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Case study of the cascading effects on critical infrastructure in Torbay coastal/pluvial flooding with climate change and 3D visualisation

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ABSTRACT

Critical infrastructures (CIs) are commonly designed, built and maintained based on rigorous standards in order to withstand the climate and weather-related pressures. However, shifts in climate characteristics may result in increases of the magnitude and frequency of potential risks, or expose specific CI to new or increased risks not previously considered. As vital components of the normal functioning of modern societies, their resilience encompasses the operational elements, their structural integrity and the capacity to maximise business output under climate stressors. In this work, we apply an integrated and participatory methodological approach to assess the risk and enhance the resilience of interconnected CIs to urban flooding under climate change. The proposed methodology has been applied to an extended case study in Torbay to extend previous works, which seeks to protect coastal communities from future events through using the proposed methodology to justify future investment in coastal defences, as a part of the validation of EU-CIRCLE projects developed methodologies.
Key words | cellular-automaton, climate, coastal, critical-infrastructure, hazard, pluvial

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INTRODUCTION

Flood hazards are a major threat to urban systems and societies (Gibson *et al.* 2018). A better understanding of the potential impacts caused by flood hazards under various climate and socioeconomic scenarios is essential to developing resilience strategies for critical infrastructures (CIs) planning, design, operation and management (Boin & McConnell 2007). Various studies have developed different approaches to evaluate flood risks (Hall *et al.* 2003; Apel *et al.* 2006; Chen *et al.* 2016) and/or to quantify resilience for decision supporting to develop climate adaptations (Engle *et al.* 2014; Vojinovic 2017; Hammond *et al.* 2018). Such analyses often consider not only direct tangible impacts but also indirect (e.g. economic losses (Andreoni & Miola 2014; Kreibich *et al.* 2017) and/or intangible consequences (e.g. health; (Alderman *et al.* 2012; Mark *et al.* 2015) of natural climate-related hazards.

In addition, society in the modern age, living in cities requires a number of infrastructures which are critical to continued function of cities and modern society, for example: clean water supply and sewer treatment system, public transportation/road/rail networks, energy generation and transmission networks and telecommunication/ICT networks. With each of these services having become critical to modern society, the increasing interconnectivities among these CIs have formed a more complex system than any individual network. A disruption in one infrastructure has a ripple or cascading effects into other infrastructures. As large-scale systems, whose lifetime

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exceeds the order of decades, infrastructures are heavily exposed to natural disasters, often with devasting consequences to the society, economy and the environment. The increasingly dependent, interdependent and interconnected nature of CIs may expose societies to previously unseen risks, new vulnerabilities and opportunities due to disruption across multiple CI networks. Meanwhile, 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 a relationship conceptually or at an aggregated high level (Araya-Munoz *et al.* 2017), and details regarding where, when and how such a knock-on effect propagates during disasters are still unavailable.

Acknowledging that infrastructure's vulnerabilities and impacts go far beyond physical damage (Hokstad *et al.* 2012), the work presented here is concerned with an assessment of the impacts on the services provided by CI. We considered not only the impacts associated with the repair and/or replacement of services but also included the externalities of the CIs operation, societal costs, environmental effects and economic consequences due to suspended activities. Interdependencies among infrastructures dramatically increase the overall complexity of the 'systems of systems'. There is therefore a need to consider multiple interconnected infrastructures and their interdependencies in a holistic manner (Galbusera *et al.* 2014).

The EU H2020 funded project EU-CIRCLE (a pan-European framework for strengthening CI resilience) developed a holistic framework for identifying 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. For 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.

METHODOLOGY

The EU-CIRCLE methodology is detailed in the literature (Sfetsos *et al.* 2018), but the primary features are also presented here. Shown in Figure 1 is the resilience framework developed in the EU-CIRCLE project and is applied in this work. The generic resilience framework has three main sections which are interconnected and allows for tailoring to the local specific CI, or the area or challenges of interest in the given case study it is applied to. The generic resilience framework consists of three main interacting and interconnected sections (shown in Figure 1):

1. A step-by-step precedure climate risk management framework;
2. An interactive risk and risk modelling framework;
3. Outputs to the end-users.

A key to the implementation of this framework is the interaction of stakeholder and end-users at both the development and tailoring of the framework to the given case and the output required. This framework is very flexible and allows for the inclusion of multiple or different modelling methodologies given the stakeholder and end-users interests in the given target area.

The climate risk management framework begins with establishing relevant climate change resilience policies and decisions which are of interest to stakeholders and end-users in the given area. What policies are in place and what questions are to be answered? These issues may have life spans of many years and may cross many different service providers. Climate data may come from any number of sources, including global climate models at higher and lower resolutions, statistically downscaled climate information and historical data. Given the target area, it is possible to establish which infrastructures are critical and which systems interconnect these, and what the risks to these systems are. Some areas are prone to forest fires, or typhoons/hurricanes, and others as in the case study presented in this paper are susceptible pluvial and coastal

