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Flood vulnerability of critical infrastructure in Cork, Ireland

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Abstract. Recent flood events in Ireland and particularly in County Cork have caused significant disruption to health service provisions, interruption of water and power supplies, and damage to roads and other transportation infrastructure, affecting the lives of hundreds of thousands of people over a prolonged period of weeks. These events clearly reveal- the vulnerability of the critical infrastructure to flooding and the dependence of society on critical infrastructure. In order to reduce the flood vulnerability and increase the resilience of the critical infrastructure networks in the future, detailed evidence-based analysis and assessment is essential. To this end a case study has been carried out on Cork City which analyses this vulnerability as it was in 2009, and as it is currently, and identifies adaptation options to reduce the future vulnerability of critical infrastructure to flooding and to build a more resilient society. This paper describes the storyline approach and *CIrcle* tool and their application to Cork City which focused on the analysis of the flood vulnerability of critical infrastructure and the impacts of failure of the infrastructure for other critical functions and on society.

1. Introduction

Recent flood events in Ireland, but also elsewhere have shown that critical infrastructure (CI) is vulnerable and that damages to CI elements may affect large areas over a longer period of time (see for example [1-4]). CI may be affected both directly from the flood waters and indirectly through cascading effects from the direct impacts [6].

Societies depend on the well-functioning of CI. “CI includes those physical resources, services, information technology facilities, networks and infrastructure assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of Citizens or the effective functioning of governments.” [5]. CI failures should therefore be considered in flood risk management (all activities aiming to enable societies to cope with flood risks) and flood event management (all activities related to responding to an imminent flood threat).

In Cork, the largest city in the southwest region of Ireland, a severe flood event occurred in 2009. Due to the scale of flooding and impacts on the city and surrounding hinterland, a state of emergency was declared in the city. While flooding lasted less than 24 hours, substantial damage was incurred including the closure of main transportation routes, temporary closure of the roads to and from the hospital, severe damage to the university and a 2-week interruption in the supply of fresh water to residents. Approximately 87,000 persons were impacted as a result of having no access to drinking water in their homes, the majority of whom were located in the north of the city.

The on-going flood risk mapping and planning actions implemented as a result of the Floods Directive were advanced by this event, as it brought greater awareness to the risk of flooding and the vulnerability of society. The expected future increase of flood severity due to climate change further showed the importance of effective flood risk management [7]. To prevent events like the 2009 flooding from reoccurring, some urgent flood protection measures have been implemented already and additional measures are proposed in and around Cork.

To evaluate past, current and future vulnerability of CI to flooding, information on flood risks related to CI is crucial. There are many flood risk analysis methods and tools available, but most of them are generic and not specifically designed for CI analyses. Whereas general flood impact and risk analysis methods focus on direct damage due to the force of water on objects, damage related to CI generally is associated with interruptions in services. The impacts depend mainly on the network layout, and the dependencies of society and other networks on the services and less on the flood characteristics itself. Furthermore, generic methods often require data, which is difficult to obtain in the case of CI, due to issues surrounding security and competition. Because of these differences, the use of generic methods and tools for analysing flood risk associated with CI is difficult and other methods need to be applied.

We used the storyline approach and *CIrcle* tool here in order to obtain information on past, current and future vulnerability, which serves as input for a risk analysis. This paper discusses the method used and the resulting insight into the vulnerability of CI for flooding. The paper concludes with a discussion on the applicability of the methods used, the relevance of the results for Cork and other areas experiencing similar problems.

2. Method

2.1 Risk assessment methods

There is an on-going transition from more reactive flood risk management which responds after the latest flood event, towards a proactive flood risk management approach. In proactive flood risk management, strategies and measures are designed based on information of flood risks now and in the future (see e.g. [7 -10]). To obtain flood risk information, analyses are carried out including statistical analysis of weather events, hydrological

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modelling to obtain runoff statistics and hydrodynamic modelling to derive probability distribution functions of discharges or water levels. Furthermore, flood inundation modelling and impact assessments are carried out to assess flood impacts. These analyses can be combined to obtain insight in flood risks. However, since most flood impact assessments focus on direct effects and link flood characteristics to their direct impacts, the impacts of disruption in services of CIs are often neglected [4].

The analysis of impacts of CI damage requires an analysis of the vulnerability of the CI elements, the structure of network and the effect of failure on other CI networks. The redundancy, dependency and centrality of the network determines the effect of one damaged element on other elements, network parts, and other networks and thus the total impact. The analysis of CI impacts thus requires network analyses and analysis of cascading impacts which is not possible with standard flood impact models such as the Dutch HIS-SSM or the English method [11, 12].

The analysis of CI is often hampered by a lack of data. Data of CI is often confidential due to reasons of security and competition. It is therefore difficult to obtain a comprehensive overview of the impacts of flooding on CI and the effects of CI service disruptions on society. The commonly used flood risk analysis methods require data.

