IDENTIFYING THE EXPECTED IMPACTS OF CREDO

A report prepared for the Centre for Digital Built Britain

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frontier economics

EXECUTIVE SUMMARY

The Centre of Digital Built Britain (CDBB) at the University of Cambridge has worked with a number of partners, including three asset operators – Anglian Water Services, BT and UK Power Networks – to develop the Climate Resilience Demonstrator CReDo. CReDo is a climate change adaptation digital twin project aimed at improving resilience across infrastructure networks. CReDo also contributes to the development of and shows how the Information Management Framework (IMF) approach can enable data sharing across connected digital twins in a scalable way.

FLOODS ARE LIKELY TO HAVE A SEVERE IMPACT ON THE INTERCONNECTED SYSTEM OF UTILITY ASSETS

Electricity, water and telecoms assets are owned and operated separately, but they form an interconnected system. This means that the failure of one asset, for example in the event of a flood, can cause assets of other operators to fail. For example, electricity substations provide power to water and wastewater pumping stations and telephone exchanges; cooling water systems can be used to remove waste heat from telephone exchanges; and telephone lines are installed at electricity substations where a mobile telephone signal cannot be received.

Flooding can cause failures to utility assets, which can propagate through the system. This results in costs to asset operators as well as service interruptions and associated costs for customers. For example, the Environment Agency estimated that the total economic damage of the winter floods of 2015 and 2016 to asset operators (electricity and water) and their customers was more than £100m.[1] Because of climate change, the likelihood of these potentially damaging floods is expected to increase over the next century.

CREDO CAN HELP ADDRESS A KEY INFORMATION BARRIER PREVENTING INVESTMENT IN SYSTEM RESILIENCE

Asset operators invest in their assets to ensure that they are resilient to climate change, including floods. Asset operators understand their own networks and, when deciding whether and how to invest in resilience, they take account of a number of factors. These include how critical each asset is for their networks and the financial resources they have available for resilience investment.

It is unlikely that asset operators have complete information on 1) the resilience of other operators' assets on which their assets depend or 2) how critical their assets are for other operators. For these reasons, investment decisions may not be as cost effective across the system as they could be. For example, an asset operator may decide not to invest in a specific asset because it is not critical for its network, not knowing that it may be critical for another asset operator's network. It may also decide to increase the resilience of one of the assets which is critical for its network, not knowing that the other asset operators' assets on which its assets depend are already resilient. Hence, there is an information barrier that prevents asset operators from assessing the resilience of the whole system and making investment decisions accordingly.

The combination of a system-wide view of infrastructure resilience provided by CReDo and improved information management is expected to lower the information barrier. Frontier Economics was commissioned by CDBB to identify the expected impacts of CReDo and provide a simulation of the subset of potential social benefits related to flood resilience.

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[1] EA (Jan 2018), *Estimating the Economic Costs of the 2015 to 2016 Winter Floods.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672087/Estimating_the_economic_costs_of_the_winter_floods_2015_to_2016.pdf .

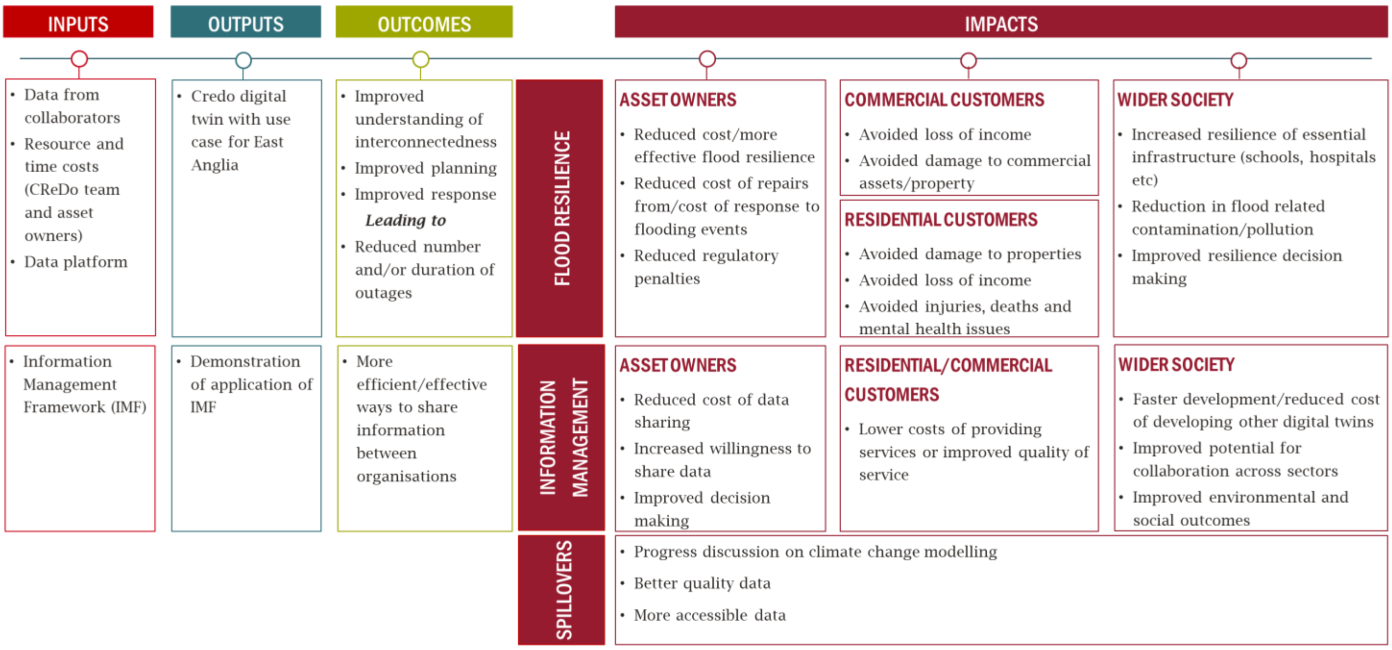
CREDO IS EXPECTED TO BRING A RANGE OF BENEFITS TO ASSET OPERATORS AND THEIR CUSTOMERS

Figure 1 below sets out a logic model for CReDo. It maps out the outputs, outcomes and impacts that we identified and expect to flow from CReDo relative to a counterfactual scenario.

The expected impacts of CReDo include those that relate directly to the current application of CReDo to flood resilience, those that relate to the enabling role of the IMF and the potential spillover impacts that flow from one or both of these. Impact beneficiaries are divided into three broad groups: asset operators, residential and business customers, and wider society.

The comparison relative to a counterfactual enables us to trace which of the impacts from CReDo would not be expected to materialise in its absence. We focussed on understanding how CReDo can enable a system-wide view of infrastructure resilience and improve information management. Therefore, in the counterfactual scenario, we assumed that individual asset operators do not have a tool to enable a system-wide view of infrastructure resilience and do not use a common information management system across sectors. Instead, we assumed that asset operators will (at some point in the future) use digital twins of their own infrastructure to inform resilience activities.

FIGURE 1 A LOGIC MODEL OF CREDO



Source: Frontier Economics

OUR SIMULATION OF POTENTIAL BENEFITS PROVIDES AN INITIAL, BUT PARTIAL VIEW OF THE ORDER OF MAGNITUDE OF BENEFITS LIKELY TO BE ASSOCIATED WITH CREDO

CReDo is an innovative demonstrator project still in the relatively early stages of its development. Given this, it has been necessary to rely on a version of CReDo with synthetic data to simulate potential benefits. This version of CReDo is an abstract from the digital twin. Synthetic asset data has been created by the CReDo project team to protect the confidentiality of the asset data under the terms of the data licence. The synthetic data was created to be representative of the type of assets and connections between assets found in the asset data. This version of CReDo with synthetic data is limited to simulating the impact of a single surface water flood event in a stylised area of East Anglia, assumed to be home to approximately 10,000 people. The level of resilience modelled depends only on the connections between the assets; CReDo does not currently take into account resilience provided by other mitigation strategies, such as on-site or mobile generators, batteries, satellite communication systems. The infrastructure modelled is assumed not to change over the next 30 years.

This version of CReDO provides only a partial view of the potential benefits of CReDo. It is partial in terms of the impact of different types of flooding events in the stylised area, the source of resilience modelled, and in terms of being able to robustly scale the impact in the hypothetical area to other areas of the country. For example, this version of CReDo does not model the impact of other types of flooding event, e.g. coastal or fluvial floods, nor of storm-related factors, such as wind, nor of other types of extreme weather events, such as heatwaves. As a demonstrator project, the role of scaling is particularly important as it is through scale that substantial benefits tend to be unlocked.

These limitations mean that, at this stage, it has not been possible to provide robust estimates of the potential benefits that CReDo can generate. Instead, we present a conservative and partial simulation of the potential benefits associated with scaling the impact of the surface water flood event in this version of CReDo with synthetic data. Data limitations also mean that our simulation is limited to the impact of CReDo on *planning* for resilience (excluding flood response benefits) and is limited to a subset of the benefits identified in our logic model. We focus on the benefits to asset operators and customers associated with improved flood resilience, excluding wider societal benefits, benefits associated with the IMF and any spillovers. For these reasons, our simulation of the potential benefits is likely to underestimate the potential benefits of CReDo for increasing resilience to any type of flooding events across the infrastructure system.

Despite these limitations, our results show that, based on the sensitivity analysis performed, this subset of simulated benefits is worth between £6 and £13 million across East Anglia over 2022-2050, and between £81 and £186 million across the UK over the same period. In our central case, this amounts to a simulated public return on investment (related only to the simulation with synthetic data) of 23:1 over 2022-2050. As mentioned above, these results are not robust estimates of the potential benefits, but a *simulation* of potential benefits. The results are presented as ranges to reflect the significant uncertainty in the estimates. An important dimension of this uncertainty relates to the probability of occurrence of the storm event causing the flood in the version of CReDo with synthetic data in any given year to 2050. The ranges of the benefits reflect different probability of occurrence (increasing from 0.5% in 2022 to 1% in 2050; constant at 1% per year; increasing from 1% in 2022 to 2% in 2050).

TABLE 1 SIMULATION OF EXPECTED SOCIAL BENEFITS – (2022-2050, £M 2022 CONSTANT PRICES)

SCOPE	LOWER SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 0.5% TO 1%)	CENTRAL SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 1% CONSTANT)	UPPER SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 1% TO 2%)
East Anglia	£6m	£8m	£13m
UK	£81m	£117m	£186m

Source: Frontier Economics

Note: The figures in the table represent a weighted average of the simulated benefits for different counterfactual scenarios.

The main body of this report provides details of our simulation, the assumptions that we made, sensitivity analysis, and suggestions on how this methodology could be refined to provide more concrete estimates of benefits as CReDo is refined.

It is significant to note that the grossing up of simulated benefits for East Anglia relies on assumptions, based on evidence wherever possible and conversations with asset operators and the CDBB team elsewhere, about: 1) which parts of East Anglia have assets at risk of floods; 2) which investment decisions asset operators may take; 3) that by the end of 2024, CReDo will enable the prediction of the impact of floods across the whole of East Anglia and will include some refinements which will ensure that its predictions can be used for decision making; and 4) that the regulatory regime will allow asset operators to co-invest in system resilience from 2029. Similar assumptions are used to simulate benefits for the UK. There is a further assumption that, by fulfilling its potential as a demonstrator, asset operators in other parts of the country are incentivised to develop their own regional versions of CReDo. These incentives could be direct from regulators or an indirect reflection of the reputational damage caused by a lack of such investment.

We understand that CReDo could also be developed to consider the impact of other types of climate change related weather events (e.g. heatwaves). The expected impacts of using CReDo to increase resilience to a range of weather events are expected to be larger than the benefits of increasing resilience to surface water floods. Once a more advanced version of CReDo is finalised, we recommend that quantification of the expected impacts of CReDo be undertaken again.

HOW TO USE THE FINDINGS FROM OUR STUDY

This study contributes to the understanding of the potential benefits of CReDo through the development of a logic model and theory of change of CReDo and the simulation of some of the potential benefits. The methodology used in the simulation can be applied to evaluate future versions of CReDo.

The logic model of CReDo identifies the potential benefits of CReDo for both asset operators, their customers, and wider society. This framework can be useful throughout the CReDo decision-making process, for example, supporting decisions about which outputs of CReDo to prioritise to achieve the target benefits.

