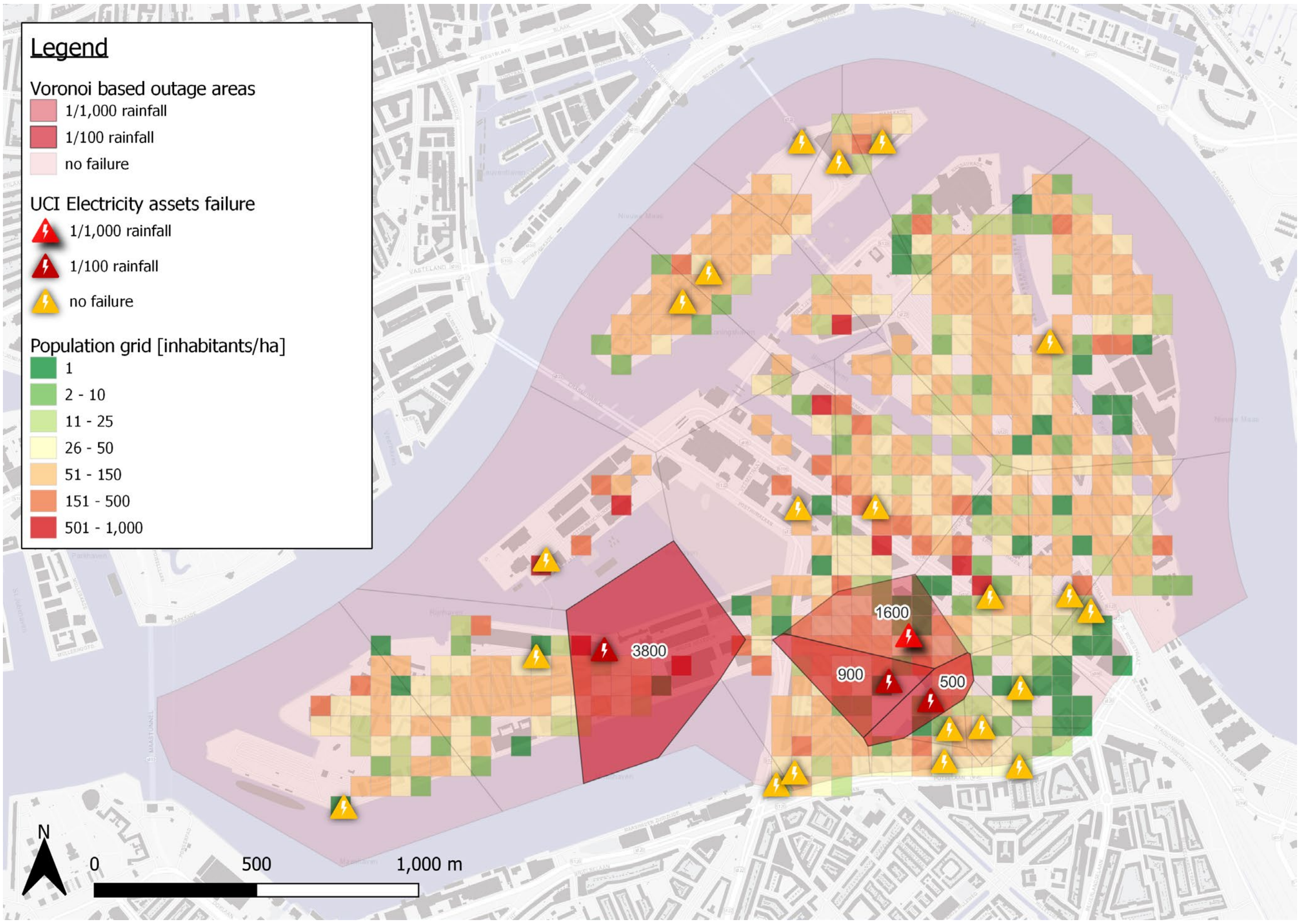


FIGURE 7 | Electricity outage areas and number of inhabitants affected based on Voronoi decomposition.

