Assessing and visualising hazard impacts to enhance the resilience of Critical Infrastructures to urban flooding

L.S. Vamvakeridou-Lyroudia [a,b,*], A.S. Chen [b], M. Khoury [b], M.J. Gibson [b], A. Kostaridis [c], D. Stewart [d], M. Wood [d], S. Djordjevic [b], D.A. Savic [a,b]

[a] KWR Water Research Institute, Groningenhaven 7, P.O. Box 1072, 3430 BB Nieuwegein, the Netherlands
[b] Centre for Water Systems, University of Exeter, North Park Road, Exeter EX4 4QF, UK
[c] SATWAYS Ltd, 3 Christou Lada Street, 15233 Halandri, Athens, Greece
[d] Torbay Council, Town Hall, Castle Circus, Torquay TQ1 3DR, UK

HIGHLIGHTS

- The design of resilience to urban flooding is complex to model and implement.
- Risk assessment to urban flooding needs to take into account cascading effects.
- The active participation of stakeholders is essential from the design stages.
- Fast flood modelling techniques are essential for examining multiple alternatives.
- High visualisation techniques are useful for making the results understandable.

GRAPHICAL ABSTRACT
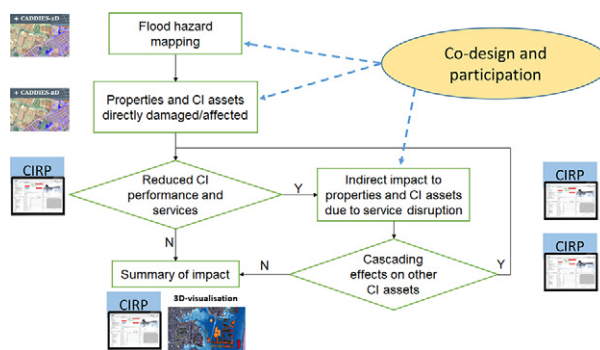
ARTICLE INFO

ABSTRACT

The design, construction and maintenance of Critical Infrastructures (CI) is commonly based on standards that are rigorous, so as to withstand any climate or weather-linked pressures. However, due to climate change, climate characteristics may shift, resulting in increased frequency/magnitude of potential failures, or exposure to new unknown risks. As vital components for the normal functioning of modern societies, the resilience of CIs under climate stressors encompasses their structural integrity, their operational elements, and their capacity to maximize business output. In this work, we propose an integrated and participatory methodological approach to enhance the resilience of interconnected CIs to urban flooding under climate change, by assessing the risk and introducing adaptation measures.

The main objectives of the proposed methodology and approach are: (i) to provide scientific evidence for better understanding of how future climate regimes might affect normal operation of interconnected CI in urban areas during their lifespan; (ii) to assess the cost-effectiveness of different adaptation measures; (iii) to involve local stakeholders and operators in the co-design of the approach, as well as the assessment and the evaluation of adaptation measures; (iv) to combine computational modelling with advanced 3D visualisation techniques for effectively engaging stakeholders in decision making; (v) to include risk assessment and damage functions co-designed by end-users and local stakeholders; (vi) to integrate all of the aforementioned components in a specifically designed cloud platform as a Decision Support System for end-users, (vii) to validate the DSS by the end users and local stakeholders.

* Corresponding author at: Centre for Water Systems, University of Exeter, North Park Road, Exeter, EX4 4QF, UK.
E-mail addresses: L.S.Vamvakeridou-Lyroudia@exeter.ac.uk, lydia.vamvakeridou-lyroudia@kwrwater.nl (L.S. Vamvakeridou-Lyroudia).

The paper presents the computational background and tools. Additionally, it describes a Case Study in Torbay, UK, where the full methodology and the proposed participatory approach have been applied, with all the specifics, i.e., the scenarios of extreme flooding, the numerical and visualisation results, the response of the stakeholders and the evaluation of selected adaptation measures.

1. Introduction

The design, construction and maintenance of Critical Infrastructures (CI) is commonly based on standards that are rigorous, so as to withstand any climate or weather-linked pressures. However, due to climate change, climate characteristics may shift, resulting in increased frequency or magnitude of potential failures. It is also possible for specific CIs to be exposed to new, unknown or increased risks that have not previously been considered. Resilience at urban level refers to the ability of the society to withstand, absorb and recover from the impact of natural hazards. CIs, i.e., energy generation and transmission, water supply and wastewater systems, telecommunications, chemical industry, Information and Communication Technology (ICT-web) networks, transportation, and emergency services are all components of a large interconnected system that keeps society at functioning level. As a consequence disruptions generate cascading and ripple effects; potential damage in one infrastructure affects other infrastructures, while the ripple effects will eventually have a larger impact to the economy and the broader community. The scale of CI systems is usually large, their lifetime exceeding the order of decades. In all this time, infrastructures are expected to be exposed heavily to natural disasters, which may have devastating consequences for the environment, the economy and the society overall. Their interconnected and interdependent mode of operation may result in exposing societies to risks which are previously unseen, to new vulnerabilities and dangerous conditions, because of the disruptive cascading effects across multiple CI assets. Vulnerability is being assessed by quantifying the impact (damage, inability to provide services) for each asset, due to specific hazards, as well as the duration of this inability (e.g. until the flooding recedes).

Current research, based on the analysis of past events and historical incidents shows that CI vulnerability is closely linked to extreme weather events, disrupting their normal operational mode, causing lasting damage and devastating impacts due to cascading effects across several infrastructures because of their interdependencies and interconnections. It is also widely acknowledged that CI vulnerabilities and impacts extend beyond physical damages, encompassing business continuity, health issues and potentially social unrest (Hokstad et al., 2012). The work presented here aims to a holistic assessment of impacts to the services that are provided by CI. It addresses impacts associated with the repair, and/or replacement of services but also addresses issues peripheral to the operation of CI, i.e., environmental effects, societal costs and economic consequences due to business disruption, due to activities that are suspended during the recovery period.

Based on the literature and recommendations and suggestions for good policy practices (Hickel et al., 2013; Intergovernmental Panel on Climate Change, 2018) risk assessment related to climate change will need to consider: (a) all the possible threats that could emerge from an extreme event; (b) the likelihood of occurrence for the event; and (c) the consequences of the actual event. Accordingly, risk assessment under climate change needs to provide the necessary information that will allow a CI operator to manage the aforementioned risks, by (a) changing the state of the system to reduce vulnerability, (b) improving resilience to reduce potential climate impacts (Dawson, 2015). According to national security and safety plans (UK Cabinet Office, 2018), CI resilience embraces a broader set of activities than conventional practices aiming solely to protect critical infrastructures against multiple threats; it includes activities for preparedness, prevention, protection and recovery against natural hazards (Galbusera et al.,

2014). This is due to the fact that the existing interdependencies among CIs result in increasing dramatically the overall complexity; they create a "systems of systems". Consequently a holistic approach is needed, in order to enhance the resilience of multiple interconnected (critical or not) infrastructures; their interdependencies need to be taken into account (Bouchon, 2006).

Multiple activities need to be taken into consideration, in order to enhance the resilience to natural hazards. Some are strategic (long term investment plans), others target preparedness and response (e.g. plans, capacity and readiness for emergency response, alerts) or impact absorption capacity, e.g. adapting the technological characteristics and operational mode of CIs to changing conditions over their long lifespan.

Flood hazards are a major threat to urban systems and societies. Better understanding of the potential impacts caused by flood hazards under various climate and socioeconomic scenarios is essential to develop resilience strategies for CIs planning, design, operation and management (Boin and McConnell, 2007). Hence, various studies have developed different approaches to evaluate flood risks (Apel et al., 2006; Chen et al., 2016; Hall et al., 2003) and/or to quantify resilience for decision supporting to develop climate adaptations (Engle et al., 2014; Hammond et al., 2018; Vojinovic, 2017). Such analyses often consider not only direct tangible impacts but also indirect (e.g. economic losses; Andreoni et al., 2014; Kreibich et al., 2016) and/or intangible consequences (e.g. health; Alderman et al., 2012; Mark et al., 2018) of natural climate-related hazards. However, the spatiotemporal evolution of hazard impacts is critical for crisis management and strategic planning to prevent cascading impacts (Mazzorana et al., 2019). Existing applications might be able to display such relationship conceptually or at an aggregated high level (Araya-Muñoz et al., 2017), details regarding where, when and how does such knock-on cascading effect propagate during disasters are still unavailable. Hence, an innovative approach is needed to fill this gap.

EU-CIRCLE is a H2020 funded project, entitled "A pan-European framework for strengthening critical infrastructure resilience" that developed a holistic framework aiming to identify the risks of multi – climate hazards to heterogeneous interconnected and interdependent CI (Sfetsos et al., 2017). In the work presented in this paper, the resilience framework was applied for urban flooding. To this purpose it was combined with fast flood modelling to evaluate possible flood scenarios, with the active participation of local authorities providing the scenarios. Thus vulnerable CIs were identified, as well as the consequences when their services are disrupted by flooding. High visualisation techniques were used to facilitate the understanding and communication of the results, while the outcomes were used for selecting suitable adaptation measures by local stakeholders. The whole approach and methodology have been applied to the Case Study of Torbay in South West UK and are presented in this paper.

The main objectives of the proposed methodology and approach are: (i) to provide scientific evidence for better understanding of how future climate regimes might affect normal operation of interconnected CI in urban areas during their lifespan; (ii) to assess the cost-effectiveness of different adaptation measures; (iii) to involve local stakeholders and operators in the co-design of the approach, as well as the assessment and the evaluation of adaptation measures; (iv) to combine computational modelling with advanced 3D visualisation techniques for effectively engaging stakeholders in decision making; (v) to include risk assessment and damage functions co-designed by end-users and local stakeholders; (vi) to integrate all of the aforementioned

components in a specifically designed cloud platform as a Decision Support System for end-users, (vii) to validate the DSS by the end users and local stakeholders.

The paper is organised as follows: Section 2 presents the methodological approach, i.e., the resilience framework to natural hazards for CI, with specific emphasis on urban flooding (Section 2.1), followed by the risk assessment approach and tool (Section 2.2), the flood modelling tool (Section 2.3) and the visualisation details (Section 2.4). Section 3 presents an application of the methodology for Torbay (South West UK), with emphasis on the involvement and participation of local stakeholders, followed by discussion on the results and conclusions (Section 4).

