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Integrating Critical Infrastructure Networks into Flood Risk Management

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Abstract: Critical infrastructure (CI) networks are essential for the survival and functionality of society and the economy. Disruptions to CI services and the cascading effects of these disruptions are not currently included in flood risk management (FRM). The work presented in this study integrates CI into every step of FRM, including flood risk analysis, risk mitigation and risk communication. A CI network modelling technique enables the flood consequences for CI to be quantified as part of the flood risk analysis. The CI consequences derived from this analysis include spatial overviews and the temporal succession of CI disruptions. The number of affected CI end-users and the duration of the disruption are arranged in a risk matrix and in a decision-making matrix. Thus, the total flood risk is extended with CI consequences. By integrating CI and CI network characteristics into the flood risk assessment and the mitigation steps, a wider range of measures for action can be considered. Additionally, the continuous participation of CI operators is introduced as beneficial for every step of the FRM. A case study in Accra, Ghana proves the benefits of CI integration for all FRM steps. During participatory CI stakeholder engagements for this study six CI sectors were identified for the assembly of the CI network. The backbone of the analysis is a multisectoral, layered CI network model with 433 point elements, 1216 connector elements and 486 polygon elements.

Keywords: flood risk management; critical infrastructure networks; model-based decision support; flood resilience; mitigation measures

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1. Introduction

Flood events have imminent and long-term consequences for people and the economy revolving around the restoration and replacement of critical infrastructure (CI) services [1,2]. In this paper, critical infrastructure services are defined as services supplied by infrastructure that are vital for a civil society. CI is the technical structures required for supplying these services and are organised in sectors such as energy, water, information and communication technology (ICT), health, emergency services, transportation and more [3]. CI networks are formed by considering the interdependencies of these individual CI sectors. A recent report from the European Commission's Joint Research Centre shows that flooding damage in the electricity sector caused by disruption exceed the repair costs. The expected damage is 6–8 times greater when indirect intangible consequences outside the inundated area are considered [4]. Researchers advocate for the inclusion of indirect flood consequences caused by the failure of critical infrastructure in the flood risk analysis [5].

In Western Europe, critical infrastructure supplies such as gas and telecommunications were still dysfunctional several months after the flood event that took place in summer 2021, and the livelihood of the affected residents remained disrupted [6]. These experiences have prompted researchers to call for the climate change resilience of CI to be audited more thoroughly, including with regard to flooding [7].

The work presented in this paper starts with a review of current FRM practises and CI analysis and assessment methods. After that, the individual steps of the state-of-the-art FRM approach are described with a focus on CI integration. Finally, the proposed integration of CI is demonstrated in a practical application: A case study in Accra (Ghana).

2. Literature Review

To tackle the current lack of focus on combining critical infrastructure resilience with strategic flood risk management, flood risk management directives can be used. These are briefly analysed below. Following the 9/11 terrorist attacks in New York, public policies started to concentrate on critical assets and infrastructure. Since then, the definition of CI has continuously evolved, from critical assets to infrastructure towards networks and, ultimately, the critical function they fulfil. The EU refers to CI as critical entities. Critical infrastructure resilience policies need to represent the impact of natural and man-made hazards as well as the dynamic of an interdependent system according to the Organisation for Economic Cooperation and Development (OECD) [8].

The United Nations (UN) Sendai Framework recommends action for critical infrastructure services in the areas of disaster risk reduction and flood risk management. The Sendai Framework highlights direct damage to CI as well as the disruption of CI services. Furthermore, it calls for a reduction of these two types of damage and an increased resilience by 2030 [9]. Additionally, the UN embeds systemic thinking in its guidance documents. It is highlighted that the impacts of climate change, among other factors, lead to a systemic risk that goes beyond conventional risk management and governance [10].

The European Union (EU) Flood Risk Management Directive [11] provides a framework for dealing with flood-related issues at European level. Flood hazard and flood risk maps are being developed, primarily for risk communication regarding selected water bodies. The flood hazard for three hydrological scenarios (with high, medium and low probability) is presented and communicated in flood hazard maps. The direct consequences are communicated in flood risk maps. However, this particular directive does not mention the critical supply infrastructure. Complementary to the previous directive is the EU directive on the resilience of critical entities, which was expected to be finalised at the end of 2022. This indicates a shift from a focus on the transport and electricity sectors in the previous directive of 2008 towards a Europe-wide strategic analysis of critical entities [12].

In 2021, the United States initiated the Bipartisan Infrastructure Deal, releasing an investment of USD 50 billion and highlighting the importance of maintaining infrastructure. The deal places a specific focus on adapting to climate change which, besides droughts, heat and other hazards, includes flooding [13]. The legislation recognises the systemic role of critical infrastructure, referring to CI as "system-wide critical lifelines", which are to be protected.

Few German regulations on CI and FRM connect both topics in detail. The regulation of the cross-state spatial plan for flood protection calls for better protection of plants and facilities of national and European importance by focusing on corresponding critical and vulnerable infrastructure [14]. The regulation emphasises the special systemic functionality and relevance of CIs as their failure and the subsequent cascading effects can exceed the magnitude of the directly impacted areas.

The German Federal Office of Civil Protection and Disaster Assistance (BBK) calls for integrated risk management that connects CI operators [3]. The German Water Resources Act deals, among other things, with water management planning and flood protection in Germany at federal level. However, it does not mention the term critical infrastructure or the systemic functionality and criticality of its supply. Individual sectors, such as transport infrastructure, are considered isolated from each other [15]. In the North Rhine–Westphalia (NRW) State Water Act, critical infrastructure is only mentioned for specific sectors. A lot of attention is paid to securing the drinking water supply for facilities in flood plains through technical measures or alternative facilities. However, there is no exploration of interdependencies with other CI sectors [16]. As the directives mentioned in the previous section show, complex critical infrastructure networks are rarely included within FRM practices. A range of the state-of-the-science literature addresses the steps of flood risk management shown in Figure 1 individually for the topic of CI. The methods for embedding CI in flood risk directives are already available, and CI models are currently used in different management contexts already, such as supply chain management, cyber security and transportation routing [17].

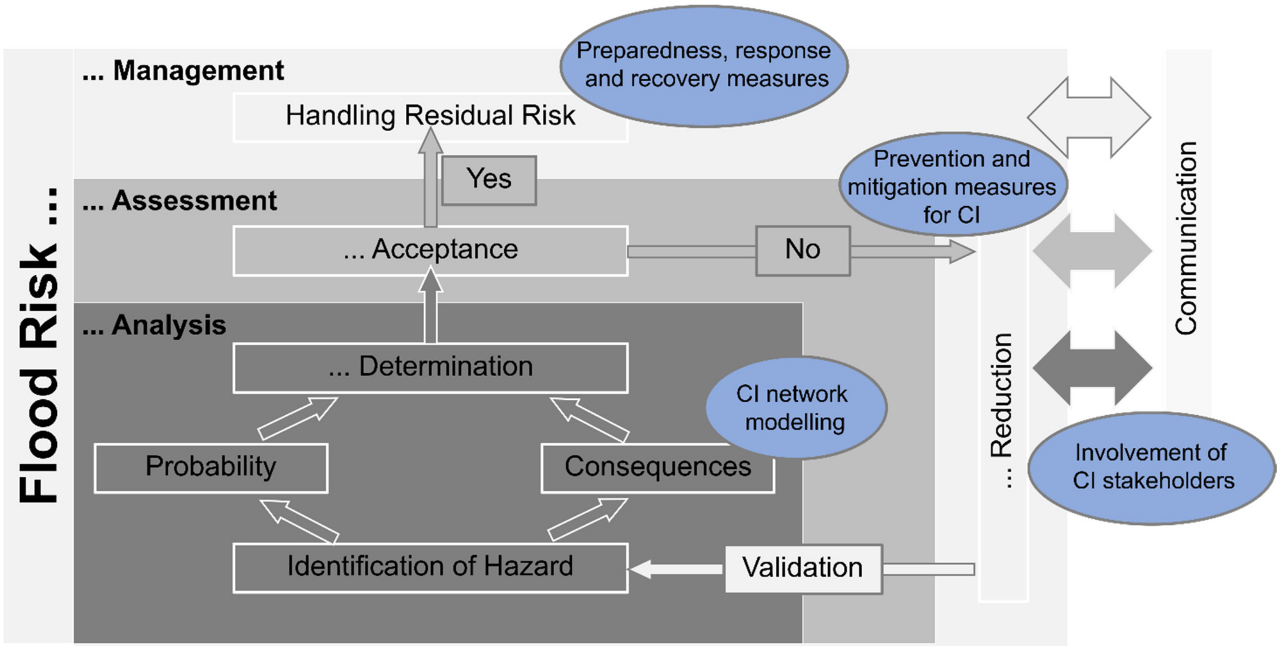

Figure 1. Generalised summary of flood risk management workflow, including ellipses marking the integration of CI.