Since common risk analysis approaches are difficult to apply on CI risks, we used the storyline method and the *CIrcle* tool. These do not require data transfer, but structure the input of key stakeholders and experts obtained through workshops and interviews to obtain a picture of what may happen during flood event, of roles and responsibilities of actors and of interrelations between different subsystems, elements and actors. These insights contribute to the development of consistent and comprehensive flood risk management strategies and adaptation measures. The methods do not replace formal risk analysis approaches, but contribute to them. The methods are explained in the next sections.

2.2 Storyline method

The storyline method is a stepwise approach which aims to analyse the sequence of events during a flood event including the responses of the most relevant actors. This method has been applied in flood risk management in Dordrecht [4]. It is principally designed to facilitate communication, information exchange and discussions in workshops. It is recommended that researchers first walk through the approach and develop storylines based on literature or interviews of key-stakeholders and then repeat the storyline development in a workshop together with representatives of the key-actors to complete and correct the storyline and exchange knowledge.

A storyline in flood risk management consists of three phases: (1) the rising of the flood threat (alarm phase), (2) the flooding itself, and (3) the recovery from the flooding. For each phase, the water levels and flooding and the functioning of CI are described, as well as the actions and responses of the most important actors, such as State agencies, local authorities, meteorological service, emergency responders, CI operators and the general public. The interrelations between actions and actors are also visualised.

The storyline approach comprises four steps [4]:

1. Provide a consistent description of the area, the hazards, the CI and the most important stakeholders and their roles and responsibilities;
2. Define the scenarios for the storyline: A scenario may for example consist of an extreme weather event and a breach in the flood protection infrastructure at a certain location.
3. Determine sequence of events during the three phases of the storyline.
4. Analyse the flood impacts: The impacts which are relevant may include damage, fatalities, number of persons impacted, number of houses damaged, and duration of the damage.

The first step involves providing a system description, which comprises amongst others, the relevant area characteristics such as: waterways, CI elements and networks and their vulnerability to flooding and also the key actors and procedures.

To describe the CI, the following questions are addressed:

1. What CI networks and elements are present in the area and where are they located?
2. What is the elements' resistance and resilience to flooding? The element's resistance is the water depth which the element can withstand without any damage and its resilience is related to the damage severity and recovery rate.
3. Will the CI be damaged by potential flood events? (Compare flood hazard information with CI information)
4. Will the damage to one or more elements disrupt the functioning of the CI network? Where? (see section 2.3)
5. Will the disruption of a specific CI have an adverse effect on other CI? (see section 2.3)
6. How will the outage of CI affect society? (number of people affected, costs, etc.).

In the second step, relevant storylines are selected. The scenarios which drive the events are selected based on the information of the system resulting from step 1. Such a scenario may result from for example a storm surge, intensive rainfall event or combinations of such events, followed by inundation of the area. In order to be relevant, the event selected must be possible and cause significant damage.

In the third step the storyline is devised, which means that a detailed description of the sequence of events in the alarm phase, during the flooding itself and in the recovery phase is provided. It is recommended that this phase is carried out with intensive collaboration with the most relevant actors.

In the fourth step, the impacts are analysed: the affected CI and the wider impact of CI failures, number of inhabitants affected, the effects of actions of local authorities and inhabitants on these impacts, and consequences for recovery of the area after the flood event.

The storylines developed serve as realistic ‘what if’ scenarios, not as forecasts. They will serve as a mutual set of assumptions in the discussion, they will reveal the crucial uncertainties and required assumptions and they will provide a picture of the roles, responsibilities and interactions of actors. There is no probability associated with the storylines. This means that although the knowledge in those storylines will be useful for risk analyses, the storylines cannot be directly converted into risk estimates. The application of the storyline approach in workshops brings together a range of diverse disciplines and actors, such as flood modellers, crisis managers, emergency services, spatial planners, CI operators and various departments from local authorities. The approach is especially useful in circumstances where data transfer to the analysts is problematic due to reasons of for example security or competition. The involvement of CI operators in flood risk management and emergency preparedness can increase the efficiency of emergency response. It was found that the storyline approach helps to communicate data needs, potential impacts and measures to all actors and to underpin new options for future strategies and measures development [4].

2.3 The *CIrcle* tool approach

CIrcle is a tool which supports working with stakeholders on cascading effects of disruption in one or more CI. It supports the collection of information from key stakeholders and experts in workshop sessions and it visualises their input for different CI and the interrelations between those CI. The tool may be used to address questions 4 and 5 of the previous section.

As part of the *CIrcle* workflow, the stakeholders are first asked about the direct flood impacts to their CI assets. A power supply operator may for example bring forward that failure will occur if water depths exceed 25 cm at the network control cabinets. In the outer circle of the diagram one block is present for each CI type (see figure 1). The threshold for direct effects of flooding on each CI is added to that block.