2. Methodological approach

2.1. The resilience framework

The Resilience Framework for CIs, developed in EU-CIRCLE, which has been applied in this work is shown in Fig. 1. The Risk and Resilience framework considers the services provided by CIs to society as a flow of goods/commodities pertinent to each type, while preserving the unique characteristics of each sector. The approach is detailed in the literature (Sfetsos et al., 2017), but the main features are also presented here.

The generic Resilience Framework consists of three main interlinked and interacting parts (Fig. 1):

(a) A step-by step procedural Climate Risk Management framework;
(b) An interacting Risk and Risk Modelling framework;
(c) An Outputs (to end users) component.

The successful implementation of this Resilience Framework needs interaction with local stakeholders and end users, both for the development and for the final use of the results, which has been followed in the work presented here. The parts for which participation is mostly needed are encircled in Fig. 1. It also should be pointed out that this general framework is flexible, allowing for the inclusion of multiple modelling methodologies, as needed. The left part (Climate Risk Management) forms the core of the procedure, structured as follows:

1. Establishment of CI (or regional) climate change resilience policy, or specific business oriented decision that will be addressed. Typically, such policies have a timespan of multiple years and their objective may be related to specific issues or cross-sectoral matters. Relative policy questions to be answered can be: What must and what should be protected? Which potential consequences are relevant (economic, social, environmental etc.) for this appraisal? What are the priorities? What is an acceptable risk and what is a non-acceptable risk? Here the participation of stakeholders and end users is crucial, since the inside knowledge of the area is paramount.

2. Identification, collection and processing of data related to climate (e.g. rainfall data) and secondary hazards (e.g. high tides). It involves analysis of the historic climate and secondary hazards data sets, mid- and long-term projections of climate regime, based on available data and application of specialised simulations.

3. Identification of assets, systems, networks, relations and functioning modes. The following approach is proposed: a) Compilation of a registry of CI assets relevant to the sectors considered in EU-CIRCLE and use an adequate level of granularity, b) Analysis of interconnections, networks and (inter-) dependencies including the various types, such as physical, cyber, geographic, logical or social (inter-) dependencies. The participation of stakeholders and end-users is also critical for this step.

4. Assessment and evaluation of risks, through a harmonized interoperable approach. Alternatively "translating solutions" are to be created between the different risk and impact criteria, specific for each Case Study.

5. Selection and implementation of protective programmes, including adaptation options, to modify risk level and to implement options to: a) reduce the likelihood of occurrence, b) reduce the impacts/consequences and exposure, c) transfer in full or partly the risk, and d) mitigate and manage the risk. Here too the participation of stakeholders is very significant, because they are needed to identify possible measures that will be assessed through modelling.

6. Measurement of effectiveness. Once one or more risk reduction measures are introduced, the progress towards achieving the relative objectives must be evaluated in detail. Risks, effectiveness, goals or other circumstances may change after initial implementation of the adaptation measures, especially is the measure require time to be
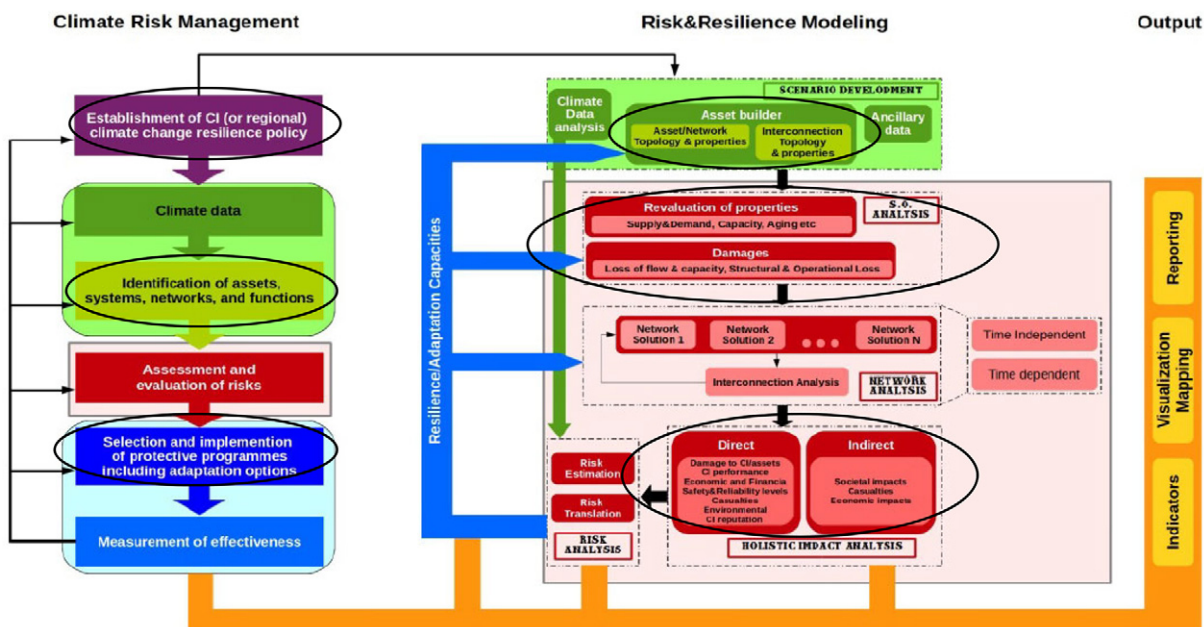

Fig. 1. The Generic Resilience Framework for Critical Infrastructures showing the steps where the participation of local stakeholders is very important (encircled boxes).

fully functional (e.g. extensive construction works or relocation of assets).

The central part in Fig. 1 details the structure of risk modelling and its different components. It starts by building critical scenarios for risk assessment. Each scenario is built separately by combining climate data (from Step2), asset lists (From Step 3) and potentially ancillary data (e.g. evacuation routes). The System Overview (S.O.) Analysis (damage curves for the assets) follows. This stage is linked to the list of assets and also needs the participation of stakeholders and end users. Computational Modelling follows, with the system analysed as a network (e.g. flood modelling) for each specific hazard scenario (Network Analysis). The resulting Holistic Impact Analysis includes direct and indirect impacts to CI. Here the role of the stakeholders involves the validation of the results, according to their in depth knowledge of the area. The right hand side column involves the display and visualisation of the analysis and results, so that they will be fully understood by the end-users. The work presented in this paper has put a lot of emphasis in the visualisation of the results, introducing advanced approaches, as detailed in the following sections.

In principle, the Resilience Framework includes three components for resilience assessment: (a) *consequence* (sectoral, referring to the particular CI affected-direct consequences); (b) *time* (related to the chronical sequence of events, representing the timeframe of occurrence of climate change related disruptive events) and (c) *interdependencies* that are likely to occur across other types of infrastructures – cross sectoral effects. Fig. 2 shows the interdependencies arising from a flooding event (natural hazard) to other CIs. This schematic diagram was drawn for the Case Study of Torbay, but it demonstrates clearly the interdependencies leading to cross-sectoral effects in a generic way.

Specifically for flooding hazards, the general framework is adapted as follows: For any given flood scenarios, the spatiotemporal evolution of flood hazards is fed into the algorithm shown in Fig. 2 for evaluating the flood impact to CIs within the resilience framework. Firstly, the primary CI assets that have direct contact with flood are pinpointed by overlapping the flood maps with the CI locations. The disruptions of their service areas are determined by considering the flood depth and the duration, the protection level, and the backup facilities/resources of these assets. The secondary CI assets that depend on the services of the compromised primary CI assets in those affected areas are therefore selected and the same analysis procedure will be repeated until no

further affected assets are found. With all the flooded and affected assets identified, the flood impact to the CIs and the timeline can be calculated, and then summarized for overall assessment and visualised for demonstration.

In this way the concept adopted in the project and in this work, advances beyond the specific boundaries of each infrastructure allowing modelling cascading effects and taking into account the related damage assessment in a systematic and holistic way. The main concept is based on the services provided by CIs to community (or society), which are perceived as a flow of goods or commodities that are pertinent to each type of CI. The types of CIs taken into account as separate sectors are: water, energy, transport, Information and Communication Technology (ICT-web) networks, and governmental services (e.g. health services). All are highly sensitive to hydro-meteorological extremes.

The analysis needs also to take into consideration damages to linked, interconnected assets, even to other types of infrastructures. It is highly likely that the procedure needs to be iterated at systemic level, due to these secondary effects to other infrastructures or assets (shown in Fig. 3). In Fig. 3, a flooding event affects directly the residential properties in blue and the transport network (Road closure). It also affects two other types of CI and assets, i.e., the electrical substation (energy CI) and an exchange centre (telecommunications CI). The damage at the electrical substation in turn affects an asset of the waste water sewer network (pumping station-water infrastructure), which in turn causes overflows and flooding for the properties shown in red and further disruption to the transport network (orange arrows).

It is very important to point out that this resilience framework cannot be applied in a reliable manner without the active participation of local stakeholders (e.g. representatives from the CI operators, the local authorities, the first responders and the business sector). This group has in depth knowledge of the area and of the CIs. Their role is crucial for several steps of the procedure: The selection of the climate change resilience policies, the selection of suitable potential adaptation measures, but, most importantly the list of assets, properties, their interdependencies, as well as the damage functions, cannot be implemented without their help, assistance and active participation.