CI modelling methods also diverge from each other in terms of their structure, function and purpose. Empirical approaches [18], economic theory-based approaches [19], network-based approaches [20,21] and multi-sectoral approaches are four of the possible approaches towards assessing the consequences relating to critical infrastructure services and flooding. Flood risk analyses including CI are executed for a range of spatial boundaries, ranging from building level to a regional level as well as the global level [22,23]. Additionally, they can be differentiated by the CI sectors that are included in the analyses. Analyses can consider one individual sector [24], one sector including dependencies on individual network elements from other sectors [20,25] or a system of CI sectors within one CI network [26].

Relevant for the work presented here is the modelling approach of Schotten and Bachmann, which focuses on flood risk modelling, including the direct and indirect consequences for a multi-sectoral CI network [21]. Murdock et al. [18] used the disruption of critical infrastructure services as the expected disruption for quantification.

In addition to a technical description, ongoing public and expert participation has proven to improve public and expert support for big infrastructure projects [27]. Due to the dependencies of CI sectors, methods have been developed for CI operator engagement [28–30]. One approach used as a reference for this work is the CIrcle (Critical Infrastructure: Relations and Consequences for Life and Environment) approach, which consists of preparing and executing a workshop in three major steps [31]: 1. stakeholder identification and involvement; 2. participatory assembly of CI network for the current risk status and future scenarios; 3. development of mitigation measures. On the one hand, international, national, and state-wide legislation considers CI for FRM only selectively. The dependencies with other sectors as well as cascading effects are not always considered. On the other hand, research methods are available with the potential to support the individual steps of FRM [32].

3. Integrating Critical Infrastructure in the Steps of Flood Risk Management

The method introduced in the following chapter closes the existing gap between FRM and CI. The main purpose of this method is the integration of CI into each step of FRM. The steps of FRM are described in their current form as used in practice. In parallel, the integration of CI is defined. Universally accepted definitions of an integrated FRM include four steps: Analysis, assessment, management and communication [33–38]. Figure 1 summarises these steps and their connections in an FRM workflow. The initial step of FRM is the analysis of the current state of an area being investigated. The assessment of the current state is then concluded based on the findings of a flood risk analysis (FRA). This results in either acceptance of the current state or denial. Acceptance triggers the question of how to deal with the residual flood risk. Denial results in the development of measures to improve the flood risk situation. The potential measures put in place are validated in a flood risk analysis of the new desired state. This whole process is accompanied by ongoing communication with stakeholders.

In this paper, these steps of FRM are elaborated on further in the beginning of the subchapters. The focus is then to describe the integration of CI in every step extensively.

3.1. Flood Risk Analysis of Critical Infrastructure Network

The first step of the flood risk management is the FRA, which first identifies potential hazards and then derives a range of consequences and associated probabilities. In this paper, "probability", "hazard" and "consequences" are used as terms where the consequences are a combination of exposure and vulnerability [39]. This paper describes catchment-based flood risk analyses based on Bachmann and Schüttrumpf [40]. The focus on entire river catchments ensures that hydraulic responses of potential measures up and down the river are considered.

3.1.1. Hazard Identification and Probability of Occurrence

For flood risk management, the hazard is inundation due to fluvial, pluvial or coastal flooding or flash floods. The key aspect is the identification of flooded areas as well as associated water depth and velocity. For the suggested integration of CI into FRM, the existing methods for hazard identification and their associated probabilities are used. Inundation maps are used to derive the water level at CI structures during flooding events. Hydrological and hydraulic modelling are the state-of-the-art tools to achieve this identification for operational and strategic flood risk analysis, from a local to a global scale [22,40–43].

Realistic flood risk analyses operate within the boundaries of uncertainty and therefore include the probability of the consequences, as shown in Figure 1. Probability is introduced by the hydrological boundaries and the determination of the associated extreme events [44]. Discrete probabilities are derived from return periods of discharge or precipitation events (e.g., HQ10, HQ100 or HQ1000) and transformed into continuous probabilities, considering the lower and higher class boundary of every hydrological event [39]. Further on in this paper, these continuous probabilities are referred to as probability of occurrence p_{hyd} [1/a].

3.1.2. Flood Consequences for the Critical Infrastructure Network

Integrated flood risk management requires a broad view of different types of flood consequences, as shown in Table 1. State-of-the-art FRA considers direct, tangible [45,46] and direct, intangible flood consequences [47–50]. However, a wide range of flood damage consequences are not yet considered as standard in model-based consequence analysis in FRA. CI disruptions on a multisectoral level as direct and intangible consequences are added to the categorisation of flood consequences in Table 1. In addition, the CI service disruptions due to cascading effects are added to the category of intangible and indirect consequences. Cascading effects describe the transmission of disruptions through the dependencies of CI structures within a CI sector (sectoral) and between different CI sectors (intersectoral).

Table 1. Categorisation of flood consequences, including the integrated categories for CI [21].

	Tangible (Monetary)	**Intangible (Non-Monetary)**
Direct (contact with water)	Buildings, Houshold Industry, Business Agriculture, Forestry Infrastructure Cars	Affected People Ecological Values Cultural Values Personal Values **Critical Infrastructure Services**
Indirect (No contact with water)	Business Disruption Traffic Disruption Cost of Emergency Measures Unavailability of Agricultural Land	Loss of Trust in Region Psycho-Social Consequences Epidemics and State of Emergency **Cascading Effects on Critical Infrastructure Services**

For the quantification of these cascading effects in CI networks, the modelling approach of Schotten and Bachmann is applied [21]. In general FRA, a combination of exposure and vulnerability is used to define consequences [34]. The same applies to critical infrastructure networks. To represent CI networks exposure, three types of network elements are used in the chosen modelling approach: point elements, polygon elements and connector elements. Point elements represent CI structures and have attributes that assign them to a sector and a level in their sector (see Table 2). The threshold attribute of the point element defines the vulnerability to water depth causing a disruption. The connector elements are used to connect point elements and polygon elements. Additionally, connector elements cascade the disruption to other elements that are connected. Polygon elements define the spatial extent that their connected point elements are associated with or at least partially associated with. In addition, the polygon is defined by the number of end-users or consumers it supplies with a service. Table 2 summarises all the previously described attributes and others. For more information, refer to [21].

Table 2. CI network elements and their associated attributes [21].

Element	**Input Attributes**	**Description**
Point (Nodes, Vertices)	Point-, Sector Index	Unique identification for point; Sector specific identification.
	Sector Level	Quantitative representation in the hierarchy per sector.
	Threshold	Waterlevel threshold for which exceedance results in failure of CI structure
	Recovery Time	Time until functionality of a structure is regained
Polygon (Area)	Polygon-, Sector Index	Unique identification for polygon; Sector specific identification
	End Users	Number of users represented by polygon
Connector (Edge)	Connector Index	Unique identification for connector
	Source-, Sink Index	Source point identification or sink point/polygon identification
	Type of Source and Sink	Sector identification of source and sink element

Network characteristics are derived in this modelling approach to simplify the understanding of the network formed by the network elements. The cascade potential value p describes the potential of a network element to cause a disruption in other network elements. p stands for an estimate of potentially indirectly disrupted network elements from one directly affected point element. Complementary to this, the cascade vulnerability value V describes how many network elements can disrupt the associated network element that is directly associated with end-users. V describes the vulnerability to cascading effects in a network arrangement and can highlight specific locations or sectors for further assessment. Additional sources on the derivation of other network characteristics can be found here: [21,51].

Two calculation modes are available to determine the consequence for CI: (1) a steady state calculation of the CI network based on the maximum water depth in the connected hydrodynamic 2D element, and (2) an unsteady state calculation, connecting the water depth for every time step of the hydrodynamic to the point elements.

Figure 2 shows a basic CI network model with one inundated CI structure from the energy sector in the centre, as replicated from the calculation. From there, cascading effects transmit the disruption to two point elements in the water and health sector and subsequently their connected polygon elements. The polygon elements are associated with a number of end-users. If there is disruption, this determines the number of disrupted people per sector $P_{dis,sec}$ [people]. The recovery time of the centre element indicates the time of disruption t_{sec} [s] for the other network elements. Based on [18,21] a combination of $P_{dis,sec}$ and t_{sec} of all end-user elements per sector e results in the population time per sector T_{Pop} [people · s]:

$$T_{Pop,\ Sec} = \sum_{i=0}^{e} P_{dis,Sec,\ i} \cdot t_i \tag{1}$$

In addition to $P_{dis,sec}$, this modelling approach provides other insights into the consequences for CI. Spatial overviews of the disruption per sector, cascade chains and the chronological sequence of impacts are some examples.