As noted above, CReDo is a demonstrator project still in the relatively early stages of its development. We did not attempt to evaluate CReDo. Instead, we simulated the impact of some of the potential benefits of CReDo. Our simulation is partial and conservative. As such, the results of our simulation provide a conservative preliminary indication of the order of magnitude of benefits that CReDo could be expected to generate. The methodology underpinning our results can be adapted and refined to form the basis of a more detailed evaluation of a future version of CReDo.

1 INTRODUCTION

The Climate Resilience Demonstrator CReDo is a climate change adaptation digital twin demonstrator project aimed at improving resilience across infrastructure networks. CReDo also contributes to the development of and shows how the Information Management Framework (IMF)[2] approach can enable data sharing across connected digital twins in a scalable way. The first use case of CReDo was developed in less than a year and focusses on surface water flood resilience in a small region of East Anglia.[3]

The first phase of CReDo has been led by the Centre of Digital Built Britain (CDBB) at the University of Cambridge. Three asset operators are collaborating on the project: Anglian Water Services (AWS), BT and UK Power Networks (UKPN). CReDo has been delivered through a collaboration of research centres (the Universities of Cambridge, Edinburgh, Exeter, Newcastle and Warwick along with the Science and Technology Facilities Council and the Joint Centre of Excellence in Environmental Intelligence) working alongside CMCL Innovations, funded by UK Research and Innovation (UKRI) and the Connected Places Catapult.

The box below explains CReDo in CDBB's own words.

WHAT IS CREDO?

CReDo is a pioneering project to develop, for the first time in the United Kingdom, a digital twin across infrastructure networks – providing a practical example of how connected data and greater access to the right information can improve climate adaptation and resilience. CReDo is the pilot project for the National Digital Twin programme, demonstrating how it is possible to connect datasets across organisations and deliver both private and public good.

Enabled by funding from UKRI, the University of Cambridge and Connected Places Catapult, CReDo looks specifically at the impact of extreme weather, in particular flooding, on energy, water and telecoms networks. CReDo brings together asset datasets, flood datasets, asset failure models and a system impact model to provide insights into infrastructure interdependencies and how they would be impacted under future climate change flooding scenarios. The vision is to enable asset operators, regulators and policymakers to collaborate using the CReDo digital twin to make decisions which maximise resilience across the infrastructure system rather than from a single sector point of view.

CReDo's purpose is two-fold, demonstrating:

- *The benefits of using connected digital twins to increase resilience and enable climate change adaptation and mitigation.*
- *How principled information management enables digital twins and datasets to be connected in a scalable way as part of the development of the Information Management Framework (IMF).*

Source: CDBB

[2] See the DT Hub Glossary for a definition. https://digitaltwinhub.co.uk/glossary/imf/

[3] With a population of about 50,000.

1.1 PURPOSE OF THIS REPORT

Frontier Economics was commissioned by CDBB to identify the expected impacts of CReDo and provide a simulation of the subset of potential social benefits related to flood resilience.

This report presents our findings, which are based on information gathered from CDBB, CMCL Innovations, the three asset operators involved in the development of CReDo and publicly available sources.

1.2 STRUCTURE OF THIS REPORT

The remainder of this report is organised as follows:

- In Section 2, we summarise the expected impacts of CReDo that we have presented in the form of a logic model.
- In Section 3, we describe the methodology that we used to develop a simulation of a subset of the expected impacts of CReDo. We focussed on the social benefits related to flood resilience that affect asset operators and their customers.
- In Section 4, we present our simulation of the subset of potential social benefits.
- In Section 5, we recommend how to use the findings from our study, and how our simulation could be refined.

2 EXPECTED IMPACTS OF CREDO

In this section, we summarise the expected impacts of CReDo, presented in the form of a logic model, which is a best-practice tool for identifying causal pathways to impacts. Logic models also help to articulate the necessary and sufficient conditions for outcomes and impacts to be achieved and to highlight potential risks and dependencies.

The remainder of this section is organised as follows:

- In Section 2.1, we present a logic model of CReDo.
- In Section 2.2, we describe each of the expected impacts from CReDo.

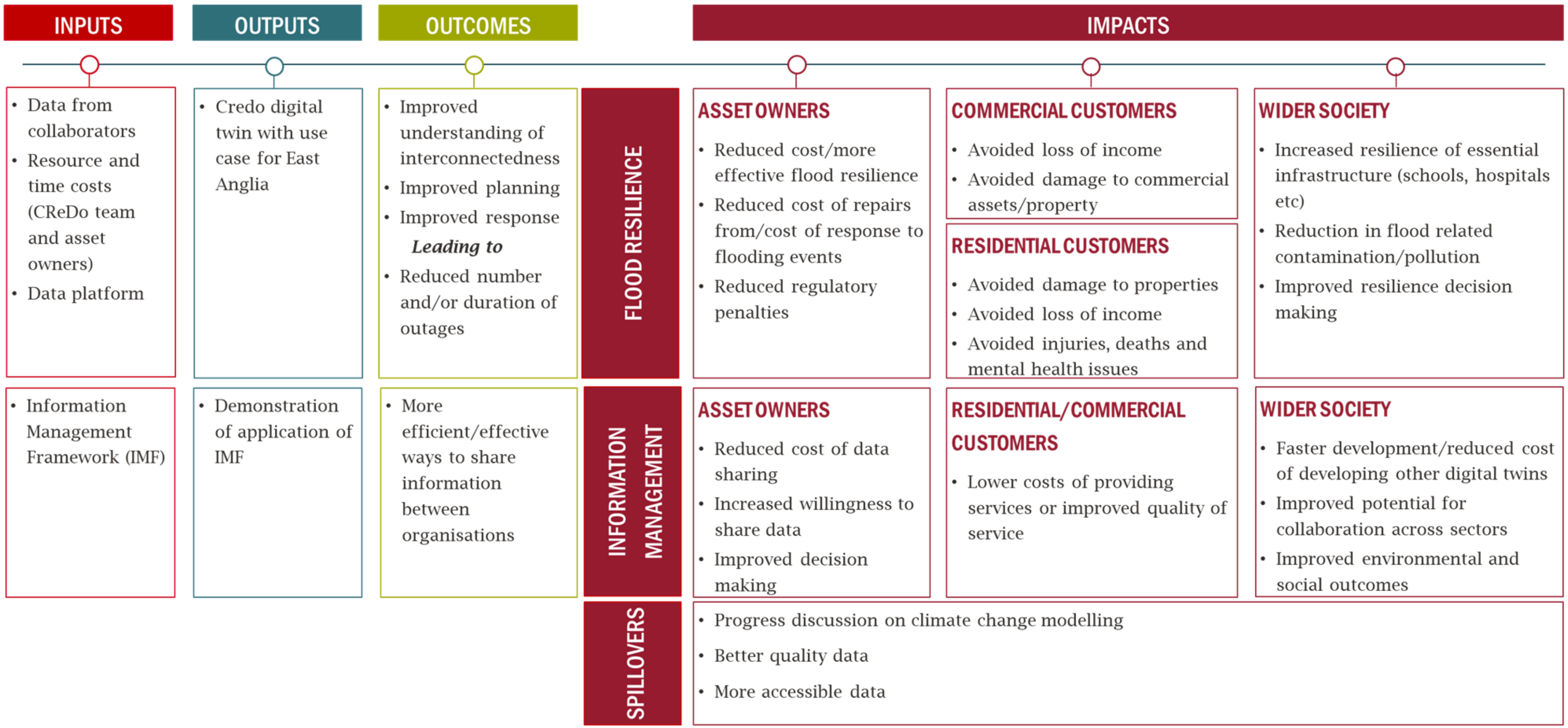
2.1 A LOGIC MODEL OF CREDO

Figure 2 sets out a logic model of CReDo. It maps out the outputs, outcomes and impacts that are expected to flow from CReDo relative to a counterfactual scenario.

The expected impacts of CReDo include those that relate directly to the current application of CReDo to flood resilience, those that relate to the enabling role of the IMF and the potential spillover impacts that flow from one or both of these. Impact beneficiaries are divided into three broad groups, asset operators, residential and business customers, and wider society.

The comparison relative to a counterfactual enables us to trace which of the impacts from CReDo would not be expected to materialise in its absence. We focussed on understanding how CReDo can enable a system-wide view of infrastructure resilience and improve information management. Therefore, in the counterfactual scenario, we assumed that individual asset operators do not have a tool to enable a system-wide view of infrastructure resilience and do not use a common information management system across sectors. Instead, we assumed that asset operators will (at some point in the future) use digital twins of their own infrastructure to inform resilience activities.

FIGURE 2 A LOGIC MODEL OF CREDO



Source: Frontier Economics

2.2 DESCRIPTION OF EXPECTED IMPACTS

In this section, we describe each of the expected impacts we identified. For each impact, we describe the expected theory of change, which is how CReDo is expected to lead to those impacts.

2.2.1 IMPACTS RELATED TO FLOOD RESILIENCE

ASSET OPERATORS

CReDo can provide information to asset operators about which assets will be flooded in a given flood scenario and how failures of these assets propagate through the system made up of the three networks (energy, telecoms and water). In the event of an electricity primary substation losing power, CReDo is able to trace which other infrastructure assets (electricity, telecommunications and water) will consequently lose power.

This is different to what is possible now, where each asset operator focusses on the resilience of its own network without clear visibility of the whole system, i.e. of the links with the networks of the other asset operators. CReDo is expected to enable each asset operator to have a better-informed system view of resilience. By having a system view, asset operators can improve flood resilience by becoming better at:

- **Planning** to improve resilience to flooding events on a system-wide basis, reducing the number of outages that occur across all assets. For example, in any area, asset operators may decide to co-invest in particular asset(s) rather than investing in their individual assets. Asset operators may also be better able to jointly decide where to stock resources that can be deployed in the event of a flood.
- **Responding** to flooding events.[4] CReDo can tell asset operators whether or not assets are likely to fail because of a power outage or because of direct flooding, something that would not currently be visible. This will allow asset operators to respond more efficiently and effectively to flooding events. Similarly, CReDo can inform asset operators of where to deploy response teams to prioritise the restoration of the system.

Improved approaches to planning and responding to flood events facilitated by CReDo are expected to lead to a reduction in the number and/or the duration of outages that occur in the result of a flood event. Consequently, one would expect asset operators to incur:

- Lower overall costs of flood response activities;
- Lower overall costs for repairs required in the event of a flood; and
- Lower incentive revenues and compensation costs.[5]

[4] Response activities can include using sandbags, flood defence assets and mobile generators. While the current version of CReDo uses static data, future versions plan to use live data, meaning that flood response can be even more targeted.

[5] The current regulatory regimes provide financial incentives to asset operators to meet or exceed quality of service targets. In certain circumstances, asset operators compensate customers if service standards are not met (e.g. in the case of service interruptions).

RESIDENTIAL AND BUSINESS CUSTOMERS

In tracing through the impact on residential and business customers, it is important to note that we are concerned only with changes in customer outcomes that arise as a result of network outages from flooding rather than any direct consequences of a flood on an individual consumer. For example, we are concerned with changes in customer outcomes due to power supply interruptions or sewage overflows but we are not concerned with changes due to properties being flooded. CReDo cannot change the likelihood, severity or impact of flooding events, but it can influence what actions are taken to mitigate against the impacts or to respond to the impact of those events on infrastructure availability.

Residential customers affected by an outage (e.g. electricity, water, telecoms) due to a flooding event can experience a range of negative consequences, such as:

- Income losses – if a customer runs their business from home and is no longer able to work or run that business effectively for a period of time;
- Injuries (potentially fatal injuries) – if home-based life support equipment no longer functions or perhaps as a result of trying to put in a place a hazardous temporary fix to an outage;
- Mental health issues – stress or anxiety provoked or exacerbated by an outage or sewage overflow; and
- Damage to properties as a result of outages – for example, sewage overflows caused by failure of sewage pumping stations.

The number or severity of these consequences depends on the number or duration of outages. Business customers affected by an outage will experience similar negative consequences. These can include income losses, for example if the business needs to close to customers or is unable to communicate with them, or if equipment does not function properly such that production lines must shut for a period. Businesses can also experience issues with damage to properties from outages. As for residential consumers, a reduction in the number or duration of outages will result in a reduction in these negative consequences for businesses.

WIDER SOCIETY

Expected impacts on wider society include increased resilience of essential infrastructure, environmental goals and improved resilience decision making. We describe each of these expected impacts in turn.

