CREDO PHASE 2: DEVELOPING DECISION-SUPPORT USE CASES

A report prepared for the Connected Places Catapult

10 OCTOBER 2023

WWW.FRONTIER-ECONOMICS.COM

CONTENTS

1 Context and scope of this report 10

1.1 Overview of CReDo 10

1.2 Scope of work 11

1.3 Structure of this report 11

2 Operationalising CReDo as a decision-support tool 13

2.1 Overview of the Phase 2 methodology 14

2.2 Phase 2 core development areas 18

2.3 Assumptions adopted when implementing the methodology 24

3 Implementation outputs from Phase 2 28

3.1 How to interpret these outputs 28

3.2 Comparison of criticality 29

3.3 Illustration of investment benefits 30

4 Development areas for future phases of work 32

4.1 Aggregating across flood scenarios and over time 32

4.2 Extending the scope of resilience measures considered 33

Annex A: Calculation of total economic cost 34

Total economic costs 34

Lost economic surplus (sum of producer and consumer surplus) 34

Externalities 36

Business costs 37

FOREWORD

The opportunities from digital twins lie in their ability to operationalise real world data to support better decision-making. Here we lay the groundwork for CReDo as a decision-support and cost-benefit analysis tool for the strategic resilience planning use case. Developing and embedding economic cost models and decision-making algorithms in this phase of work will enable CReDo to generate actionable insights from complex infrastructure and weather data.

There are many other high impact decision intelligence use cases for CReDo and connected infrastructure digital twins that have the opportunity to provide real benefits to customers, network operators, and wider society. Machine learning and artificial intelligence systems will enable CReDo to optimise across richer and more dynamic sources of data. Exploring these will be the subject of future work.

Dr Elliot Christou – CReDo Technical Lead, Connected Places Catapult

EXECUTIVE SUMMARY

CREDO CAN BE A HELPFUL DECISION-SUPPORT TOOL FOR ASSET OPERATORS AND REGULATORS

CReDo brings together data from different infrastructure asset operators to model the impact of extreme weather events, taking account of interdependencies within and across infrastructure boundaries. CReDo can be used by asset operators and regulators to make more informed decisions about where best to take action for the benefit of the infrastructure system as a whole (a so-called ‘connected approach’).

In Phase 1, we designed an economic evaluation methodology to simulate the potential net benefits of CReDo’s strategic resilience planning use case. We found that CReDo, as a connected digital twin, had the potential to bring a range of benefits to asset operators, their customers and wider society by enabling asset operators to identify cross-network dependencies and pool their strategic investments.

The current phase of CReDo (Phase 2) has contributed to the development of CReDo as a decision-support tool by identifying cross-network interdependencies and where coordinated investments across asset operators can achieve a given level of resilience at lower cost.

IN PHASE 2, CREDO HAS DEVELOPED TO BETTER REFLECT REALITIES FACING ASSET OPERATORS

During Phase 2 of the project, we focused on developing CReDo to better reflect the realities facing asset operators. Real asset data from UK Power Networks, Anglian Water Group and BT Group was used to characterise the current resilience properties of their networks, including the costs of asset failures to their business and customers, and to reflect the incremental measures that they could undertake at the asset level to improve resilience.

We then applied the economic evaluation methodology developed in Phase 1 to this data and compared the potential net benefits of different resilience strategies, from both an individual operator perspective and a system perspective. This economic evaluation is based on a set of cost models that quantify the benefits of avoiding flood-induced asset failures for infrastructure owners, customers and wider society.

THE OUTPUTS FROM PHASE 2 COULD HELP OVERCOME COORDINATION CHALLENGES FOR RESILIENCE PLANNING

One of the key outputs from this phase of work is the CReDo measure of ‘asset criticality’. CReDo estimates the criticality of individual assets from a system perspective and an individual ‘siloed’ asset operator perspective by taking account of the total economic costs that are incurred if the asset fails as a result of direct flooding or cascading failures from other assets, whilst also accounting for existing levels of resilience in the system.

This measure illustrates where and how a connected approach is likely to add value when making strategic investment decisions, compared to a world where asset operators make those decisions independently of one another. Other outputs from this phase include identifying the pathways of cascading asset outages and the budget impact of resilience investments.

WE SIMULATED A CASE STUDY FLOOD SCENARIO IN EAST ENGLAND AS AN ILLUSTRATION OF THE OUTPUTS THAT CREDO IS ABLE TO PRODUCE

To demonstrate the current decision-support functionality of CReDo, we simulated the impact of different investment decisions for a flood scenario in an area within the East of England. This case study showed that asset operators may prioritise interventions differently depending on their assessment of the criticality of their assets for their networks compared to the criticality of their assets for the system. In particular, we found that a connected approach to system planning can lead to better economic outcomes for a given level of resilience investment, as the system view can identify interventions with larger net benefits by prioritising assets with greater system criticality.

THIS PHASE OF WORK ALSO IDENTIFIED FURTHER WAYS THAT CREDO CAN ADD VALUE TO DECISION-MAKERS

This phase of work also identified further ways that CReDo can add value to decision-makers. For example, in the future, CReDo may be able to run numerous flood scenarios for a given intervention strategy and approximate the overall *expected* net benefits of that investment. Additionally, future phases may consider operational response measures, such as rediverting network flows or deploying mobile resources to affected areas, by incorporating inputs such as average response times, site access and other operational factors.

AKNOWLEDGEMENTS

The methodology and implementation from this phase of work are the result of collaboration between Frontier Economics and staff of the Connected Places Catapult (CPC), in particular: Elliot Christou, Loren Chamberlain, Sarah Hayes, Stephane Fernandez-Garcia and Yanjie Dong. Constructive input was provided by Professor Chris Dent (University of Edinburgh).

Frontier Economics would like to thank the organisations who took part in workshops or interviews and provided valuable input for this work, in particular: Matt Webb (UK Power Networks), Tom Burgoyne (Anglian Water Group) and Justine Webster (BT Group).