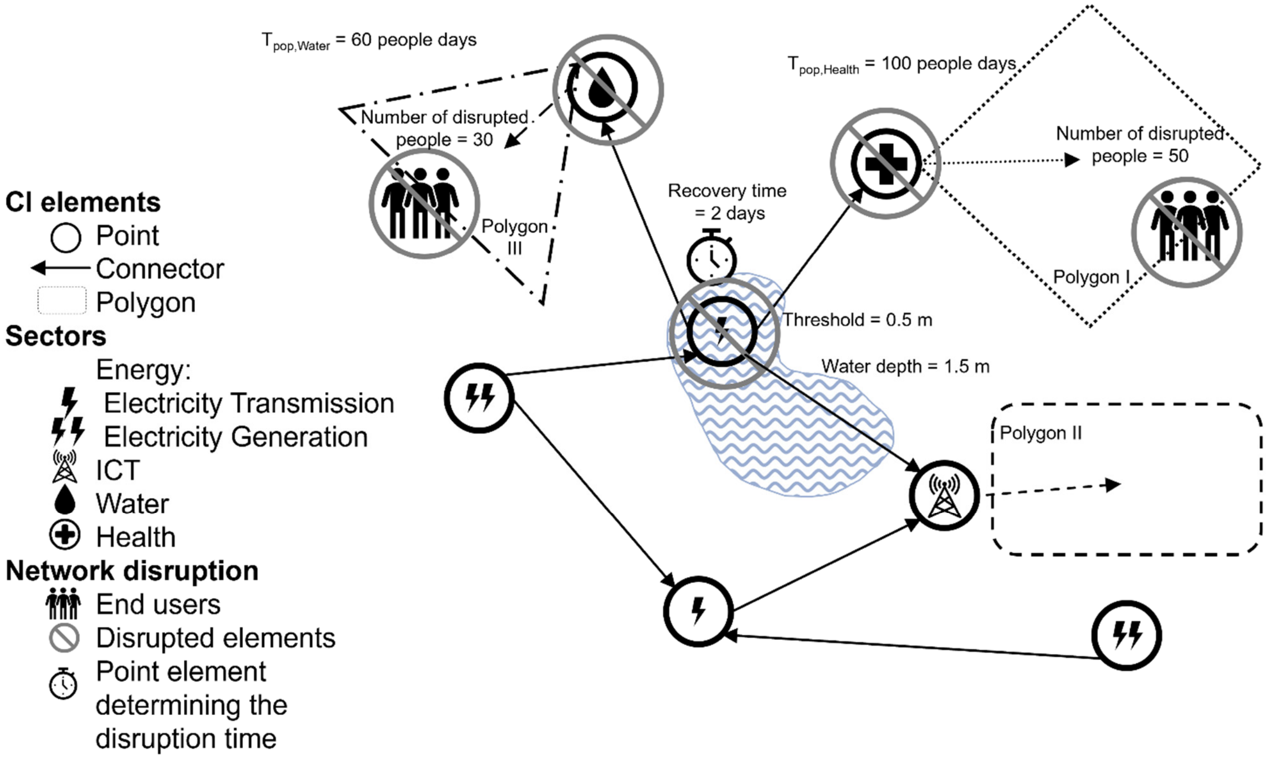

Figure 2. Determination of population time T_{Pop} in a representative small network impacted by a flood [21].

The modelling approach is implemented as CI network module to the flood risk management software PROMAIDES. This software enables the flood risk analysis of other flood consequences categories in parallel such as affected and endangered population or economic damage [52]. The PROMAIDES software framework is supported by a GIS system, a PostgreSQL database and plugins for pre- and postprocessing [53]. Documentation supports the model generation and analysis of the CI network modelling approach [54].

Data acquisition is a key challenge for the input and validation of this modelling approach. Data quality significantly impacts the CI network model's level of granularity and fidelity. Examples have shown how this information is derived in a participatory workshop setting [28,55] or through empirical sources [56,57].

3.1.3. Determination of Risk for CI Consequences

The concept of risk as applied in this paper considers the probability of occurrence p_{hyd} in combination with the consequences for each hydrological hydraulic event C_{hyd}. Table 3 summarises the risk for a range of consequence types relevant for decision-makers, such as ecological damage and people affected and endangered. As well as the risk, hydraulic and hydrological boundaries need to be addressed to account for compulsory maximum or minimum discharges and the planning of retention areas, for example.

The derivation of risk as a decision-making unit is applied for the consequences to CI as introduced for example by Murdock et al. [18]. The consequences in this calculation are T_{Pop} as the quantified consequences of flooding for CI. The sum of all products of T_{Pop} and p_{hyd} per return period scenario k result in the risk of consequences for CI R_{CI} [people·s/a]:

$$R_{CI} = \sum_{k=0}^{n} T_{Pop,sec,k} \cdot p_{hyd,k} \tag{2}$$

The expected disruption in population time per year can be derived in total or differentiated per sector. In the case study, an example matrix introduces these options.

This adds another type of flood consequence to the range of potentially relevant flood risks that are considered in decision-making processes, as shown in Table 3. The well-established consequence types are economic damage, people affected and endangered and maximum discharge which needs to be ensured. The CI service disruption is to be added to the risk matrix of consequences.

Table 3. Current flood risk categories complemented by flood risk for CI.

Flood Risk Categories	Unit
Direct economical damage	Expected annual damage [€/a]
Ecological damage	Expected annual damage [€/a]
People affected	People directly affected by water [people/a]
People endangered	Danger to life due to flooding [people/a]
Maximum discharge	Maximum discharge [$(m^3/s)/a$]
CI service disruption	Population time risk [people · s/a]

3.2. Flood Risk Assessment: Acceptance or Denial

After the flood risk analysis is finished, the next phase of FRM is the flood risk assessment. The assessment answers the question whether a determined flood risk is accepted by society through its decision-makers and political representatives. If there is no acceptance of the flood risk, a set of prevention or mitigation measures must be developed. Those risk reduction measures are designed to create an acceptable flood risk situation [58]. The set of reduction measures is validated again through a risk analysis and then finally selected by decision-makers changing the current flood risk situation. If the flood risk is accepted, preparedness or response measures such as early warnings, action protocols and awareness-raising with all stakeholders need consideration (see Figure 1).

This paper integrates the consequence category of CI into the assessment step of FRM. For this, a range of aspects can be considered for the decision-making related to acceptance of a flood risk situation. First, there is the quantification of CI flood risk as R_{CI} (see Equation (2)). Additionally, the CI modelling approach identifies the areal spread of CI disruptions per CI sector. This supports the acceptance of potential measures since people affected by disrupted CI are included in the assessment of the flood risk situation. Lastly, the inclusion of CI paves the way for measures not yet considered in flood risk management. The availability of these newly included measures can have an impact whether a situation is accepted or not.

The network characteristics derived from the arrangement of the network elements identify especially vulnerable or influential CI structures without looking at the inundation maps. During the assessment phase, CI structures with high C and V can be combined with flood maps. This gives additional criteria for the acceptance or denial of a flood risk situation. The denial and the acceptance of a flood risk situation lead to the development of measures to improve the flood risk situation.

3.3. Risk Reduction—Enabling Prevention and Mitigation Measures for CI

The denial of a flood risk situation results in the commitment to risk reduction. Current mitigation and prevention measures for risk reduction can range, for example, from technical flood protection and adaptation planning to flood water retention. The types of measures listed previously are referred to as established measures. Favourable measures are tested as scenarios by adapting the boundaries in hydrodynamic or hydrological models. The risk these scenarios is compared to the risk of the initial state [39].

The integration of CI into risk reduction efforts allows consideration of a spectrum of measures that is not included in FRM. The range of possible measures in general is wide and is divided into three categories for this paper: (1) prevention and mitigation; (2) preparedness; (3) response and recovery measures. (see Table 4). The risk reduction in this paper is achieved using prevention and mitigation measures. Examples of these types of measures are given in Table 4. A range of these measures can be integrated into the CI network model, such as the elevation of electrical structures to raise the threshold value for a specific CI point element. Another example is the installation of a redundancy for a CI element.

The possibility to include potential measures in the CI network model allows a CI risk to be derived for particular scenarios. This allows scenarios of CI measures to be compared with the current state and also allows scenarios to be compared with one another. Based on these comparisons, decisions can be made regarding the most effective measures for CI. These decisions can be based on the biggest effects of prevention and mitigation measures on R_{CI} in general or per sector.

Table 4. Categorisation of flood risk measures based on the stages of disaster risk management cycle. Examples are shown for primary sectors in general and the energy, water and ICT sectors.