As well as understanding the connectedness of infrastructure assets, CReDo can, in principle, show the connections between infrastructure assets and critical local services such as hospitals and schools. Better understanding of the reliance of these services on infrastructure assets and, in turn, the reliance of these assets on others means that actions can be taken to better prioritise critical services in resilience planning. For example, based on information provided by CReDo, asset operators could prioritise actions to ensure a specific asset is resilient to flooding because of its direct link to the local hospital.

Understanding what type of assets will fail because of a flood event, and whether they fail as a direct result of flooding or the indirect result of losing power or connectivity, can support wider environmental goals. For example, resilience improvements or responses could prioritise sites at risk of sewage overflows, thus lowering the risk of sewage discharge into rivers.

Coupled with information on the costs of different resilience and response actions and information on the benefits of avoiding certain flood-related consequences, CReDo may, in future, be able to support decision making for regulators and governments. A range of incentives for investment in resilience have already been set but with limited information about the relative costs and benefits. A future version of CReDo which builds in cost and benefit information could be used to inform discussions about the trade-offs between different courses of action, prioritising those that offer better value for money.

If CReDo shows that resilience actions taken by individual asset operators are more expensive than coordinated resilience actions, this could enable conversations about how to create the right regulatory environment. Similarly, by revealing the links between infrastructure assets and critical local services, regulators could also consider whether there is a lower cost or more effective way to ensure the resilience of those services, via coordination.

A future, more comprehensive version of CReDo could include additional factors that influence the flood resilience of infrastructure assets, critical services, and residential and business properties. For example, it could include information on surface water drainage features which would allow CReDo to predict more accurately, in the event of a flood, the likelihood of asset failure or negative consequences for other local stakeholders. This information could indicate whether the water from a storm-based flooding event will flow away or pool and, if so, where.

Such information is currently fragmented across a range of both public and private parties, including local authorities, highway authorities, internal drainage boards, water companies, and private individuals and businesses. Powers and duties to manage drainage features are also often less than clear cut. CReDo could help to emphasise the importance of these features for flood resilience and potentially create incentives for surface water drainage to be improved if it is a far cheaper response to floods than actions taken to improve asset resilience in other ways (e.g. raising the level of the asset). Coupled with this information, CReDo could also be used by developers and local planners to determine the impact of new residential or commercial developments on the flood resilience of the network.

CASE STUDY: ENVIRONMENT AGENCY'S ESTIMATES OF COST OF FLOODS IN THE UK

FLOODS GENERATE A WIDE RANGE OF ECONOMIC COSTS

Floods can generate costs for people and infrastructure. In 2018, the Environment Agency (EA) estimated the costs related to the winter floods of 2015 and 2016.[6] The cost categories considered by the EA included physical damage to residential and commercial property and land, health impacts such as psychological distress and loss of life, disruption to transport, damage to utility networks and the additional burden on emergency services. They also included education days lost, repairs to flood defences and impacts on tourism, heritage and wildlife sites.

Don Lodge, Unsplash

RECENT EXPERIENCES IN THE UK DEMONSTRATE THAT THESE COSTS ARE SIGNIFICANT

The winter floods of 2015 and 2016 were the most severe on record on a national scale, when considering intensity of rainfall. The EA estimated total economic damage for these floods equal to £1.6bn, £107m of which was borne by utility companies (electricity and water) and their customers due to asset failures and supply interruptions. The EA's estimates of previous floods[7] are also significant: £3.9bn for the 2007 summer floods and £1.3bn for the 2013/14 winter floods.

INCREASED FLOOD RISK MAY LEAD TO INCREASED COSTS IN FUTURE

The 2017 Climate Change Risk Assessment (CCRA) estimated that, at the time, 1.8 million people in the UK were living in areas with a greater than 1-in-75 chance of flooding. By the 2050s, this was projected to rise to 2.6m under a scenario where temperature increases by 2°C by 2100 or to 3.3m if temperature increases to 4°C. The CCRA suggested that a sea level rise of 0.5-1m could make 200km of coastal flood defences in England "*highly vulnerable to failure*".[8] The exact level of future costs associated with flooding will depend on a number of factors. However, with the level of risk projected to increase, the potential for high costs also increases.

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[6] EA (Jan 2018), *Estimating the Economic Costs of the 2015 to 2016 Winter Floods.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672087/Estimating_the_economic_costs_of_the_winter_floods_2015_to_2016.pdf .

[7] *Ibid.*

[8] CCRA (2017), *UK Climate Change Risk Assessment 2017: Evidence Report, Chapter 5.* https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Chapter-5-People-and-the-built-environment.pdf .

2.2.2 IMPACTS RELATED TO THE IMF

ASSET OPERATORS

The IMF is being developed as *"a collection of open, technical and non-technical standards, guidance and common resources* [. It] *is intended to enable better information management and information sharing at a national scale and provide the building blocks to be (re) used by those wishing to be part of the NDT* [National Digital Twin]*".*[9] For example, it is intended to ease the process of agreeing on data licences and data sharing agreements between data owners. The sharing of data between asset operators has been found to be a key barrier to the development of system-level digital twins. CReDo is intended to be a demonstration project for the IMF.

By applying the IMF approach, CReDo is anticipated to demonstrate that the IMF can enable more efficient and effective ways to share information within and between organisations. Ensuring that information is clean and interoperable and that there are clear licence conditions and robust security protocols in place can lead to positive impacts for asset operators by:

- Reducing the cost of sharing information within or between asset operators;
- Increasing the willingness to share data within or between asset operators; and
- Improving decision making by enabling more and better information to be used, by enabling the automation of some decisions (reducing the risk of mistakes).

These impacts could lower the operating costs of an asset operator (relative to what might be expected absent this information sharing).[10] There is a range of literature that points to the benefits of increased data sharing on company performance, as summarised in Coyle et al. (2020).[11] For example, Brynjolfsson, Hitt and Kim (2011)[12] found that firms that adopt data-driven innovation have output and productivity that is 5-6% higher than what would be expected given their other investments and information technology usage. Similarly, Nesta (2014)[13] found that firms in the top quartile of online data use are, other things being equal, 13% more productive than those in the bottom quartile.

RESIDENTIAL AND BUSINESS CUSTOMERS

Any reductions in cost may be passed on to residential and business customers. While there is no guarantee that cost reductions will be passed through to customers, regulatory incentives are aligned with this principle over the medium term. This will lead to improved value for money or better service for customers relative to the counterfactual.

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[9] DT Hub Glossary. https://digitaltwinhub.co.uk/glossary/imf/

[10] Cost reductions, quality improvements or revenue increases in this context are relative to a counterfactual where individual asset operators develop their own digital twins and hence the IMF is not required to facilitate information sharing between operators. Absolute costs, for example, could be expected to increase relative to today for a range of reasons including climate change, supply chain issues, population growth, etc. Cost reductions are against this backdrop and not relative to today's costs.

[11] Coyle et al. (2020), *The Value of Data.* https://www.bennettinstitute.cam.ac.uk/publications/value-data-policy-implications/

[12] Brynjolfsson, Hitt and Kim (2011), *Strength in Numbers: How Does Data-Driven Decision making Affect Firm Performance?* https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1819486

[13] Nesta (2014), *The analytical firm: Estimating the effect of data and online analytics on firm performance.* https://media.nesta.org.uk/documents/1405_the_analytical_firm_-_final.pdf

WIDER SOCIETY

As a demonstrator project, CReDo and the IMF, by lowering the cost of sharing data between asset operators, could speed up the development or lower the cost of developing other digital twins. The IMF could also become a tool or framework for sharing data for collaboration purposes across a range of other sectors. Finally, by improving decision making by asset operators, it should be possible for decisions to take greater account of environmental and social implications.

CASE STUDY: OFWAT'S VIEW OF POTENTIAL BENEFITS OF OPEN DATA

OPEN DATA HAS THE POTENTIAL TO PROVIDE BENEFITS WITHIN THE UTILITIES SECTOR

Ofwat's 2021 paper *H2Open – Open data in the water industry: a case for change*[14] outlines Ofwat's initial views of the potential benefits of open data in the water sector. Ofwat identified three main categories of benefits:

- **Innovation:** Stimulating innovation, supporting the development of new business models and services and enhancing the customer experience through these developments;
- **Efficiency:** Improving data quality, providing key information and insights to companies, enabling collaboration and improving decision making; and
- **Transparency:** Improving transparency for customers and company owners, building trust in companies.

THE POTENTIAL BENEFITS HAVE BEEN DEMONSTRATED IN RECENT EXAMPLES

In its paper, Ofwat presents a number of case studies that show the benefits of open data. We summarise two of these case studies below.

NUAR

One example of the potential benefits of open data in the utilities sector is the Geospatial Commission's National Underground Assets Register (NUAR). The NUAR aims to create a map of the existing underground utilities assets (phone cables, gas pipes, water pipes). Making this data open and readily available is intended to reduce the level of accidental damage to existing assets and improve safety for workers and for the public. The estimated total benefit of the NUAR programme is £3.4bn, or £347m[15] per year over ten years.

Data Mill North

Another example is Data Mill North, originally set up by Leeds City Council. This is an online open data platform which draws input from a number of data publishers, including utility firms, government departments, councils and universities. Yorkshire water currently publishes 26 datasets on Data Mill North, including customer meter datasets and leakage data.[16]

[14] Ofwat (October 2021), *H2Open – Open Data in the Water Industry: A Case for Change.* https://www.ofwat.gov.uk/wp-content/uploads/2021/10/H2Open-2.pdf .

[15] Cabinet Office and Geospatial Commission (November 2021), *National Underground Asset Register (NUAR): Economic Case Summary.* https://www.gov.uk/government/publications/national-underground-asset-register-unlocking-value-for-industry-and-the-wider-economy/national-underground-asset-register-nuar-economic-case-summary .

[16] See https://datamillnorth.org/publisher/yorkshire-water .

2.2.3 SPILLOVER EFFECTS

As well as direct benefits from CReDo and the IMF, there are also likely to be spillover benefits that result from the project. For example, by using a range of climate data as inputs to the CReDo model, the CReDo modellers discovered data inconsistencies which they were able to feed back to the data owner, improving the quality of that data. This will have benefits for all users of the data, not just the CReDo team.

Separately, the modelling and forecasting capabilities associated with the CReDo model can be used for discussions with other climate modellers, enabling best practice to be shared and improving conversations on how climate change modelling can be done. This includes supporting the development of other digital twins that can in turn unlock similar benefits to CReDo across other parts of the country.

The CReDo team also plans to make the flood data available and accessible to others for use. There is an emerging literature on the benefits for firm productivity associated with access to data, as noted above. This literature also recognises the role that data can play in tackling wider societal and environmental issues. Open data, such as that provided by CReDo, can support a wide range of decision-making processes including planning flood defences and helping to design sustainable developments.

3 OUR SIMULATION METHODOLOGY

In this section, we summarise the methodology which was developed to provide a simulation of a subset of the potential social benefits of CReDo. Given the data and time available for this engagement, we focussed on the expected impacts for asset operators and their customers of using CReDo to increase the resilience of the system to surface water floods through improved *planning*.[17]

The remainder of this section is organised as follows:

- In Section 3.1, we summarise the aim of our simulation.
- In Section 3.2, we present the version of CReDo that we used for our simulation.
- In Section 3.3, we describe our simulation methodology.
- In Section 3.4, we show how we applied our simulation methodology.

The results of our simulation methodology are shown in Section 4. The assumptions underlying our simulation methodology and details of how we quantified the potential benefits can be found in Annex A. Sensitivity analyses around the cost of increasing resilience and the time horizon for the simulation are presented in Annex B.

3.1 AIM OF OUR SIMULATION

The aim of our simulation is to provide an indication of the order of magnitude of the benefits that CReDo is expected to generate.