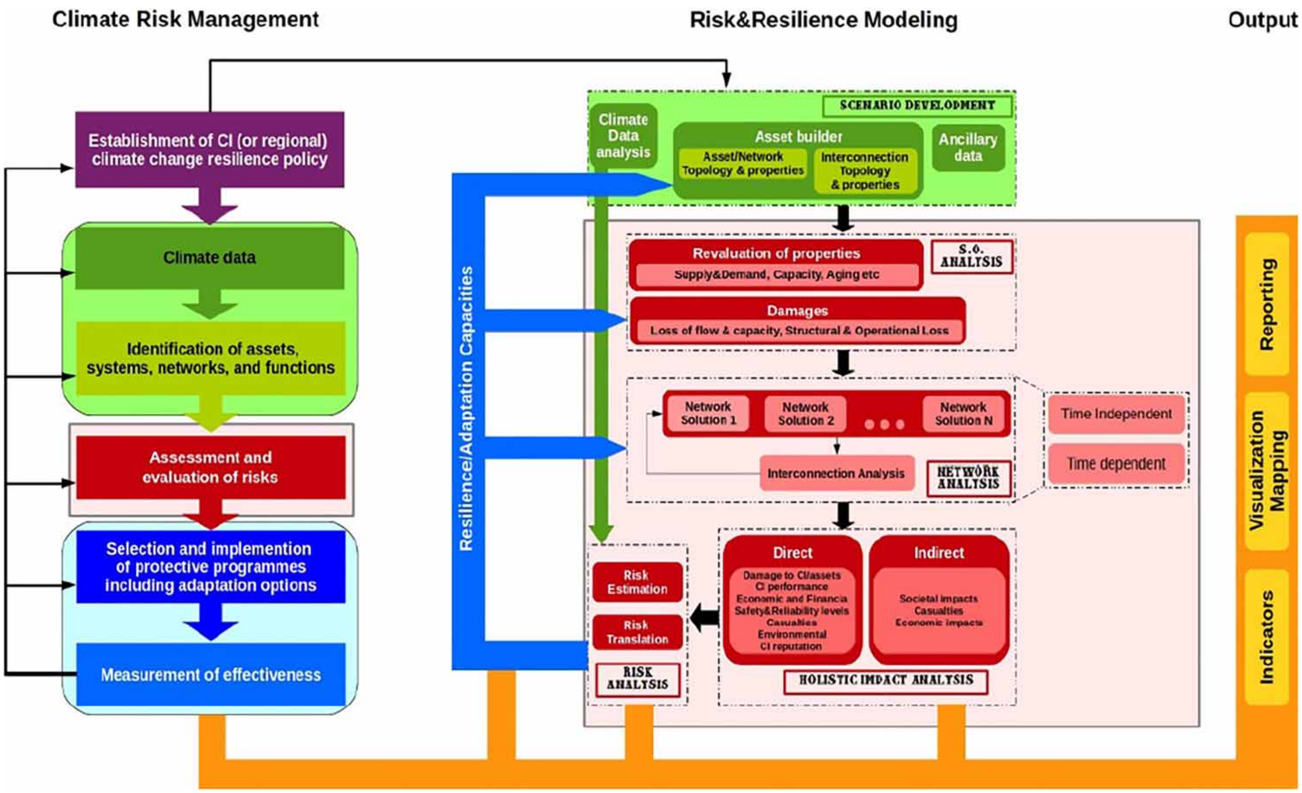

Figure 1 | Generic resilience framework for the CIs for the EU-CIRCLE framework.

flooding. Each area will have different risks stemming from the combination of current risks and how climate change may exacerbate these, for example, increased sea levels or more extreme storms. At this stage, any protective programmes, including adaptation options to be investigated as part of the framework, are established.

The risk and resilience modelling section details the structure of risk modelling and its different components and interactions. A number of scenarios are constructed using the climate data and projections, which are combined with a list of relevant CI and risks established in the climate risk management section. The system overview analysis establishes damage curves for the various different types of CI. With a number of different scenarios, it is important to select an appropriate level of computational modelling such that a large number of scenarios can be modelled in a timely manner. The resulting holistic impact analysis includes direct and indirect impacts to CI, and here the role of stakeholders and end-users is critically important in the validation of the results. Further information on the overall EU-CIRCLE methodology can be found in Sfetsos *et al.* (2017) and Sfetsos *et al.* (2018).

The last section involves the display/visualisation of analysis and result and is connected to all stages, as stakeholder and end-user involvement is so critical. To this end, there is a large focus on using modern computing techniques to fully visualise the results and analysis in order to engage and effectively communicate to stakeholder and end-users. The work in this paper presents a single case study using the EU-CIRCLE methodology.

CASE STUDY SETUP

Torbay case study background

Torbay is a major tourist location on the South Devon coast line (Figure 2), UK, which covers approximately 62 km^2, bordering Teignbridge and the South Hams. Lying between

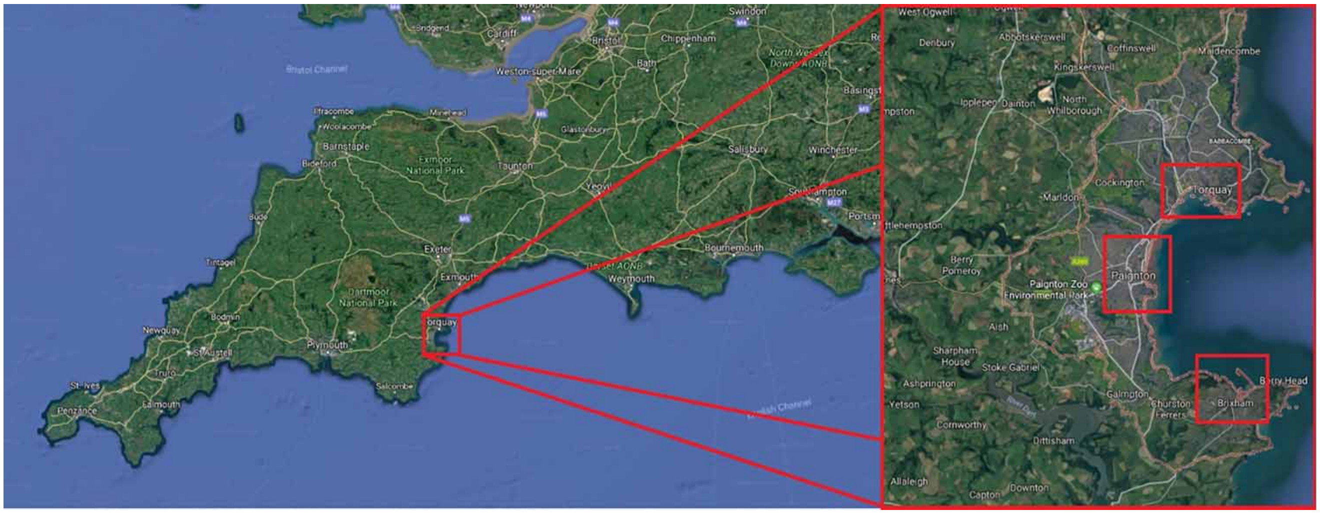

Figure 2 | Location of the case study (left) in the South West of England, Torbay – Torquay, Paignton and Brixham (right).

the major cities of Exeter and Plymouth, Torbay has developed with its major industry being that of tourism, due to its relatively warm climate for the UK and beautiful coast lines, and is known as the English Riviera. Due to the steep hill leading down to the coast, it suffers from frequent pluvial (surface) flooding, but also from extreme storms causing the sea to overtop or breach the coastal defences. There are three large towns of Torquay, Paignton and Brixham which constitute the majority of the catchment area, meaning that the vast majority of the catchment is urban in nature.