The right hand part in Fig. 1, which is labelled as Output, refers to the interaction with the stakeholders and end users and underlines the significant role that participation of local stakeholders has for the building of a reliable and relevant risk assessment procedure. It comprises the communication of the results to the locals, who need
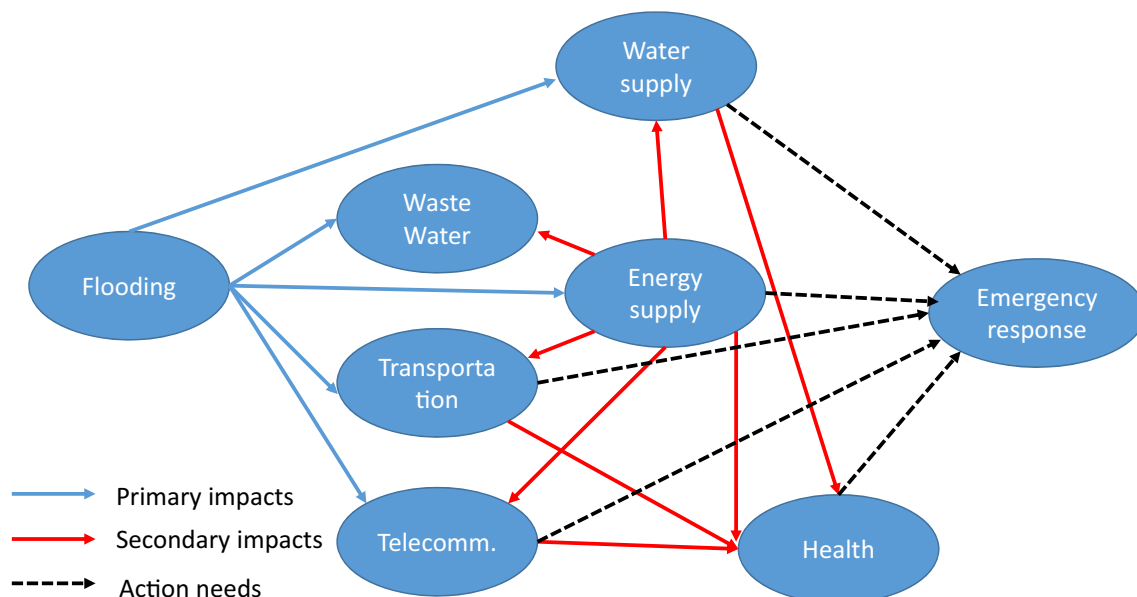

Fig. 2. Impacts of flooding to various types of CI and interdependencies.
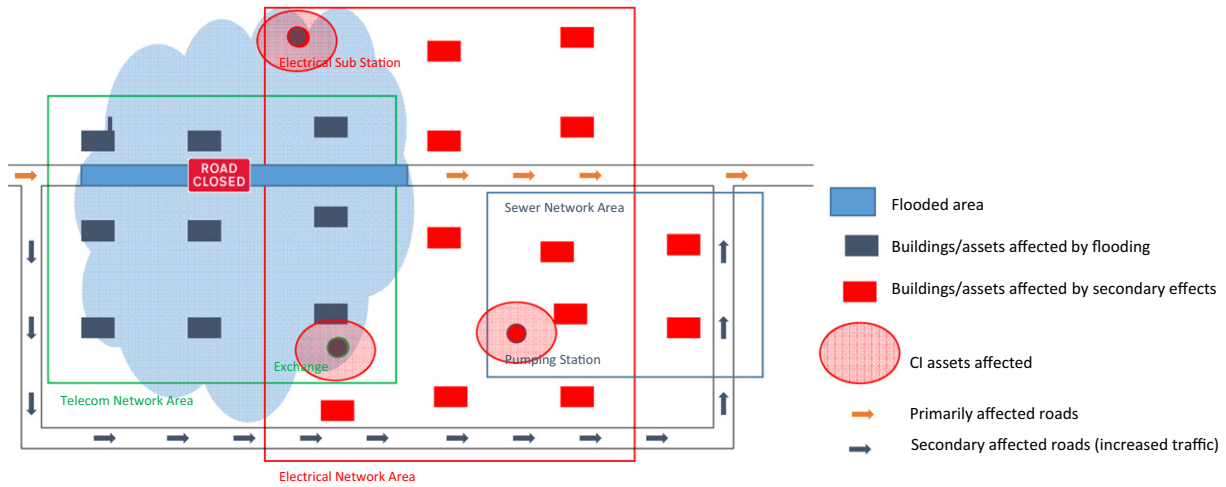
Fig. 3. Flood impacts to CI assets: two CI assets (Electrical Sub Station and Exchange station) are directly affected and one (Pumping station) indirectly.

to understand the impacts, validate them and increase their own awareness to the threats to particular CIs in their region, due to climate related natural hazards. The importance of communicating the results is not to be underestimated, since even the most complicated and detailed mathematical model will be practically useless, unless the local stakeholders can understand the issues at hand and experiment with alternatives, measures and outputs; hence the importance of user-friendly high visualisation. The CIRP platform for risk assessment (detailed in Section 2.2) and particularly the flood modelling tool (detailed in Section 2.3) have both enhanced capabilities for high visualisation (Section 2.4), which are considered an integral part of the Resilience Framework.

This approach has been adapted and applied also to other types of natural hazards (forest fires) (Katopodis et al., 2018). In this paper this generic methodological approach has been specified and adapted for urban flooding as follows:

For each selected flood scenario, the evolution of flood hazards (in space and time) is fed into the algorithm shown in Fig. 1 (central part) to evaluate the flood impact to CIs and assets, according to the resilience framework. Initially, the primary CI assets that have direct contact with flood are defined by overlapping the flood maps (changing over time) with the spatial CI locations. The disruptions of their service areas are determined, taking into consideration the flood depth and duration of flooding, any protection thresholds (as levels) and the facilities (services) linked to these assets. Then, all the indirectly affected CI assets (secondary assets) depending on the services of the directly affected primary CI assets are defined (see also Fig. 3). The same procedure continues to be applied iteratively, until all the indirectly affected assets are defined and no further affected assets are found. Then the overall flood impact to the CIs can be estimated (as well as the timeline), summarized and displayed for the overall assessment and/or fed to the visualisation tools for demonstration. The process is schematically displayed in Fig. 4.
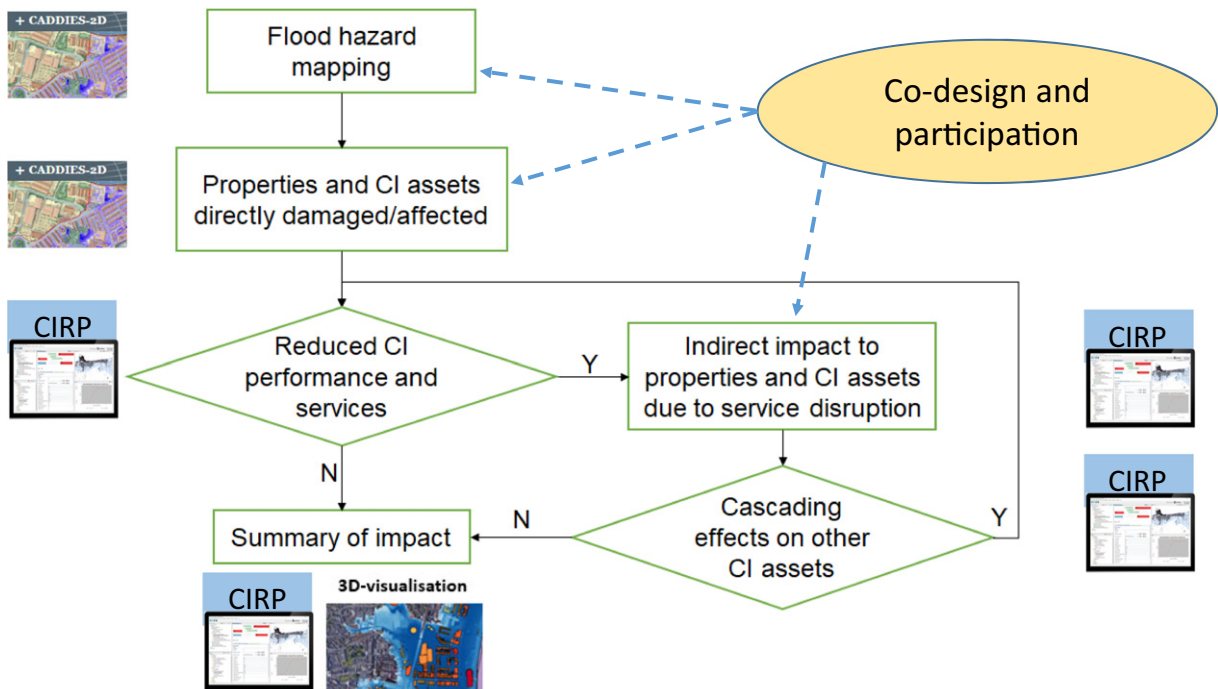

Fig. 4. Flowchart and procedure for assessing the cascading effects to CI assets and the computational tools involved.

2.2. Risk assessment - the CIRP platform

The risk assessment is carried out through the collaborative software environment CIRP (Kostaridis et al., 2017) (Fig. 4) that allows policy-makers, decision makers, and scientists to use different and diverse modelling and risk assessment solutions for developing risk reduction strategies and implement mitigation actions to minimise the impact of climate change on CIs, due to various hazards (e.g., flooding, forest fires, etc.). CIRP offers an environment for what-if scenario analyses with the selection of modelling chains, climate data, and CI inventories to calculate damages and assess the resulting risk, for any combination of climate hazard and CI assets. This provides an efficient, pragmatic, and effective solution that integrates existing modelling tools and data into a holistic resilience model in a standardised fashion, in a modular and expansible way. CIRP is able to accommodate different types of datasets (e.g. hazard, assets, interconnections, fragilities), file formats, and risk analysis algorithms and provide an intuitive user interface for scenario and data repository management, analysis workflows setup, intuitive results (2D/3D) visualisation and reporting.

The essential elements for impact assessment are hazard, inventory, and fragility. Hazard is considered as the descriptive parameter quantifying the possible phenomenon within a region of interest. The assets in a region exposed to hazards are defined by inventory. Finally, fragility is the sensitivity (conceptually referring to the susceptibility of system components) of certain types of inventory items when subjected to a given hazard.