CReDo is an innovative demonstrator project still in the relatively early stages of its development. Given this, it has been necessary to rely on a version of CReDo with synthetic data to simulate potential benefits. Figure 3 below shows a visualisation of the version of CReDo with synthetic data. This version of CReDo is an abstract from the digital twin. Synthetic asset data has been created by the CReDo project team to protect the confidentiality of the asset data under the terms of the data licence. The synthetic data was created to be representative of the type of assets and connections between assets found in the asset data. The level of resilience modelled depends only on the connections between the assets; CReDo does not currently take into account resilience provided by other mitigation strategies, such as on-site or mobile generators, batteries, satellite communication systems. The infrastructure modelled is assumed not to change over the next 30 years.[18]

This version of CReDo with synthetic data is limited to simulating the impact of a single surface water flood event in a stylised area of East Anglia, assumed to be home to approximately 10,000 people.[19] As such, it provides only a partial view of the potential benefits of CReDo. For example, this version of CReDo does not model the impact of other types of flooding event, e.g. coastal or fluvial floods, nor of storm-related factors, such as wind, nor of other types of extreme weather events, such as heatwaves. Data limitations also mean that our simulation is limited to the impact of CReDo on *planning* for resilience (excluding flood response

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[17] We did not include in our simulation the expected impacts in *responding* to flood events.

[18] A future version of CReDo could model how the infrastructure networks could change over time.

[19] In our quantification exercise, we scaled down the population of the settlement (about 50,000) for consistency with the network configuration considered in the version of CReDo with synthetic data model, which is assumed to be between three and four times smaller than in reality.

benefits) and is limited to a subset of the benefits identified in our logic model. We focus on the benefits to asset operators and customers associated with improved flood resilience, excluding wider societal benefits, benefits associated with the IMF and any spillovers.

The version of CReDo with synthetic data predicts which assets are likely to be flooded and consequently fail. It also shows how these failures could propagate through the system of interconnected networks. The current version allows approximate predictions of impacts, as not all relevant features that affect asset failures are included in the version of CReDo with synthetic data. For example, the current version does not take account of the impact of mitigation measures that asset operators may have already installed (e.g. on-site generators and batteries that could be used in the case of a power outage).[20]

For the reasons set out above, our simulation is partial and conservative, as not all benefits were included.

There is already a confidential version of CReDo which shows the actual location and type of assets in the region of East Anglia under consideration. We also understand that over the coming years there will be the opportunity for the team working on CReDo to:

- Extend the geographic scope of CReDo;
- Add infrastructures;
- Model the impact of other extreme weather events on the networks; and
- Implement some features to increase the accuracy of the predictions.

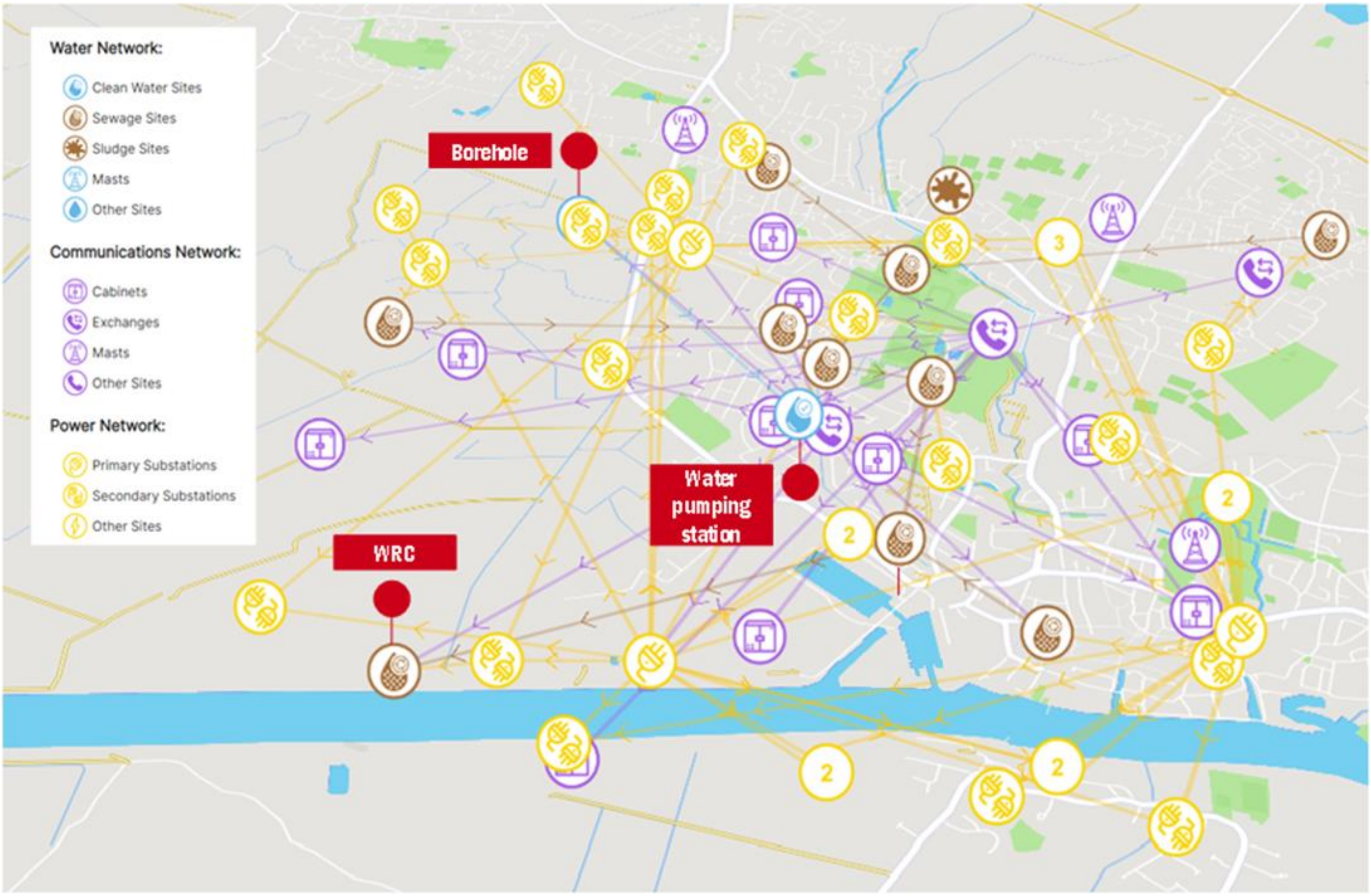
The cost-benefit analysis methodology underpinning our simulation could be used as a basis for the evaluation of a more advanced version of CReDo. In Section 5.2, we indicate how our methodology could be refined.

3.2 VERSION OF CREDO USED FOR OUR SIMULATION

As mentioned above, our simulation is based on the current version of CReDo with synthetic data. Figure 3 below shows the three networks and their connections in the area of East Anglia that are currently modelled in this version of CReDo.

[20] As we did not consider the impact of responding to flood events, our quantification does not take account of the possibility that asset operators could deploy temporary mitigation measures (e.g. mobile generators, batteries, or temporary flood defences). Asset operators will incur a cost to install and operate such mitigation strategies.

FIGURE 3 OVERVIEW OF THE VERSION OF CREDO WITH SYNTHETIC DATA



Source: CReDo

Note: Power assets are coloured in yellow, clean water assets are coloured in light blue, wastewater assets are coloured in brown, and telecom assets are coloured in purple. The type of assets is described in the main body of this section.

As can be seen from the figure, the networks' configuration is the following:

- The power network consists of three primary substations which feed 30 secondary substations. Some secondary substations have dual power supply.
- The water network consists of both clean water and wastewater assets. There are two clean water assets: one borehole where water is abstracted and one water pumping station to pump clean water to customers. There are 11 wastewater assets: 9 sewage pumping stations which collect sewage from customers and direct it to one water recycling centre (bottom left of the figure, near the river), and one sludge tank (top right).
- The telecom network consists of three exchanges, 10 cabinets and three mobile masts.

The assets of the power, water and telecom assets are interconnected. For example, secondary substations provide power to water and sewage pumping stations and exchanges. Exchanges provide telecom services to primary substations, the water pumping stations and some of the sewage pumping stations.

Table 2 below summarises the total number of assets by asset operators in the version of CReDo with synthetic data.

TABLE 2 NUMBER OF ASSETS IN THE VERSION OF CREDO WITH SYNTHETIC DATA

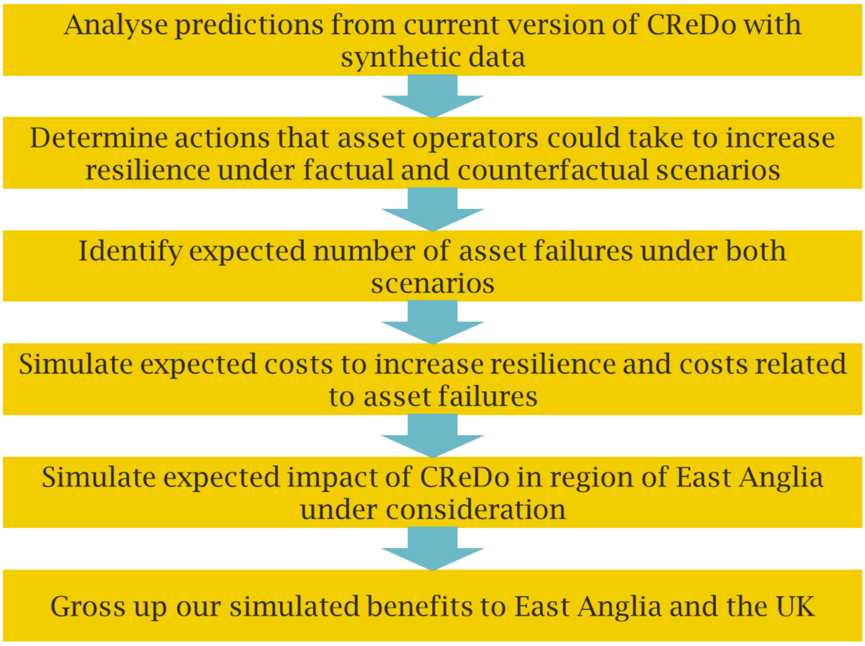
ASSET OPERATOR	ASSET TYPE	NUMBER OF ASSETS
UKPN	Primary substations	3
UKPN	Secondary substations	30
AWS	Borehole	1
AWS	Water pumping station	1
AWS	Sewage pumping station	9
AWS	Water recycling centre	1
AWS	Sludge site	1
BT	Exchanges	3
BT	Cabinets	10
BT	Mobile masts	3

Source: Frontier Economics

3.3 KEY ELEMENTS OF OUR METHODOLOGY

As shown in Figure 4 below, our methodology consists of six steps. We describe each step in turn.

FIGURE 4 STEPS OF OUR METHODOLOGY



Source: Frontier Economics

First, we analysed the predictions from the version of CReDo with synthetic data to understand the impact of a surface water flood on the networks in the region of East Anglia under consideration. This provided us with information on which assets are likely to be flooded and fail, and on which assets will fail due to a cascade effect.

Second, we determined which actions asset operators might be expected to take to increase surface water flood resilience to prevent these failures. When deciding how to invest in flood resilience, asset operators consider a range of factors, including the resilience and criticality of the infrastructure, with reference to constraints of time and available resources. We determined the actions likely to be taken for three scenarios:

- **Factual scenario.** Asset operators have access to CReDo and can assess the level of resilience of the whole system. This means that asset operators have full visibility of which assets in the system are flooded and which consequently fail. We assumed that the regulatory environment allows asset operators to co-invest in the same assets (e.g. all asset operators invest to increase the resilience of a primary substation). We also assumed that the overall budget constraint might be larger than the sum of the three asset operators' budget constraints under the counterfactual. This is because the asset operators may use CReDo to provide stronger evidence of their investment requirements to their sector regulators. Given this budget constraint, asset operators decide which investments to make to improve system resilience.

- **Counterfactual scenario 1 (individual digital twin with partial intervention).** Asset operators do not have access to CReDo, so can only assess the level of resilience of their own networks. This means that as asset operators have visibility only of their own assets they will not be able to predict which of their own assets will fail because of the failure of a third party's asset. Accordingly, they make investments (from a constrained budget) to improve the resilience of their assets based on this assessment. Given budget constraints, asset operators prioritise which assets they invest in.
- **Counterfactual scenario 2 (individual digital twin with no intervention).** As counterfactual scenario 1 but, due to budget constraints, asset operators decide not to increase the resilience of any of the assets identified by CReDo as critical.[21]

We validated these scenarios with the asset operators.

Third, we identified the expected number of asset failures in the event of a surface water flood under each scenario. This tells us which assets are still expected to fail in the scenarios (because mitigating actions have been prioritised elsewhere) and which assets would have been expected to fail but no longer do so.