Next, the cascading effects are discussed. For instance, if a failure in the power supply occurs, will, for example, the hospitals be able to continue normal functions and if so, for how many hours? These effects will be entered as causal links between the blocks in the outer circle (see figure 1). The group discussions amongst the different stakeholders of a region often expose more interdependencies then discussions with individual stakeholders may reveal. Finally, the effect on society is assessed. This effect may be expressed qualitatively or quantitatively e.g. by the number of people effected and the number of days that they are affected. The diagram and associated database may be linked to a GIS database which is then used to visualise both the direct and cascading effects of one or multiple flood scenarios over time.

By visualising and structuring discussions, much information can be obtained from stakeholders, even in cases when transfer of, for example, GIS data or other sensitive data is not possible. It also contributes to the flood risk awareness of the critical infrastructure operators and the local authorities.

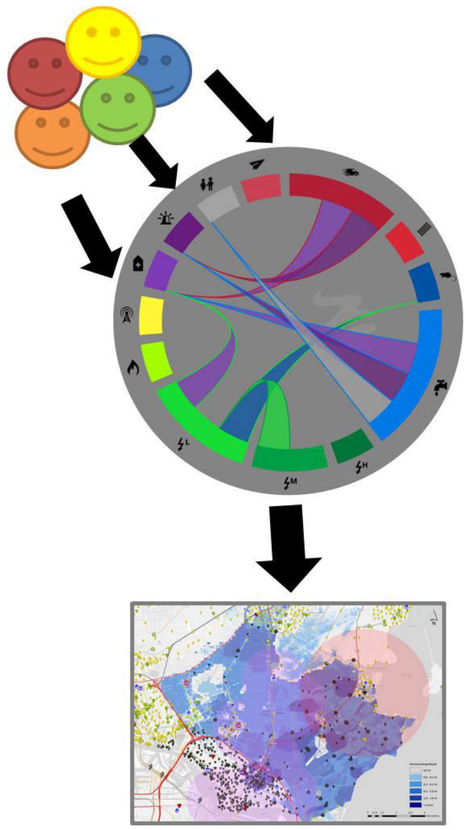

Figure 1. Flow diagram of the *CIrcle* approach: stakeholders’ input on both direct and cascading effects of flooding on CI is captured in a database and diagram and visualised in the diagram and on a map or movie.

When the storyline approach is used the *CIrcle* tool can be applied to structure and visualize information on cascading effects. Whereas the storyline focuses on one clearly specified event, the *CIrcle* tool enables the storage of thresholds and interactions which are not-depending on the event choice. The same *CIrcle* diagram can thus be used for different events in the same area, or for different areas with similar CI characteristics.

3. Area description

The storyline approach and *CIrcle* tool were applied on the Lower Lee catchment in Cork City and its stakeholders in order to obtain insight in the vulnerability of CI for floods in the past, current situation and future. This section gives an overview of the area (step 1 of the storyline approach).

3.1 River Lee catchment and flood hazards

The River Lee is located in the Southwest of Ireland. The River Lee flows from the Shehy Mountains in the west of County Cork, eastwards through Cork City where it divides into two branches, creating an island on which Cork's city is built. The River Lee then flows into the Celtic Sea at Cork harbour on the southern coast. The river flow is controlled by two dams (Carrigadrohid and Inniscarra) which were constructed for power supply. The river has a length of 90 km, an average discharge of 40 m^3/s and a basin area of 1,253 km^2. Approximately ten tributaries flow in to the River Lee. Next to the discharge of water and power supply, the river is also important for recreation, fishery and it has important ecological values. The area has a history of flood events. The lowest streets of Cork are frequently flooded due to a combination of heavy rain, high tide and a south-westerly wind. More severe floods may also occur due to long periods of intensive rain in combination with some days with extreme rainfall intensities and high tides as happened in 2009 when the Cork City centre became flooded. The city of Cork, located along the river, is one of the two most important cities in the country. Figure 2 shows the location of the case study area.

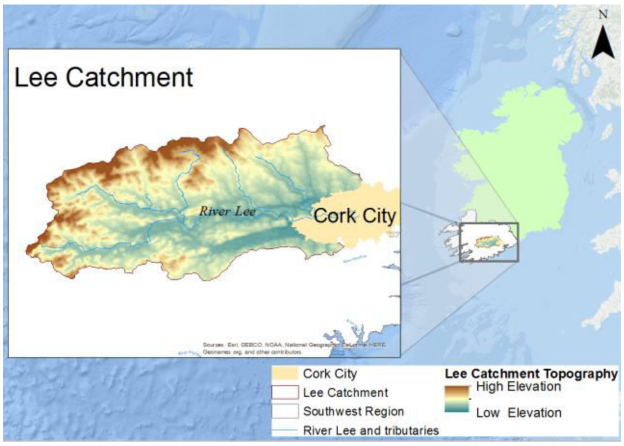

Figure 2. The case study area

3.2 CI present and its vulnerability

The city of Cork plays an important role regionally and nationally as it is home to a variety of nationally important CI. The city and surrounding area contain national and regional roads, railways, water treatment facilities, waste water treatment plants, and high, medium and low voltage power supply networks and a gas supply network (see figure 3). Furthermore, there are a number of hospitals located in and near the city centre including the Cork University Hospital and Mercy University Hospital. Cork City is also a university city and consequently has a large student population in excess of 25,000, with the two main third level institutions comprising University College Cork and Cork Institute of Technology. The city also has a large port of national significance and an international airport located to the south of the city.