Measure Category	Prevention & Mitigation	Preparedness	Response & Recovery
Exemplary Measures for Critical Infrastructures	No construction of CI in flood prone areas	Training of operational readiness of technical maintenance team	Protection of electrical components through premature switch-off
	Elevated positioning of electrical components	Stocking of spare parts for quicker repair	Prioritization of CI structures with short recovery times
	Redundancies in supply for substations	Raising awareness among the affected population—Stocking at household level	Provision of bottled drinking water
	Increased water level threshold through flood protection	Informing the public about limited network availability	Drying of solid fuels
	Increased battery storage for network masts	Education of CI operators with flood maps	Prioritized repair of ICT structures without redundancy

The integration of CI into FRM is not intended to replace the consideration of flood risk for population and economy. The aim is to present R_{CI} as another criterion in addition to risk criteria that already exist. The summary of these risk criteria for several consequence categories is derived for the current state as well as for scenarios considering flood risk measures. Further on in this paper, this overview is introduced as a decision-making matrix. An example of the decision-making matrix is presented in the case study (see Section 4.4).

3.4. Coping with Residual Risk

After identifying and pursuing options for reducing flood risk, a certain degree of residual risk remains. Dealing with residual risk is a task for civil society, CI operators and public actors (e.g., operators of flood forecast systems). Again, the focus is on the integration of CI into the FRM approach, at the step of handling residual risk.

From the point of view of CI operators and stakeholders, the results of the flood risk analysis including CI provide valuable information for taking response and recovery measures (see Table 4). That information can be useful for response measures for emergency services (fire services, ambulance services or police) as well as for CI providers in the water, gas and electricity sectors. These CI suppliers become emergency operators during extreme hazard events and have to take response and recovery measures. The accessibility of spatial CI network datasets in relation to inundation maps, return periods and, subsequently, risk allows individual CI sectors to improve their prioritisation of response measures such as premature switch-offs of electrical components or the provision of bottled drinking water. Additionally, individual CI operators can benefit from the awareness of interdependencies with other CI sectors and can prioritise their recovery measures.

Participation of CI operators in FRM enables quick connection to other sectors for emergency management. It increases their ability to act. Currently, organisational connections between CI operators are often lacking [57,59].

Another angle to tackle residual risk is the raising of public awareness and preparedness in areas potentially affected by CI disruption. For CI operators, this involves identifying and notify individual homes that may be under threat of CI disruption during flooding events. This encourages individuals to take action to ensure self-sufficiency and decreases dependency. Examples of preparedness measures at household level are: provision of generators and fuel, freshwater storage in bathtubs or tanks, foregoing minor health treatments in hospitals.

3.5. Communication in Flood Risk Management and among CI Operators and Stakeholders

Integrated concepts of FRM highlight the importance of continuous communication during all stages of analysis, assessment and management [60]. For big infrastructure projects, successful communication is built upon the possibilities of public participation [27]. The flood risk analysis benefits from experts and planners communicating information to civil society and vice versa. Public participation during hazard modelling, also known as participatory modelling, ensures a robust outcome [61]. During the assessment, it is important to communicate bi-directionally about the decision-making process. Communication is also important for identifying potential measures and the presence of residual risk [61,62].

The integration of CI into FRM communication is another aspect of this paper. Figure 1 highlights that communication is an ongoing effort. Therefore, it is particularly important to involve CI operators and stakeholders continuously. There are five good reasons for the involvement of CI operators and stakeholders: (1) the acquisition of data and information for the flood risk analysis; (2) the development of feasible and realistic prevention and mitigation measures; (3) the generation of awareness among CI operators for flood risk; (4) the development, communication and implementation of preparedness, recovery and response measures; (5) the organisational cross-linking of CI operators with each other.

The five reasons given are all addressed by the CIrcle method previously mentioned (see Section 2). In this paper, the CIrcle method is used to integrate CI operators into FRM communication and is accompanied by a web tool [30,31].

The first step of the CIrcle method is to identify local core CI operators and particularly the relevant CI sectors for the area of interest, depicted as circular sectors in Figure 3. Contacts are established and information is gathered for the individual sector; this is also in preparation for the second step. In the second step, the operators and stakeholders participate together in a workshop. Based on their expert judgement, the potential dependencies of CI sectors are gathered and summarised in the CIrcle. Participants are asked to state their individual positions and the potentially relevant interdependencies of their sectors during a flood event, as marked by the connecting elements of the circular sectors. The third and concluding step offers an outlook on where the cascading effects are identified, and potential measures to break cascading effects are discussed. The three steps of this method align with the analysis, assessment and measure planning.

Each application of this method delivers results specific to the CI networks in the area of interest and also depends on the background of the participating CI operators and stakeholders. The CIrcle method can accommodate a qualitative discussion focussing on the CIrcle itself (see Figure 3) and the dependencies. The method can also be used to derive more quantitative information including hazard, consequence and risk-based maps. The more quantitative contributions participants give during this exchange, the more additional information and data flows into the CI network model setup.

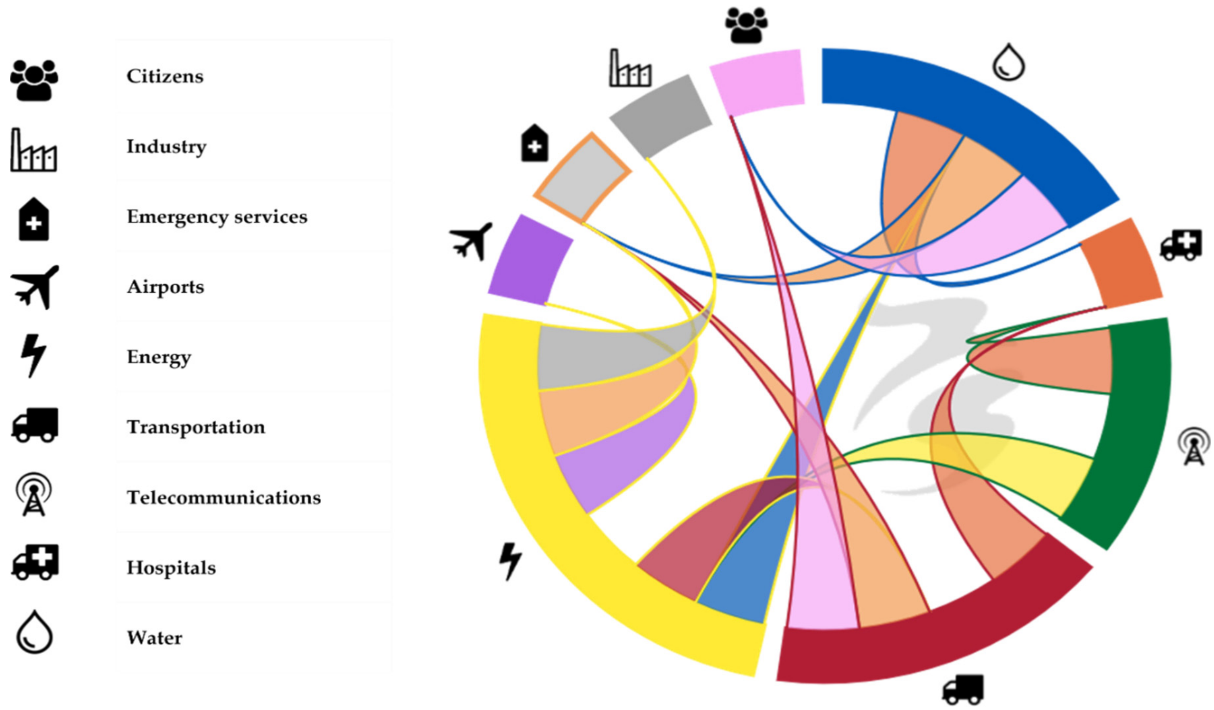

Figure 3. Fictional composition of a “CIrcle” depicting the cascading effects within CI sectors [30,31].

To ensure development towards control implementation and an effectiveness evaluation as concluding steps of risk management [17], it is of crucial importance to address the question of how to trigger suggested mitigation measures. Cascading effects of the flood impacts and consecutive network disruptions cause a cascade of responsibilities for initial action-taking and resource allocation on the operator side. This carries the risk that no action will be taken at all after such an analysis. To overcome this issue, communication is highlighted extensively in this workflow’s description.

4. Case Study in Accra and CI Integration into Flood Risk Management

The integration of CI into FRM is presented in a case study in Accra, the capital of Ghana. The PARADeS (participatory assessment of flood-related disaster prevention and development of an adapted coping system in Ghana) project provides the framework for this work, including opportunities for contact with the relevant stakeholders [63]. Key partners are the Ghanaian National Disaster Management Organisation (NADMO) and Water Resources Commission (WRC) [64].

The flood risk analysis is catchment-based, focusing on the Odaw River catchment and considering CI in the surrounding catchments of Lafa, Chemu-West, Kpeshie and Odu-Klottey, as shown in Figure 4. The Odaw catchment covers about 271 km^2 and is located close to the sea. The total size of all the catchments is roughly 360 km^2, and the area is predominantly urban. For the hydraulic analysis and the analysis of consequence, the PROMAIDES framework is used [53]. Hydraulic calculations are made with a combined 1D-2D approach. A digital elevation model (DEM) with a 30 m resolution is used, and the floodplains are represented by 414,000 25 m $\times$ 25 m raster cells. Synthetic block rain events of 24 h with three different return periods (HQ10, HQ100, HQ1000) are applied, uniformly distributed over the whole area. The typical flood consequences are based on an economic damage model using stage-damage functions as well as land usage data [47,65]. To establish the consequences for people, high-resolution population density maps have been combined with the approach to estimate the loss of life due to flooding [50,66].