- *EL to TC*: Telecom towers have backup batteries to sustain electricity interruptions up to 120 min. Failure may be absorbed by other towers in the area; however, accessibility is reduced significantly, which can be an issue when emergency services need to be called.
- *EL to HC*: people in critical state or dependent on oxygen resuscitation apparatus can only sustain short electricity interruptions, emergency medical support or evacuation may be necessary (FMS 2024). Failure of TC and TR may lead to compounding risks here.
- *EL to WW*: Contamination of surface water and flood water due to sanitary sewer overflow (SSO) as a consequence of failure of pumping stations

Figure 6 shows further that the criticality thresholds for the access roads are exceeded about 10 cm in the 1/100 event and about 25 cm in the 1/1.000 intense rainfall event. This means that interfaces $I_{TR,1}$ and $I_{TR,2}$ are affected and that both hospitals may not be accessible temporarily, leading to an increase in travel times and traffic congestion and thus, reduced accessibility for emergency services. The remaining interfaces appear to be unaffected in both intense rainfall scenarios.

5.4 | Step 4: Evaluation

In the last step, the risks for each hazard scenario are evaluated using the proposed risk matrix. This classification is carried out for each UCI sector for the four types of consequences: A—impacts on UCI assets, B—cascades to other UCI sectors, C—effects for inhabitants and D—economic and other consequences. Table 7 shows the result of the risk evaluation.

In this study, the likelihood of the 1/100 rainfall event was rated as 'II—likely' and the 1/1.000 rainfall as 'III—possible'. This is a conservative assumption to demonstrate the methodology and is based on the fact that the probability of intense rainfall events can double by the end of this century due to climate change (klimaateffectatlas 2024).

From the risk evaluation in Table 7 it can be seen that most risks are evaluated as medium to low risk. For a number of criteria the risk for the 1/100 hazard scenario is higher than for the 1/1.000 hazard. This is due to the fact that the lower probability of the hazard event and a similar classification of potential consequences is leading to a lower risk classification in the risk matrix.

TABLE 7 | Risk evaluation for two intense rainfall scenarios for different types of consequences based on the proposed risk matrix.

UCI sector	Category	Evaluation of consequences	Risk evaluation 1/100	Risk evaluation 1/1.000
EL	Inhabitants	Disruption of electricity is evaluate to have *minor consequences* for about 5.200 (1/1000: 6.800) inhabitants, as long as it can be limited to a few days.	Medium	Low
	Assets	Intense rainfall can lead to damages and failure of 15% (1/1000: 19%) of electricity street cabinets and therefore *minor consequences*.	Medium	Low
	Cascades	*Moderate consequences* due to cascades to *multiple* UCI sectors within the AoI: DW (hydrophores), HC (oxygen resuscitation apparatus), TR (street and traffic lights), TC (mobile network), WW (pumping stations)	Medium	Medium
	Economic and other	*Minor consequences* when outage is constrained to few days. Supermarkets need to discard cooled and frozen goods after few hours (see FS). Small businesses suffer impacts from business disruption. No major business activities in the AoI.	Medium	Low
HC	Inhabitants	For people dependent of oxygen resuscitation apparatus, EL failure can lead to *major consequences* when outage exceeds few hours.	High	Medium
	Cascades	Hospitals outside of the case study area may be inaccessible due to flooding of access roads (TR). Given the short duration of flooding evaluated as *insignificant consequences*.	Low	Low
TR	Inhabitants	Short disruption of road network and public transport due to submerged local and access roads (*insignificant consequences*)	Low	Low
	Cascades	Disruption of public transport (bus, metro) will impact areas outside the AoI, cascades to several UCI sector (EL, PS, HC, PR), e.g., for repair work due to disruption of access roads (*moderate consequences*)	Medium	Medium
	Economic	Limited economic consequences due to short disruption of transport network (*minor consequences*)	Medium	Low
FS	Inhabitants	Supermarkets are particularly vulnerable to intense rainfall due to barrier free entrances, affecting 27% (1/1.000: 48%) of all FS assets and therefore *moderate consequences* for inhabitants.	Medium	Medium
	Economic and other	Supermarkets need to discard cooled and frozen goods after few hours and suffer limited loss of income (several days), thus *minor consequences*.	Medium	Low

Note: The highlights were used to highlight the evaluation of the level of consequences.