To assess the vulnerability of the critical infrastructure, a workshop with all relevant actors was held and the storyline approach was applied and the *CIrcle* tool was used. The vulnerability of each CI to flooding is briefly discussed here and visualised in figure 4.

The roads are will be temporary closed if they are flooded. Also the main access roads and one tunnel (the Jack Lynch Tunnel) will need to be closed when flooded, but as soon as the water has receded they may be re-opened again, providing no obvious physical or structural damage has occurred.

The railway service will cease operation when excessive water is observed by drivers on the rail line. Pending authorisation from the signaller, rail drivers may be permitted to proceed at restricted speed (5kph). Railway personnel will continue to monitor water levels and track formation in keeping with weather protocol measures. Where flood waters are 80mm above the rail level, all rail movement is halted and any approaching trains will be prevented from entering the affected area while the water levels are monitored.

The power network contains of high voltage, medium voltage and low voltage networks with different vulnerabilities. The high voltage power supply is not vulnerable for flooding. The transformer stations are located outside the flood-prone area. Two 110kV MV transformation stations which serve a significant part of the city are present in the flood-prone area. They will fail when they are flooded. Vulnerabilities at these stations relate to building design including the location of equipment at ground level and the omission of specialised flood barrier doors. Safety protocol means that at-risk electricity assets are to be switched out from a safe location before they are compromised due to flooding (exceptions are vital water pumps, emergency lighting, etc.). If the transformer stations fail, power supply will be interrupted in a large part of the city. The lower voltage electricity network is not susceptible to flooding if water depths are below one meter.

A significant amount of key infrastructure including wastewater and water treatment plants in the region and indeed, nationally, depends on reliable supplies of electricity for their successful operation, and therefore, the vulnerability of the supplying electricity substation is of key importance. Also communication systems, traffic management systems public street lighting and railroad signalling will all be affected if power supply fails. The hospital and airport have their own emergency source of power supply and will not be affected by interruptions in power supply.

The gas supply and communication network are not susceptible to floods. However, they may be affected in the event that the power supply fails.

The wastewater and drinking water treatment plants are susceptible to flooding. The Lee Road Water Treatment Plant is the city's main source of drinking water and produces 46Ml/d, which amounts to over 70% of the water consumed in Cork City. The drinking water facility will be overloaded by the volume of water entering the station and the pumps will cease operation. Contamination of the water occurs and the water treatment plant will stop functioning. This will affect more than 25,000 households for a period of up to 2 weeks and boiling notices will be needed to be issued for a time afterwards, until the risk of contamination has fully passed.

The schools, universities, hospitals and emergency management location, port and airport will be out of function if they are directly impacted due to flooding or when they have become inaccessible due to flooding occurring on the access roads.