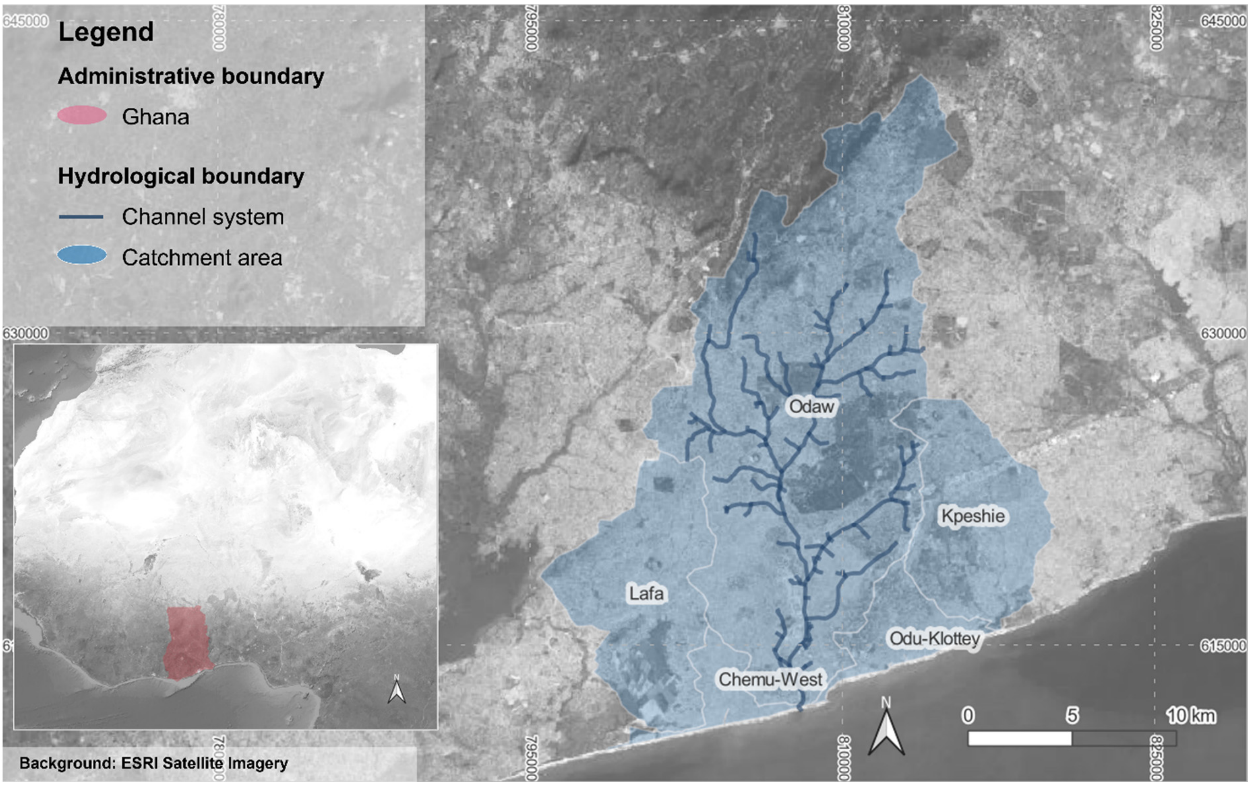

Figure 4. Geographical location of case study area. (**Left**): Western Africa highlighting Ghana in red and defining the boundary around Accra. (**Right**): the river catchments considered.

4.1. CI Network Model Setup

The CI network model shown Figure 5 evolved in steps, resulting in three versions of the model. The first version (V1) was generated with no stakeholder interaction and was derived from publicly available data such as OpenStreetMaps and other web mapping services [67]. The second version (V2) is a modified version including feedback from individual stakeholder interaction based on interviews. The third version (V3) was derived from feedback from a collaborative stakeholder participation meeting involving the CIrcle method. This stakeholder participation meeting was organised in the form of a CIrcle workshop, as described above (see Section 3.5). Figure 6 shows how the different participation levels raised the number of CI network elements, which underlines the benefit of involving CI stakeholders in the FRA. Additionally, the model versions including individual and collaborative stakeholder involvement do not vary greatly by the number of CI network elements but by the quality and relevance to the CI stakeholders. The point elements added to the third CI network model version are highlighted as particularly relevant to the CI stakeholders during the participatory sessions. An example for this case study are three major radio stations, which were identified during the workshop and are also placed close to the Odaw main channel. They have been highlighted as an important tool of information for the public as well as for the emergency services. Additionally, the most relevant factories in the centre of the area of investigation have been added. For the analysis of the CI network, they play a minor role, but they were included at the request of the CIrcle workshop participants.

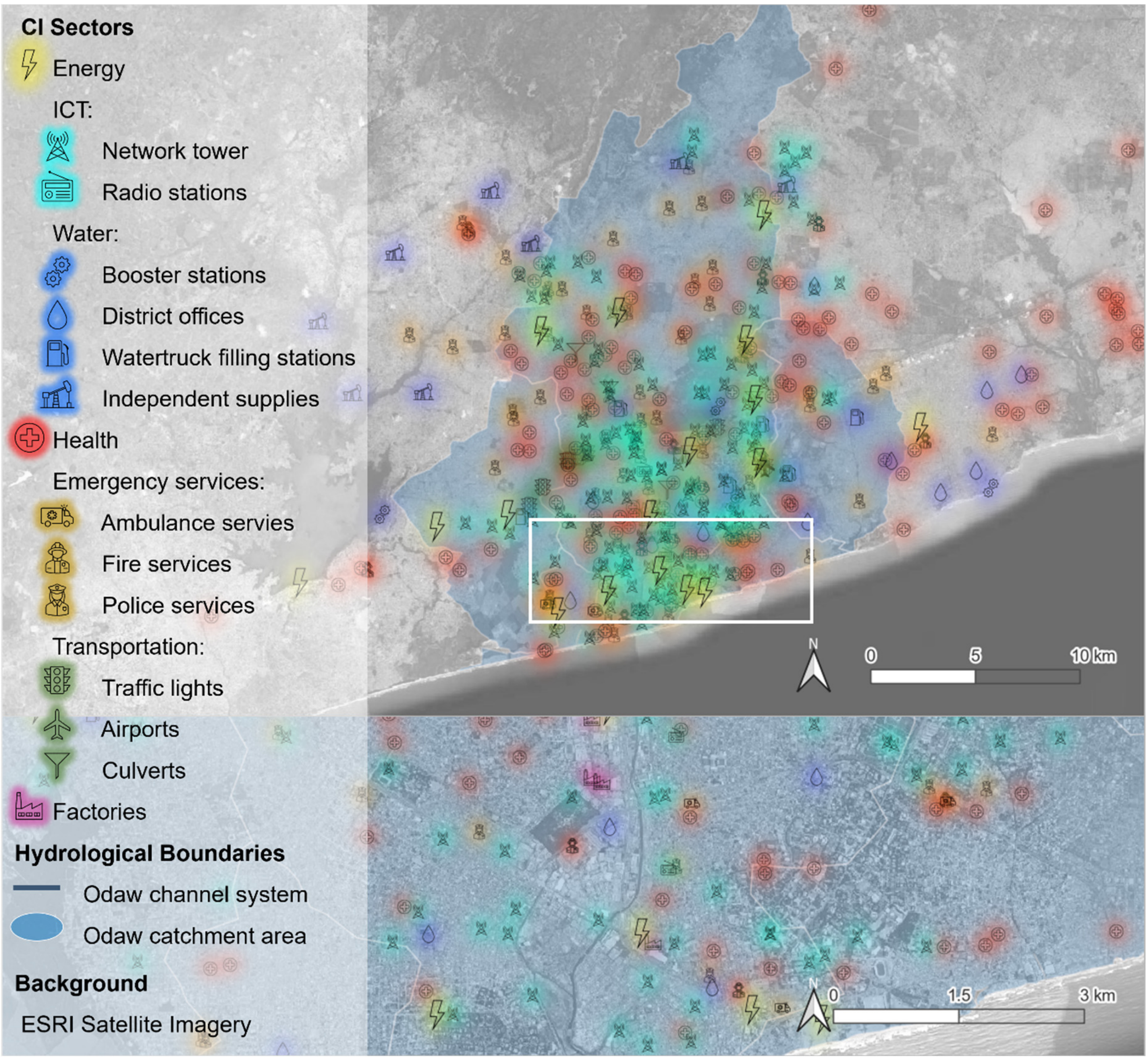

Figure 5. Overview of CI network model of Accra, including locations highlighted by CI stakeholders. The highlighted area in the centre of the model shows the proximity of CI network elements to the Odaw channel.