The results in Table 7 show that the largest risk is identified for HC, with significant health risks for vulnerable people, in particular people dependent on oxygen resuscitation apparatus which can only sustain electricity outages up to 4 h (FMS 2024). This finding was discussed and validated with an expert from the local Safety Region Rotterdam-Rijnmond. It was also discussed that cascading effects may lead to other consequences due to dependencies which have not yet been identified.

Furthermore, the insights supported the discussion about climate adaptation of UCIs, and particularly the interaction with measures taken by the municipality. For example, in the past the municipality has increased the street level and sidewalks due to subsidence and complaints from citizens about ponding, in some cases leading to UCI assets being situated relatively lower and therefore more vulnerable to rainfall.

Given the uncertainties from using open data and a number of assumptions on underlying dependencies, the largest risks identified in this risk screening need to be assessed in more detail and discussed in a cross-sectoral risk dialogue with UCI operators in a subsequent step. For this, the municipality has established contact with UCI operators. Particular focus should be put on the identification of further cascading effects.

6 | Discussion and Conclusions

This paper presents a method for flood risk assessments of UCIs based on crowd-sourced and open data on hazard, exposure and vulnerability. The method is developed to support local authorities around the world in their efforts to identify and prioritise flood risks for UCI in order to mitigate risks and increase resilience of their communities. The applicability has been demonstrated through a case study for an urban district in Rotterdam for two intense rainfall scenarios.

One of the main contributions of this research is the use of crowd-sourced and open data for risk assessments of UCI to overcome the limitation of data unavailability from UCI operators. Official Open Data is becoming more available thanks to open data directives and advocacy of the benefits by international organisations such as UN and the World Bank. For example, in the United States, the Homeland Infrastructure Foundation-Level Data (HIFLD) has been established through CISA that can be used 'to support planning and assessment activities, and to help communities improve their preparedness and resilience' (CISA 2025). In the United Kingdom, the National Receptors Dataset (NRD) is available from the Department for Environment, Food & Rural Affairs (DEFRA).

Moreover, the worldwide growing coverage of OpenStreetMap, with a combination of official open data and crowd-sourced data, despite varying levels of completeness, fosters the development of scientific and practical applications directly utilising OSM data and enables the transferability to other countries.

The use of open and crowd-sourced data does, however, come with a number of challenges. Crowd-sourced data is potentially incomplete, inconsistent and not current. Collecting additional data and ground-truthing OSM data through field work is found to be a valuable alternative and shown to be possible for the extent of a district in an urban case study. Nevertheless, this also poses a limitation of the proposed method. In the future, this limitation could be solved by utilising more resources for crowd-sourcing data or combining OSM data with synthetic datasets for larger areas beyond the urban district level. Nevertheless, the proposed approach is also suitable in data-sparse environments, as it is possible to involve citizens or other stakeholders in the data collection process and field work.

However, data collection is mainly limited to UCI assets above ground which are visible from publicly accessible areas, as underground infrastructure networks are more difficult to identify, trace and map. On an asset level it is possible to consider underground assets by mapping connections to ground level as for example openings, ventilation inlets and entrances, however this is not sufficient for mapping network characteristics of UCI. Hence, the second limitation of the proposed method is, that characteristics of UCI networks cannot be assessed and hence cannot be considered in the risk assessment. This means that general assumptions about network characteristics and dependencies need to be made using spatial relationships, as for example done in this case study for the outage areas of electricity substations. The uncertainties arising from this limitation can lead to misjudgement, that is, over- or underestimation of risks. The verification and discussion of identified risks with UCI operators through collaborative risk dialogues should, therefore, be the next step of the process.

Further uncertainties need to be attributed to the fact that the interaction between surface flooding and the stormwater and drainage system can have a significant influence on flood depths, particularly for intense rainfall. Maintenance of street inlets, unexpected blockage as well as failure of pumping stations as a consequence of electricity outages can potentially lead to higher flood depths, and in turn, to failure of more UCI assets and cascading effects, yet those aspects are not considered in this study. To solve this in the future, the national official open dataset used in this study can be replaced by more detailed modelling results from local studies or being coupled to a rainfall-drainage model for analysis of different scenarios.