From the technical point of view, CIRP is primarily based on the Eclipse Rich Client Platform (RCP) technology and two distinct frameworks each compliant with RCP: the ERGO-CORE of the ERGO consortium and the Chameleon Enterprise Foundation (CEF) of Satways Ltd. (Kostaridis et al., 2017). Both frameworks are a collection of OSGi (Open Services Gateway Initiative) plugins (or bundles). The ERGO-CORE is the base IT infrastructure of the ERGO (ERGO, 2018) an open-source project that was originally developed to perform seismic risk assessment. The ERGO-CORE RCP bundles provide the functionality related to inventory, data and metadata management, and the ability to wrap new analysis types and execute them on a workflow engine. The CEF framework on the other hand provides the user, role and access rights management bundles, and the 3D GIS viewer and editor modules. The CIRP User Interface consists of one or more (in case of using multiple workstation monitors) main application windows, offering different views: Scenario Manager, Catalog (access to remote and cache files), Loss Curve and Mapping Editors, 2D and 3D mapping viewers and editors. CIRP provides support for five different Plugin types as platform extensions: Type Definition, Local Execution Java, Local Execution Hybrid, Remote Execution and Local Scripting (Kostaridis et al., 2017). Sample views of CIRP applications can be found other publications (Katopodis et al., 2018), while the CIRP tool can be accessed in http://www.eu-circle.eu/cirp/, with videos and training material.

2.3. Flood modelling

The fast flood model CADDIES 2D (Guidolin et al., 2016) has been used as a Local Execution Hybrid plugin in CIRP, in order to simulate pluvial and coastal flooding, so as to identify vulnerable CIs and the consequences (impacts) when their services are disrupted by flooding. The CADDIES 2D modelling framework applies cellular automata (CA), an Artificial Intelligence methodology, combined with parallel computing technologies. Thus it can perform fast flood simulations on Graphics Processing Units (GPUs) for multiple scenarios. These scenarios usually include a wide range of weather conditions causing storms and flooding, together with possible measures or interventions. It would be impossible to run and analyse within reasonable time, such variety and large numbers of scenarios and interventions using traditional hydraulic modelling techniques. The main reason that CADDIES 2D was used was to enable a comprehensive investigation of current and future

capacities of the system (CI) under multiple scenarios, with the ultimate goal to identify CIs and assets that are susceptible to flood risk. A combination of possible projections was possible, thus enabling the overall system ability to cope with different "futures" related to climate change, as detailed in the next section (Results), where scenarios of pluvial and fluvial flooding have been combined to examine the ability of the system to cope with climate change conditions. A specific list of the scenarios under climate change ("futures" under climate change), as applied in the Case Study is given in Section 3. As a result, it was possible to take into account uncertainty in a comprehensive way, by examining a full spectrum of future conditions and associate them with the capacity of the system infrastructures, as they change over time (e.g. ageing pipes) or by specific interventions (e.g. flood protection works). In this way it is possible to obtain a comprehensive flood risk assessment.

For each scenario, the propagation of flood hazards and related impacts were investigated, so as to fully understand cascading effects over the whole urban area, as well as the way this evolves with time (Chen et al., 2018). This same procedure was repeated for each timeframe of flood condition and for each simulated event. As a result it was possible to deliver a comprehensive assessment and appraisal with suitable recommendations to enhance the resilience of the CI infrastructure, which, in turn, has been used by the end users to strengthen their bid for adaptive measures protecting the CIs and enhancing flood resilience. It was needed to repeat this procedure for multiple scenarios and different urban areas in the region, which required an abundant amount of information to be analysed. Consequently, an automatic algorithm has been developed for this purpose. The algorithm also includes a 3D visualisation function that enables the users to investigate easily the spatial relationships among flooding and different types of CIs, as described in Section 2.4 in more detail (Khoury et al., 2018a).

In one of the application areas, coastal flooding was also important, due to overtopping a sea wall. In this case, the overtopping discharges along the sea defences were produced by the AMAZON model (Haskoning, 2017), which simulates the random waves travelling as bores. The discharges for the current and the future climate change scenarios of selected return period events were used as inputs to the CADDIES model as the boundary conditions for the cells along the coastal defences. The overtopping rates follow the 12-hour tidal cycle with a total duration of 4 days.

2.4. Visualisation

The results are displayed using the 3D visualisation plugins qgis2threejs and GEarthView in QGIS (Akagi, 2017; QGIS Project, 2018), which allow end-users to interactively navigate the modelling results using a standard browser or the Google Earth without installing specific software. A user can easily explore the 3D space to investigate the flood impact to individual properties and their surroundings in detail. This provides an enhanced user experience and strengthens the understanding of spatial correlation between hazard, CIs and their service areas.

To demonstrate the modelling results in a more user-friendly way that improves risk communication, the flood depth data were exported to Google Earth Pro allowing stakeholders to explore the study area using the interactive 3D mapping tool. The approach only requires a simple public available software that is easy to operate. Users do not need to install complicated GIS software or purchase the software licence. However, in this way only static flood information (i.e. maximum flood depth) can be displayed and it cannot demonstrate how flood propagates within the city during an event. It also has limited ability to highlight the level of damage and the impact of cascading effects due to CI failures. Therefore, an advance visualisation tool has been further developed using Unity3d Game engine to create a 3D animated visualisation of flood events (Khoury et al., 2018a) and has been successfully tested in the context of Serious Gaming (Khoury et al., 2018b).

3. The case study of Torbay

3.1. Description and participatory process

Torbay is located in South Devon (UK) and has an area of approximately 62 km². Torbay has an extensive coastline extending from the boundary with Teignbridge to the boundary with South Hams. It is on the south west coast between the main cities of Exeter and Plymouth. As Torbay has developed over the years it has become one of the main tourist resorts within England and is known as the English Riviera. Much of the catchment area is urban comprising three main towns of Torquay, Paignton and Brixham (Fig. 5).

The area has suffered from flooding over many years from a number of different sources, including surface water run-off, highway flooding, sewer flooding, main river and ordinary watercourse flooding during intense rainfall events. In addition the coastal areas of Torbay suffer from coastal flooding due to overtopping of the sea defences during high tides that coincide with easterly winds. It should be noted that the surface water, highway, sewer, main river and watercourse flooding is exacerbated in the low lying areas around the coast of Torquay, Paignton and Brixham during high tidal cycles when the capacity of the surface water outfalls discharging to coastal waters is impeded, leading to road closures. The main coast road linking Torquay to Paignton and Brixham has to be closed on a regular basis due to overtopping of the sea wall during high tides that coincide with easterly wind conditions. These closures result in long traffic diversions and delays. Fig. 5 shows the areas most affected by flooding in Torbay and the types of flooding that incur more often.

The full methodology for improving the resilience of CIs under climate change, was applied for the region. In order to reduce the risk of coastal overtopping at Paignton a new sea wall has been proposed in the area of Preston (in the north of the town centre). A number of adaptation options were selected that would be feasible and relevant. These options included:

- Increase the height of the existing sea wall at Paignton and Preston
- Provide a secondary set back sea wall at Paignton and Preston at the seaward side of the greens
- Provide a secondary set back sea wall at Paignton and Preston at the landward side of the greens
- Provide a wave return wall to the existing sea wall at Paignton and Preston

The assessment of each of these options was undertaken using coastal modelling techniques outside of the CIRP Tool. The results of this modelling work identified the adaptation option that provided most benefit. Providing a secondary set back wall at the seaward side of Paignton and Preston Greens was selected as the most effective intervention. Additional simulations that models this secondary defence has been undertaken, as described in Section 2.3.

Based on the historic flooding within Torbay and the proposed scenarios to be included within the case study an assessment was made of the CI that could be affected by both coastal and pluvial/fluvial flooding. The responsible authorities for the identified CI were selected to participate as stakeholders within the case study. The authorities invited were as listed in the following table (Table 1). Full details on the participants can be found in a project public Deliverable (EU-CIRCLE, 2018, Deliverable 6.7).

During the stakeholder workshop, Torbay Council and Exeter University presented an overview of the EU-CIRCLE project and the application to the Torbay case study. This included an introduction to the CIRP tool and a demonstration of the visualisation tool to be used within the case study.

The second part of the workshop involved round table discussions on the CI that could be affected by flooding, what CI has already been identified and what additional information relating to CI is available from the CI operators for use within the case study. These discussions progressed to the effects of flooding on CI and the interaction between the different types of CI assets. In addition resilience of CI assets to flooding was discussed and each CI owner identified the level of flooding that would result in the failure of their CI assets.

The final section of the workshop involved a general discussion on how the tools developed as part of the EU-CIRCLE project could be utilised by the CI owners. In order to demonstrate the potential benefits of the tools a number of scenarios to be tested within the case study were agreed.

The scenarios ("futures" under climate change) chosen to be assessed were as follows:

- Scenarios to be tested are coastal flooding, pluvial/fluvial flooding, breach failure and a joint coastal/pluvial/fluvial flooding event.
- Climate change scenarios to be used were the present day, 20, 50, 100 years taking into account climate change
- Storm events to be used are the 100 year pluvial/fluvial, 200 year coastal and a joint probability coastal/pluvial/fluvial event.

During the project Torbay suffered extensive coastal flooding due to Storm Emma (March 2018). As a result of this it was decided by the
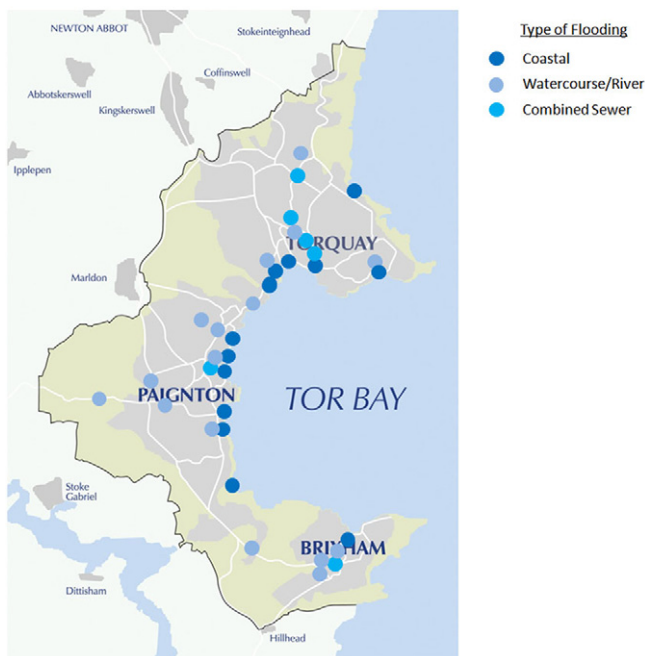

Fig. 5. Torbay: The three areas Torquay, Paignton and Brixham, with the locations most affected by flooding.