GLOSSARY OF TERMS

Key term	Definition
Asset operator-level criticality	The criticality of an asset with respect to total economic costs that its failure generates within that organisation or network
Business costs	The costs to asset operators associated with asset repair, service restoration or asset resilience measures
Cascade effects	The process through which the disruption of an asset's outputs or services generates economic costs for a separate downstream asset which may or may not be part of the same organisation or network.
Consumer surplus loss	The cost to customers of asset outages because they no longer receive a service that they value. This value is measured by customers' ' maximum willingness to pay for a unit of service, minus the amount they are actually charged for it. Where that unit of service is lost due to an outage, consumers lose all of this incremental value.
Containment measures	Measures which contain the impact of floodwater faults from causing service disruption. Containment measures may further be split into: 1) automatic containment measures (i.e., standby assets or built-in redundancy) and 2) emergency response activities (i.e., deploying resources reactively).
Criticality	A score or ranking assigned to each asset based on the total economic costs to either the asset operator or the system associated with the failure of that asset
Do nothing scenario	The set of outcomes expected as a result of a flood given existing levels of resilience, also known as the counterfactual scenario.
Intervention scenario	The set of outcomes expected as a result of a flood given a change to the existing levels of resilience (i.e., a resilience intervention), also known as the factual scenario.
Negative externalities	The costs to stakeholders when asset outages result in impacts beyond the customers served by that asset (e.g., pollution incidents)
Net economic benefit	The value of a resilience intervention as measured by the economic costs that would have been incurred as a result of a flood event but which are avoided as a consequence of the intervention, minus the upfront investment costs associated with that intervention.
Outcomes	The states of all assets in the system at a point in time, including the services they receive and provide and level of flood damage. Scenarios results in different outcomes which in turn are associated with different economic costs.
Preventative measures	Site-level measures which act to prevent floodwater from reaching critical equipment.
Producer surplus loss	The cost to asset operators as a consequence of not being able to deliver and charge for the same number of units of service that they would have done in usual outcomes.

Key term	Definition
Resilience intervention	An incremental action which increases the ability of an asset to withstand a flood or power outage event or mitigate the economic costs an event would otherwise occur
Siloed view	A resilience planning perspective which only considers net economic benefits that are contained within the organisational or network boundary of the decision-maker.
System	A group of interdependent networks which provide services to one another as well as their own customers.
System view	A resilience planning perspective which considers net economic benefits irrespective of network or organisational boundaries which these benefits are contained within
System-level criticality	The criticality of an asset with respect to total economic costs that its failure generates across the whole system
Tolerance level	An attribute associated with a particular resilience measure, representing either the level of floodwater (for preventative measures) or duration of upstream service outages (for containment measures) which an asset can withstand before it begins to incur economic costs.
Asset operator-level criticality	The criticality of an asset with respect to total economic costs that its failure generates within that organisation or network

Source: Frontier Economics

1 CONTEXT AND SCOPE OF THIS REPORT

1.1 OVERVIEW OF CREDO

CReDo is a climate change adaptation digital twin led by the Connected Places Catapult (**CPC**). CReDo brings together data from across different infrastructure assets to model the impact of extreme weather events, taking account of interdependencies with and across infrastructure boundaries. CReDo can model which assets would be expected to fail as a result of an extreme weather event and how those failures would be expected to propagate to other assets given the dependencies both within and across network boundaries. This cross-sector picture of the impact of extreme weather events can enable asset operators and regulators to make more informed decisions about where best to take action for the benefit of the infrastructure system as a whole.

The current version of CReDo reflects the electricity, water and telecom networks in an area in East Anglia. It includes assets across several key asset classes of Anglian Water Group (AWG), BT and Openreach (BT Group), and UK Power Networks (UKPN), as well as how these assets are connected. The extreme weather events modelled include a range of flood events of different types and severity. Using this information, the current version of CReDo can model the impact that a flooding scenario can have on the electricity, water and telecom infrastructure. For example, it can determine whether a primary power substation would be expected to fail due to flooding, resulting in secondary substation power outages. These power outages could cascade further into the water network, whereby a sewage pumping station stops functioning because of lack of power.

There have been two phases of CReDo development since 2021:

- **Phase 1 (2021-2022).** The first phase of CReDo development launched in April 2021 and was led by the National Digital Twin programme through the Centre for Digital Built Britain partnering with the CPC. In Phase 1, the CReDo team created *a proof-of-concept* connected digital twin. The team used *synthetic data* of the three infrastructure networks in *a specific geographic area of East Anglia* to show the functionality of the CReDo digital twin.[1] Phase 1 modelled the impact of *a specific type of flooding scenario* (i.e., a particular surface water flooding event) on the infrastructure networks.

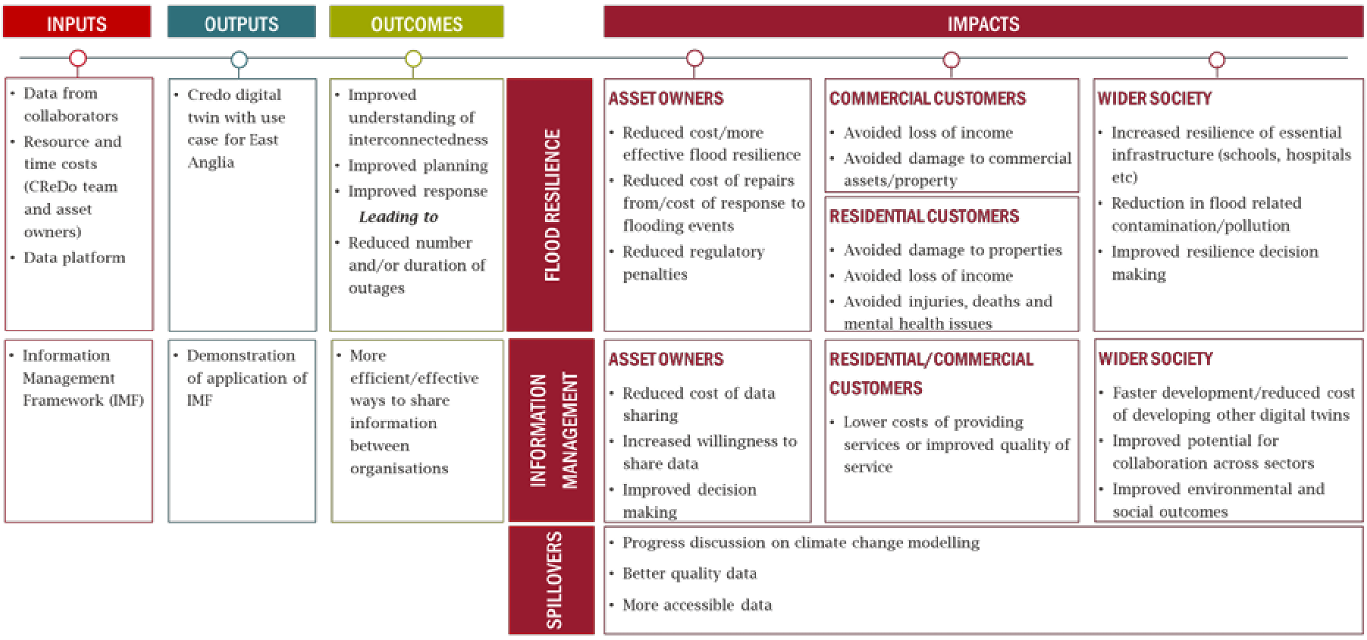
  As part of Phase 1, Frontier Economics (**Frontier**) designed and implemented an economic impact evaluation to simulate the potential net benefits of CReDo. We found that CReDo had the potential to bring a range of benefits to asset operators, their customers and wider society. These benefits can be expected to flow when CReDo is used to support asset operators in planning and responding to flooding events. These are summarised in the logic model in Figure 1 below. Refer to our Phase 1 report for more details.[2]