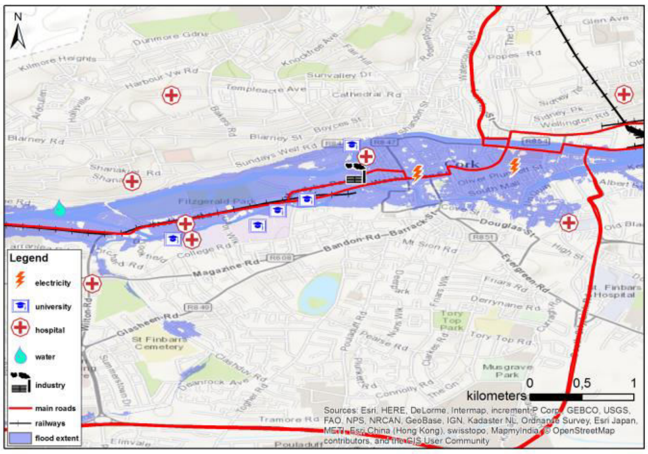

Figure 3. The most important CI in and around Cork City centre

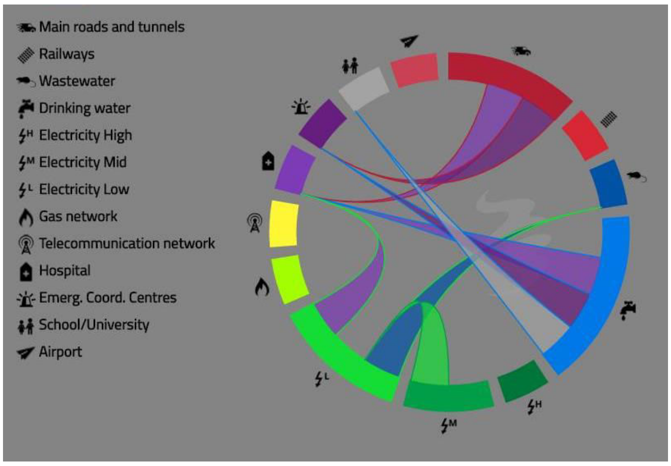

Figure 4. Overview of cascading effects and *CIrcle* diagram

3.3 Stakeholders, their roles and responsibilities

In Ireland, the Office of Public Works (OPW) has been assigned as the lead State agency for the coordination and implementation of government policy and flood risk management at national level. The OPW has commissioned the Catchment Flood Risk Assessment and Management (CFRAM) Pilot study [7] for the Lee River which provided amongst others maps of flood prone area and flood depths. The OPW is also the lead authority for the implementation of the EU Directive on the Assessment and Management of Flood Risk (2007/60/EC). At local scale, the local authorities, Cork County Council and Cork City Council are responsible for flood risk management, spatial planning and emergency management in their respective functional areas. The emergency services work together with the City Council in case of emergencies. Their work is guided by the 'Major Emergency Management Framework' [14].

The CI in the region is managed by different operators. The Transport Infrastructure Ireland (TII) is a semi-state body responsible for the operation of the national roads network and light rail infrastructure in Ireland. The TII assesses flood risks and adapt national roads, if necessary. The Electricity Supply Board (ESB) is responsible for building, operating, maintaining and developing the electricity network and serving all electricity customers in the Republic of Ireland. The ESB also operates the reservoirs in the River Lee catchment (Carrigadrohid and Inniscarra Dams). Irish Water is a commercial semi-state organisation that delivers water and gas infrastructure and services nationally, including the provision of drinking water and waste water treatment in Ireland. Iarnród Éireann is a state body and owns, operates and maintains the railway infrastructure in the Republic of Ireland, providing passenger and freight rail services. Met Éireann, the Irish National Meteorological Service is relevant since they provide weather forecasts.

4. Storyline results

4.1 Selection of the storyline scenarios

Since the 2009 flood caused severe damage to CI and is still fresh in the memory of all stakeholders, we also select a river flood scenario for the storyline. We use a flood pattern corresponding with a 1/1000 year event probability of exceedance, which is more severe than the 2009 flooding was. The flood pattern is derived from the CFRAM Lee Pilot results [7]. We show the effects of this severe event in two situations and thus discuss two storylines: (1) The impacts of the 1/1000 year event as it would have been before 2009 and (2) the impacts and responses due to such an event which are expected currently. Furthermore, we give a future outlook. We discuss the first one in detail and describe the second one more briefly, by focusing on the differences with the first one.

4.2 A fictional fluvial flooding and responses triggered before 2009

Alarm phase

In this hypothetical flood scenario, after a very wet autumn, several days with extreme rainfall intensities are forecasted by Met Éireann. The ESB foresees that they must release large quantities of water from the Inniscarra Dam in order to protect the integrity of the dam. They contact stakeholders (including the county's two local authorities of Cork City Council and Cork County Council) by means of telephone and more recently, text message, to inform stakeholders that they will release in excess of the normal operating level of water ($80m^3/s$). At $150m^3/s$, traditionally localised flooding is anticipated in areas in close proximity to the dam, including roads. In this hypothetical flood scenario, increased spilling leads to more than $400m^3/s$ of water being released downstream.

Cork City Council quickly activates the Major Emergency Plan alerts the National Coordination Group, Flood Risk Team and Flood Response Group, which, considering the large releases and the high rainfall in the downstream tributaries and the coincidence with high tide, expects floods may occur and triggers the local crisis management group (see figure 5 for an overview of the flood emergency management process). There is no flood forecasting system in operation to make detailed assessments.

The local crisis management group ensures that the most vulnerable roads, parking places and junctions are closed to traffic and that emergency service personnel are on-call in the event of large scale emergencies. The local crisis management group at the City Council now coordinates the fire brigade, army, An Garda Síochána and civil defence. If the event becomes disastrous, they may declare it a 'Major Emergency' and then the National Coordination Centre is established.