Fourth, based on the above, we calculated the expected costs that asset operators and their customers would incur under each scenario over the medium term. We assumed that the time horizon is 2050.[22] We divided the costs into two broad categories: those that relate to increasing resilience and those that relate to asset failures.[23]

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[21] This counterfactual is broadly equivalent to asset operators not having access to an individual digital twin.

[22] It is likely that there will be benefits beyond 2050. The Green Book indicates that a time horizon beyond 60 years may be suitable for interventions that reduce climate change risks. Therefore, we simulated benefits to 2080 as a sensitivity analysis. See Annex B.

[23] For our illustrative quantification, we did not take account of the costs of developing CReDo and the individual digital twins. CReDo is funded by UKRI, the Connected Places Catapult and the University of Cambridge and, therefore, most of the costs of building

Fifth, we simulated the expected impact of using CReDo to increase surface water flood resilience in the region of East Anglia under consideration to 2050. The expected impact was calculated as the difference in expected costs over this period for the two scenarios, using the formula:[24]

Expected impact in region of East Anglia = Expected factual costs – Expected counterfactual costs.

In our formula, we took account of a number of factors, including when CReDo and the individual digital twins are expected to start being used and the probability of occurrence of surface water flood events to 2050. The main drivers of the expected impact are the number and type of asset failures, the number of customers affected by the failure, the costs of increasing resilience and the probability of occurrence.

Finally, we simulated the expected impacts for East Anglia and the whole of the UK. Assets in different regions of the country may have different levels of resilience to surface water flooding than in the region of East Anglia under consideration. For each region where assets are not resilient to surface water floods, asset operators may decide to not intervene, make a partial intervention or make a full intervention. As we do not currently have access to this information, we made some assumptions around the level of flood resilience and the type of intervention that asset operators will make. We used these assumptions to determine scaling factors, which we used to gross up our simulated estimates from the previous steps. The scaling factors were based on population at risk of floods as a proxy for assets at risk of floods. For East Anglia, the formula is:

*Expected impact in East Anglia = Expected impact in region of East Anglia Counterfactual 1 * scaling factor 1 + expected impact in region of East Anglia Counterfactual 2 * scaling factor 2.*

We followed the same approach to simulate the expected impact in the UK.

In the following sections, we provide more details of our factual and counterfactual scenarios, the impacts that we considered and how we calculated the scaling factors. We show how we applied our simulation methodology in Section 3.4.

3.3.1 OUR FACTUAL AND COUNTERFACTUAL SCENARIOS

Our factual scenario assumed that asset operators have access to CReDo. Under this scenario, we assumed that asset operators will be able to predict the impact of a surface water flood event on the system. They will be able to understand which assets fail because they are flooded and which assets fail because of the failure of a third party's assets. Asset failures have a range of implications for both asset operators and their customers (e.g. costs related to repair and supply interruptions). Using CReDo, asset operators will take actions to increase the resilience of the whole system. As mentioned above, we assumed that the regulatory environment will allow asset operators to co-invest in the same assets; the overall budget constraint may be larger than the sum of the individual budget constraints under the counterfactuals.

Under our two counterfactual scenarios, we assumed that asset operators do not have access to CReDo. Instead, asset operators use their own individual digital twins to inform their resilience activities. We

CReDo are not borne directly by asset operators and their customers (these costs are ultimately borne by taxpayers). We understand that asset operators are expected to develop their own digital twins in the future. When doing so, the lessons from the CReDo demonstrator may result in cost savings. For the purpose of our illustrative quantification, we conservatively assumed no cost savings.

[24] A mathematical representation of the formula that we used can be found in Annex A.

assumed that these digital twins will be available to be used from 2025, at the same time as CReDo. These digital twins allow each asset operator to model the effect of surface water floods on their own networks. Each asset operator will be able to understand which of its assets failed because they were flooded, and how these failures propagate within their networks. For example, AWS will be able to understand which of its sewage pumping stations flooded but not which of their assets failed because of the failure of a third party's assets. AWS will not be able to use the digital twin to understand which of their sewage pumping stations lost power supply. As a consequence, asset operators will decide which investments to make to increase resilience based only on the assessment of resilience of their own networks (rather than of the whole system). These investments are more tightly constrained by the budget available than in the factual scenario.

AVAILABILITY OF CREDO AND INDIVIDUAL DIGITAL TWINS

CDBB informed us that it is possible that asset operators will be able to start using CReDo in about three years. However, it is unlikely that they will be able to co-invest in the same assets. CReDo is expected to bring benefits to both asset operators and their customers. We assumed that sector regulators will anticipate this potential and make changes to the regulatory environment to allow these benefits to be fully realised. We assumed that asset operators will be able to fully take advantage of CReDo from 2029 (which is broadly aligned with the beginning of the price controls for UKPN and AWS). We also assumed that it will take about three years for asset operators to start using their individual digital twins. We assumed that asset operators can use their individual digital twins under both the factual and counterfactual scenarios.

As a consequence of these assumptions, the expected impact of using CReDo to increase surface water flood resilience between 2022 and 2029 is zero.

3.3.2 IMPACTS THAT WE CONSIDERED

In Section 2, we described a range of expected impacts from CReDo. As mentioned above, given data and time limitations, for the purpose of this simulation, we focussed on the impacts related to increasing system resilience to surface water flooding through improved *planning*. We acknowledge that, given that we focussed only on a subset of the expected impacts, our simulation is likely to underestimate the overall impact of using CReDo.

Table 3 below lists the impacts that we considered for our simulation. For each of these impacts, we estimated relevant costs under the factual and counterfactual scenarios. Our methodology for estimating these costs is outlined in Section 3.4.

TABLE 3 IMPACTS CONSIDERED IN OUR SIMULATION

	IMPACTS
Asset operators	• Costs to increase resilience of assets • Costs to repair assets damaged by floods • Compensation costs to customers in case of water, power and telecom interruptions, and sewage overflows (internal and external) • Costs related to loss of toilet facilities • Costs related to compliance failures

	IMPACTS
	• Costs related to pollution incidents
Customers	• Benefits from avoided water, power and telecom interruptions, internal sewage overflows and pollution incidents

Source: Frontier Economics

3.3.3 SCALING

In the future, we expect that CReDo will be expanded to include a larger geographic region. Initially, it could include all of East Anglia. Other asset operators may also decide to partner up to develop their own regional versions of CReDo. We understand that, ultimately, CReDo could be expanded to cover all of the UK. For this reason, it would be important to understand the expected impacts of this future version of CReDo with a broader geographic scope.[25] Given that CReDo is a demonstrator project, the role of scaling is particularly important as it is through scale that substantial benefits tend to be unlocked.

A detailed assessment of the expected impacts of CReDo over a larger geographic region would require an understanding of the characteristics of that region which affect flood resilience decisions, such as network configuration, flood risk and population density. As we do not currently have access to this information, we provide a simulation of the potential impact by making the following assumptions:

- The proportion of regions where assets are at flood risk can be proxied by the proportion of regions where the population is at flood risk;
- Of these regions:
  - one-third has assets that are fully resilient or asset operators decide to intervene to make the assets fully resilient;
  - two-thirds have assets that are not resilient.
- Of the regions where assets are not resilient, asset operators decide to make a partial intervention in 50% of the regions (Counterfactual 1) and to not intervene in the remaining 50% of the regions (Counterfactual 2).

From these assumptions, we can simulate the proportion of regions at flood risk where CReDo is assumed to have no impact, an impact equal to Counterfactual 1 or an impact equal to Counterfactual 2:

- One-third of regions – expected impact is zero;
- One-third of regions – expected impact assumed to be equal to expected impact under Counterfactual 1;
- One-third of regions – expected impact assumed to be equal to expected impact under Counterfactual 2.

[25] A future version of CReDo might also model the impact of other extreme weather events. We did not take this into account in the current simulation.

Using information published by the Climate Change Committee, we estimated that 2.35% of people in the UK are currently at risk of surface water floods in a 1-in-100 years event.[26] Using information published by Norfolk Council, we estimated that 5% of people in East Anglia are at risk of surface water floods in a 1-in-100-year event. [27] According to the CCC,[28] the proportion of people at risk is likely to increase by between 50% and 100% over the next 30 years due to a combination of climate change and population growth. Our illustrative quantification already accounts for the impact of climate change and population growth. The surface water flood scenario modelled includes a climate change allowance of 45%,[29] and we assumed that population grows at an average of 0.2% per year. Therefore, to avoid double counting we did not consider climate change and population growth when calculating our scaling factors.

We calculated the scaling factors by multiplying the population at risk of surface water floods by the proportions calculated above, and then by dividing by the population we considered in our simulation. Table 4 below summarises these scaling factors. As mentioned above, we assumed that for one third of the regions the expect impact is equal to Counterfactual 1, and for one third to counterfactual two. Hence, the scaling factors for the two counterfactuals are the same.

TABLE 4 SCALING FACTORS FOR OUR SIMULATION

	EAST ANGLIA	UK
Scaling factors for Counterfactual 1 and 2	4[30]	53[31]

Source: Frontier Economics
Note: Numbers in this table are rounded.

3.4 HOW WE APPLIED OUR SIMULATION METHODOLOGY

In this section, we present how we applied the simulation methodology described in the previous sections:

- First, we present our analysis of the output of the version of CReDo with synthetic data.

[26] The Future Flood Projections research commissioned to support the CCRA identifies that in 2020 there are about 1.2m people at risk of a 1-in-75 years surface water flood. For the simulation, we have scaled up this number by the ratio of the return period under considerations (100/75). See Table 5.11 from Kovats, S. and Brisley, R. (2021), Health, Communities and the Built Environment. In: *The Third UK Climate Change Risk Assessment Technical Report*, Betts, R.A., Haward, A.B., Pearson, K.V. (eds.). Prepared for the Climate Change Committee, London. https://www.ukclimaterisk.org/wp-content/uploads/2021/06/CCRA3-Chapter-5-FINAL.pdf.

[27] In Norfolk, there are 87,000 people at risk of surface water flood due to a 1-in-200 year event in Norfolk. For our simulation we assumed the same proportion of people at risk in East Anglia, and then adjusted down the estimate by the ratio of the return periods of the event under considerations (100/200). https://www.norfolk.gov.uk/what-we-do-and-how-we-work/policy-performance-and-partnerships/policies-and-strategies/flood-and-water-management-policies/local-flood-risk-management-strategy

[28] CCC projects that the proportion of people at risk of surface water flooding will increase up to 50% to 2050.

[29] Centre for Digital Built Britain (2022) CReDo Technical Paper 2: Generating flood data

[30] 4 = ((5% * 2,200,000) * 33%)/ 10,000. According to the Office for National Statistics (ONS), the population in East Anglia in 2020 was 2.2m.

[31] 53 = ((2.35% * 67,000,000) * 33%) / 10,000. According to the ONS, the UK population in 2020 was 67m.