---

[1] A visualisation of Phase 1 output is available at: https://digitaltwinhub.co.uk/credo/visualisation/

[2] 'Identifying the expected impacts of CReDo, A report prepared for the Centre for Digitally Built Britain' (March 2022, Frontier Economics).

FIGURE 1 LOGIC MODEL OF CREDO PHASE 1



INPUTS

- Data from collaborators
- Resource and time costs (CReDo team and asset owners)
- Data platform

- Information Management Framework (IMF)

OUTPUTS

- Credo digital twin with use case for East Anglia

- Demonstration of application of IMF

OUTCOMES

- Improved understanding of interconnectedness
- Improved planning
- Improved response

Leading to

- Reduced number and/or duration of outages

- More efficient/effective ways to share information between organisations

IMPACTS

FLOOD RESILIENCE

ASSET OWNERS

- Reduced cost/more effective flood resilience
- Reduced cost of repairs from/cost of response to flooding events
- Reduced regulatory penalties

COMMERCIAL CUSTOMERS

- Avoided loss of income
- Avoided damage to commercial assets/property

RESIDENTIAL CUSTOMERS

- Avoided damage to properties
- Avoided loss of income
- Avoided injuries, deaths and mental health issues

WIDER SOCIETY

- Increased resilience of essential infrastructure (schools, hospitals etc)
- Reduction in flood related contamination/pollution
- Improved resilience decision making

INFORMATION MANAGEMENT

ASSET OWNERS

- Reduced cost of data sharing
- Increased willingness to share data
- Improved decision making

RESIDENTIAL/COMMERCIAL CUSTOMERS

- Lower costs of providing services or improved quality of service

WIDER SOCIETY

- Faster development/reduced cost of developing other digital twins
- Improved potential for collaboration across sectors
- Improved environmental and social outcomes

SPILLOVERS

- Progress discussion on climate change modelling
- Better quality data
- More accessible data

Source: 'Identifying the expected impacts of CReDo, A report prepared for the Centre for Digitally Built Britain' (March 2022, Frontier Economics)

- **Phase 2 (2022-2023).** The second phase of CReDo development was launched in April 2022. The focus of Phase 2 has been to develop a working prototype where asset operators can access the real data and insights from CReDo. Phase 2 focuses on the 'planning for resilience' use case. Compared to Phase 1, Phase 2 CReDo relies on *real asset data* and covers *a broader geographic area of East Anglia.* Phase 2 can model the impact of *a number of different flooding scenarios.*

1.2 SCOPE OF WORK

As part of Phase 2, Frontier was commissioned by CPC to develop a methodology to support the development of **CReDo's strategic resilience planning use case for asset operators.** In particular, we were asked to co-develop a methodology that could ultimately be embedded within the CReDo model and would allow asset operators to compare the costs and benefits of different resilience intervention scenarios across a range of flooding scenarios. This was intended to support asset operators being able to decide amongst competing interventions when planning for resilience.

1.3 STRUCTURE OF THIS REPORT

This report summarises our methodology and how it was implemented by the CPC to estimate the benefits of CReDo. The remainder of this report is structured as follows:

- In Section 2, we provide an overview of the Phase 2 methodology, the core development areas which have been taken forwards since Phase 1 and assumptions that we adopted when implementing the methodology to arrive at the case study outputs presented in the report.

- In Section 3, we provide an illustrative set of outputs from case study implementation of the methodology to illustrate how asset operators can use CReDo to inform resilience planning from a system view.
- In Section 4, we discuss development areas for future work that have been identified through the course of the Phase 2 project.

2 OPERATIONALISING CREDO AS A DECISION-SUPPORT TOOL

The objective of this phase of work is to lay the groundwork for CReDo to develop as a decision-support and cost-benefit analysis tool for the strategic resilience planning use case.

CReDo aims to help decision-makers to synthesise large amounts of data into a manageable set of actionable insights. A key benefit of digital twins is their ability to operationalise data to inform decisions in the real world. As well as reading infrastructure and weather data as inputs, CReDo can generate a large amount of data as outputs from the asset failure and system impacts simulation and economic impact evaluation framework.

Asset operators face a set of choices over where and how to allocate their resources to maximise the resilience of their networks. These choices depend on weighing up the anticipated costs and benefits of alternative resilience interventions and identifying those which are expected to deliver the greatest net benefits in light of different climate events.

CReDo can support decision-makers in choosing between different resilience interventions by modelling the costs and the benefits that these interventions would deliver. The costs related to an intervention comprise the capital and operational costs to deploy that intervention; the benefits of an intervention comprise the costs to asset operators and wider society that can be avoided through that intervention (e.g., avoided flood damages, avoided lost economic output, etc.).