Table 1
External stakeholders involved in Torbay CS.

Authority	Critical infrastructure responsibility
South West Water	Water supply and wastewater
Western Power Distribution	Electricity supply
British Telecommunication	Telecommunications
Torbay Council – Highways	Highways
Torbay Council – Emergency Planning	Health, major incident planning/response, business continuity
Torbay Council – Engineering	Coastal defences, ordinary watercourses and harbour structures
Wales and West	Gas supply
Environment Agency	Main rivers and strategic overview for flood and coastal defences
Network Rail	Rail infrastructure

stakeholders that the breach scenario would not be assessed. In place of this, a new scenario was included to demonstrate the performance of the model against the actual storm event, which would also serve for the verification of the model. In addition the adaptation scenario for Paignton and Preston coastal defences would be included in the scenarios for the future. Table 2 shows the details of the scenarios applied.

Finally during the stakeholder workshop it was discussed and agreed that in order to demonstrate the application of the CIRP Tool, the following questions should be answered as part of the process:

- Which roads will be closed due to 0.15 m depth of flooding?
- How many residential and commercial properties would be flooded?
- Identify all critical infrastructure (assets) affected directly or indirectly by flooding
- How many residents are affected by the storm event in question?
- What is the cost of a particular storm event?

These questions were to be answered for the following flooding and climate change scenarios:

Flooding scenarios to be tested as part of Torbay Case Study

- Coastal Overtopping Flooding (1 in 200 year event). Coastal overtopping due to high tide, without any pluvial event with return period 200 years.
- Pluvial/Fluvial Flooding (1 in 100 year event). Flooding due to a pluvial event (storm) with return period 100 years.
- Joint pluvial/fluvial and coastal overtopping event (1 in 50 year rainfall and 1 in 50 year coastal event with 50 years climate change). This is a combined event, where a storm (return period 50 years) is

coinciding with high tide (return period 50 years). It was accepted that because fluvial and coastal flooding would be combined, it would be acceptable to lower the return period in both.

- Adaptation (1 in 200 year coastal event). Coastal flooding affects the region more than pluvial flooding and is crucial for the assessment of mitigation measures. Consequently an extremely rare event of coastal flooding has been added and examined.

Climate change scenarios

- Present. This scenario refers to the present climatic conditions and related rainfall for the above designated return periods, with the sea-level as it is today.
- 20 years horizon. This scenario refers to the future climatic conditions and sea-level in 20 years' time.
- 50 years horizon. This scenario refers to the future climatic conditions and sea-level in 50 years' time.
- 100 years horizon. This scenario refers to the future climatic conditions and sea-level in 100 years' time.

3.2. Simulation and modelling

For each of the three geographical locations considered, a high resolution 1 m grid was applied to simulate flooding scenarios that include coastal, pluvial and combined conditions for the current and future climate change situations of 20, 50 and 100 year ahead. The procedure involves various and different types of input data, as shown in Fig. 6.

The UK Environment Agency's (EA) Light Detection and Ranging (LiDAR) digital terrain model (DTM) data were used as the ground elevations for modelling. The LiDAR DTM was filtered from the digital surface model (DSM) (Priestnall et al., 2000) using algorithms that removed surface features to build the so-called bare earth terrain. The following computational issues have been resolved and implemented in the computations:

1. *Background cleaning*: The process removed superfluous features of the data, which are temporary and therefore should not be modelled, such as vehicles, people, animals or trees. It also removed structures within terrain data which are critical to flow movements, e.g. buildings and curbs, and can even leave large indentation where buildings should be present.

2. *Blockages to the flow due to buildings*. In order to simulate the effects of building blockages on flow paths, while also allowing the flow to penetrate into buildings through doors and windows, the DSM data were pre-processed, following the EA's approach for surface water mapping (EA, 2013), using the building and road layouts from the Ordnance Survey's Mastermap. All grid cells covered or touched by the road polygons were lowered by 0.125 m from their existing terrain level to account for the true elevation of roads, while buildings were treated differently to produce a level surface for each buildings polygon. The highest elevation within each building polygon was identified and all cells within or touched by the polygon were raised to this level plus a threshold of 0.15 m. This was designed to simulate the door step level of the building, after which flow will be able to enter the cells that represent buildings. However, without further parameter settings this would neglect the influences of buildings' external and internal walls, and contents on flow propagation. To take into account these effects, flow into and within buildings should be limited. Hence, CADDIES 2D was further amended to allows for the roughness, infiltration (water loss to the surface), and rain to be tailored for each cell, or groups of cells. In this case, the desired effect of increased building blockage was achieved by increasing the Manning's roughness from 0.015 to 0.1 to slow down the flow within buildings areas.

Table 2
Scenarios taken into account for Torbay

| Cause/scenario	Impact driver	Response
Coastal flooding Scenario 1: Overtopping of sea wall due to storm surge combined with spring tide	Water depth and extent, duration of event (i.e. duration of tide event)	Pumping of sea water, evacuation, temporary flood defences (e.g. sandbags), flood warnings, Instigate major incident plan.
Coastal flooding Scenario 2: Breaching of sea wall due to storm surge combined with spring tide	Water depth and extent, velocity of incoming water, duration (i.e. duration of event until repairing)	Pumping of sea water, evacuation, temporary defences
Combined flooding. Scenario 3: Pluvial/fluvial flooding	Water depth and extent, runoff, duration of event (I.e. duration of storm-runoff). Combined Sewer Overflow (CSO) restricted discharge to coastal waters.	Pumping of mixed water (sea water, waste water), evacuation, temporary flood defences (e.g. sandbags), Flood warnings
Combined flooding. Scenario 4: Pluvial/fluvial flooding combined with coastal flooding as in Scenario 1	Water depth and extent, runoff, duration of event (I.e. duration of storm-runoff). Combined Sewer Overflow (CSO) restricted discharge to coastal waters.	Pumping of mixed water (sea water, waste water, muddy water) Debris to remove, evacuation, controlled flooding areas (detention areas), temporary flood defences (e.g. sandbags) Flood warnings
Coastal flooding Adaptation Scenario 5: Overtopping of sea wall due to storm surge combined with spring tide at Paignton and Preston with adaptation measures in place	Water depth and extent, duration of event (i.e. duration of tide event)	Pumping of sea water, Evacuation, temporary flood defences (e.g. sandbags), Flood warnings, Instigate major incident plan.
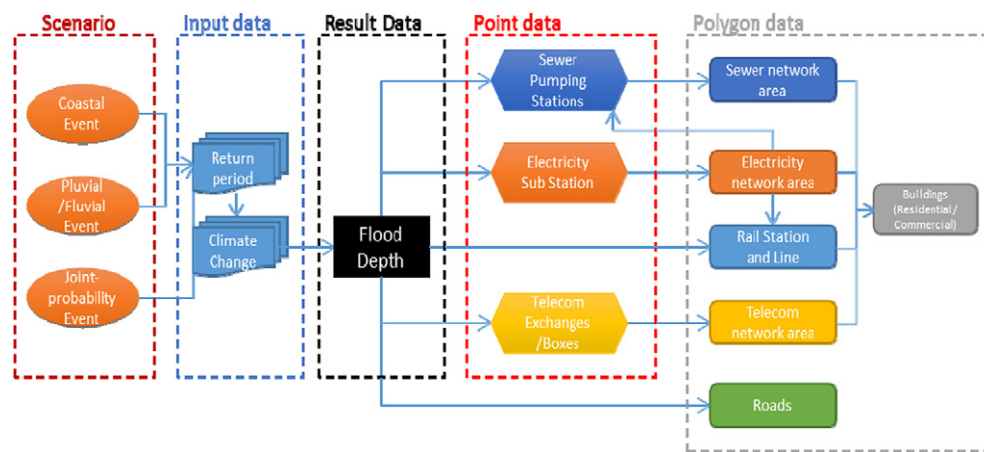
Fig. 6. Types of data and procedure for assessing flood impact on CIs applied to Torbay.

3. *Infiltration rates*. To account for the capacity of sewer systems removing water from the urban surfaces and the ability of green areas to absorb water, infiltrations rates were set for these areas. Although most of the sewer pipes in Torbay were designed to cope with 1 in 30 year return period pluvial event, the current inlets and gullies along the roads do not provide equivalent capacity, so that the road drainage is reduced to 1 in 5 year return period event. Additionally a rainfall reduction of 12 mm/h was applied to cells in green areas to account for the soil infiltration of natural surfaces (initially 12 mm/h), whereas infiltration rates for Roads were set at 19 mm/h and for buildings at 28 mm/h. However, it should be pointed out that this modelling strategy of rainfall reduction directly from precipitation may distort the pluvial/fluvial flood results, in case stormwater that flows into the sewer network overflows on lower downstream areas.

4. *Terrain assumptions*: Two different sizes of the modelling domain were used in the analysis. Firstly a smaller domain was created, limited to just the coastal flood extent, by delineating the areas lower than 30 m, allowing enough buffers for coastal floods to propagate. For the pluvial and combine cases, a larger area is required to simulate the collection of runoff from the local catchment. This was done through terrain analysis to obtain the catchment boundaries.

5. *Assumptions for flood events*: The overtopping rates follow the 12-hour tidal cycle with a total duration of 4 days (96 h). The pluvial flooding analysis adopted a design rainfall (spatial-uniformly distributed across the terrain) for the first hour of these simulations, while a further 3 h of simulation time is used to allow the flow to propagate through the catchment. The rainfall values for events with different return periods were obtained from the Flood Estimation Handbook (CEH, 2013) for each location. These rates were scaled up based on the EA's guidance (EA, 2016) to account for future climate change scenarios, 10% for 20 years, 20% for 50 years, and 40% for 100 years of climate change.