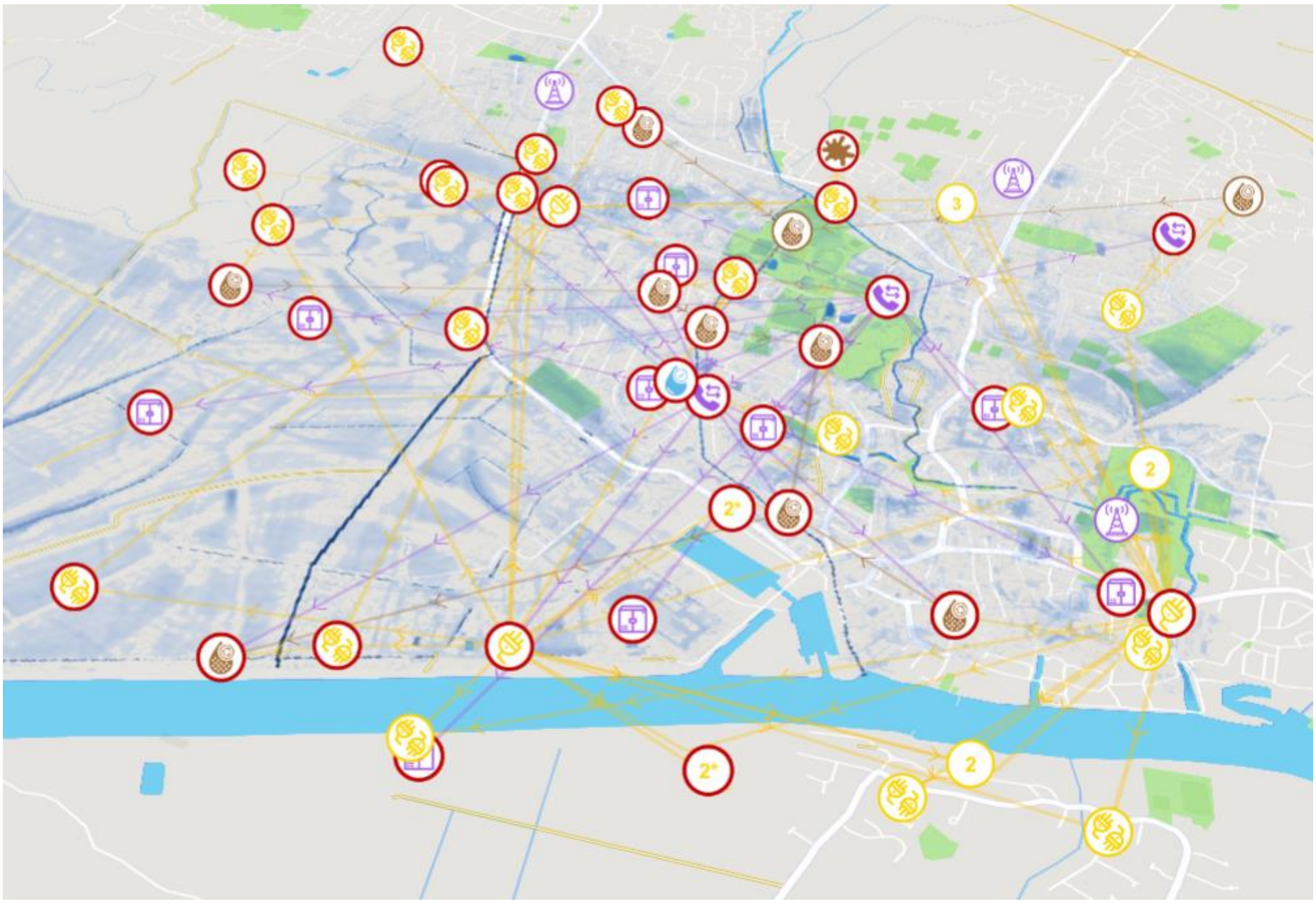
- Then, we describe the actions that we assumed the asset operators will take to increase resilience of their networks under each scenario, and the consequences of those actions on the outages.
- Finally, we discuss the assumption that we made on the probability of occurrence of the surface water flood.

Details of how we have estimated the costs to increase resilience and the costs related to asset failures can be found in Annex A.

3.4.1 SIMULATION FROM THE VERSION OF CREDO WITH SYNTHETIC DATA

The figure below shows the simulated impact from the version of CReDo with synthetic data of a 1-in-100-year surface water flood event on the system. The figure shows the impact after 11 hours. The assets circled in red are the assets that are predicted to fail either because they are flooded or because of the failures of other linked assets.

FIGURE 5 SIMULATION OF IMPACT OF SURFACE WATER FLOOD USING THE VERSION OF CREDO WITH SYNTHETIC DATA



Source: CReDo

Note: Impact of a 1-in-100-year flood with duration of six hours and 45% uplift 11 hours after the storm started.

We analysed the output of the version of CReDo with synthetic data and determined that the root cause of the failures observed is the flooding of two primary substations. Because of that, 15 secondary substations lose power supply. These secondary substations provide power to a number of other assets which also lose power: exchanges, borehole and water pumping stations, sewage pumping stations and the water recycling centre. Cabinets linked to exchanges also stop working. Some assets, for example the primary substations at the bottom right of the picture, lose telecom connectivity. As a simplifying assumption, for the purposes of our simulation, we assumed that there are no asset failures caused by a loss of telecom services. We did not assess the level of resilience of the assets to telecom outages (e.g. whether there are satellite systems in place). The number and cause of failures are summarised in Table 5 below.

This simulation assumes that as soon as the primary substations lose power, all assets linked to those primary substations also lose power. As mentioned earlier, we assumed that there are no mitigation measures, such as on-site generators or mobile generators which can provide back-up power, that asset operators can deploy. This is a worst-case scenario. In reality, asset operators may have invested in mitigation strategies to be used in these circumstances. If mitigation strategies are deployed, the number and duration of outages caused by the failures of the two primary substations will be lower. For example, an on-site generator could provide a back-up source of power at an exchange. Asset operators are expected to deploy mitigation strategies only if it is cost effective to do so. This is a simplifying assumption; we did not assess the current level of resilience of the assets which could be achieved through these mitigation strategies.

TABLE 5 NUMBER OF ASSET FAILURES AND CAUSE OF FAILURE

ASSET OPERATOR	ASSET TYPE	NUMBER OF ASSETS IN CREDO	NUMBER OF ASSET FAILURES	CAUSE OF FAILURE
UKPN	Primary substations	3	2	Asset flooded
UKPN	Secondary substations	30	15	No power as the primary substations are flooded
AWS	Borehole	1	0	A secondary substation stopped providing power
AWS	Water pumping station	1	1	No water flowing from the borehole
AWS	Sewage pumping station	9	7	Secondary substations stopped providing power
AWS	Water recycling centre	1	1	Secondary substations stopped providing power
AWS	Sludge site	1	0	No failure
BT	Exchanges	3	3	Substations stopped providing power
BT	Cabinets	10	10	No connectivity from exchange
BT	Mobile masts	3	0	No failure

Source: Frontier Economics

3.4.2 ACTIONS TO INCREASE RESILIENCE

FACTUAL SCENARIO

As mentioned above, under the factual scenario asset operators have access to CReDo and can assess the level of resilience of the whole system. Therefore, asset operators identify the root cause of the failures in the system as being the flooding of two primary substations. Had the two primary substations not been flooded, there would not have been any failures in the system nor any outages.

When deciding how to invest in resilience, asset operators undertake a number of interim steps. These steps are important as they tell them which equipment (if any) is at risk or whether there are third-party flood defences that the substation could rely on. For the purposes of our simulation, we assumed that asset operators determine that the most cost-effective solution involves increasing the resilience of the two primary substations. We assumed that all three asset operators invest in the two primary substations and will be able to provide strong evidence of the need for this investment to their regulators. Therefore, we assumed no budget constraints.

Once the investment is completed and the system level of resilience is increased, there will be no outages.

COUNTERFACTUAL SCENARIOS

Under the counterfactual scenarios, asset operators do not have access to CReDo, so can only assess the level of resilience of their own networks using their own digital twin. Under these scenarios, only UKPN will be able to identify that two of its primary substations have been flooded. The other asset operators will not be able to use their individual digital twins to predict that the surface water flood event will impact their assets, as none of their assets is predicted to be flooded.

When deciding whether and how to invest in resilience, UKPN will take account of a number of factors, including the criticality of the assets being flooded for its network and the resources it has available. UKPN's assessment of criticality is unlikely to consider how critical its assets are for the other asset operators. UKPN will also be subject to budget constraints. For example, in its December 2021 business plan, UKPN proposed to invest £17.1m to increase the resilience of 85 of its primary substations.[32] There are about 800 primary substations in UKPN's service area[33] and therefore the implied budget constraint is between 20k and £200k per primary substation.

For our simulation, we assumed that, for the reasons outlined above, UKPN will decide not to invest in both primary substations. Instead, UKPN will choose between a partial investment in a primary substation or no investment. We made this assumption to illustrate the impact that investment decisions which do not take account of other networks can have on the system. As mentioned earlier, we defined two counterfactual scenarios:

- **Counterfactual 1 – partial intervention.** UKPN decides to invest in increasing the resilience of one of the two primary substations that are predicted to be flooded. We assumed that UKPN will invest in the primary substation at the bottom left of Figure 5.

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[32] https://ed2.ukpowernetworks.co.uk/

[33] https://www.ofgem.gov.uk/sites/default/files/docs/2014/11/frontier_-_ena_final_report_-_01-04-11_-_stc.pdf

- **Counterfactual 2 – no intervention.** UKPN decides to prioritise other primary substations in its service area. Therefore, UKPN decides not to invest in either of the two primary substations.

In the event of a surface water flood, under Counterfactual 1, one primary substation will still be flooded. The failure of the primary substation will propagate through the system and cause power supply interruptions and some outages. Under Counterfactual 2, the two primary substations will be flooded.

Table 6 below compares the number of simulated asset failures under the factual and counterfactual scenarios.

TABLE 6 NUMBER OF ASSET FAILURES BY SCENARIO

ASSET OPERATOR	ASSET TYPE	COUNTERFACTUAL 2 – NO INTERVENTION	COUNTERFACTUAL 1 – PARTIAL INTERVENTION	FACTUAL – FULL INTERVENTION
UKPN	Primary substations	2	1	0
UKPN	Secondary substations	15	6	0
AWS	Water borehole	0	0	0
AWS	Water pumping station	1	1	0
AWS	Sewage pumping station	7	2	0
AWS	Water recycling centre	1	0	0
AWS	Sludge site	0	0	0
BT	Exchanges	3	0	0
BT	Cabinets	10	0	0
BT	Mobile masts	0	0	0

Source: Frontier Economics

3.4.3 PROBABILITY THAT PRIMARY SUBSTATIONS ARE FLOODED

The probability of occurrence of an event with severity equal to or exceeding the 1-in-100-year surface water flood is modelled as 1% in any given year. The storm modelled in the version of CReDo with synthetic data has a probability of occurrence of 1% in 2070. This storm causes a surface water flood that affects two primary substations. Therefore, there is a 1% probability in 2070 that the two primary substations will be flooded.

For the purposes of our simulation, we need to determine what is the probability that the two primary substations will be flooded in each year between 2022 and 2050. It is possible that a storm less severe than the storm modelled by the version of CReDo with synthetic data will also cause the two primary substations to be flooded. Such a storm will have a probability of occurrence higher than 1% in 2070. As climate change is expected to increase the severity of storms over the next 30 years, the probability of occurrence of that storm will increase as we move towards 2050. It is also possible that other events, such as river overflows, may cause the two primary substations to be flooded. These events will also have a certain probability of occurrence. We expect that a future version of CReDo could be used to identify the probability that the primary substations will be flooded in a range of different circumstances.

To reflect the uncertainty around the probability of occurrence, we have simulated the potential benefits under three scenarios, which are used to simulate a range of benefits.

- **Lower simulation.** The probability of occurrence increases linearly from 0.5% in 2022 to 1% in 2022.
- **Central simulation.** The probability of occurrence is constant at 1% per annum.
- **Upper simulation.** The probability of occurrence increases linearly from 1% in 2022 to 2% in 2022.

4 FINDINGS FROM OUR SIMULATION

In this section, we summarise the findings from our simulation of the subset of potential benefits.

In Section 4.1, we present the simulated benefits of CReDo under consideration to 2050 scaled up to East Anglia and to the national level using the scaling factors defined in Section 3.3.3. Annex B shows the baseline estimates for the region of East Anglia under consideration for the two counterfactual scenarios, as well as our sensitivity analyses around the assumed cost of repairing damaged assets and the time horizon for the simulation of the benefits.

In Section 4.2, we calculate an expected return on investment.

4.1 SIMULATION OF POTENTIAL IMPACTS OF CREDO

The table below shows our simulation of a subset of the potential impacts of the version of CReDo with synthetic data over 2022-2050 in East Anglia, and across the UK. The simulated benefits are expressed in 2022 constant prices. As mentioned in a previous section, the results below are a conservative and partial simulation of the potential benefits of CReDo. Our results show that this subset of simulated benefits is worth between £6 and £13 million across East Anglia over 2022-2050, and between £81 and £186 million across the UK over the same period. These results are not robust estimates of the potential benefits, but a *simulation* of the potential benefits

In Section 5, we explain how these findings should be interpreted, and how the cost-benefit analysis underpinning our simulation could be refined.

TABLE 7 SIMULATION OF EXPECTED SOCIAL IMPACTS – EAST ANGLIA AND THE UK (2022-2050, £M 2022 CONSTANT PRICES)

SCOPE	LOWER SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 0.5% TO 1%)	CENTRAL SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 1% CONSTANT)	UPPER SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 1% TO 2%)
East Anglia	£6m	£8m	£13m
UK	£81m	£117m	£186m

Source: Frontier Economics
Note: The figures in the table represent a weighted average of the simulated benefits for different counterfactual scenarios.