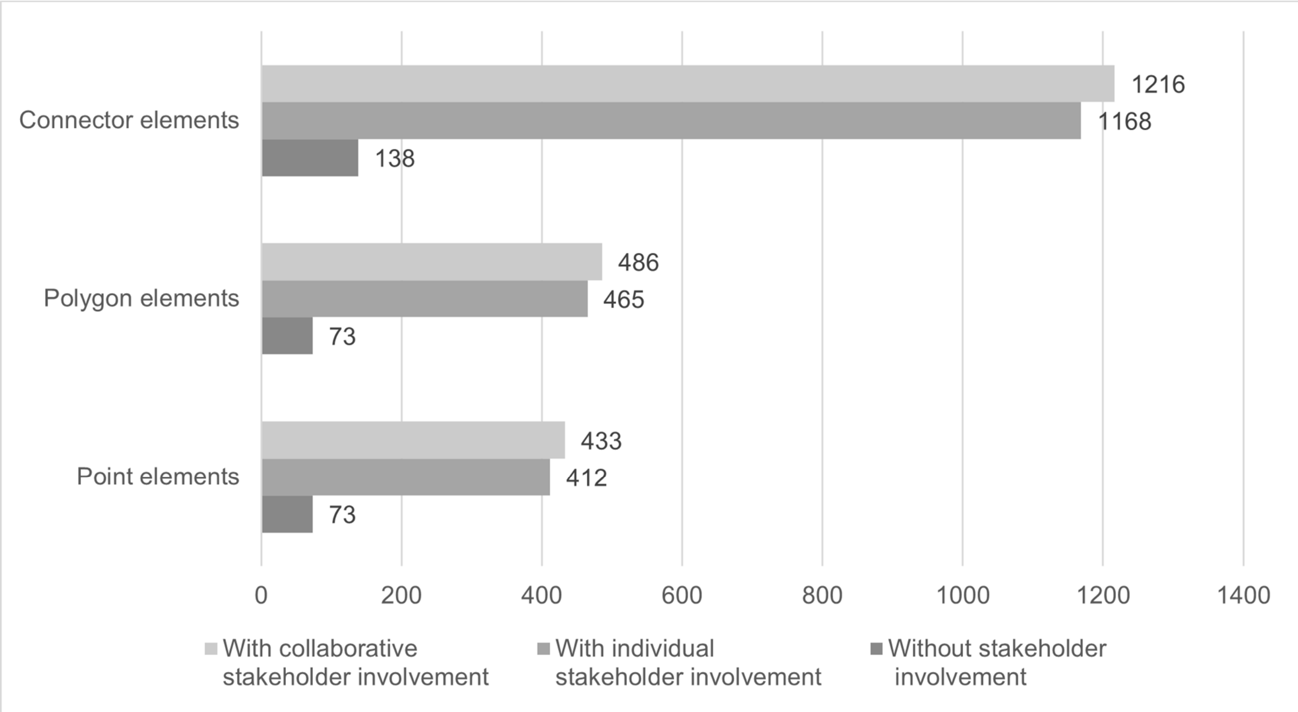

Figure 6. Number of critical infrastructure network model elements for the case study in Accra, Ghana at different stages of the model depending on stakeholder engagement levels.

4.2. Model Characteristics

After the assembly of the CI model, network characteristics are used to describe its characteristics. Figure 7 gives an overview of all point elements on the x-axis. The background colours relate to the corresponding CI sectors which are included in this CI network model: electricity, emergency responders, health, fresh water, transportation hubs and telecommunications. The y-axis represents the cascade potential value p, which quantifies the number of end user elements in the CI network disrupted by a failure of this specific point element. The point elements are ranked from the highest p to the lowest. The electricity and the water sectors have the highest p values since they are connected to many more final CI elements that are at the receiving end of a cascade, such as health, the emergency services and the transportation sector, whose points have the lowest p within this model's arrangement. The telecommunications sector is to be found in areas with both high and low p values. The p values characterise the CI network and can help to identify potential sectors and structures for mitigation measures.

Figure 8 presents a graphical overview of the points in the network with the highest cascade potential value p. Based on these flood independent network characteristics, potential mitigation measures are developed and discussed with the CI stakeholders.

4.3. Results and Risk Matrix

For the results of this case study, the consequences for the economy and population are combined with the probability of occurrence as the flood risk. The economic damages are expressed as the flood risk in USD per year. The risk for people is expressed as the number of people affected and endangered per year. The results of the risk calculation for the typical consequences are shown in the lighter grey section at the top of Table 5, the CI network analysis are highlighted in the white part of the table.

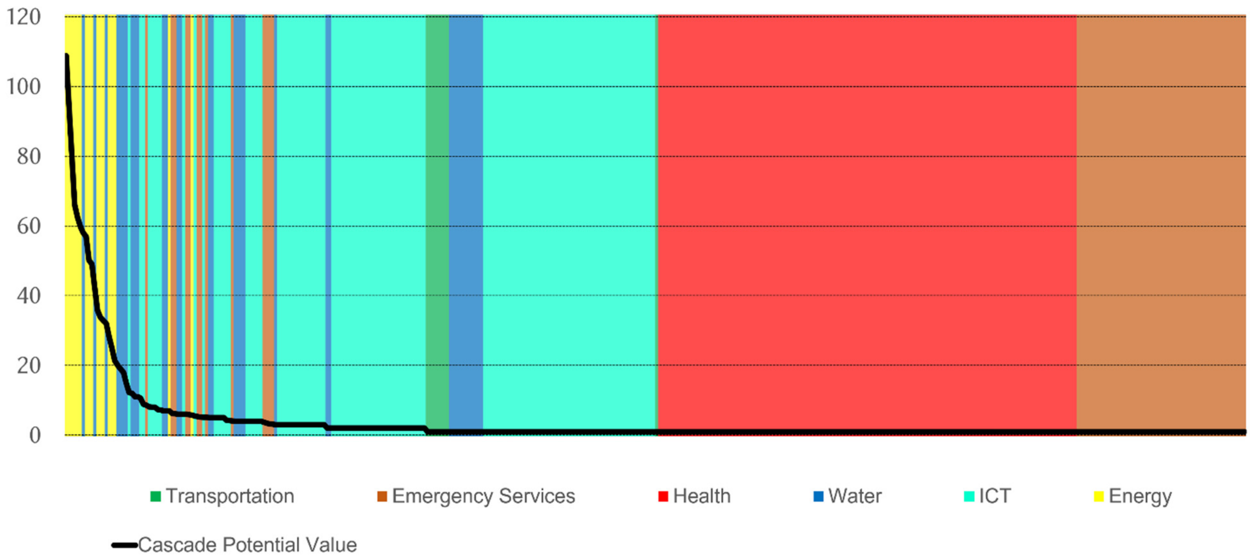

Figure 7. Cascade potential value p of all CI point elements in CI network model of Accra (V2).