CReDo can estimate the costs and benefits of these interventions by considering the impact that the intervention has on the whole system. This '**system-view**' use case is enabled by the fact that CReDo can show which assets across the system of interdependent networks are likely to be flooded, and which of their assets and those of others' fail because of cascade effects which originate and propagate from both within and outside their network boundaries. CReDo can also estimate the costs and benefits of an intervention for a given asset operator by considering only the impacts originating and propagating within an asset operator's own network. We refer to this as a '**siloed-view**' use case. Decision-makers could then use this information to understand the trade-offs between different resilience interventions for the system as a whole and the asset operator's own networks.

To operationalise and evaluate the system-view use case, we developed an economic impact evaluation methodology which allows users to compare the benefits of a range of possible resilience interventions under both the siloed view and the system view. In this section, we describe the steps of this methodology and discuss some of the key development areas. Key technical terms used in this report are defined in the glossary of terms.

The remainder of this section is organised as follows:

- In Section 2.1, we provide an overview of our Phase 2 methodology.
- In Section 2.2, we describe the core development areas of the Phase 2 methodology in more detail.
- In Section 2.2, we discuss the key three developments of Phase 2 in more detail.

2.1 OVERVIEW OF THE PHASE 2 METHODOLOGY

To help asset operators decide amongst competing interventions when planning for resilience, we developed a methodology that allows CReDo users to calculate the net benefits of incremental resilience interventions.

The methodology presented in this section can be applied to a given year and flood scenario. However, when making investment decisions, asset operators are likely to consider the impact that a given intervention has over a given time horizon and under a range of flood events, taking account of the probability of those events occurring and causing damage to their networks. To this end, this methodology could be generalised to take account of a time horizon and include a range of flood events (discussed further in Section 4.1).

For a given flood scenario, our methodology enables calculation of the net benefits of incremental resilience interventions for both the system and each asset operator. The net benefits for the system are calculated as the difference between the costs to the system estimated under the following two scenarios:

1) **A 'do nothing' scenario (i.e., 'counterfactual').** This scenario reflects the current level of resilience of the system. We assume that no additional resilience intervention is made.

2) **A series of 'intervention' scenarios (i.e., 'factual').** This scenario reflects the level of resilience achieved after an intervention on top of the current level of resilience.

Similarly, the net benefits for each asset operator are calculated as the difference between the costs to each asset operator estimated under the two scenarios above.

When estimating the costs, the methodology accounts for network interdependencies and existing levels of resilience. The costs include the repair and restoration of flooded assets, the value of lost economic output to customers caused by outages, externality effects and the cost of any resilience investments or activities undertaken.

This methodology can be implemented in CReDo to enable the decision-support use case. The decision-support use case of CReDo consists of the following five steps:

- In **Step 1**, CReDo combines real data from asset operators in order to simulate the interdependencies and existing levels of asset resilience to flooding or outage events.
- In **Step 2**, CReDo simulates the set of outcomes associated with a selected flood in a 'do nothing' scenario and calculates the economic costs of the flooding event to stakeholders.
- In **Step 3**, CReDo undertakes a criticality assessment of all assets in the system to identify where the greatest vulnerabilities lie.
- In **Step 4**, CReDo identifies different interventions that can improve the resilience of the system to the selected flood and simulates the economic costs associated with the new resilience level provided by the interventions (i.e., the 'intervention scenarios').
- In **Step 5**, CReDo identifies which interventions maximise net benefits given the selected flood.

These steps are summarised in Figure 2 below. We describe each of these steps in turn. There are three key development areas, which we describe in more detail in Section 2.2. These are: modelling current and incremental levels of resilience, determining criticality measures for individual assets and a framework to identify the range of plausible interventions.

FIGURE 2 STEPS THAT ENABLE THE DECISION-SUPPORT USE CASE OF CREDO

1	Characterise network interdependencies and existing levels of resilience	Real network data has been used to characterise the asset interdependencies and their existing levels of structural resilience to floods and service disruptions under a 'do nothing scenario'.
2	Simulate the impact of weather events on network and stakeholder outcomes	CReDo simulates the outcome of a flood with respect to asset outages in a 'do nothing' scenario (i.e., counterfactual), including those directly caused by the flood and those transmitted via cascading service outage effects. These outcomes are then translated into economic impacts, in the form of private costs to asset operators, welfare impacts to customers and externality costs to other stakeholders
3	Assess the criticality of assets across the system and identify key vulnerabilities	CReDo then calculates the criticality of each asset in the system as defined by the total economic impact that its failure has on the system, including impacts transmitted through interdependencies.
4	Estimate the net economic benefit to the system from a range of possible interventions	CReDo sequentially simulates the impact of different combinations of asset-level resilience interventions where each 'intervention scenario' (i.e., factual) increases one or more critical assets' level of resilience (as compared to the 'do nothing' scenario). This creates a long-list of possible intervention options with associated investment costs and economic impacts. Economic impacts are calculated for each year in the modelling horizon (i.e., 2023 to 2050) and aggregated to an expected Net Present Value (NPV).
5	Identify solutions which maximise net economic benefit to each network and the system	CReDo reflects the incremental costs of each intervention scenario to calculate the net benefit which each intervention delivers compared to the 'do nothing' scenario.

Source: Frontier Economics

STEP 1: CHARACTERISE NETWORK INTERDEPENDENCIES AND EXISTING LEVELS OF RESILIENCE

The first step consists of characterising the existing configuration and resilience of the system. The current version of CReDo uses real data on assets, including their within-network and across-network interdependencies. We developed a methodology that allows us to characterise each asset's current level of resilience. We captured existing resilience interventions such as flood defences (so-called 'preventative measures') and automated standby measures already installed (so-called 'containment measures'). This is a key development compared to the Phase 1 model. We discuss these measures in more detail in Section 2.2.1.

STEP 2: SIMULATE THE IMPACT OF WEATHER EVENTS ON NETWORK AND STAKEHOLDER OUTCOMES

The second step consists of determining the impact that a flood has on the current system, assuming that the asset operators continue to operate as usual and no resilience intervention is made.[3] This is the 'do nothing' scenario.

This simulation is done in two steps:

---

[3] Or, equivalently, that any 'business as usual' intervention taken under this scenario will also be taken under the factual scenario.