There are three target areas in Torbay centred around the three main towns: Torquay, Paignton and Brixham (shown in Figure 2). In order to process comprehensive climate change/adaptation scenarios for each of three target areas in a tractable amount of time for analysis, a fast modelling approach is needed. The CADDIES framework (Guidolin *et al.* 2012, 2016) and associated caFlood(Pro) application provide a fast means for 2D flood modelling and visualisation, which are utilised in the study. The caFlood application is based on the cellular automata system and uses the weighted model (Guidolin *et al.* 2016) to distribute water flows between each cell of the computational grid. This model was validated against a number of UK Environment Agency test cases, a hypothetical test cases and also compared to the industry standard infoworks model on a test case in Torquay (Guidolin *et al.* 2016). At Paignton, a new secondary sea wall has been proposed. 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, Greens
- provide a secondary set back sea wall at Paignton and Preston, Greens at the seaward side
- provide a secondary set back sea wall at Paignton and Preston, Greens at the landward side and
- provide a wave return wall to the existing sea wall at Paignton and Preston, Greens.

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 model this secondary defence have been undertaken, for a range of different wall heights and returns periods, given the climate change projects for the given planning period for the construction of the wall. This allows for a cost-benefit analysis to be performed.

The Torbay area is particularly vulnerable to a number of flooding sources, including highway flooding, main river and ordinary watercourse, surface water run-off and coastal overtopping. This coastal overtopping occurs when large storms push waves up and over the existing sea wall defences, which can then threaten the low-lying coastal town areas. This occurs when high tides coincide with storm surges and easterly winds. During these times, main river, sewer, surface water, highway and watercourse flooding are exacerbated due to the lack of the capacity of the surface water outfalls, which discharge to the sea. These flood events threaten a large number of commercial and residential properties on a regular basis and also affect numerous roads to some extent. A number of roads are closed due to flooding from such storm events, and this can have critical knock-on effects on the road network when large capillary roads are closed, resulting in long traffic diversion and delays.

Terrain data/parameters

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 years ahead. 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 smooth the surface and thus remove such superfluous features as vehicles, people, animals and trees, but also remove more permanent features such as buildings. Buildings however are critical to flow paths, along with the kerb on roads which acts as a primary water transport system during flood events. Therefore, the use of the DTM has the problem of temporary features such as traffic, etc., while the DSM has its own problems of lacking critical permanent features such as buildings. The solution to this problem is to further preprocess the DSM, in combination with the buildings and road layouts from the Ordnance Survey's Mastermap, in accordance with the EA approach to surface water mapping (E.A. UK 2013). Road cells, including those which touch a road polygon, are lowered by 12.5 cm from their existing terrain levels, which leaves their slopes intact. However for buildings, it would be expected that there would be a uniform level across each building, i.e. assuming all buildings have flat roofs. Whereas apart from the terrain smoothing, buildings built on the steep slopes tend to take on these characteristics. Therefore, the cells within each building polygon are set to the same uniform level, based on that of the highest elevation plus a 15 cm threshold, which is designed to simulate the doorstep level of the building. After the doorstep level, water is allowed to enter the building polygon, but in order to account for the structural walls and content effects on flow within buildings, further parametrisation is required. To account for the reduced flow into, out of and inside of buildings, the caFloodPro application allows for Manning's roughness factor to set for individual or groups of cells. In this case, Manning's roughness is increased from 0.015 to 0.1, which slows down the flow within building areas.

CaFloodPro also allows for an infiltration rate to be set on any particular cell or group thereof, which is utilised to simulate the effects of the sewer system to drain water from the urban surfaces, while also being used to account for the capacity of the green area to absorb water. The infiltration rates used for these areas are shown in Table 1. Torbay's sewer systems are designed to cope with up to a 1 in 30-year return period pluvial event; however, it is thought due to blockages of vegetable matter, gullies and inlets along roads do not provide the equivalent capacity. Therefore, road drainage is reduced to the equivalent of a 1 in 5-year return period event, as well as a rainfall reduction of 12 mm/h to green areas, which is in line with the EA procedure.

A smaller domain was utilised when modelling the coastal events, as these events only affect the low lying area next to the coastal line, by delineating the areas which are lower than 30 m above sea level. Whereas pluvial events are largely affected by the area upon which they fall, especially when designed storms are utilised where rain falls the same amount everywhere in the given area. Therefore, a terrain analysis is used to determine the area which is capable of contributing to towns flooding.

Table 1 | Infiltration/water loss rates per surface type

Area type	Infiltration (mm/h)
Green (any other)	12 + (rainfall reduction of 12 mm/h for pluvial cases)
Roads tracks and paths	19
Buildings	28

Overtopping conditions

The AMAZON model (Hu 2000; H.U. Ltd 2017) was used to produce the overtopping rates at the defensive sea wall, which was then fed into the CADDIES model as a 2D flood input. The AMAZON model simulates random waves travelling as bores, given the tide levels and storm inputs. Climate change scenarios of the present, 20, 50 and 100 years at a 1 in 200-year return period storm were modelled in AMAZON and then used to assess the 2D flooding in CADDIES. Given that there is a 12-h tide cycle, the highest tides affect the rate at which the waves overtop the sea defences, and this can be seen in the inflows to caddies, as shown in Figure 3.

Pluvial conditions

A designed rainfall was utilised for pluvial events, which uses a spatially uniform distribution across the terrain. A 60-min duration of rainfall is simulated, and in order to allow time after the last rain has fallen for the surface flood to flow, a further 3 h of simulation time is used. The rainfall values for events with different return periods were obtained from the Flood Estimation Handbook (C. f. E. & Hydrology 2013) for the three towns. These rates were scaled up based on the EA's guidance (UK Environment Agency 2016) to account for future climate change scenarios, 10% for 20 years, 20% for 50 years and 40% for 100 years of climate change.

Combined pluvial and overtopping conditions

There is a reasonably low chance of either the extreme pluvial or overtopping conditions to occur independently, and while there is obviously some casual connections in that a storm may create the conditions for both cases, it is still considered to be less likely that the conditions for both exist at exactly the same time. Therefore, a more likely pluvial and coastal set of storms are modelled together, using a 1 in 50-year design rainfall for 1 h which was aligned with the peak of a 1 in 50-year coastal event, at the 36th hour of the simulation.