6. *Combination of coastal and pluvial/fluvial flooding*: Considering the chance that both extreme pluvial and overtopping conditions occurring at the same time is low, the combination of moderate pluvial and overtopping conditions were modelled as a plausible situation. A 1 h design rainfall with 1 in 50 year return period was aligned with the largest peak of the inflow for 1 in 50 year overtopping event at the 36th hour of the simulation. The scenario was applied to analyse the climate change impact for a 50 year projection, as well as to investigate the effectiveness of a possible adaption scenario with an extra sea defence being built.

7. *Cascading effects*: To assess the cascading effect of flood impact to CIs, we have adopted the framework described in Section 2, with the use of the CIRP platform, taking into account not only the direct flood damage costs based on flood hazards (e.g. water depth) (Sušnik et al., 2015), but also the cascaded costs from damage to other types of CI and to properties in the area (Vamvakeridou-Lyroudia et al., 2018). For example, if flood damages CI assets such as electrical substations, other properties that are not directly affected by the flooding may still lose power due to the failure of substations. Therefore, CIs such as sewer pumping stations, electricity sub-station, and telecom exchanges will affect a much larger area beyond their locations when they are flooded beyond a certain threshold depth, as detailed in Fig. 3 (Section 2.1). The flood information obtained from CADDIES modelling were overlapped with the building layouts, together with the building use information and the depth damage relationships from the Multi-Coloured-Manual (Penning-Rowsell et al., 2010) to evaluate the direct flood damage of each property. For CIs, the first level of cascading effect was evaluated using the algorithm shown in Fig. 2. The interdependencies among CIs and other properties were further analysed through a looped analysis (Chen et al., 2018). Direct, indirect damages and costs are presented in Fig. 7 (legend up left).

3.3. Flood protection measures and related analysis

As it was mentioned in Section 3.1, Torbay includes three towns: Torquay, Paignton and Brixham (Fig. 6). The analysis was carried out for all three of them. However Paignton (the central area in Fig. 6) is much more prone to flooding than the others. Additionally it is vulnerable to coastal flooding. Consequently, we are showing in detail here only the results from Paignton, because the flooding effects with their cascading impacts are more pronounced. Paignton received a lot of attention by the stakeholders participating to the project. Apart from being the most flood prone area, it was also the area where major future flood protection works were considered by Torbay Council. The holistic risk assessment of these flood protection works was a key point for the active participation of Torbay Council to the project.

In particular they were interested in assessing potential solutions to coastal flooding for Paignton, which is a major threat. A sea wall exists, but still flooding occurs frequently, especially when high tide concurs with storm events. They were considering different options, i.e. raising the existing sea wall higher or building a second sea wall behind the first, so that the area between them would be flooded, but the flood would not expand more inland. The question of the adequate height of these walls was also under consideration. This is where the economic aspects of the assessment came into consideration. Any alternative would cost and the best way to justify the cost and measure the effectiveness of the solution is through a quantitative cost/benefit analysis. Consequently the "benefits" from potential flood protection measures needed to be calculated.
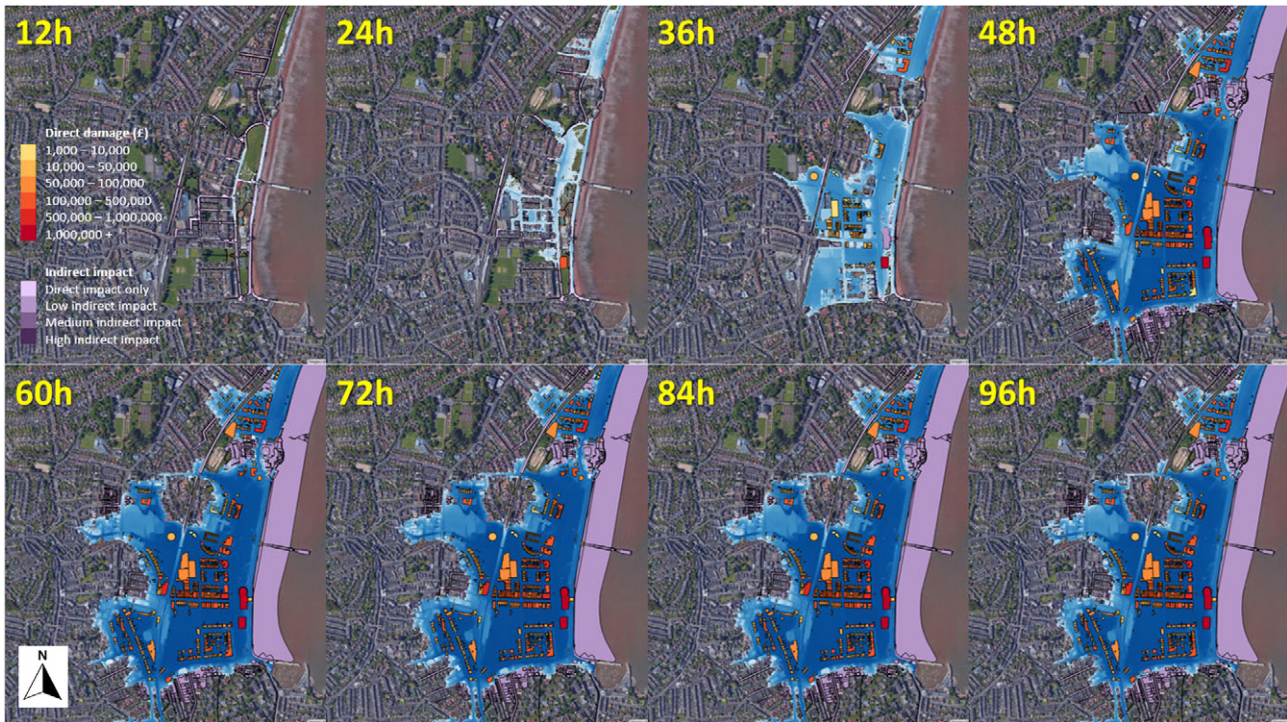
Fig. 7. Coastal overtopping flood propagation in Paignton. The coloured parts in orange and red show the calculated impact (damage) in financial terms.

In order to calculate the benefits from each alternative sea wall solution the following approach has been adopted:

(a) For each climate hazard scenario there have been two simulations: The first simulation was based on the existing situation (i.e., no additional flood protection sea wall), while the second one implemented the additional work under consideration (e.g. a second sea wall or increased height for the existing wall).

(b) For each simulation the inundated area and the related cascading effects have been calculated (damages).

(c) The economic valuation of the damage from each flood scenario was calculated with the help of the stakeholders, by estimating the costs associated with flood depths to the buildings at the flooded area, as well as other secondary effects (i.e. business continuity losses due to transport and energy/telecommunication failure and reparation costs) (Vojinovic, 2017). A function was used in CIRP that linked specific damage curves to costs. The participation of the local stakeholders at this stage was crucial. They provided quantitative data and estimations of financial losses in detail for the region of Torbay, especially for the inundated areas and the areas affected by cascading effects. Full details are given in the related report (EU-CIRCLE, 2018).

(d) The benefits from each potential flood protection works (alternatives) was estimated as the difference between the damages between the two options: No additional works and the specific works examined in each scenario. This was compared to the cost of each solution, leading to the reported Cost/Benefit figures.

Fig. 8. Flood extents of 1 in 100 year return period pluvial event (left) and 1 in 200 year return period overtopping event (centre), and combined 1 in 50 year pluvial and coastal overtopping event (right), each for the 50 years of climate change scenario.

Fig. 9. Flood extents of 1 in 200 year coastal overtopping event with 50 years of climate change: (Left) no sea wall, (Centre) Smallest wall option, (Right) Largest wall option.

(e) For the visualisation of the results, different colourings have been used to inform the end-users in a user-friendly way about the severity of the damages and the impact. A numerical example is shown in Fig. 10 in the next section, as a visualisation sample, where linguistically, the impact to the buildings is characterised as High/Medium/Low, giving also additional information about whether the damage was due to direct or indirect (cascading) effects from flooding.

3.4. Results and discussion

This section shows indicative results from specific simulations and scenarios investigated for Paignton, the most vulnerable area in Torbay. Fig. 7 shows the flooding results from the coastal overtopping event with 50 years horizon for climate change.

Fig. 7 shows the progression of flooding in the area for 96 h from high tide. Large populated areas are under risk, with the majority of buildings at risk at the town centre. The overtopping has a wide spread flood extent along coastal area and following the road network. The flood area is mainly bounded by the railway line and station, however with the increased rail fail and/or overtopping for 50 years of climate change, the railway line and station are completely overwhelmed.

Fig. 8, shows the maximum inundations at the present time for 1 in 100 year pluvial event, 1 in 200 year overtopping event, and 1 in 50 year combined events; demonstrating how Paignton is particularly vulnerable either pluvial or coastal, but is at greatest risk from the combination of both pluvial and simultaneously.

Fig. 9 shows the resulting flood depths for a 1 in 200 year coastal overtopping event, given 50 years of climate change; firstly on the left, without any additional sea defences, then centre showing with smallest planned sea defensive wall, finally on the right with the largest sea defensive wall. The planned improvements to the sea wall drastically reducing the amount of flow, and clearly protecting Paignton from the majority of flooding.

The affected buildings and the level of damage (impact) are summarized and displayed graphically and with relevant legends, as shown in Fig. 10.

As described in Section 2.4, the flood simulation data and results have also been exported to Google Earth Pro, allowing the stakeholders to understand better and explore in a more user friendly way flood impact and hazards in Torbay, using unlicensed software and an interactive 3D mapping tool, enhanced with the use of the Unity3d Game engine to create a 3D animated visualisation of flood events, as shown in Fig. 11. The flooding scenario in this Fig. 7 (i.e., with 50 year return period).