- First, given a flood and the characterisations of the existing level of resilience made in Step 1, CReDo simulates which assets fail because they are flooded or because of cascading effects.
- Then, CReDo calculates the total economic costs associated with these outages for both the asset operator and the system.

In our methodology, we define total economic costs as the costs incurred by society. We grouped these costs into four categories as described in Figure 3. We describe each of these four categories in turn below, with supporting detail on how these elements are calculated given in Annex A.

FIGURE 3 ECONOMIC COSTS RELATED TO FLOOD THAT WE CONSIDERED

Source: Frontier Economics

Business costs associated with flooding depend on the physical and operating characteristics of the assets that are affected by the flood. Asset operators provided us with estimates of the costs to repair their assets.[4] The costs of asset resilience measures (e.g., the operating costs of an existing containment measure, or incremental costs of an additional preventative measure) are based on business planning assumptions (discussed further in Section 2.2.1).

Producer surplus losses occur as a result of flooding-induced asset outages because the asset operator is unable to deliver and charge for the same number of units of service that they would have done if the asset had been unaffected. For each unit of service that the asset operator is unable to deliver, it loses an amount equal to the price for that unit of service less the (marginal) cost of providing that unit. In practice, this is expected to be a small contribution to total economic costs for the asset operators involved, as the network-tariff component of customer bills is largely fixed with respect to marginal units consumed and the networks' marginal costs are close to zero. We therefore assume that producer surplus for the current set of asset operators is equal to zero.

Consumer surplus losses occur as a result of flooding-induced asset outages because consumers lose something that they value. Typically, consumers will place a value on a unit of service from an asset operator that is at least as high as the price they pay for it (if they value it less than the price, they will go without). Where that unit of service is lost, consumers lose all the value they place on it. Consumer surplus is typically proxied by willingness to pay (WtP) for the unit of service. To proxy the consumer surplus loss associated with each asset outage, we multiply the average WtP for a unit of service from that asset by the number of

---

[4] These estimates are based on the repair costs of vulnerable electrical or mechanical components of those assets (e.g., switchgear, transformers).

customers affected by the outage and the assumed duration of the outage. The duration parameter is based on the assumption that it takes 48 hours for normal service to resume from assets which experience an outage event.[5] The number of customers per asset was sourced from real network data provided by asset operators. The WtP is informed by incentives or penalty rates used by the sector regulators, which are informed by customer research on WtP (discussed further in Annex A).

Negative externalities occur as a result of flooding-induced asset outages if the failure of the asset imposes costs on other groups beyond the asset operators and their customers. In principle, this may include a broad range of spillover effects from asset outages such as environmental degradation (e.g., from sewage overflows), traffic congestion (e.g., power losses to road or rail signalling infrastructure) or public safety incidents (e.g., from loss of emergency services communication infrastructure). The current CReDo model captures the cost of pollution incidents that occur as a result of asset failures caused by flooding. To proxy these negative externalities, we adopt AWG's assessment of these costs on a £/incident basis.

STEP 3: ASSESS THE CRITICALITY OF ASSETS ACROSS THE SYSTEM AND IDENTIFY KEY VULNERABILITIES

The third step involves determining how important each asset is to each of the asset operators and the system, i.e., the 'criticality' of each of the assets. For a given flood, the criticality of an asset is defined as the total economic costs to either the asset operator or the system associated with the failure of that asset. We refer to these as 'asset operator-level' criticality and 'system-level' criticality. Both measures of criticality are based on the total economic costs calculated in Step 2. The criticality measure of each asset will include any costs associated with cascading outages caused by the failure of that asset.

After defining the criticality of each asset, we can compare these criticalities both at the asset-operator level and at the system level. These criticality measures can be used to inform what actions network operators could take to mitigate the expected consequences of the simulated flood event, which is described in the next step.

The definition of criticality is a key development area from Phase 2 and is discussed further in Section 2.2.2. This measure of criticality could be improved in a subsequent phase of work to take account of a range of factors that asset operators consider when assessing the importance of their assets. We discuss this in more detail in Section 4.

STEP 4: ESTIMATE THE NET ECONOMIC BENEFIT TO THE SYSTEM FROM A RANGE OF INTERVENTIONS

The fourth step consists of defining the intervention scenario(s) to be evaluated and estimating the (net) economic benefits associated with these interventions. To do this, we specified a selection rule to identify the range of plausible interventions that could be modelled by CReDo (discussed in more detail in 2.2.3). This would allow asset operators to compare the impact of different interventions.

The set of all possible intervention scenarios to make the system resilient is exponentially large[6] and so computationally intractable. Based on discussions with the asset operators, the current version of CReDo constrains the set of possible solutions by making generalising assumptions for two types of possible

---

[5] This assumption is discussed in further detail in Section 2.3.

[6] For example, if there are 10 assets that fail because they are flooded or because of cascading effects, and if there are three resilience measures that could be implemented at each asset to avoid the asset failing, the total number of possible interventions is more than 1 million (=4^{10}, given that for each asset we can take four actions: do nothing, or make one of the three possible interventions).

intervention for each asset: (i) equipment-level measures, which provide up to 0.4m of flood height tolerance, and (ii) perimeter-level protection measures, which provide up to 0.8m of flood height tolerance.

For each intervention scenario, CReDo identifies whether an intervention exists that increases its resilience beyond the 'do nothing' scenario whilst also preventing it from being flooded. Having identified an intervention which satisfies these criteria, CReDo increases the resilience of the asset(s) that receive the intervention. CreDo then calculates the total economic costs of the flood under that intervention. The economic benefit associated with the intervention is then calculated as the difference between the total economic costs under the 'do nothing' scenario (from Step 1) and the total economic costs calculated under this scenario. The net economic benefit associated with the scenario is calculated by subtracting the cost of the interventions made.[7]

STEP 5: IDENTIFY INTERVENTIONS WHICH MAXIMISE NET ECONOMIC BENEFITS

The last step consists of comparing different intervention scenarios. The intervention which maximises net economic benefit is that which generates the greatest reduction in total economic costs (less the cost of the intervention itself) compared to the 'do nothing' scenario. This can be considered from a system perspective (i.e., across all asset operators and stakeholders) or from each individual asset operator's perspective (i.e., within each asset operator's network and direct stakeholders).