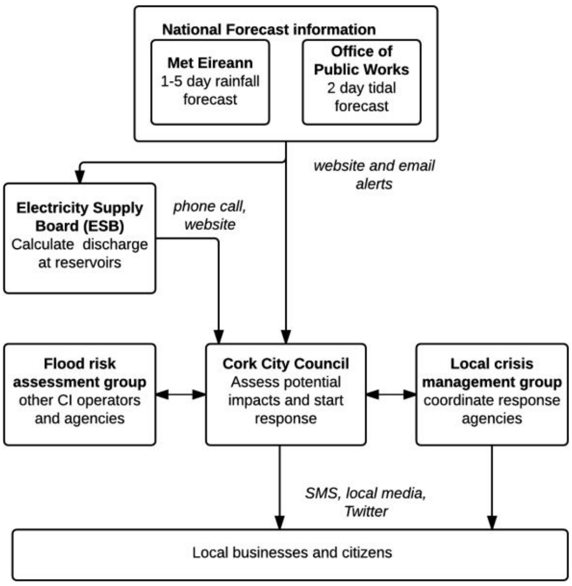

Figure 5. Overview of the emergency management process

During the flooding (hypothetical 1/1000 year flooding occurring before 2009)

The flooding is unexpectedly severe (see figure 6) and causes a lot damage. The storyline matrix in figure 7 shows the CI affected, the direct and indirect impacts and the response actions. The most important actions and reactions are discussed below.

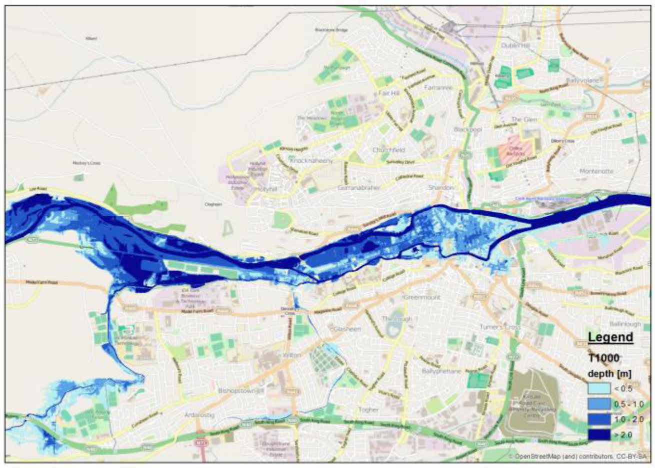

Figure 6. Flood map of the 1/1000 year flooding near Cork (based on the CFRAM Lee Pilot [13]

When the citizens see the water in the streets they begin to respond and try to protect their homes and belongings. Due to the flooding, the roads along and across the rivers have become inaccessible, including the national primary roads comprising the N22, N27 and N8. Cork City Council closes part of the N8 and N22, diverts traffic away from the city centre and arranges diversions for the N20 and N27 access routes in order to restrict movement through the affected areas. Cork City Council also issues public information which includes warnings against driving through flood waters.

Two transformer stations (medium voltage) which were almost flooded in the 2009 flooding and deliver power to over 14,000 persons, now become flooded in this hypothetical but realistic extreme weather event and power is out in a large part of the city.

The drinking water treatment facility (The Lee Road Water Treatment Plant) is submerged under meters of water and shuts down. This causes an interruption in drinking water supply to areas of the cities which have not been flooded. In 2009 about 25,000 households (87,000 persons) were out of drinking water for up to 12 days.

The buildings of the University College Cork which is located adjacent to the south channel of the River Lee and the Tyndall National Institute which is located in the city centre island, are both flooded deeply and are closed. Students living in the on campus student resident accommodation are quickly evacuated in the night and temporary accommodation is arranged for them. All students are able to reach safety in time and there are no casualties or fatalities.

In Cork City centre, flood waters breach the quay walls resulting in large scale flooding of roads. In addition, flood waters enter the ground floor of the Mercy University Hospital which is the hospital's emergency department. The hospitals main power generators are also located on the ground floor and flood waters come dangerously close to these generators. The Mercy University Hospital becomes inaccessible and the emergency services including the army is called in to bring hospital staff to the hospital and to deliver crucial hospital supplies. The hospital still has power from generators and declining flood waters ensures that the hospital does not need to be evacuated. Furthermore, Cork City Council personnel work through the night to fill the gap in the quay wall with boulders to prevent further flood waters from entering. The emergency services now also ensure that no traffic is driving through flooded areas, other than emergency services where necessary. This is not allowed because they may cause waves and increase damage, and they might endanger themselves and others in the process.

The power and drinking water service interruption results in the closure of education and commercial services and any non-essential services in both flooded and non-flooded areas,

The railway network, the gas supply and communication networks were not affected in 2009. However, in this event scenario, these services are affected indirectly due to the large power disruption caused by the flooding of the two transformer stations.

Time		-24 hrs	0	24 hrs	0.5 - 2 months
Flooding		Floods expected within 24 h	Severe flooding	The area is dry again	Normal
CI	Power supply		Transformer stations flooded. Power is out.	No power	Power supply works
	Roads	Lowest carparks & roads closed	Roads in city centre are flooded	Roads open again	Normal
	Other		Hospital inaccessible, university closed drinking water supply & communication fail.	NO Drinking water supply or communication	CI normal, university open
Emergency responders		Close lowest roads and parking places.	Communication difficult. Divert traffic, call in the army to transport people to and from the hospital.	Repair, arrange drinking water for people, people, hospital, fire fighters	Back to normal
Society		No awareness yet	When the water comes, people start rescuing cars, homes and belongings.	Return home, clean up and repair.	Back to normal.