Critical infrastructure

Shown in Figures 4 and 5 are the footprints and locations, respectively, of CI in the Paignton area used in this case study. For CI which has the coverage of other properties (electrical substation, ambulance stations and pumping

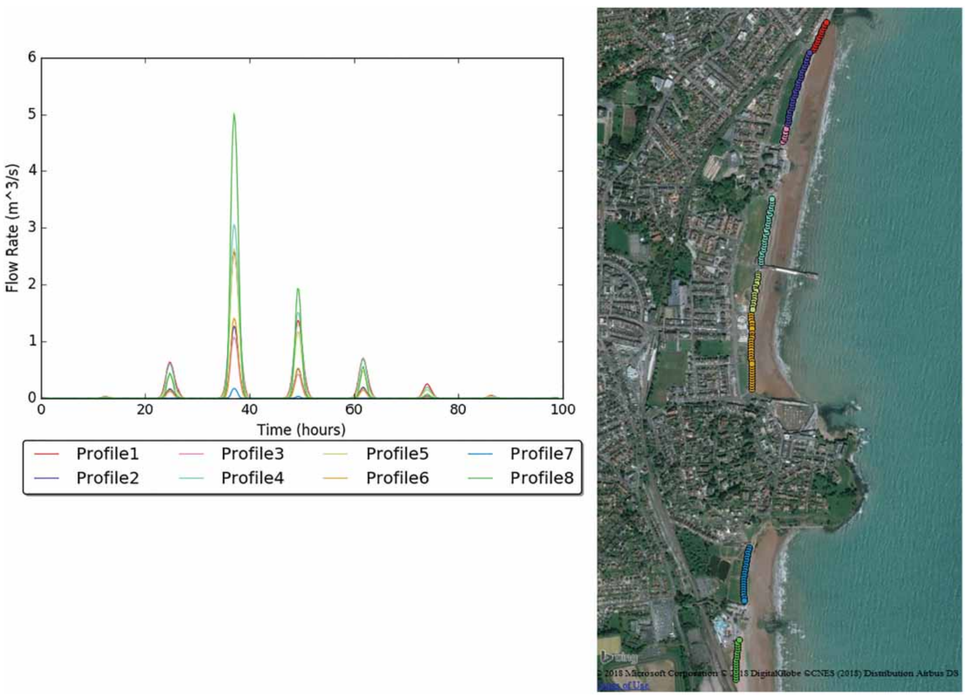

Figure 3 | Discharge profiles for a 1 in 200-year overtopping event (left) for various coastal sections for Paignton (right).

Figure 4 | Shows the footprints of CI in the Paignton area, where the road and rail networks are clearly visible.

stations), Thiessen polygons are used to establish which areas are covered. Shown in Figure 6 are the depth–damage curves utilised to calculate the direct damage, and a rate from the Multi-Coloured-Manual (Penning-Rowsell *et al.* 2005) is used to establish additional damages from the cascading effects of CIs.

RESULTS

Paignton

Figure 7 shows a 1 in 200-year coastal overtopping event (right) and a 1 in 100-year pluvial event (left) for current climate conditions. Figure 7 shows the difference between the coastal risks and pluvial risks to Paignton, both of which affect large areas of the residential area, and the coastal floods particularly affecting Paignton's tourism industry like hotels, cafes, bars and shops which are located near the coast. While obviously coastal flooding is limited to a local area of the coast, depths and damages are more severe. Whereas the pluvial flooding is mainly restricted to the road network and steep valleys of the terrain, it is clearly more widespread than the coastal event. Figure 8 shows a 1 in 100-year pluvial (left) and a 1 in 200-year coastal (right), with 50 years of climate change, where risk is only set to increase. Whereas in Figure 7, the coastal events are largely bound by the rail line, given the 50 years climate change projection, both the line and rail station are completely overwhelmed.

Paignton's coastal flooding represents the largest risk discovered in this case study and can be clearly seen when contrasted to Brixham (Figure 10) and Torquay (Figure 11). An adaptation plan has been proposed to build additional sea defences to mitigate this risk.

Shown in Figure 9 are 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 right showing the largest defensive sea wall. The planned improvements to the sea wall drastically reduce the amount of flow and clearly protect the large

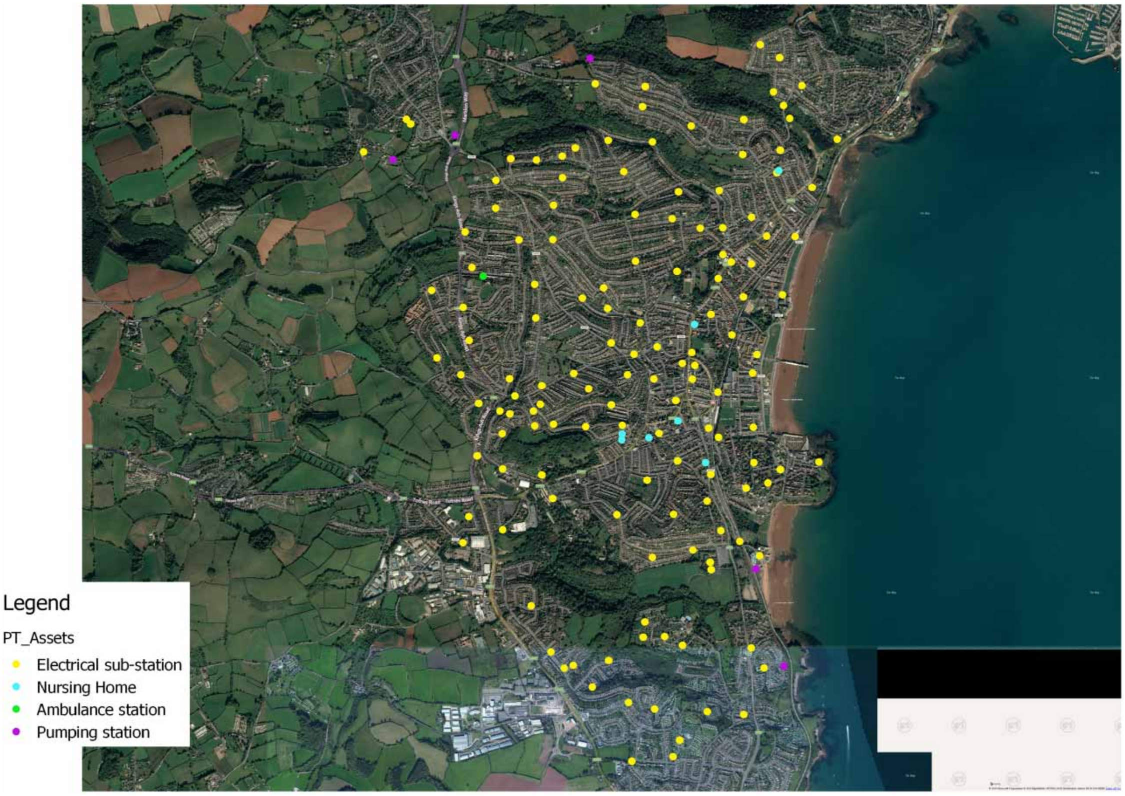

Figure 5 | Shows the locations of small footprint CI in the Paignton area, including electrical substations, nursing homes, ambulance stations and pumping stations.