4.2 RETURN ON INVESTMENT

We understand from CDBB that CReDo is expected to cost £5m. This estimate includes the cost already incurred to build the current version of CReDo and the cost of further developing CReDo over the next three years. This estimate excludes costs to asset operators.

We assume that by the end of 2024, CReDo will cover the whole of East Anglia and will include some refinements that will ensure that its predictions can be used for decision making. According to our simulation, if the regulatory regime allows asset operators to co-invest in system resilience, then the simulated benefits of CReDo are expected to be about £8m in our central scenario.

By realising the extent of these benefits, sector regulators may decide to incentivise other asset operators in the UK to develop their own regional version of CReDo. This should be facilitated by the fact that the framework to build CReDo is expected to be available to interested parties. If sector regulators provide an innovation fund or an additional allowance to asset operators, the government may not need to fund the development of these regional versions of CReDo. Under these conditions, we expect that asset operators across the country will develop their own regional versions of CReDo (or join up their individual digital twins). As mentioned in the previous section, we assume that it would take about four years for these changes to take place. By 2028 we expect that all asset operators will participate in a regional version of CReDo and that they will be able to fully take advantage of CReDo from 2029. According to our simulation, the aggregated benefits of these regional versions of CReDo could amount to about £117m under our central scenario. Therefore, in our central case, this amounts to a simulated public return on investment (related only to the simulation with synthetic data) of 23:1 over 2022-2050.[34]

[34] 23:1 = £117m : £5m.

5 RECOMMENDATIONS

In this section we explain how the findings from our study should be used, and how our cost-benefit analysis underpinning our simulation could be refined

5.1 HOW TO USE THE FINDINGS FROM OUR STUDY

This study contributes to the understanding of the potential benefits of CReDo through the development of a logic model and theory of change of CReDo and the simulation of some of the potential benefits. The methodology used in the simulation can be applied to evaluate future versions of CReDo.

The logic model of CReDo identifies the potential benefits of CReDo for both asset operators, their customers, and wider society. A wide range of benefits are identified. This framework can be useful throughout the CReDo decision-making process, for example, supporting decisions about which outputs of CReDo to prioritise to achieve the target benefits.

As noted above, CReDo is a demonstrator project still in the relatively early stages of its development. We did not attempt to evaluate CReDo. Instead, we simulated the impact of some of the potential benefits of CReDo. Our simulation is partial and conservative. As such, the results of our simulation provide a conservative preliminary indication of the order of magnitude of benefits that CReDo could be expected to generate. The methodology underpinning our results can be adapted and refined to form the basis of a more detailed evaluation of a future version of CReDo. A refined version of this cost-benefit analysis methodology could be integrated in CReDo and would help the users of CReDo to understand the costs and benefits of different strategies to increase resilience of the infrastructure networks.

5.2 IMPROVING OUR SIMULATION OF POTENTIAL BENEFITS

Our simulation could be improved in three areas:

- Using a less stylised version of CReDo;
- Expanding the scope of benefits included in the estimation; and
- Refining the methodology and assumptions used to quantify the impacts.

We describe each of these areas in turn.

USING A LESS STYLISED VERSION OF CREDO

Our simulation of the expected impacts is based on the version of CReDo with synthetic data. A quantification based on a version of CReDo which more closely represents the networks, how they are connected and how they are related to customers and other infrastructure is likely to be more robust. We consider that a version of CReDo which includes the following characteristics would improve the quantification of the benefits of increasing flood resilience:

- Configuration of networks and location of assets reflect actual configuration and location;
- A higher level of granularity of assets;
- Connections between assets and properties served, distinguishing by property type (e.g. residential, commercial, industrial, essential infrastructure);

- Location and impact of permanent defences and other infrastructure that mitigate impacts of floods; and
- The modelling of mitigation strategies (e.g. on-site back-up generators, batteries).
- How the infrastructure could evolve over time.

We understand that CReDo could also be developed to consider the impact of other types of storm damage (e.g. wind) and other types of weather events (e.g. heat waves). The expected impacts of using CReDo to increase resilience to a range of weather events are expected to be larger than the benefits of increasing resilience to surface water floods.

EXPANDING THE SCOPE OF THE BENEFITS INCLUDED IN THE ESTIMATION

Our simulation considered only the expected impacts of using CReDo to increase the resilience of the system to surface water flooding through improved *planning*. Therefore, a refinement of our simulation would attempt to incorporate other expected impacts of CReDo:

- Benefits related to *responding* to flood events;
- Benefits related to the IMF; and
- Spillover effects.

Benefits related to IMF and spillover effects may be more difficult to identify and quantify because they may take longer to realise. Case studies could be used to provide evidence of the potential benefits.

Because of data and time limitations, we were also unable to incorporate all of the expected impacts resulting from improved planning. A refinement of our simulation would attempt to incorporate the following impacts:

- Costs to asset operators due to the impact of outages on companies' financial incentives set by their regulators; and
- Costs to customers, such as costs due to telecom supply interruptions or potential environmental costs from compliance failures.

REFINING THE METHODOLOGY AND ASSUMPTIONS USED TO QUANTIFY THE IMPACTS

There is scope to improve the cost-benefit analysis methodology and assumptions that we used to simulate the impacts of using CReDo to increase flood resilience through *planning*. Areas for consideration include the following:

- Our methodology is based on a specific surface water flood event where two primary substations are flooded. It would be important to consider whether other events may cause other assets to be flooded and how those failures may propagate throughout the network.
- Costs of increasing resilience. The costs of increasing resilience can vary substantially depending on the asset and resilience strategy adopted. Understanding which strategies are more likely to be used for each asset and under which conditions would help narrow down the range of costs.
- Costs of repair. The costs of repairing an asset also vary substantially depending on the asset and the damage. Understanding in more detail the type of damage caused would help narrow down the range of costs.

- Costs to asset operators and customers. Mitigation strategies will impact the expected impacts of CReDo. It is therefore important to consider the costs of implementing these strategies (e.g. cost of buying and operating an on-site generator) and how they can be used to mitigate the impact of outages. It would also be important to consider the cost of different mitigation strategies.
- Costs to customers and society. For this simulation, we estimated societal benefits using a top-down approach that relies on willingness to pay (WtP) estimates. WtP estimates are usually thought to capture a broad set of societal benefits. Alternative approaches to estimate societal benefits, such as bottom-up approaches which estimate the impact of specific benefits (e.g. avoided loss revenue, avoided injuries because of power outages), could be tested. The results from different approaches could then be compared. Consideration should also be given to the extent to which compensation payments offset some of these costs to customers.
- Scaling factor. Our scaling factor is illustrative. The scaling factor could be refined by assessing how comparable the region modelled by CReDo is to other areas in the country in terms of risk to surface flood events, asset configuration and resilience, and customers served.
- Probability of occurrence. For our quantification we considered the impact of a specific surface water flood. We then made some assumptions around the probability of occurrence of that event. A refined version of our methodology should attempt to consider the probability of the system being susceptible to failure due to any type of flood. This would enable better understanding of the expected impacts related to increasing flood resilience.

ANNEX A - TECHNICAL DETAILS

A.1 - MATHEMATICAL REPRESENTATION OF OUR METHODOLOGY

The expected impact of CReDo was calculated using the following formula:

$$Expected\ impact\ of\ CReDo = ENPV(C^{factual}) - ENPV(C^{counterfactual})$$

where:

- $ENPV(C^{i}) = \sum_{t=2022}^{2050} \frac{C^{i}_{resilience,t} + p_t * C^{i}_{outages,t}}{(1+r)^{t-2022+1}}$
- *i* = factual, counterfactual
- *C_resilience* are the costs of increasing resilience
- *C_outages* are the costs related to outages for both asset operators and their customers
- *r* is the real discount rate
- *p_t* is the probability of occurrence.

A.2 - ASSUMPTIONS UNDERLYING OUR SIMULATION

In this section, we list some of the assumptions underlying our simulation.

SURFACE WATER FLOOD EVENT MODELLED

The surface water flood event modelled by the version of CReDo with synthetic data under consideration corresponds to a 1-in-100-year surface water flood event caused by a six-hour storm in a region of East Anglia. The rain intensity was uplifted by a climate change allowance of 45%.[35] This allowance is an estimate of the increase in rain intensity by 2070. Figure 6 below shows the expected flood depth 11 hours after the start of the storm in the area of East Anglia modelled by the version of CReDo with synthetic data.

FIGURE 6 FLOOD DEPTH MODELLED

Source: The version of CReDo with synthetic data
Note: 11 hours after the storm started. The flood is shown with different shades of blue. The darker the blue, the higher the flood depth.

[35] Centre for Digital Built Britain (2022), *CReDo Technical Paper 2: Generating Flood Data.*

DURATION OF OUTAGES

We understand that after a severe weather event power supply is usually restored within 48 hours, but this could be up to five days in remote areas. For our simulation, we assumed that the duration of the power outages were 48 hours.

We assumed a worst-case scenario where no mitigation solutions had already been deployed and/or could be deployed to minimise the impact of the failure of the primary substations. This means that the duration of the interruption is assumed to be the same across all asset operators. In reality, asset operators may have deployed or be able to deploy solutions to provide power supply to their assets (e.g. on-site or mobile generators, batteries). This is a simplifying assumption used for the purposes of our simulation. We did not assess the current level of resilience of the assets in CReDo which is provided by existing mitigation strategies.

NUMBER OF PROPERTIES SERVED BY EACH ASSET

Table 8 below summarises the number of properties served by each asset type. We estimated the number of properties served using publicly available information.

TABLE 8 RESIDENTIAL PROPERTIES PER ASSET

ASSET	NUMBER OF ASSETS IN CREDO	RESIDENTIAL PROPERTIES PER ASSET	TOTAL OF RESIDENTIAL PROPERTIES
Secondary substations	10	142	10,000
Water pumping stations	1	4,251	10,000
Sewage pumping stations	9	472	10,000
Water recycling centres	1	4,251	10,000
Cabinets	15	425	10,000

Source: Frontier Economics

POPULATION GROWTH

We used projections from the ONS to estimate how the population might increase in the region of East Anglia under consideration to 2050. The larger the population, the higher the number of people who could be potentially affected by a surface water flood. As a simplifying assumption, we assumed that there is sufficient spare capacity in the current networks to serve the population in the region up to 2050 without the need for new assets.

DISCOUNTED CASH FLOW

We estimated the expected costs under the factual and counterfactual scenarios by using discounted cash flow analysis. We followed best-practice guidance from the *HMT Green Book* and applied a real discount rate of 3.5% to values expressed in real prices.[36]

INFLATION

All our cost measures are in 2022 constant prices.

[36] HMT Green Book. https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

A.3 - DETAILS OF QUANTIFICATION OF COSTS

In this section, we explain how we quantified the two broad categories of costs: the costs to increase resilience and the costs related to asset failures.

A.3.1 - COST OF INCREASING FLOOD RESILIENCE

There are a number of flood mitigation strategies that can be adopted at a primary substation:

- Temporary (mobile) defences (e.g. flood barriers and pumps);
- Permanent defences (e.g. bunding and fixed pumps); and
- Electrical reconfiguration (e.g. increase resilience to associated high-criticality secondary substations by being fed from an alternative primary substation).

The costs associated with these flood mitigation strategies and the time required to implement these strategies vary considerably and depend on a number of factors. There are also a number of circumstances in which a strategy may not be adopted at a site. For example, for technical reasons it may not be possible to install permanent defences around a primary substation. Table 9 below lists the main flood mitigation strategies together with the cost of implementation and the time required to implement the strategy.

TABLE 9 FLOOD MITIGATION STRATEGIES FOR PRIMARY SUBSTATIONS

STRATEGY	COST (£ 2022)	TIME OF IMPLEMENTATION
Temporary defences	[redacted]	[redacted]
Permanent defences	[redacted]	[redacted]
Electrical reconfiguration	[redacted]	[redacted]

Source: Frontier Economics, UKPN

For the purposes of our simulation, we assumed that the cost of increasing resilience is £200k and the time of implementation is one year. This cost is in line with the average cost per substation in UKPN's December 2021 business plan. We assumed that the life of the strategy is more than 30 years and that there are no maintenance costs.

A.3.2 - COSTS RELATED TO OUTAGES

As explained in Section 2, there are a number of costs related to outages. We estimated these costs using a mix of information taken from publicly available reports and provided confidentially by the asset operators.