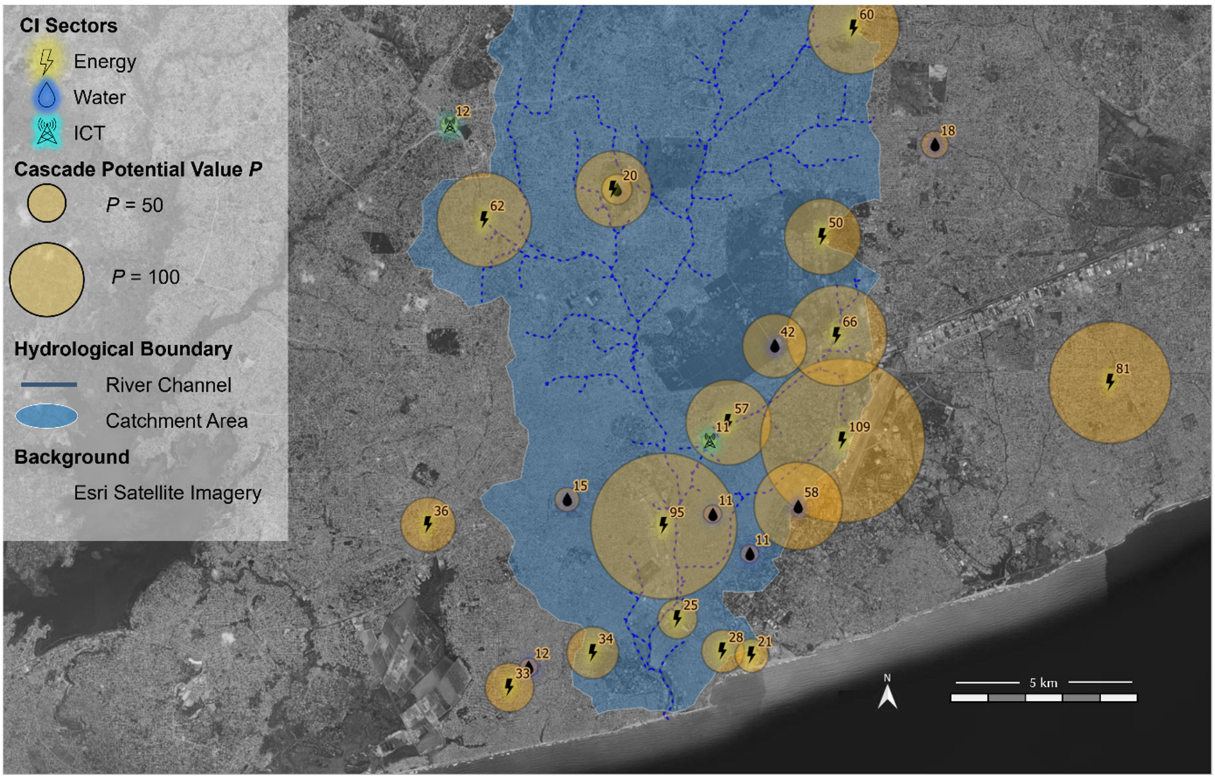

Figure 8. Point elements in the CI network model (V2) of Accra with cascade potential values $p > 10$ featuring the energy, ICT and water sectors; 1 km radius equals a cascade potential value $p = 50$ [21].

The CI consequences derived from the CI network model are then summarised as R_{CI} (see Equation (2)). The range of consequences summarised in this case study cannot be expressed in one unit. Thus, a multi-criteria analysis matrix is created (see Table 5), referred to as the risk matrix later in this paper. The risk matrix summarises the quantitative results for the R_{CI} per CI sector in every row and the hydrodynamic simulation per return period in every column. The concluding column on the right sums up the risk per sector. The bottom right number concludes the total risk for CI RCI for the current situation of the area of interest.

Table 5. Risk matrix including economic damages, population affected and critical infrastructure disruptions for flooding events with different return periods and the accumulated risk.

	Annuality [a]	**HQ10**	**HQ100**	**HQ1000**	**Risk *R* [. . . /a]**
	Probability of Reoccurence p_{hyd} [-]	0.145	0.0495	0.0055	
Classic flood consequences *C*	**Economic damage [USD]**	295.71 Mio.	465.83 Mio.	631.01 Mio.	**69.41 Mio.**
	Affected [people]	1.12 Mio.	1.3 Mio.	1.49 Mio.	**234,618**
	Vulnerable [people]	12,688	20,099	34,510	**3024**
Population Time T_{Pop} per CI Sector	**Energy [people · days]**	2.23 Mio.	8.1 Mio.	9.53 Mio.	**776,546**
	Water [people · days]	1.61 Mio.	1.61 Mio.	2.43 Mio.	**326,465**
	Emergency services [people· days]	1.53 Mio.	13.16 Mio.	16.53 Mio.	**964,744**
	Information and communication technology [people· days]	2.03 Mio.	6.15 Mio.	7.47 Mio.	**640,264**
	Health Care [people· days]	3.15 Mio.	7.79 Mio.	11 Mio.	**903,260**
	CI risk sum [people· days]	10.56 Mio.	36.8 Mio.	46.95 Mio.	**3.61 Mio.**

Other results from the CI network model feature the spatial overview of disrupted CI services for every sector derived from the maximum water depth, also introduced as steady state results. The spatial overview of disrupted CI services is generated also for the unsteady state of the hazard model determining the water depth for every time step of the simulation. Figure 9 summarises the progression of the unsteady state results for the energy and ICT sector. The progression shows the order in which CI point elements and associated polygon elements disrupt. Additionally, it also shows the order in which CI elements gain their functionality again. The ICT elements disrupted by their intersectoral connection to the energy point elements are disrupted the longest due to the longer recovery time of point elements from the energy sector. This information and data can support the measures for the preparedness and response phase (see Section 3.4).

4.4. Potential Measures for CI and Decision Making-Matrix

For this case study, two simple measures are suggested and implemented in a copy of the current state CI network model. The analysis of the CI characteristics shows that one electricity substation should be investigated further (see Figure 10, left). This electricity substation is the source element for 42 other point elements and has a cascade potential value p of 105.6. This indicates that the cascading effect would be able to account for a total of over 100 CI elements disrupted by a failure of this substation. Additionally, the information generated for the flood risk analysis confirms that this substation would be affected by a flood event. Thus, this element was selected as an object for a potential mitigation measure that raises the threshold value from 0.2 m to 1 m in the model. In practice, the threshold can be raised by building a flood protection wall around the substation or elevating the technical equipment. This measure is tested in a scenario model and is referred to as Scenario 1 (S1).

The second scenario-tested measure aims to reduce the impact on the mobile network system by decreasing the recovery time of affected mobile network towers. In reality, a modular approach for the internal energy storage components and the stockpiling of spare parts are suggested in order to reduce the recovery time. This scenario is referred to as Scenario 2 (S2). Figure 10, right, depicts the mobile network towers as well as the electricity substations that supply the energy.

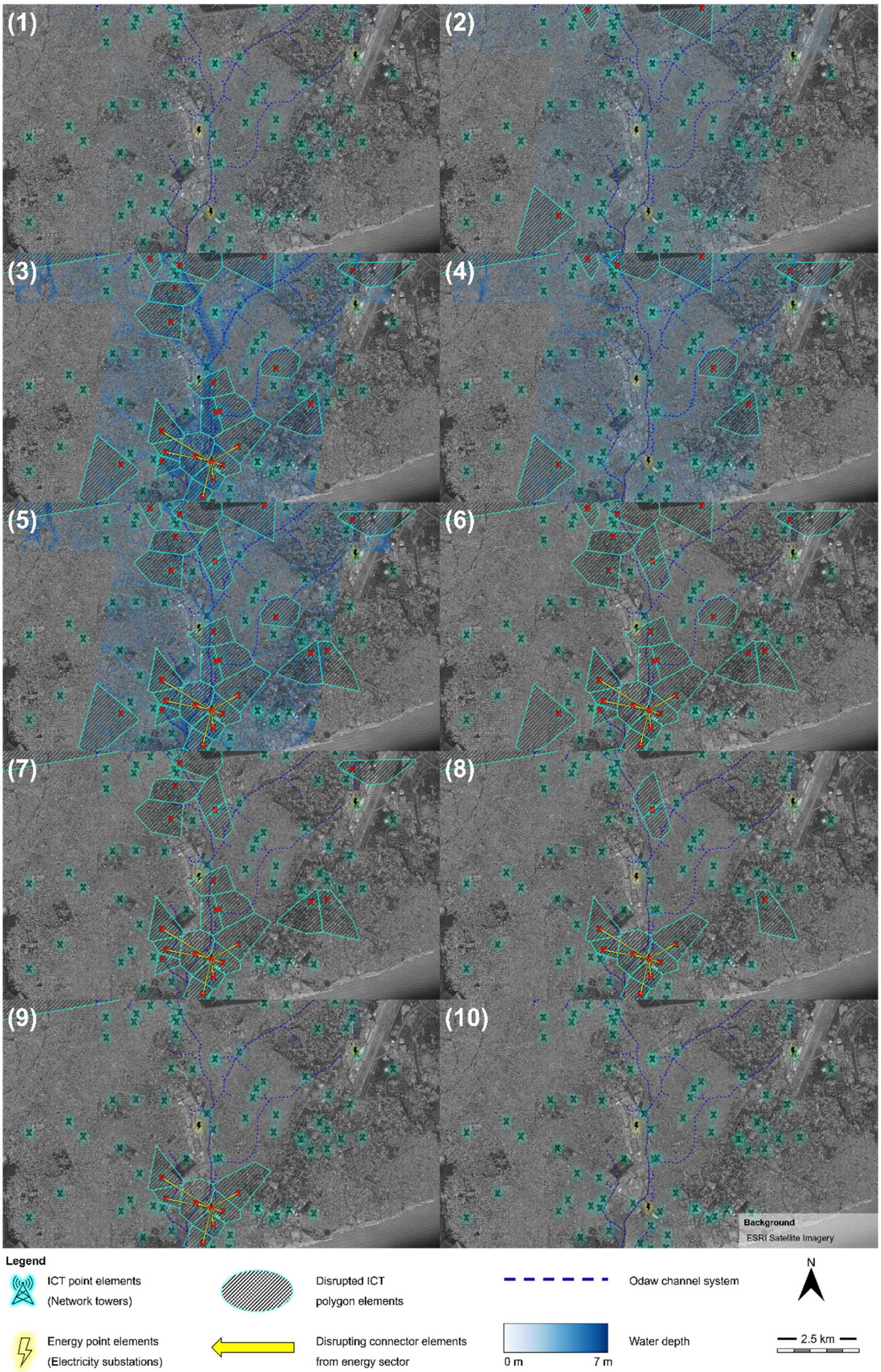

Figure 9. Time steps of CI disruptions in a part of the Odaw catchment. Figure partitions 1–10 summarise the order in which the CI point and polygon elements from the ICT sector are disrupted. Energy point elements disrupted transmit the disruption to other ICT point elements. Blue cells in the background indicate a water depth, derived from the hydraulic model for every time step.