CReDo provides a short list of recommendations based on net economic benefit for decision-makers to consider within the broader context of their network planning such as budget constraints or other feasibility considerations.

2.2 PHASE 2 CORE DEVELOPMENT AREAS

In this section, we discuss three areas which have been the focus of development since Phase 1 (as signposted in Section 2.3). These are:

- **Modelling current and incremental level of resilience** (Section 2.2.1). We defined a taxonomy and data characterisation for resilience measures. This allowed us to model the current and incremental level of resilience of the system. Modelling the current level of resilience was one of the key development areas identified during Phase 1.
- **Determining criticality measures of individual assets with respect to the networks and the system** (Section 2.2.2). We developed measures of criticality from both the system level and the asset-operator level. This allowed us to identify which assets were critical for the system and for different individual asset operators. When making decisions around resilience, some asset operators assess the criticality of their assets. These measures could be added to that toolkit.
- **Designing a framework to identify a range of plausible interventions** (Section 2.2.3). We identified a framework that could be used to identify which sets of interventions could be modelled by CReDo. This would allow asset operators to compare the impact of different interventions.
- **Embedding the economic impact evaluation into CReDo** (Section 2.2.4). We set out a methodology for evaluating the net economic benefit of different resilience interventions for a given flood scenario

---

[7] We note that this calculation of net economic benefits does not account for the probability with which the benefits occur. Taking this probability would be important to evaluate the *expected* net benefit of an intervention. To do so, CReDo requires a reasonable estimate of the probability of the outcome occurring (so-called 'probability of occurrence'). We discuss the conceptual challenges associated with this exercise in Section 4.

(Section 2.1). This methodology has been embedded in CReDo. It combines flood simulation outputs with real data on economic costs which were captured through a generalisable data reporting template. Based on the prescribed methodology and populated inputs, the calculation of net economic benefit for a range of intervention scenarios has been automated within CReDo.

2.2.1 MODELLING CURRENT AND INCREMENTAL LEVEL OF RESILIENCE

One of the key development areas identified during Phase 1 was to model the existing level of resilience of the networks and the system. This is important as, over the years, asset operators have made a number of interventions to make their system resilient to weather events. These existing interventions should be taken into account when deciding whether additional interventions are needed.

To operationalise this, we defined a taxonomy of resilience measures and a generalisable data characterisation. The taxonomy allows us to classify a broad range of measures in different groups with similar characteristics. The generalisable data characterisation allows us to assign to each resilience measure information that is used in the modelling (e.g., cost of installing the measures). This information can be taken from real-world examples. This approach also makes it possible to adjust the characteristics of existing measures or model new measures in the future.

This taxonomy and data structure also allow CReDo to model the existing level of resilience within CReDo under a ‘do nothing’ scenario as well as under an intervention scenario.

TAXONOMY OF RESILIENCE MEASURES

Resilience measures can be broadly divided into three groups, according to who implements the measures: (i) civic infrastructure measures (e.g., river embankment defences); (ii) asset operator-level measures (e.g., asset defences); and (iii) customer-level measures (e.g., household defences). In the current phase, CReDo focuses on asset operator-level measures installed at the site level.[8] Within this group, we distinguish between:

- **Preventative measures.** Measures which act to prevent floodwater from reaching critical equipment; and
- **Containment measures.** Measures which contain the impact of floodwater faults from causing service disruption. Containment measures can further be split into (i) automatic containment measures (i.e., standby assets or built-in redundancy) and (ii) emergency response activities (i.e., deploying resources reactively).

Each of these measures can prevent an asset from being flooded and/or prevent a loss of power, telecoms and water service.