Figure 7. Overview matrix of the event and its impacts and recovery

After the flooding

After approximately 24 hours, the flood waters recede. The roads and bridges are accessible again, but power supply and water supply remain interrupted. Cork City Council uses large mobile tanks to distribute water to the affected areas and hotels and leisure centres which do have power and water offer their facilities to local residents for showers. It takes weeks to get power running and one to two months to get the transformer stations repaired. Drinking water remains out of function for two weeks, after which boil water notices are issued to 25,000 homes. Businesses, public services and educational facilities whose premises were affected by flooding commence with a post-flood clean-up and after two weeks, businesses quickly reopen, university classes start again and life returns.

At the university temporary lecture locations and accommodation are organised. About 10,000 students and 30 staff are relocated. There were no casualties or fatalities. However, it takes the city's largest university, which is located adjacent to the River Lee south channel, 8 months to repair all damage caused from the flooding.

Flood impacts

The social and economic impacts are very large. Almost all of the almost 125,000 citizens suffer directly or indirectly during the flooding. Monetary impacts exceed the €60 million flood damage costs of 2009, and recovery lasts much longer (2-9 months). Although there were no casualties, the flooding is considered disastrous. The city is considered vulnerable and not resilient to flooding.

4.3 Changes after 2009 and its effects on the storyline of 2017

After the real flooding event of 2009, measures were taken in order to prevent such an event from happening again to such a large scale and to increase the resilience of the area. The most important features are:

- The transformer stations are protected by walls of one meter high.
- The emergency management and coordination has improved a lot.
- The lowest embankments and quay walls have been raised and repaired
- The largest university now has flood protection.
- Some first crucial steps have been made in protecting the Lee River Water Treatment Plan better.

As a result, the storyline of a 1/1000 year flood now differs from the storyline devised in the pre-2009 flood event (detailed in the previous section). This post-2009 scenario would start in the same way, however, its impacts would be significantly less and recovery would be much faster.

In this storyline, the alarm phase is comparable with the one described in the previous section, although communication may have been improved slightly. When the ESB foresees that they must release large quantities of water from the Inniscarra Dam, they warn the Cork City Council which activates the Flood Risk assessment group. This group then activates the Local Flood Emergency Management group and they immediately restrict traffic on the most vulnerable roads and parking places, prior to flooding of these areas occurring.

The flood pattern is also similar, but now citizens have received warning and are prepared for the flooding. They take precautionary measures protected their homes, which reduces property damages.

Due to the flooding the roads along and across the rivers have become inaccessible and are blocked for local travellers and commuters.

The drinking water production facility (the Lee Road Water Treatment Plant) has improved flood defence measures and, is therefore better protected and more reslient, however, in this scenario, the level of protection is still not sufficient and the facility remains under threat from flooding. As a result of the increased awareness and preparedness, the emergency managers (fire brigade, army, civil defence) now succeed to protect the facility with sandbags and temporary measures and the drinking water treatment facility is saved.

The two transformer stations are not flooded, since they are protected by flood barriers of 1m high and a new flood drainage system has been installed at each door to mitigate risk, all of which were conducted after the 2009 flooding. The power supply is therefore not interrupted. The low voltage transformers can withstand 1m of water. In most places power supply is thus not endangered and all CIs depending on power supply are not impacted. The buildings of the University College Cork along the south channel of the River Lee and the Tyndall National Institute in Cork City island are now protected and resist the high water levels without damage. Students have received warnings to be alert, but they do not need to leave their dormitories or classes.

As a result of the flooded roads, the Mercy University Hospital in the centre of Cork becomes inaccessible and the emergency services including the army are called in to bring hospital personnel to and from the hospital. Schools and businesses are closed during the flooding, but reopen after one day. Some buildings need to be cleaned and carpets must be replaced, but business and education can continue. Rail services, Cork International Airport, the gas supply and communication networks are not affected.

The flooding causes disruption, but impacts are not as significant as they would have been before 2009. After approximately two days, normal life resumes in the city. The area has become much more resilient than it was before 2009.

4.4 Outlook to the (near) future

In the future, rainfall levels are expected to increase and also higher sea levels are anticipated. These factors combined with increased storm surges, aggravate flood hazards and increase the vulnerability of CI and increase risks and disruption incurred by society.

To reduce the vulnerability of the area for flooding and to increase its resilience, a flood relief scheme has been proposed in 2014 [15]. It consists of:

- Flood defences along the River Lee downstream of Inniscarra dam and through Cork City;
- Improved operating procedures for the Carrigadrohid and Inniscarra reservoirs for purposes of flood risk management;
- A flood forecasting system to help the dam operators and the emergency managers, and if necessary, the erection of temporary/demountable defences downstream and in Cork City.