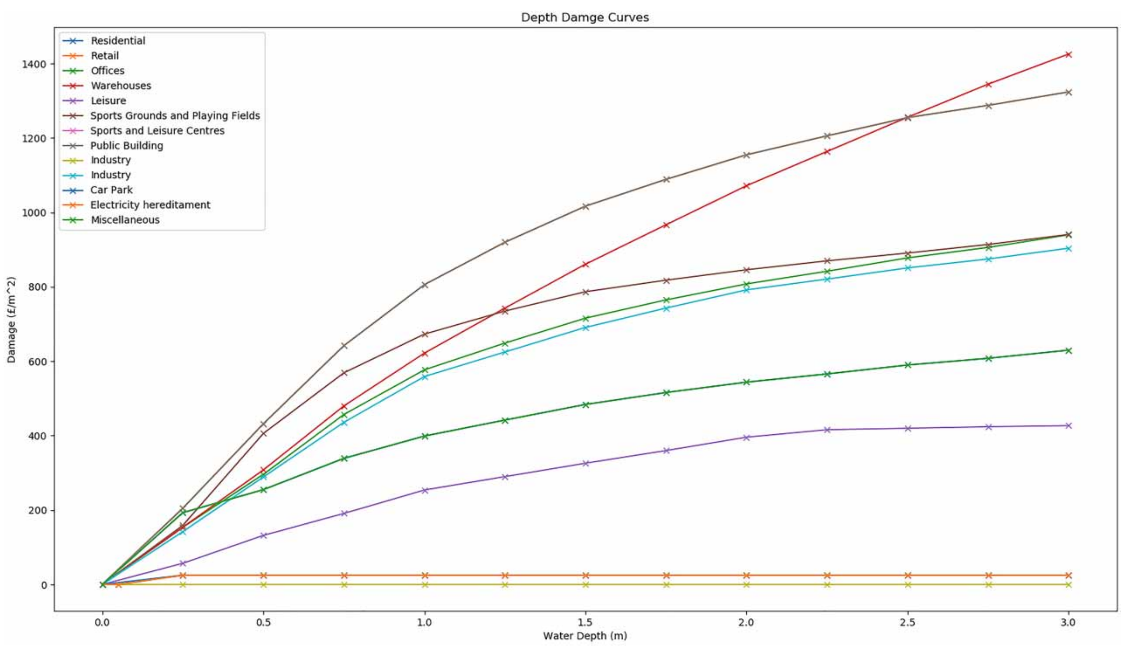

Figure 6 | Shows the depth–damage curves used in this case study for direct damages.

Figure 7 | Flood extents of a 1 in 100-year return period pluvial event (left) and a 1 in 200-year return period overtopping event (right) for the present scenario.

Figure 8 | Flood extents of a 1 in 100-year return period pluvial event (left) and a 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.

northern area of Paignton from the majority of flooding. However, this does leave a sizable risk of flooding and damage to the critical rail wall line and station.

Brixham

Figure 10 shows Brixham's pluvial 1 in 100-year case on the left and a 1 in 200-year coastal case on the right. Figure 11 shows Torquay's pluvial 1 in 100-year case on the left and the 1 in 200-year coastal case on the right. Unlike the Paignton case (shown in Figures 7–9), Brixham (Figure 10) and Torquay (Figure 11) are at a greater risk of pluvial flooding compared to the coastal, and this is due to the steep terrain in these areas and relatively the low lying area in Paignton which faces directly out into the bay.

Figure 9 | Flood extents of a 1 in 200-year coastal overtopping event with 50 years climate change: (left) no sea wall, (right) sea wall option.

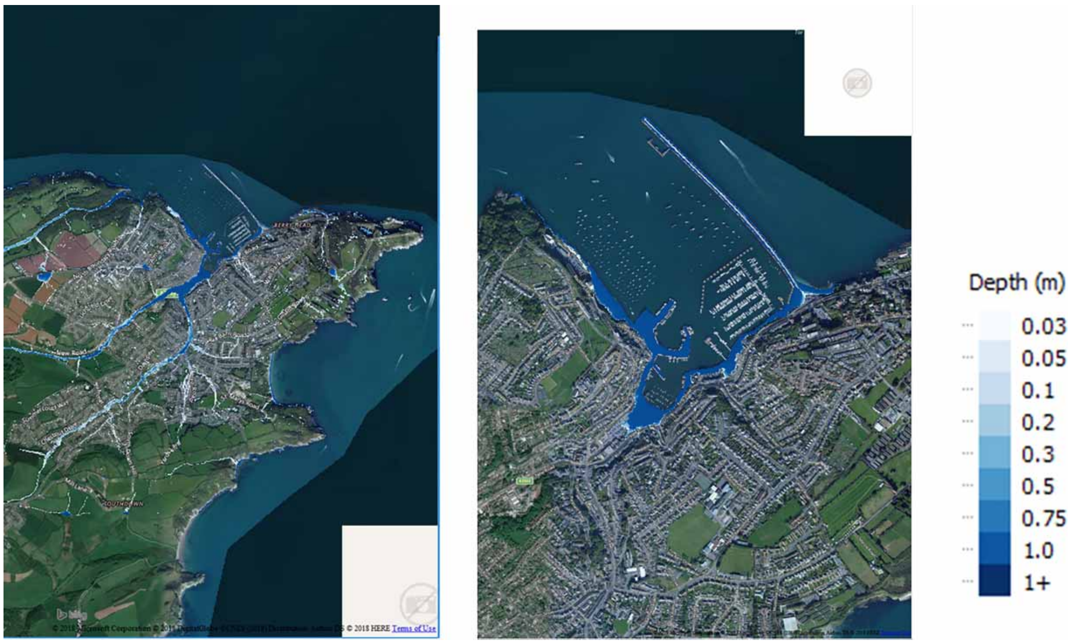

Figure 10 | Flood extents of a 1 in 100-year return period pluvial event (left) and a 1 in 200-year return period overtopping event (right) for the present scenario for the Brixham area.

ANALYSIS

Cascading effects of flooding upon CIs have been assessed using the EU-CIRCLE framework (Sfetsos *et al.* 2017; Chen *et al.* 2018) in the study. The EU-CIRCLE project considers not only the direct flood damage costs based on flood hazards (e.g. depth) but also the cascaded damage to other types of CI and to properties in the area. For example, if flood damages CI assets such as electrical substations or telecommunication, 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 substation and telecom exchanges, will affect a much larger area beyond their locations when they are flooded beyond a certain threshold depth. A single property may be affected by not only the flood but the failure of other CIs which are affected by the flood.