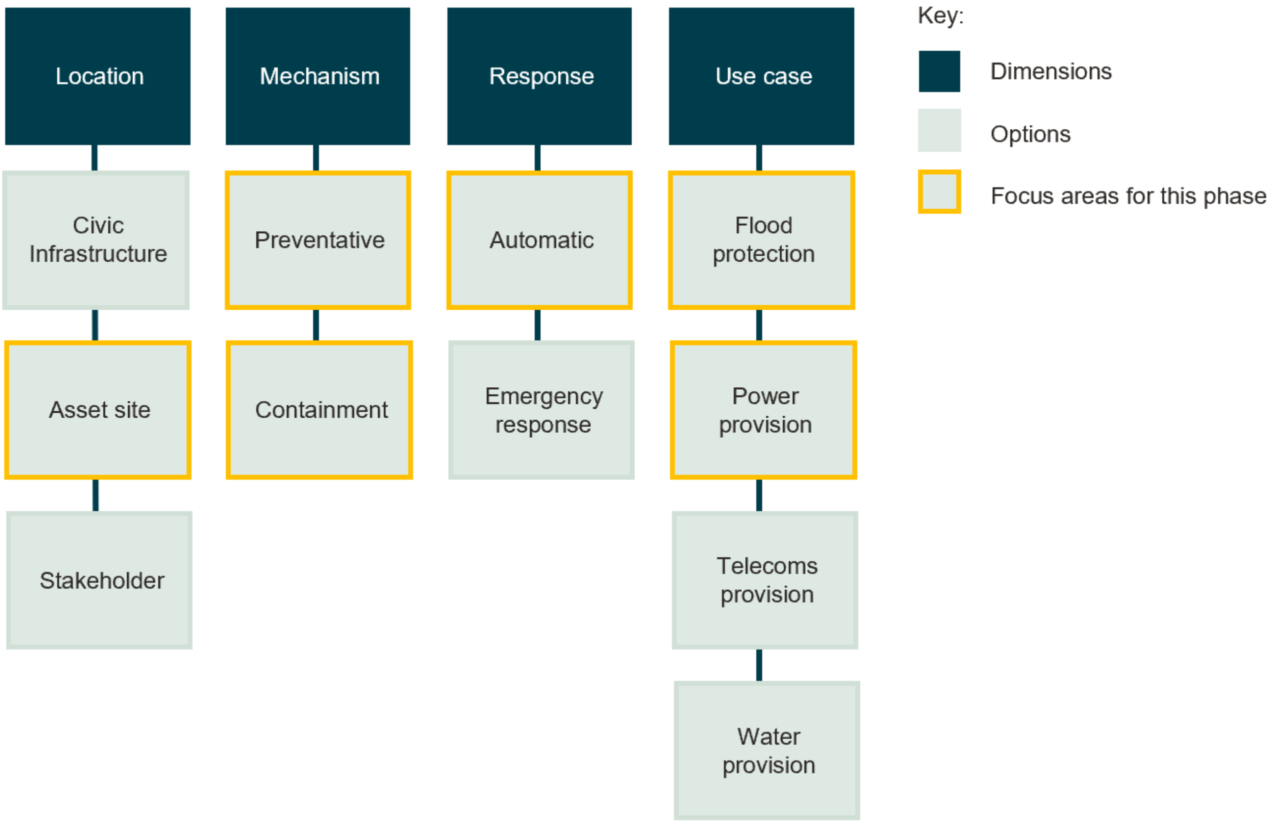
---

[8] We note that, in principle, resilience measures can be targeted at any stage across the sequence of cause and effect through which a flood event results in a stakeholder cost. Indeed, we learned through our engagement that customer-level interventions are also within the remit of actions considered by asset operators (particularly within emergency response activities). In future phases of work, CReDo could seek to broaden its focus to both civic infrastructure and customer-level measures and consider how networks can reconfigure their networks to better cope with climate events in the medium to long term.

In this phase of work, we modelled preventative measures for all asset operators and the subset of automatic containment measures[9] that can be used to prevent a loss of power. We focused on measures to prevent a loss of power, as power outages are likely to cause the largest cascade events to the other networks.[10]

Our classification of resilience measures is represented in Figure 4. The areas we focused on for this phase of work are highlighted in yellow.

FIGURE 4 A TAXONOMY OF RESILIENCE MEASURES



Source: Frontier Economics

ASSET RESILIENCE CHARACTERISTICS

We characterised each preventative and containment measure according to two parameters:

---

[9] Further detail on this scoping decision, the limitations this represents and opportunities for further work are discussed in Section 4.

[10] For this phase of work, we did not focus on measures that can be used to mitigate telecoms and water service outages. Whilst a loss of telecoms or water service can present operating challenges for other asset classes and therefore strengthen cascade effects, this is not expected to have as large an impact as a loss of power. For example, electricity substations and water assets use fixed and mobile communications networks for telemetry and remote operation, but a loss of telecoms network services is not expected to lead to large disruption for electricity or water customers. Likewise, a small subset of telecommunications assets may use water networks for cooling of electrical or mechanical processes (e.g., operating data servers) but may also operate with default airflow cooling. Whilst their services are not directly disrupted, asset operators may still experience operating challenges either in the form of reduced visibility of their asset portfolio or difficulty in deploying emergency response measures in the field to contain an outage event. These effects should be explored in future phases of work.

- The level of tolerance; and
- The cost to implement/deploy the measure.

The level of tolerance is used to characterise the level of resilience that the measure can achieve. Preventative measures are defined by a flood height tolerance (i.e., metres of floodwater), whilst containment measures are defined by an event duration tolerance (i.e., hours of service disruption that can be contained).

The costs of preventative and containment measures are relevant for the economic impact evaluation. In principle, both preventative and containment measures can incur fixed capital costs (per measure installed), variable capital costs (per year of depreciation), fixed operating costs (per year of overhead operations) and variable operating costs (per incident or hour of use case provided).

For this phase of CReDo, we focused on a subset of these costs based on the available data. In the 'do nothing' scenario, we assume that containment measures incur variable operating costs per hour of tolerance called upon (e.g., fuel costs associated with running standby generators). We assume that preventative measures installed in the 'do nothing' scenario do not incur any incremental costs.[11] In the 'intervention' scenarios, we assume that incremental preventative measures incur fixed capital costs per number of interventions (i.e., purchase and construction costs), whilst incremental containment measures incur both fixed capital costs per intervention and variable operating costs per hour of tolerance called upon.[12] The cost data itself is expressed as 'unit costs' to enable the methodology to apply and scale costs according to the simulation outputs.

POPULATING THE DATA

Working with asset operators, we identified a long list of preventative and containment measures for each of their critical asset classes and how these measures provide their resilience use case. From this long list, we collected data on tolerance levels and unit costs which are generalisable at the asset-class level. Unit cost data was sourced from asset operator's historical business planning processes, regulatory submissions and other sources of business intelligence. Data on the tolerance levels of particular measures were sourced from asset operators' historic flood risk assessments and response plans.

This resulted in the short list described in Table 1 below.

TABLE 1 RESILIENCE MEASURES CONSIDERED

Use case	Mechanism	Measure	Applicable asset classes
Flood protection	Preventative	Perimeter floodwall	All (excl. mobile mast site, cabinet)
		Stilted platform	Secondary substation, cabinet
		Internal bunding	All (excl. mobile mast site, cabinet)

---

[11] This is because preventative measures included in the current scope relate to strategic long-lived capital investments. Whilst there may be some ongoing costs associated with these measures (e.g., maintenance), the majority of total costs are sunk.

[12] In the current phase of work, we excluded variable capital costs (e.g., repair and maintenance) and fixed operating costs (e.g., overheads such as labour costs) from consideration. However, in future phases of work this could be revisited to provide a more complete account of the costs associated with system resilience.

Use case	Mechanism	Measure	Applicable asset classes
		Critical component elevation	All
	Containment	Wet well retention	Sewage pumping station
Power provision	Containment	Back-up generation	All (excl. ground water source)
	Containment	Standby battery	Cabinet

Source: Frontier Economics, based on discussions with asset operators

2.2.2 DETERMINING CRITICALITY MEASURES OF INDIVIDUAL ASSETS WITH RESPECT TO THE NETWORKS AND SYSTEM

DEFINITION OF CRITICALITY

For each asset, we defined two measures of criticality related to the flood events simulated:

- **Asset operator-level criticality.** This would allow us to identify the most critical assets from the point of view of the asset operator.
- **System-level criticality.** This would allow us to identify the most critical assets from the point of view of the system. This might provide a different assessment of criticality compared to the asset operator-level criticality (for example, a substation might not be as critical for UKPN as it is for the whole system if that substation powers many of AWG's and BT's assets).