The magnitude of these costs depends on the number and type of asset failures, the duration of the failures and the number of customers affected by those failures. The number and type of asset failures vary according to our scenarios, as indicated in the main body of our report. We made an assumption about the duration of the failure, as indicated in this annex.

Below, we describe how we estimated the number of customers affected by the failures and how we quantified the costs to asset operators and customers.

NUMBER OF CUSTOMERS AFFECTED BY FAILURES

First, we calculated the number of customers and people served by each asset by multiplying the number of properties by the average number of households per property. We assumed that the number of households and properties is the same. We also assumed that each household is a customer of each of the three networks. The average number of people per property is assumed to be 2.35 throughout the period. This was estimated using ONS data for the region in East Anglia under consideration for the year 2020.

Then, we assumed that if an asset fails, all properties served by that outage will be affected by a service supply interruption. The only exception is failure of a sewage pumping station where we assumed that not all properties will be affected. We understand from discussion with AWS that failures of sewage pumping stations are more likely to affect properties in the proximity of the pumping stations. AWS provided these proportions. Table 10 below summarises our assumptions.

TABLE 10 PROPORTION OF PROPERTIES AFFECTED

ASSET FAILING	IMPACT	PROPORTION OF PROPERTIES SERVED BY ASSET AFFECTED
Substation	Power supply interruption	100%
Water pumping station	Water supply interruption	100%
Cabinet	Telco supply interruption	100%
Sewage pumping station	Internal sewage overflow	[redacted]
Sewage pumping station	External sewage overflow	[redacted]
Sewage pumping station	Loss of facilities	[redacted]
Sewage pumping station	Pollution incidence (Category 3)	[redacted]
Water recycling centre	Compliance failure	100%

Source: Frontier Economics based on information from asset operators

COSTS FOR UKPN

We assumed that UKPN will incur only costs to repair the primary substations being flooded and pay compensation to customers. UKPN may incur other costs, such as costs related to restoration and costs due to loss of regulatory financial incentives for customers being off supply, which we did not take into account in our quantification.

The costs related to repairing the primary substations can vary largely depending on the outage. In some instances there will be no permanent damage and it will be sufficient to wait for the water levels to subside. In other cases, however, damages could be extensive and it may be necessary to replace some critical assets within the primary substation. The cost of replacement varies greatly depending on the assets that are damaged. For example, a recent study[37] by the Climate Research Foundation found that damages to primary substations caused by floods in Barcelona and Bristol could vary between £1.9m and £5.6m. For the purposes of this simulation, we assumed that repair costs are £1m. We ran a sensitivity analysis on the repair costs – see Annex B.

Compensation costs to customers are set by Ofgem.[38] In the case of severe weather, the claim depends on the category of the storm and the amount of time the customers were without power supply. Both domestic and non-domestic customers can claim £70 per customer per day for Storm Category 1 if supply interruption is 24 hours and £70 per customer per day for Storm Category 2 if supply interruption is 48 hours. Customers can also claim a further £70 for each additional 12 hours of being off supply, up to a cap of £700. For our quantification, we assumed a Category 1 storm.

COSTS FOR AWS

According to the version of CReDo with synthetic data, the following assets fail because of power outages: water pumping station, sewage pumping station, water recycling plant. In our worst-case scenario, we assumed that asset operators will not have or not use any back-up solutions to restore power. As a consequence, AWS's customers will be affected by service interruptions. This is a simplifying assumption for our simulation. We did not assess the level of power redundancy of the water assets provided by solutions that are not currently modelled in CReDo (e.g. on-site/mobile generators or batteries). AWS will incur a range of costs related to these failures. We discuss the costs that we considered in our quantification in turn.

A water pumping station failure will cause customers to suffer water supply interruptions. According to AWS, these costs vary depending on the outage duration but are equal to about £[redacted] per property for an outage lasting two days.

A sewage pumping station failure can cause a number of incidents:

- Internal and external sewage overflows. Properties in the proximity of the sewage pumping station may be affected by sewage overflows;
- Loss of facilities. Customers may be unable to use their facilities; and
- Pollution incidents. Sewage may be discharged into rivers.

We used AWS's estimates of the costs of such incidents. This information is summarised in Table 11 below.

TABLE 11 ASSUMED IMPACT OF SEWAGE PUMPING STATION FAILURE ON PROPERTIES

ASSET	COST PER PROPERTY AFFECTED
Internal sewage overflows	£[redacted] (residential) - £[redacted] (non-residential)
External sewage overflows	£[redacted] (residential) - £[redacted] (non-residential)
Loss of facilities	£[redacted]

37 Electrical Grid Risk Assessment Against Flooding in Barcelona and Bristol Cities

38 https://www.ofgem.gov.uk/information-consumers/energy-advice-households/check-compensation-rules-power-cut-or-supply-problem.

Source: Frontier Economics' calculations, AWS inputs

For pollution incidents, the cost depends on the severity of the incident and whether it was a first time offence. In discussion with AWS, we assumed that the likelihood of an incident is £[redacted]%. We treated all incidents as Category 3 incidents (first time offence). According to the EA, Category 3 incidents are relatively mild incidents. Ofwat defines these incidents as having *"minor or minimal impact or effect on the environment, people and/or property".*[39] We assumed a cost of around £[redacted] per incident according to information provided by AWS.

A water recycling centre failure may cause untreated sewage to be discharged into a river. In this case, AWS will incur costs related to failing to comply with its duties. The costs will depend on the amount of untreated sewage being discharged into the river. AWS provided to us these costs on a per population equivalent basis.

COSTS FOR BT

A power outage at an exchange can impact the services provided by BT. In our worst-case scenario, we assumed that asset operators will not have or not use any back-up solutions to restore power. As a consequence, BT's customers will be affected by service interruptions. This is a simplifying assumption for our simulation. We did not assess the level of power redundancy of the telecom assets provided by solutions that are not currently modelled in CReDo (e.g. on-site/mobile generators or batteries).

BT has signed up to Ofcom's Automatic Compensation Scheme.[40] According to the scheme, a landline or broadband customer is entitled to receive a compensation of £8.06/customer/day for each day the service is not repaired. The compensation is payable if the service is not fully fixed after two working days.

COSTS FOR CUSTOMERS

We estimated the value that customers assign to avoided outages using willingness to pay (WtP) measures.[41] WtP measures reflect a broad range of societal costs that can be caused by an outage, such as distress, loss of revenue and environmental costs. Because of data and time limitations, we estimated the value that customers assign to the following outages: power supply interruptions, water supply interruptions, sewage overflow incidents and pollution incidents.

For power outages, we were advised by UKPN to use an estimate for customer interruptions and customer minutes off supply of £[redacted]/hour per costumer. This is implied by Ofgem's incentive scheme for energy companies at RIIO-1.

For outages related to the failure of water and wastewater assets, we estimated WtPs using information that Ofwat used at PR19 to set its incentive schemes (Outcome Delivery Incentives (ODI) rates). Ofwat's ODI rates are based on WtP estimates submitted by companies. These estimates differ greatly from company to company. To address this large variation in estimates, at PR19 Ofwat used triangulation and cross-checks to

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[39] https://www.ofwat.gov.uk/wp-content/uploads/2017/12/20171129-Incidents-and-their-classification-the-Common-Incident-Classification-Scheme-CICS-23.09.16.pdf

[40] https://www.ofcom.org.uk/phones-telecoms-and-internet/advice-for-consumers/costs-and-billing/automatic-compensation-need-know

[41] Compensation payments from asset operators to customers may offset some of these costs. For the purposes of this quantification, we did not adjust for this potential impact.

assess the quality of the WtP estimates submitted by the companies. It then used the outcome of these checks to identify more robust WtP estimates, which were then used to set the ODI rates for the price control. The WtP estimates for sewage overflow incidents and pollution incidents reflect the collective WtP across all AWS's customers to avoid an additional incident.

For our simulation, we based our WtP estimates on those used by Ofwat to define ODI rates. These estimates were taken from Ofwat's PR19 final determination workbook, which calculates ODI rates for customer-facing performance commitments (PC).[42] For each PC, there are two value ranges: an outperformance range and an underperformance range. For our simulation, we estimated a WtP as the average of the mid-points of the outperformance and underperformance WtP ranges.

Table 12 below shows the WtP estimates that we used for our analysis.

TABLE 12 WILLINGNESS TO PAY ESTIMATES

	WTP
Power outage	Each customer affected is WtP £[redacted]/hour
Water supply interruption	Each customer affected is WtP £26.4/hour (above 3 hours)
Internal sewage overflows	All AWS's customers are WtP £43,000/incident
Pollution incident	All AWS's customers are WtP £75,000/incident

Source: Frontier Economics, Ofgem, Ofwat

The output of the version of CReDo with synthetic data did not allow us to distinguish between which properties are affected by each asset. Therefore, we could not distinguish whether a customer was affected by one or more of the outages listed above. When calculating the cost of outages to customers, we therefore assumed that the WtP to avoid a combined outage (i.e. an outage that affects both water and power supply, for example) is equal to the aggregation of the WtPs to avoid the individual outages. We recognise that this could overestimate the customers' WtP for avoiding a combined outage.

[42] Ofwat uploads – PR19 Final determination – ODI Rates - Customer facing performance commitments. https://www.Ofwat.gov.uk/wp-content/uploads/2019/12/ODI-Rates-Customer-Facing.xlsx

ANNEX B - SIMULATED BENEFITS IN REGION OF EAST ANGLIA AND SENSITIVITY ANALYSIS

In this annex, we present:

- The simulation of expected impacts in the region of East Anglia under consideration.
- Sensitivity analyses for our central scenario around repair costs and time horizon.

B.1 - SIMULATION OF EXPECTED IMPACTS IN REGION OF EAST ANGLIA

Table 13 below summarises the simulation of the subset of potential benefits in the region of East Anglia under consideration for the two counterfactual scenarios. As described in the main body of this report, these estimates have been scaled up to simulate the potential benefits in East Anglia and the UK.

TABLE 13 SIMULATION OF EXPECTED IMPACTS TO 2050 – REGION OF EAST ANGLIA (2022-2050, £M 2022 CONSTANT PRICES)

SCENARIO	LOWER SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 0.5% TO 1%)	CENTRAL SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 1% CONSTANT)	UPPER SIMULATION (PROBABILITY OF OCCURRENCE OF FLOOD: 1% TO 2%)
Counterfactual 1 – partial intervention	£0.6m	£0.9m	£1.4m
Counterfactual 2 – no intervention	£0.9m	£1.4m	£2.2m

Source: Frontier Economics
Note: 2022 constant prices. Totals may not correspond to the sum of the parts due to rounding.

B.2 - REPAIR COSTS

Table 14 below shows the impact of changing the cost of repairing a damaged primary substation between £500k and £2m for our central scenario where we assumed a 1% constant probability of occurrence. The time horizon is 2050.

TABLE 14 SENSITIVITY ANALYSIS FOR CENTRAL SCENARIO: REPAIR COSTS (REGION OF EAST ANGLIA) (2022-2050, £M 2022 CONSTANT PRICES)

REPAIR COSTS	RELATIVE TO COUNTERFACTUAL 1 – PARTIAL INTERVENTION	RELATIVE TO COUNTERFACTUAL 2 – NO INTERVENTION
500k	£0.8m	£1.3m
£1m (baseline)	£0.9m	£1.4m
£2m	£0.9m	£1.5m

Source: Frontier Economics
Note: All figures in 2022 constant prices. Totals may not correspond to the sum of the parts due to rounding. 1% constant probability of occurrence

B.3 - TIME HORIZON

Table 15 below shows the impact of expanding the time horizon of the analysis to 2080 for our central scenario where we assumed a 1% constant probability of occurrence. This time horizon is in line with the EA's climate change scenarios and The Green Book recommendations for interventions which reduce climate change risks. Following The Green Book's recommendation, we have used a real discount rate of 3% after 2050.

TABLE 15 SENSITIVITY ANALYSIS FOR CENTRAL SCENARIO: TIME HORIZON (REGION OF EAST ANGLIA)

TIME HORIZON	RELATIVE TO COUNTERFACTUAL 1 – PARTIAL INTERVENTION	RELATIVE TO COUNTERFACTUAL 2 – NO INTERVENTION
2050 (baseline)	£0.9m	£1.4m
2080	£1.8m	£2.8m

Source: Frontier Economics
Note: All figures in 2022 constant prices. Totals may not correspond to the sum of the parts due to rounding. 1% constant probability of occurrence.

frontier economics