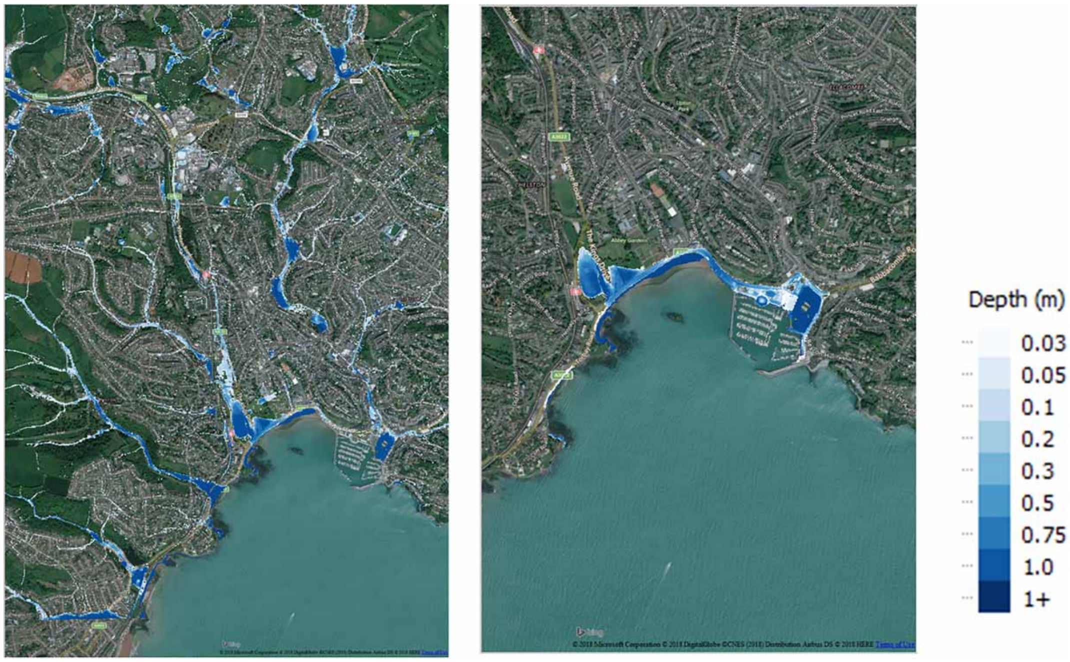

Figure 11 | Flood extents of a 1 in 100-year return period pluvial event (left) and a 1 in 200-year return period overtopping event (right) for the present scenario for the Torquay area.

The resulting flood depths obtained from CADDIES modelling were overlapped with the building layouts, and together with the building use information and the depth–damage relationships from the Multi-Coloured-Manual (Penning-Rowsell *et al.* 2005), these are used to evaluate the direct flood damage of each property.

For CIs, the first level of the cascading effect was evaluated using the algorithm shown in Figure 12. The interdependencies among CIs and other properties were further analysed such that the cascading effects can be assessed using the EU-CIRCLE framework through a looped analysis (Chen *et al.* 2018).

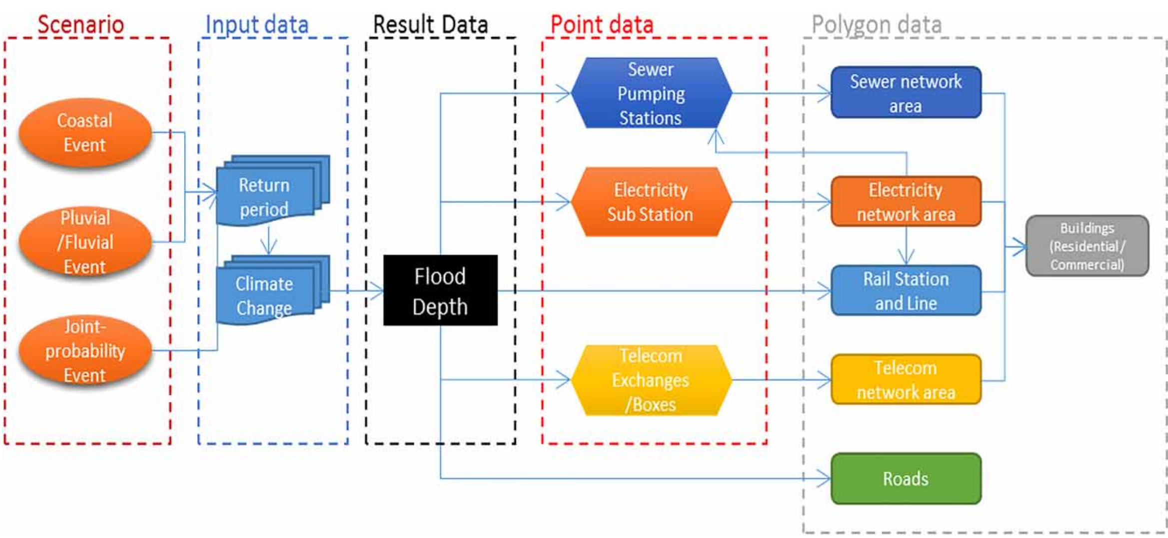

Figure 12 | EU-CIRCLE methodology for assessing flood impact on CIs.

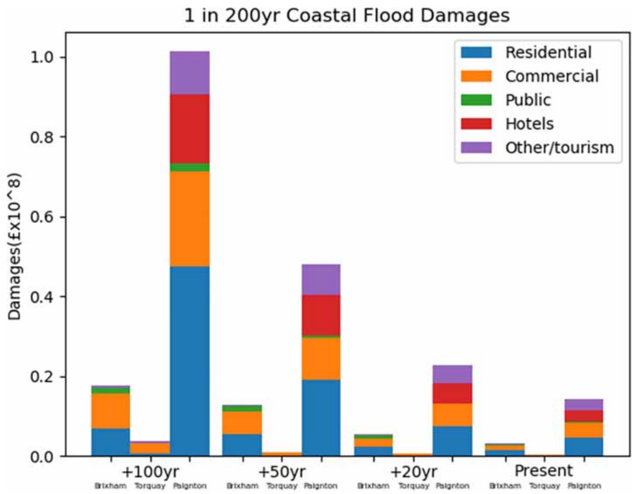

Figure 13 | Calculated flood damages at Brixham, Torquay and Paignton, for a 1 in 200-year coastal flood, for the present, 20, 50 and 100 years climate change conditions.

Figure 13 shows the calculated damages for each sector for the Brixham, Torquay and Paignton areas comparatively when using a 1 in 200-year coastal flood, for the present, 20, 50 and 100 years of climate change. Clearly, Paignton is most at risk from coastal flooding, and this presents an especially high risk to the tourism and hotel industries in the area compared to Brixham and Torquay.