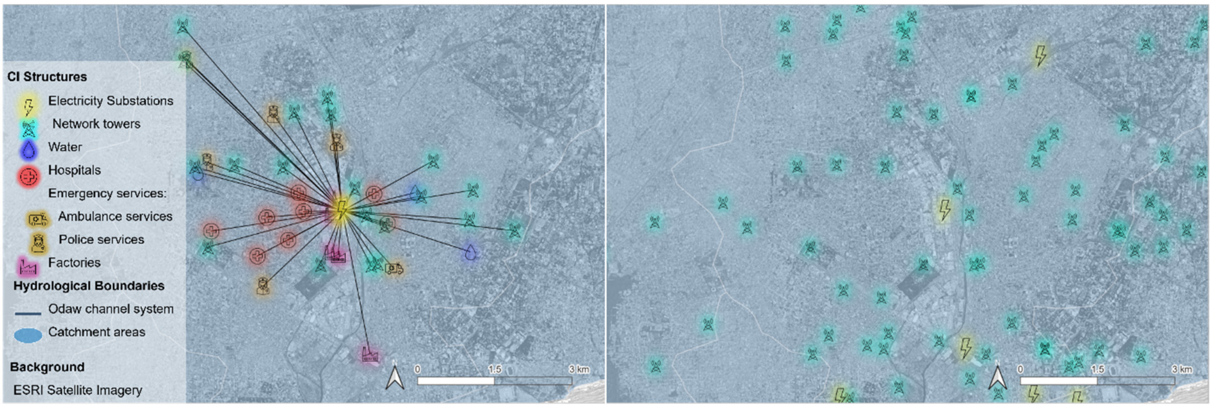

Figure 10. Critical infrastructure network elements involved in flood mitigation measures in and around the Odaw river system. (**Left**) In the centre, an electricity substation is highlighted which is connected to 43 sink elements. (**Right**) Mobile network towers and electricity substations.

The comparison of the risk sum of every sector and particularly the difference compared to the current state offers robust guidance for decision-makers in order to quantify the effectiveness of both scenarios. Table 6 compares the two measures of S1 and S2 in a decision-making matrix derived from the model analysis, with the current state based on their risk. It highlights the difference of the flood risk regarding the disruption of CI services per sector. Compared to S2, S1 shows a bigger spread of influence on the R_{CI} of other sectors but a smaller difference in total. Scenario S2, which shortens the recovery period of mobile network towers, affects fewer sectors but has a much bigger magnitude in the difference of R_{CI} compared to the current state. Once the price for these measures is derived, the price and R_{CI} reduction can be compared in order to validate the best option.

Table 6. Decision-making matrix comparing current flood risk with two mitigation measure scenarios S1 and S2 using the CI disruption in population time per year.

	Flood Risk	**. . . in the Current State (CS)**	**. . . with Protected Substations (S1)**	**Differences (S1-CS)**	**. . . with Batteries in Network Towers (S2)**	**Differences (S2-CS)**
Classic flood consequences C	Economic damages [USD]	69.41 Mio.	69.41 Mio.	0	69.41 Mio.	0
	Affected [people]	234,618	234,618	0	234,618	0
	Vulnerable [people]	3024	3024	0	3024	0
Population Time T_{Pop} per CI Sector	Electricity [people · days]	776,546	322,896	−453,649	776,546	0
	Water Supply [people · days]	326,465	26,470	−299,995	326,465	0
	Rescue Services [people · days]	964,744	639,490	−325,255	964,744	0
	Passenger Transport [people · days]	0	0	0	0	0
	Information Technology [people · days]	640,264	226,246	−414,018	640,264	0
	Health Care [people · days]	3.61 Mio.	341,437	−3.26 Mio.	903,260	−2.71 Mio.

When conducting a plausibility check, it is reasonable that S1 results in a reduction of the disruption in R_{CI} for all sectors, whereas S2 only impacts the sectors of telecommunications and the receiving emergency services.

5. Discussion

The integration of CI into the steps of FRM functions. As regards theoretical integration and practical application, a few challenges and limitations arise. The lack of connection between flood risk management and CI operation is the primary challenge. Little awareness and collaboration between CI and FRM is present on a day-to-day basis, leading to decreased quality at every step of FRM. Ongoing participation processes are designed specifically for the context of multisectoral CI operations and proven to benefit the CI network model generation (see Section 4.1). These participation processes have enormous potential to bridge data and information gaps. An important condition for these participation processes is the commitment of CI operators to spend resources on this participation and the willingness of flood risk managers to invite CI stakeholders. The resources of CI operators refer here to specific staff who are in charge of operation and maintenance, and also the accessibility to network and operations data.

The flood risk analysis for this CI network relies on a range of data inputs that determine the quality of the model results. On the one hand, CI data is sensitive due to the potential for damage if the data comes into the possession of people and parties with a harmful intent. Data protection regulations also make accessibility and application difficult. On the other hand, the CI asset data relevant for the modelling process has specific requirements, is scarce and often not gathered with the intent to represent multisectoral cascading effects or natural hazard events (e.g., data on interdependencies of CI structures, spatially homogeneous information on CI users per asset, time of disruption due to flooding, hierarchical structure within CI sectors, location of interdependent CI assets and cross-sectoral and sectoral redundancies). Therefore, public institutions and CI operators need to be more willing to assemble and share datasets. This could ensure the quality of CI network model outputs and allow CI network modellers to conduct validation. The literature and field reports on past events from other investigation areas supplement and substitute missing data [19].

The lack of precise data sets leads to a range of assumptions and the generalisation of specific expert judgements. These assumptions can be categorised as extrinsic and intrinsic assumptions. Extrinsic model assumptions are made during the specification of network element properties and the arrangement of these elements. Extrinsic model assumptions replace datasets and have a potential impact on the quality and significance of the model output. One example for an extrinsic model assumption is the impact of preparedness measures on recovery times. The reduction of the recovery time is ensured by the stocking of spare parts, but this is hard to quantify without close contact with CI operators and is thus assumed for the network element properties.

Intrinsic model assumptions describe the methodology of the modelling approach and its inherent limitations. The binary state of the CI point and polygon elements is one example of inherent limitations. It is either fully functional or disrupted, as explained in Schotten and Bachmann [53]. This intrinsic assumption and also the extrinsic model assumptions mentioned above add a level of uncertainty to the model. This uncertainty needs to be communicated with CI operators and other parties involved as data and information sources. It is recommended that the data needs for CI modelling are categorised and defined further.

In an ideal world where all desired information and data is available, the integration of CI into FRM, as presented in this paper, would help to create a society that is more robust and resilient in the event of a flood.

6. Conclusions

This paper presents a step-by-step integration of CI networks into FRM. The integration of CI begins at flood risk analysis stage with a CI network modelling approach that allows consideration of the consequences for critical infrastructure. This includes sectoral and intersectoral cascading effects, a quantification of CI service disruptions as population time T_{Pop} (see Equation (1)) and also information on the areal spread of CI network disruptions. Based on the consequences, the CI flood risk is introduced as R_{CI} (see Equation (2)). R_{CI} is arranged in a flood risk matrix to support decision-makers during flood risk assessments. Further support for decision-making at the assessment stage is delivered with the network characteristics C and V, which allow information about especially vulnerable and influential CI elements in flood prone areas to be included. A catalogue of measures for CI is introduced based on the stages of the disaster risk management cycle. The integration of CI into FRM shows that these measures can now be considered in measurement planning. The capacity to act regarding flood risk reduction and also regarding coping with residual flood risk has been increased. The aspect of ongoing communication between flood risk stakeholders is also addressed in this paper, by including CI operators more closely in all steps of flood risk management.

With the test case, it is proven that the suggested integration of CI into FRM is possible. A CI network model has been used to derive T_{Pop} and R_{CI} for CI from six different sectors. The CI network model results showed the potential to support the flood risk assessment. The CI network characteristics were proven to benefit the identification of potential mitigation measures. The measures have then been implemented successfully in CI network model scenarios and, in a decision-making matrix, were compared to the initial state of the area of investigation. In the case study, the ongoing participation of CI operators was demonstrated to be beneficial for individual FRM steps. In conclusion, it can be said that the integration of CI into flood risk management has been proven effective and is now ready for practical implementation in situations where there is collaboration between CI operators and flood risk management.

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