The future flood forecasting system will use weather forecasts and it will alert the ESB a few days before the peak discharges are expected to occur. The ESB then has time to lower reservoir levels in anticipation of the extreme event and increase in water volumes. The flood forecasting system will also take into account inflows of the River Shournagh and River Bride, downstream of the Inniscarra dam and the tide levels which also influence the probability and severity of flooding in Cork City. Furthermore, it has been proposed to increase the river capacity with the installation of new flood defences and by the identification of upstream flood storage /washlands, which may be periodically flooded. The washlands will have warning sirens to give advance warning to land owners which will, for example, allow them to move livestock or take other actions. The sirens will also alert recreational users of the river. Cork City Council will use the warnings for the erection of demountable elements and emergency response services, if needed. The warnings will also be sent out on local authority websites, social media, and the local authority text-alert systems, in addition to media.

Furthermore, spatial planning and new critical infrastructure developments will be based on knowledge of flood risks, such as data derived in the CFRAM project [7]. The CI operators will use the data from the CFRAM study and combine it with their own data which will assist users when undertaking their own risk analysis and measures to make their respective infrastructure more resilient.

As a result, resilience is expected to increase in future. Risk information generated to comply with the Floods Directive and the lessons learned from recent flood events enable adaptation measures to be incorporated, resulting in improved resilience in terms of withstanding flooding events and improved recovery following such events, thereby leading to a more resilient society.

The high level of awareness caused by the recent floods creates momentum for change to a more resilient society. In future awareness, improved forecasts, warning and communication systems and self-reliance could further improve resilience. These measures will enable more informed decision-making in advance and during a flood event and a faster and more efficient response and recovery.

In the long-term, if tidal floods would become significantly more frequent and if fluvial flooding would also increase, other long-term solutions may be needed. These may be explored for long-term planning outlooks.

5. Discussion and conclusions

The case study in Ireland was chosen because of the many recent floods and especially because of the large impacts of the 2009 flooding event in Cork City. During the case study, it was determined that the most urgent measures and improvements are currently in the process of being implemented, while further improvements are also proposed. These measures increase resilience of the society significantly. The study determined that if the

2009 flooding event were to occur again in Cork City, its impacts would be significantly less than in 2009.

This section discusses (1) the method, (2) the results for Cork and (3) the implications for other areas with similar issues.

On the method

The approach used resulted in a valuable overview of the locations of CI in the flood-prone area in and around Cork and in knowledge on the effects of floods on those CI elements, the cascading effects and the impacts on society.

The stakeholder workshop provided the opportunity to exchange ideas and information and was determined beneficial by the participants. It provided insight in actions, reactions, methods used for risk analyses and information flows. The joint discussions with many stakeholders were found to be very valuable.

The method does not result in flood risks. To obtain flood risks, flood probability information need to be added.

The Cork application was the first application in which the *CIrcle* tool was used in an area where floods had occurred recently. It was therefore difficult to distinguish between impacts corresponding with the hypothetical event and the real historic event. The participants at the workshop had far more knowledge on potential flood impacts than participants from areas without recent flood events (e.g. in The Netherlands [4]).

On CI vulnerability of the area

Before the flooding of 2009, the awareness and preparedness in respect to flooding were low and CI elements were vulnerable towards flooding. The 2009 flooding caused significant and widespread damage to properties, businesses and also to CI. The water and wastewater treatment plants, the city's largest university, the main roads all were affected and the important transformer station narrowly escaped flood damage. Due to the flooding, one of the city's main hospitals was significantly impacted from partial flooding of the emergency department, while all access roads to the hospital were inaccessible. Furthermore, essential services were compromised including the fire service. Educational institutions in the affected area were without water, forcing closure and 25,000 homes were without water for nearly two weeks.

Since then much has been improved: the transformer stations have been protected, the lowest embankments/city quay walls have been raised and reinforced, improved flood defence measures have been installed at the university, and the emergency management has improved.

At the moment, if an extreme fluvial flood event occurs, the roads, and drinking water production facility are at most risk. The forecasting, warning and emergency management procedures have been improved already and will be improved further as part of the Cork Flood Relief scheme. Response will therefore be even more efficient than in 2009. If the drinking water production facility is better protected, then flooding may still cause disruption, however, the level of disruption will be reduced. The limited damage and the fast response and recovery afterwards make the area resilient.

Value for other areas

The method applied here is beneficial for other areas in which flood risk to CI may be significant. Also, the measures taken and the new measures proposed may be useful to consider elsewhere. The case study shows that flood risks can be reduced significantly in a short time. Through this paper, and the sharing of experiences and practices, it is hoped that other vulnerable areas can learn from these experiences, and will arrange flood defence and mitigating measures, including emergency management plans, thereby increasing resilience of their vulnerable areas.

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