Figure 14 shows the calculated damage for a 1 in 100-year pluvial flood scenario, using the present condition with 2013 data, and 20, 50, and 100 years of climate change, for the three areas Brixham, Torquay and Paignton.

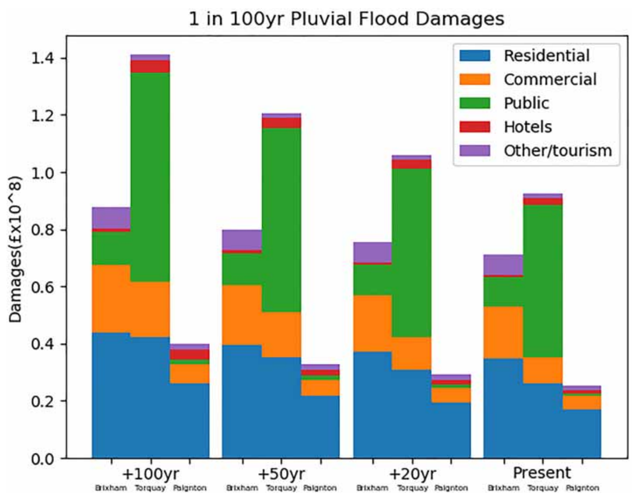

Figure 14 | Calculated flood damage for Brixham, Torquay and Paignton, for a 1 in 100 year pluvial flood, for the present, 20, 50, and 100 years of climate change conditions.

The results in Figure 14 are in stark contrast to Figure 13, showing that Torquay is at greatest risk of damage from pluvial flooding, and that Paignton is the least at risk from pluvial flood damage. The highest overall damage comes from the pluvial cases, due to the steep terrain of the area which limits coastal flooding and exacerbates pluvial cases. Furthermore, Torquay and Brixham have storage tanks to help alleviate this, which was not modelled. The next biggest risk is that of Paignton, which further justifies the work on the additional sea defences. However, this is assuming that a design rainfall occurs, that is rain falls equally for the temporal duration and spatial extent, which as discussed earlier is the maximum size of the catchment. Real-world storms have more variable spatiotemporal distributions which would lead to different spatial distribution of risks. While this work highlights all the areas at risk from pluvial flooding in this fashion, it is likely to overestimate the overall risk.

VISUALISATION

Visualisation of the resulting water depth and damages with realistic, descriptive and accurate mapping is a key to stakeholder engagement with such projects as the EU-CIRCLE framework and requires the collaboration of computer science and hydrological disciplines that form the core of the hydroinformatics discipline. Stakeholders need to be able to see the scale/breadth and be able to easily locate/relate these to real-world locations that can only be provided by a 3D realistic mapping solution. Stakeholders then need to be able to focus on the accurate details of locations of interest of heavy damage, as well as visualising the dynamics of the flood and damages both direct and indirect, in quicker than real time. This is not a trivial challenge, and the EU-circle framework includes methodologies to achieve this high visualisation and is detailed in the following section. Two main software, Google Earth Pro and the Unity3D game engine, are utilised.

Google Earth Pro

To demonstrate the modelling results in a more user-friendly way that improves risk communication, we exported the

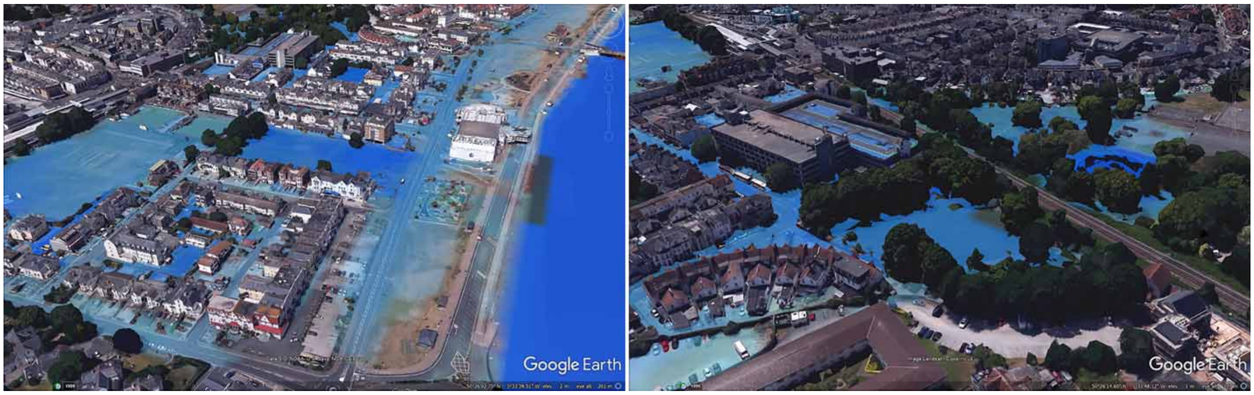

Figure 15 | Google Earth Pro visualisation coastal flood (left) and pluvial flood (right) flooding.

flood depth data to Google Earth Pro, allowing stakeholders to explore the study area using the interactive 3D mapping tool. The advantage of such a system (other than being freely available) is that the cloud-based map archive of Google is extensive and includes extruded structures and trees, although this brings the equal disadvantage of containing no permanent features such as cars. Furthermore, the difference between the specific terrain data used in the simulation and online archive can cause erroneous water depths. The application clearly presents the relationship between flood hazards and buildings, as shown in Figure 15, such that stakeholders can intuitively visualise and better understand the threats of flood hazards.

However, the current application can only display static flood information (i.e. maximum flood depth) that 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 advanced visualisation tool has been further developed using the Unity3D Game engine to create a 3D animated visualisation of flood events (Khoury *et al.* 2018).

Using the Unity3D game engine

Unity3D has by default no optimised way to visualise the change in the 3D shape of the flood over a terrain. As such, the Unity3D default terrain object has several resulting shortcomings:

1. The degree of precision used to render the terrain heightmap is insufficient as it cannot render a mesh with subtle differences in height. Presently, the terrain engine only takes 16 bits raw images as input, which limit the precision to 2^{16} or 65,536 unique values. Assuming the terrain height range was set to 2,000 m, the setting would provide an approximate resolution of 3.05 cm (2,000 m/65,536) which is too coarse as a 3 cm difference in the water level is not negligible.
2. The default terrain is unable to display consistently overlapping meshes at different altitude levels as shown in Figure 16. As soon as the user 'zooms out', high detail meshes are substituted with simplified one automatically via a forced optimisation process that is suitable for ordinary games, but not for visualising flood.
3. Finally, the default process by which detailed terrain and flood meshes are animated is too slow to allow real-time changes, especially on machines with a less powerful GPU. In the next section, we describe how our system addresses these shortcomings and then show added functionalities regarding the visualisation of a narrative framework as well as the impact of flood on CIs failure.