The third limitation in this study is that the analysis does not reflect on the duration of outages and associated restoration times, which, however, do have a significant influence on the classification of risk levels. Tsavdaroglou et al. (2018) show restoration times for high voltage network assets in the port of Rotterdam to be weeks or even months, while Koks et al. (2022) found restoration of electricity between 2 days and 8 weeks for the 2021 Central European Floods. Given that the hazard intensity of intense rainfall in this case study is significantly lower than in the 2021 flood event, restoration times are expected to be on the lower end of the spectrum. The procedure of the local system operator aims at solving outages within 24 h, but it is debatable if this is realistic when a larger area is affected by intense rainfall (De Bruijn et al. 2022). As found in this study, duration is a critical factor as longer outages pose significant health risks for vulnerable people, in particular people dependent on oxygen resuscitation apparatus which can only sustain electricity outages up to 4 h (FMS 2024; VR Twente 2025).

Overall, it needs to be acknowledged that the proposed method allows for a first, high-level risk screening of UCI, to indicate where in-depth risk assessments are necessary. Even though more sophisticated and detailed modelling and simulation approaches exist, the main advantage of the proposed method is its simplicity for potential application by local authorities aiming to improve the preparedness and resilience of their communities. At this stage, the method is not suitable for in-depth assessment or sophisticated modelling and simulation of CI failure, which requires more data on network level including topologies and dependencies.

The use of open and crowd-sourced data eliminates the need for proprietary software and complex software models as utilised by UCI operators. While UCI operators do carry out their own risk assessments in due diligence, also in response to the 2022 Resilience of Critical Entities Directive (EU 2022), risk assessments are limited to their own assets. Based on this gap of knowledge and responsibilities, we have shown that using open and crowd-sourced data enables a cross-sectoral risk screening of UCI. The screening provides valuable insights into potential flood risks due to UCI failure, which can be discussed and refined in a subsequent risk dialogue with all UCI operators.

Collecting critical thresholds for individual UCI assets relative to street level has been shown to improve the results of the risk assessment, compared to using values from literature with rather large bandwidths. When comparing critical thresholds for UCI assets collected from field work with values from literature (NKWK 2024; Hummel 2024), literature shows comparable thresholds; however, with a larger range of uncertainties. In particular, in complex urban settings, critical thresholds can vary significantly, even for the same type of assets. For example, if the street level was increased to mitigate the effects of intense rainfall, adjacent UCI assets may be situated in local depressions and be particularly prone to flooding and failure.

The results of this case study show that UCI can be affected by intense rainfall and highlight risks due to UCI failure and cascading effects. At this stage, limited assumptions can be made about possible cascading effects, which, however, may increase risk levels. The identification of further cascading effects should therefore be part of the abovementioned risk dialogue between UCI operators subsequently to this risk assessment. As part of the risk dialogue, further parameters can be determined, as for example available redundancies within the network, restoration times and operational procedures and protocols, enabling a more sophisticated risk evaluation.

Future research should aim at investigating relationships between hazard intensity and extent in relation to restoration times of UCI assets. Furthermore, it should be investigated how underground UCI networks such as drinking water, gas, electricity or TC can be identified and mapped using field work.

It can be expected that, as a consequence of a changing climate (more extreme rainfall), socio-economic developments (urban growth and demographic shifts) in combination with an increased dependency on UCIs, flood risk is likely to further increase in the future if no adaptation measures are implemented accordingly. The method proposed in this study will support local authorities to carry out risk screenings to identify the largest risks from UCI failure. The insights help to take steps towards cross-sectoral risk dialogues with UCI operators to collaboratively develop risk management measures and to identify opportunities for climate adaptation.

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Data Availability Statement

The data that support the findings of this study are openly available in 4TU.Research Data at https://data.4tu.nl/, reference number https://doi.org/10.4121/26e8ddbd-23fe-4a95-bec1-298721631104.v1.

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