The expected annual damage (EAD) is a function to summarise the consequences of a range of events and their likelihoods that can be
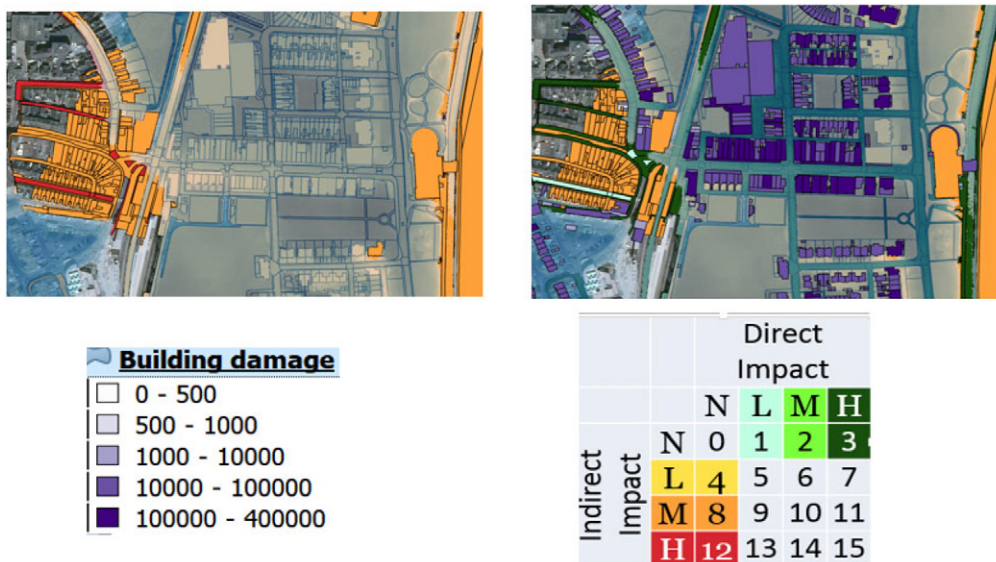

Fig. 10. Identifying all Critical Infrastructure (assets) affected directly or indirectly by flooding in Torbay with characterisation of damage impact and the level of the damage.

Fig. 11. Google Earth Pro visualisation for comparing scenarios without (left) and with (right) flooding for Torbay.

expressed as (Samuels, 2009):

$$E(X) = \int_0^\infty x f(x) dx \qquad (1)$$

where E (x) is the damage, x is a continuous variable that represents flood damage, and f(x) is the continuous probability density function of flood damage. In civil engineering, the annual exceedance probability is often adopted to evaluate the likelihood of events:

$$F_x(x) = \int_x^\infty f_x(u) du \qquad (2)$$

Hence, EAD can be expressed as:

$$EAD = \int_0^1 D(F) dF \qquad (3)$$

where D(F) is the damage as a function of the annual exceedance probability F.

In this study, we simulated multiple flood events with different annual exceedance probabilities and estimated the corresponding damage, which were therefore integrated as the EAD to support decision making.

Fig. 12 lists the cost to different sectors under coastal overtopping event with 50 years of climate change in Paignton, following the procedure explained in Section 3.3. A 1 in 200 year event will lead to over £50 million damage and economic losses caused by CIs failure and their knock-on effect. The most significant part is the damage to residential properties that accounts for £20 million (39% of total losses), while the commercial sector (excluding tourism) will suffer more than £11 million (22%). Hotels and other tourism-related business will have £10.3 million (20%) and £8.5 million (16%) losses, respectively. The sum of tourism sector losses is equivalent to the total losses in residential sector. Based on the results, the Expected Annual Damage (EAD) of
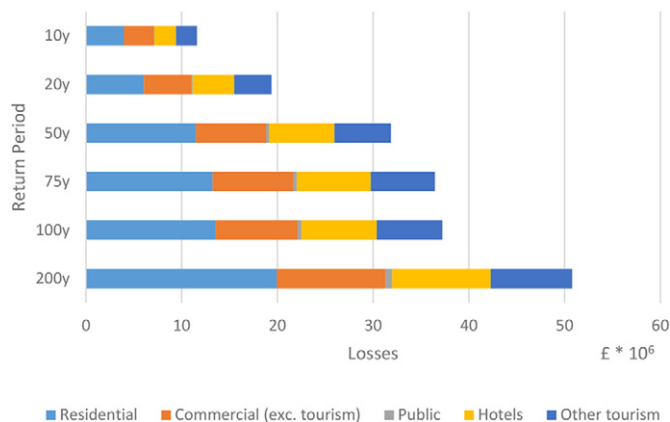

Fig. 12. Damage and economic losses caused coastal overtopping events with different return periods.

coastal overtopping events in Paignton is estimated at £2.95 million. The effectiveness and benefits for different secondary set back sea wall at Paignton and Preston (northern part of Paignton) at the seaward side of the greens were also analysed, as shown in Table 3. The results showed that the secondary flood defence can successfully reduce the flood situation in Paignton, while the south part will still have significant flood risk if there is no adaptation plan. Considering the lifetime of the flood defence as 50 years, the total benefit the CI could contribute is more than £130 million. On top of the economic benefits, the improvement of the safety to the citizens and avoided disruption to the public are also the key profits from the adaptation plan.

The results clearly show the advantages of the second see wall in Paignton (centre) and Preston (northern part of Paignton). These were discussed with the stakeholders. Ultimately the simulations and damage assessment under different scenarios will be used by Torbay Council as the Case for Support for the building of the second sea wall.

4. Conclusions

The work presented in this paper proposes an integrated and participatory methodological approach to assess the risk and enhance the resilience of interconnected CIs to urban flooding under climate change. The Methodological approach and computational background has been presented, i.e., the Resilience Framework, the CADDIES system for flood modelling, the visualisation techniques and the integrating platform CIRP for Risk Assessment. The described methodology has been applied to the Case Study of combined pluvial and coastal flooding in Torbay, South West UK, together with results (flooding and damages) for a selected extreme event being demonstrated. The future scenarios were developed with the participation of local stakeholders and validated through the simulation of an extreme storm event (storm Emma), for which the impact was already known. Enhanced visualisation techniques enabled the stakeholders to understand the flood propagation, while the use of the CIRP risk assessment tool yielded damages and costs for each selected flood scenario.

The Unity3D based visualisation system allows complex 3D meshes representing the flood and the terrain to be rendered an animated in real time with a great degree of precision and lends itself rather well to visual comparison between different flood scenarios. In this work it enabled the stakeholders to better understand the flood propagation and its impact. By extension, this work will facilitate the development of Serious Games and Decision Support Systems in future studies.

CIRP provided a modelling environment for what-if scenarios with the selection of model chains, climate data, and CI inventories in order to calculate damages and assess the resulting risk. The CIRP platform, as designed, provided a user friendly environment to enable the intuitive design and analysis of modelling scenarios created for any combination of climate hazard and CI assets. In this way, users were able to understand the impact of various adaptation strategies or to quantify the potential impact of a catastrophic events. The application has successfully tested the integration of EU-CIRCLE tools in the CIRP platform.

The participatory approach also allowed EU-CIRCLE partners to better understand the main concerns of stakeholders regarding CI resilience to

Table 3
Benefit-cost analyses for the secondary flood defence options in Paignton.

Secondary flood defence height (m)		EAD ($\pounds*10^6$)[a]	Total Benefit ($\pounds*10^6$)	Total Cost NPV ($\pounds*10^6$)	Benefit/cost ratio
Paignton	Preston				
1.6	2.1	0.342	130.33	3.38	38.5
1.4	1.8	0.342	130.26	3.18	41
1.2	1.6	0.343	130.23	3.04	42.9
1.05	1	0.350	129.85	2.74	47.5

[a] Baseline EAD $\pounds$ $2.95*10^6$.

climate change and tailored the research outcome to address those key questions. The stakeholders proposed scenarios for critical flood hazards (Table 2) and asked specific questions, detailed in Section 3.1. The methodological approach and research outcomes followed have been able to give specific and quantitative answers to these questions.

The methodology and results were demonstrated and validated via the engagement workshops that triggered more discussions among the involved parties. The research also showed the needs for further scientific research (e.g. the physical damage to underground infrastructure caused by erosion during flooding), which was not taken into account in the impact analysis carried out in this project. This shows the need for further research in the subject, so as to include more complex secondary impacts from flooding.

At the end of the dissemination workshop a question and answer session was held where stakeholders and other partners were invited to provide feedback and discuss the Case Study in Torbay, the methodological approach, the participation procedure and the usefulnesss of the results. The consensus of opinion was that the team had successfully demonstrated the tools that have been developed as part of the EU-CIRCLE Project (EU-CIRCLE, 2018). The stakeholders were impressed with the visualisation and CIRP tools that were presented and made available for further demonstration during the comfort breaks. The outcomes have attracted other local stakeholders, who participated at the workshop, who would like to implement EU-CIRCLE approach to other coastal protection planning in the Southwest England and in other locations.

In conclusion, the research carried out in this paper demonstrates (a) the complexity of holistic risk assessment from flooding in urban areas, with the cascading effects involved; (b) the need for local knowledge and active participation of local stakeholders for the design of the critical flood scenarios, the setting up of the assets and damage curves and the validation of the results; and (c) the usefulness of advanced computational tools (CIRP, CADDIES), combined with powerful and user-friendly visualisation, for understanding, interpreting and using the research outcomes for practical (real life) decision making.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

CRediT author statement

Lydia S. Vamvakeridou-Lyroudia: Conceptualisation, methodology, project administration, writing original draft, writing review and editing; **Albert S. Chen**: Methodology, software, formal analysis, investigation, writing original draft, data curation, visualisation; **Mehdi Khoury**: software, investigation, visualisation, writing original draft; **Mike J. Gibson**: Software, investigation, writing original draft; **Antonis Kostaridis**: Software, investigation, writing original draft; **Dave Stewart**: Validation, investigation, resources, writing original draft; **Mike Wood**: Validation, investigation, resources, writing original draft; **Slobodan Djordjevic**: Supervision, writing review and editing, funding acquisition; **Dragan Savic**: Supervision, writing review and editing, funding acquisition.

References

Akagi, M., 2017. [QGIS Plugin] Qgis2threejs Plugin Exports Terrain Data, Map Canvas Image and Vector Data to your Web Browser.

Alderman, K., Turner, L.R., Tong, S., 2012. Floods and human health: a systematic review. Environ. Int. 47, 37–47. https://doi.org/10.1016/j.envint.2012.06.003.