Visualisation of 3D animated floods

The 3D rendering engine has been modified to allow the terrain/flood height to be rendered with a higher degree of precision. The height data are provided by standard images in the .png format where each pixel's red, green, blue and alpha values encode in 32 bits the height of the terrain. From a practical point of view, these floating-point data of height are rescaled into large integer numbers, between 0 and 2 (Svensson & Jones 2005) (i.e. allowing the system to

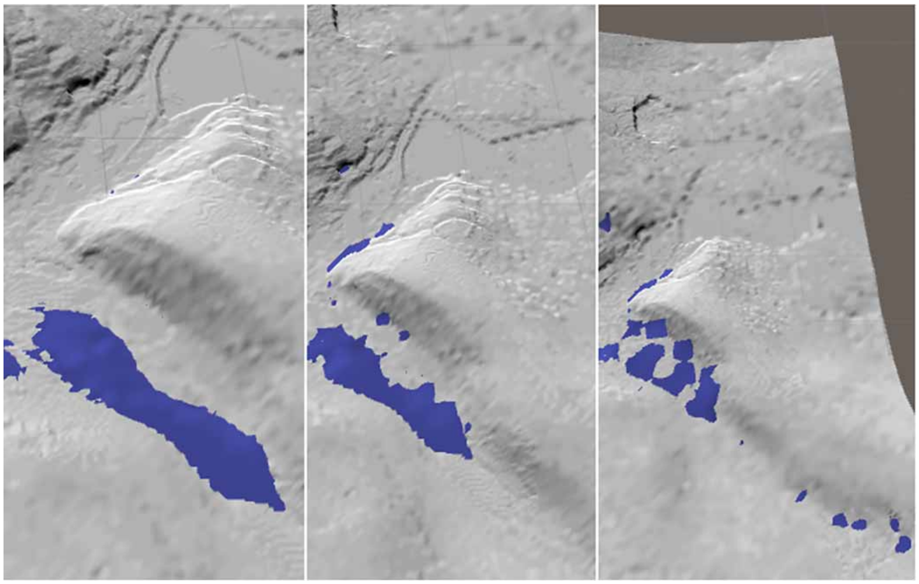

Figure 16 | By default, the further away the observer is from the terrain, the more the Unity3D terrain object does deform meshes by substituting highly detailed meshes with simplified ones.

display the tiniest difference in the height to the sub mm level). Furthermore, by using .png rather than a Unity3D default .raw file format, more compact images are produced that can easily be sent through the internet. Although so far the data are stored locally with the game, whole sequences of images could potentially then be sent from a 'game' server hosting many test cases to provide multiple animation steps through a flood sequence.

Terrain and flood surfaces can now be deformed in real time using advanced Shaders (Lammers 2013) effects exploiting graphic cards computational capabilities. Shaders – programmes implemented in the OpenGL Shading Language to display vertices and visual fragment using the accelerated computational power of the graphic card – are implemented to output in quicker than real time a 3D geometric linear interpolation of the flood 'heightmap' between the starting and the end state by looking at the 'counter' input. Flood animation is implemented by providing as input two images and a 'counter' float number between 0 and 1, expressing how far the animation is from the end stage.

The Shaders are not only engineered to deform 3D meshes efficiently but also change the flood mesh colour gradient from clear blue to dark blue with increasing flood depth (Figure 17). This works seamlessly even on fairly modest machines or small laptops, animating meshes with more than 1,440,000 triangles in real time with ease, as long as they have a DirectX 11 compatible graphic card.

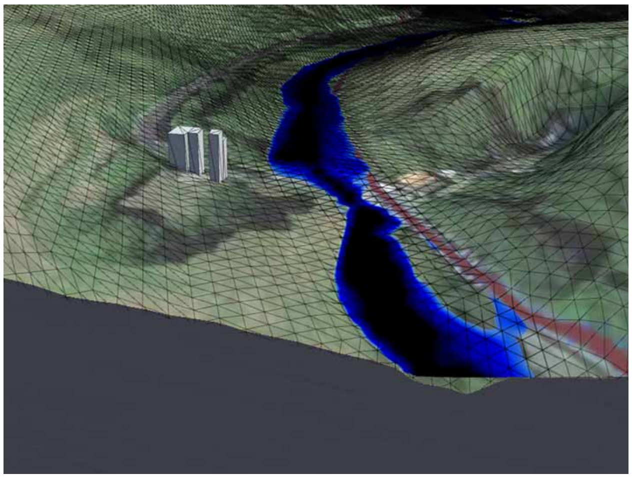

Figure 17 | Zoomed in view of the Shaders built to render in real time an animated 3D flood mesh on top of the terrain and change its colour depending on the water depth. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2019.032.

Visualising consequences of flooding on CIs

All objects such as, for example, 3D buildings can be easily changed in an interactive manner (shown in Figure 18). The

Figure 18 | Substation failures and dependent power outage areas. In yellow are the areas with small risk of the power failure and small water depth. In red are the areas with high risk of the power failure and high water depth. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2019.032.

green/yellow/red buildings indicate the locations of substations. The green ones represent the substations having less than 0.05 m water depth in the nearby area such that they are not affected by flooding. The yellow ones have the flood depth between 0.05 and 0.3 m that there is a small chance of power supply service disruption, and the areas receiving the service from those stations are shaded in yellow as well. The red buildings are the ones with 0.3–1.0 m flood depth that the substations are likely to be damaged and fail to provide service to their servicing areas shades in red. Details of the methodology are described in the related publication (Chen *et al.* 2018). The system allows for direct damage to be displayed on each building and also the area affected by cascade damage to be highlighted (shown in Figure 18).

CONCLUSIONS

In the paper, we presented an extended case study utilising the EU-CIRCLE methodology, so as to understand better how future climate regimes might affect the normal operation of interconnected CI in urban areas and how to assess the effectiveness of adaptation measures. The methodology was applied to analyse the flood impacts to Torbay due to pluvial, coastal overtopping events and their combinations under the present and future climate scenarios. Both the direct flood damage and the cascading effects due to CI failures were evaluated using flood hazards information, building characteristics, depth–damage relationship and the interdependencies among CIs and properties. By combining computational modelling with advanced 3D visualisation techniques, we also developed an effective tool for communicating with stakeholders during the decision-making process. The application can help local stakeholders and operators in the co-design of the approach, the assessment and the evaluation of adaptation measures.

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