Andreoni, V., Miola, A., European Commission, Joint Research Centre, Institute for Environment and Sustainability, 2014. Climate Vulnerability of the Supply-Chain: Literature and Methodological Review. Publications Office, Luxembourg.

Apel, H., Thieken, A.H., Merz, B., Blöschl, G., 2006. A probabilistic Modelling system for assessing flood risks. Nat. Hazards 38, 79–100. https://doi.org/10.1007/s11069-005-8603-7.

Araya-Muñoz, D., Metzger, M.J., Stuart, N., Wilson, A.M.W., Carvajal, D., 2017. A spatial fuzzy logic approach to urban multi-hazard impact assessment in Concepción, Chile. Sci. Total Environ. 576, 508–519. https://doi.org/10.1016/j.scitotenv.2016.10.077.

Boin, A., McConnell, A., 2007. Preparing for critical infrastructure breakdowns: the limits of crisis management and the need for resilience. J. Conting. Crisis Manag. 15, 50–59.

Bouchon, S., 2006. The Vulnerability of Interdependent Critical Infrastructures Systems: Epistemological and Conceptual State-of-the Art, EUR-Report.

CEH, 2013. Flood Estimation Handbook (Wallingford, UK).

Chen, A.S., Hammond, M.J., Djordjević, S., Butler, D., Khan, D.M., Veerbeek, W., 2016. From hazard to impact: flood damage assessment tools for mega cities. Nat. Hazards 82, 857–890. https://doi.org/10.1007/s11069-016-2223-2.

Chen, A.S., Khoury, M., Vamvakeridou-Lyroudia, L., Stewart, D., Wood, M., Savic, D.A., Djordjevic, S., 2018. 3D visualisation tool for improving the resilience to urban and coastal flooding in Torbay, UK. Procedia Eng. 212, 809–815. https://doi.org/10.1016/j.proeng.2018.01.104.

Dawson, R.J., 2015. Handling interdependencies in climate change risk assessment. Climate 3, 1079–1096.

EA, 2013. Updated Flood Map for Surface Water - National Scale Surface Water Flood Mapping Methodology (No. Final Report Version 1.0). Environment Agency, Bristol, UK.

EA, 2016. Flood risk assessments: climate change allowances - detailed guidance - GOV. UK. [WWW Document]. URL. https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances.

Engle, N.L., de Bremond, A., Malone, E.L., 2014. Towards a resilience indicator framework for making climate-change adaptation decisions. Mitig. Adapt. Strateg. Glob. Chang. 19, 1295–1312.

ERGO, 2018. . Available from. http://ergo.ncsa.illinois.edu/?page_id=356, Accessed date: 10 January 2018.

EU-CIRCLE, 2018. Deliverable 6.7-evaluation report. http://www.eu-circle.eu/wp-content/uploads/2018/10/D6.7.pdf.

Galbusera, L., Giannopoulos, G., Ward, D., 2014. Developing Stress Tests to Improve the Resilience of Critical Infrastructures: A Feasibility Analysis (JRC91129, EUR 26971 EN).

Guidolin, M., Chen, A.S., Ghimire, B., Keedwell, E.C., Djordjević, S., Savić, D.A., 2016. A weighted cellular automata 2D inundation model for rapid flood analysis. Environ. Model. Softw. 84, 378–394. https://doi.org/10.1016/j.envsoft.2016.07.008.

Hall, J.W., Dawson, R.J., Sayers, P.B., Rosu, C., Chatterton, J.B., Deakin, R., 2003. A methodology for national-scale flood risk assessment. Proc. Inst. Civ. Eng.-Water Marit. Eng. 156, 235–247.

Hammond, M., Chen, A.S., Batica, J., Butler, D., Djordjević, S., Gourbesville, P., Manojlović, N., Mark, O., Veerbeek, W., 2018. A new flood risk assessment framework for evaluating the effectiveness of policies to improve urban flood resilience. Urban Water J. 15, 427–436. https://doi.org/10.1080/1573062X.2018.1508598.

Haskoning, 2017. Torbay Coastal Defences - Climate Change Adaptation - Quick Wins Study. Haskoning DHV UK Ltd.

Hickel, J., Bharwani, S., Bisaro, A., Carter, T.R., Cull, T., Davis, M., Klein, R.J.T., Lonsdale, K., Rosentrater, L., Vincent, K., PROVIA (Organization), United Nations Environment Programme, 2013. PROVIA Guidance on Assessing Vulnerability, Impacts and Adaptation to Climate Change: Consultation Document.

Hokstad, P., Utne, I.B., Vatn, J. (Eds.), 2012. Risk and Interdependencies in Critical Infrastructures. Springer Series in Reliability Engineering. Springer London, London https://doi.org/10.1007/978-1-4471-4661-2.

IPCC, 2018. Global warming of 1.5°C. Intergovernmental Panel on Climate Change.

Katopodis, T., Sfetsos, A., Varela, V., Karozis, S., Karavokyros, G., Eftychidis, G., Gkotsis, I., Leventakis, G., Hedel, R., Koutiva, I., Makropoulos, C., 2018. EU-CIRCLE Methodological Approach for Assessing the Resilience of the Interconnected Critical Infrastructures of the Virtual City Scenario to Climate Change. ENERGETIKA, pp. 23–31. https://doi.org/10.6001/energetika.v64i1.3725 2018. T. 64. Nr. 1.

Khoury, M., Chen, A.S., Clark, M.J., Vamvakeridou-Lyroudia, L., Stewart, D., Wood, M., Savić, D.A., Djordjević, S., 2018a. A Serious Game to Explore Different Flooding Scenarios and Their Respective Effects on Infrastructures. Presented at the Hydroinformatics 2018, Palermo, Italy.

Khoury, M., Gibson, M.J., Savic, D., Chen, A.S., Vamvakeridou-Lyroudia, L., Langford, H., Wigley, S., 2018b. A serious game designed to explore and understand the complexities of flood mitigation options in urban–rural catchments. Water 10, 1885. https://doi.org/10.3390/w10121885.

Kostaridis, A., Antonopoulos, S., Gkortsilas, D., Troullinos, M., Perlepes, L., Moutzouris, M., Lykou, A., Koutiva, I., Karavokiros, G., Makropoulos, C., Chen, A.S., Vamvakeridou-Lyroudia, L., Gibson, M.J., Diagourtas, D., 2017. CIRP: A multi-Hazard impact assessment software for critical infrastructures. Resilience. Presented at the the 2nd International Workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment, Joint Research Centre, Ispra, Italy https://doi.org/10.2760/556714.

Kreibich, H., Botto, A., Merz, B., Schröter, K., 2016. Probabilistic, Multivariable Flood Loss Modeling on the Mesoscale with BT-FLEMO: Probabilistic Flood Loss Model BT-FLEMO. Risk Anal. https://doi.org/10.1111/risa.12650.

Mark, O., Jørgensen, C., Hammond, M., Khan, D., Tjener, R., Erichsen, A., Helwigh, B., 2018. A new methodology for modelling of health risk from urban flooding exemplified by cholera - case Dhaka, Bangladesh: a new model of health risk from urban flooding. J. Flood Risk Manage. 11, S28–S42. https://doi.org/10.1111/jfr3.12182.

Mazzorana, B., Picco, L., Rainato, R., Iroumé, A., Ruiz-Villanueva, V., Rojas, C., Valdebenito, G., Iribarren-Anacona, P., Melnick, D., 2019. Cascading processes in a changing environment: disturbances on fluvial ecosystems in Chile and implications for hazard and risk management. Sci. Total Environ. 655, 1089–1103. https://doi.org/10.1016/j.scitotenv.2018.11.217.

Penning-Rowsell, E., Viavattene, C., Pardoe, J., Chatterton, J., Parker, D., Morris, J., 2010. The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques. Flood Hazard Research Centre, Middlesex University, London, UK.

Priestnall, G., Jaafar, J., Duncan, A., 2000. Extracting urban features from LiDAR digital surface models. Comput. Environ. Urban. Syst. 24, 65–78.

QGIS Project, 2018. QGIS user guide release 2.18. [WWW Document]. URL http://docs.qgis.org/2.18/en/docs/user_manual/.

Samuels, P., 2009. Language of Risk—Project Definitions. Floodsite Project Report T32-04-01. http://www.floodsite.net/html/partner_area/project_docs/floodsite_language_of_risk_v4_0_p1.pdf, Accessed date: 12 May 2019.

Sfetsos, A., Vamvakeridou-Lyroudia, L., Chen, A., Khoury, M., Savic, D., Djordjevic, S., Eftychidis, G., Leventakis, G., Gkotsis, I., Karavokyros, G., Koutiva, I., Makropoulos, C., 2017. Enhancing the resilience of interconnected critical infrastructures to climate hazards. Proc. CEST2017. Presented at the 15th International Conference on Environmental Science and Technology, Rhodes, Greece https://cest.gnest.org/sites/default/files/presentation_file_list/cest2017_00851_oral_paper.pdf.

Sušnik, J., Strehl, C., Postmes, L.A., Vamvakeridou-Lyroudia, L.S., Mälzer, H.-J., Savić, D.A., Kapelan, Z., 2015. Assessing financial loss due to pluvial flooding and the efficacy of risk-reduction measures in the residential property sector. Water Resour. Manag. https://doi.org/10.1007/s11269-014-0833-6.

UK Cabinet Office, 2018. Sector security and resilience plans 2017: summary - GOV.UK [WWW document]. https://www.gov.uk/government/publications/sector-security-and-resilience-plans-2017-summary, Accessed date: 10 January 2019.

Vamvakeridou-Lyroudia, L.S., Chen, A.S., Khoury, M., Gibson, M.J., Kostaridis, A., Stewart, D., Wood, M., Djordjevic, S., Savic, D.A., 2018. Enhancing the resilience of interconnected critical infrastructures to urban flooding: An integrated approach. Proc. 1st International WDSA/CCWI 2018 Joint Conference, Kingston, Ontario, Canada – July 23–25, 2018 https://ojs.library.queensu.ca/index.php/wdsa-ccw.

Vojinovic, Z., 2017. A Toolkit for Holistic/Multiple Risk and Impact/Damage Assessment at Strategic and Operational Level (No. D3.3) (PEARL project).