The asset operator-level criticality is defined as the total economic cost *to the asset operator* of that asset experiencing an outage, after accounting for the existing level of resilience. This is based on the framework of total economic costs articulated in Step 2, calculated by iteratively simulating an outage at each individual asset and recording the total economic cost this generates *to the asset operator* (including all costs transmitted via cascading asset failures *within the asset operator's own network*).

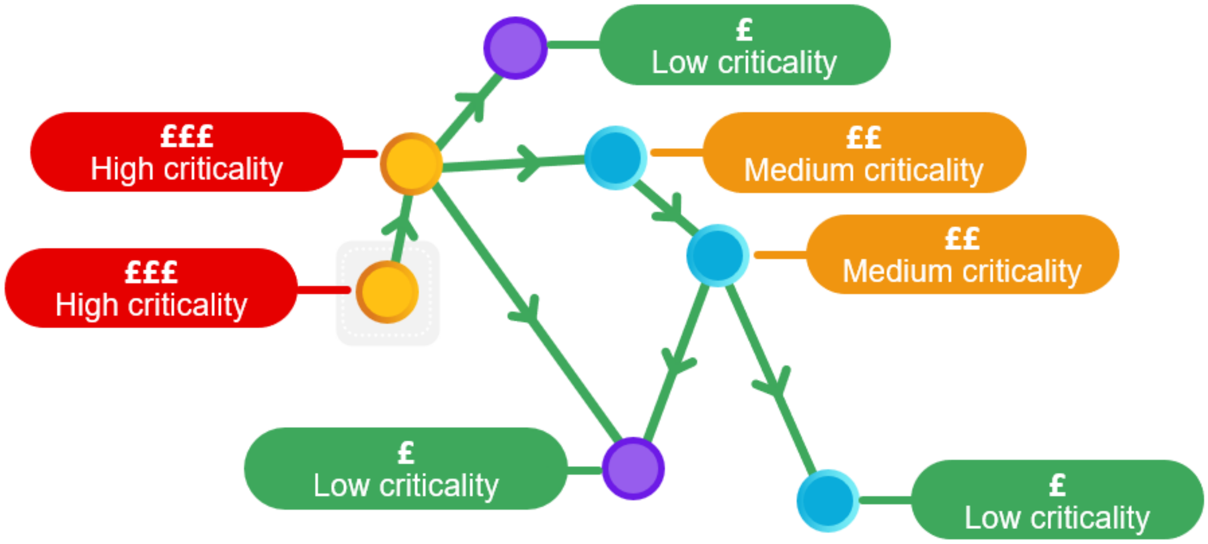
The system-level criticality is defined as the total economic cost *to the system* generated as a consequence of that asset experiencing an outage, after accounting for the existing level of resilience. This is also based on the framework of economic costs articulated in Step 2, calculated by iteratively simulating an outage at each individual asset and recording the total economic cost this generates *to the whole system* (including all costs transmitted via cascading asset failures *throughout the whole system*).

ILLUSTRATIVE EXAMPLE OF SYSTEM-LEVEL CRITICALITY

As an illustration, Figure 5 shows: a hypothetical set of electricity distribution assets (yellow nodes), water assets (blue nodes) and telecoms assets (purple nodes); how essential services flow between these assets; and the corresponding system-level criticality measure. Each asset provides services to its directly connected customers and enables downstream dependent assets to provide services to their own customers.

In the example below, the electricity distribution asset was assigned high criticality for the system due to: (i) the nature and breadth of the essential services it provides to downstream dependencies; and (ii) the lack of effective resilience measures installed on site or at downstream dependent assets.

FIGURE 5 STYLISED ILLUSTRATION OF SYSTEM-LEVEL CRITICALITY



Source: Frontier Economics

HOW THESE CRITICALITY MEASURES COULD BE USED

Some asset operators already make their own assessment of criticality, and these measures could complement that assessment. These measures could then be used by decision-makers to determine the relative importance of different assets for both the asset operator and the system as a whole. For example, an electricity substation's system criticality could be found to be largely driven by the economic impacts felt by telecommunications customers. In turn, this could help to improve the allocation of existing resilience budgets for flood resilience (as reflected in Step 4) and inform how budgets could be leveraged across sector boundaries to reflect the distribution of benefits.

2.2.3 A SELECTION RULE FOR INCREMENTAL INTERVENTIONS

When asset operators decide which resilience interventions to implement, they take account of a broad range of objectives, including the cost of the implementation and the expected benefits of that intervention in terms of avoided costs in case of a flood. To assist asset operators' with their decision-making process, we designed a process that, when implemented in CReDo, would allow them to evaluate and compare the impact of a range of plausible resilience interventions.

This process is divided into two steps:

- **Step 1. Automatically identify all effective combinations of resilience interventions.** This would allow asset operators to consider a range of plausible scenarios.

- **Step 2. Generate summary outputs that asset operators may consider as part of their decision-making process.** This is an important step as the value of the analytics capability of any decision-support tool is constrained by the accessibility of the insights it generates.

The first step is based on a selection algorithm that automatically generates a long list of possible intervention scenarios available to each asset operator. In principle, the algorithm should consider all potential combinations of interventions. The selection algorithm could take account of some constraints. For example, it could rule out interventions that are unlikely to avoid an asset becoming flooded (e.g., because the level of defence they provide is insufficient to prevent the floodwater ingress).

Automating the identification of the interventions reduces the risk that decision-makers will overlook a potentially large number of less salient intervention options. For example, CReDo may ultimately find that it is more cost effective to spread investment across multiple sites rather than undertaking a single intervention at the most critical site. The selection algorithm could consider all these possibilities.

The second step consists of producing a summary of the range of different intervention scenarios. For each scenario, CReDo would produce a summary of the cost of investments as well as the total avoided economic costs to the system and each asset operator. This information could then be enriched with asset operators' own sources of business intelligence and operational knowledge (e.g., emergency response capabilities, which have not been reflected in this phase).

2.2.4 EMBEDDING THE ECONOMIC IMPACT EVALUATION IN CREDO

For CReDo's decision-support use case to be scalable, it is important that the calculation of net economic benefits is extendable to different catchments and contexts. To this end, we designed a generalisable evaluation framework with all the calculations embedded in CReDo which we populated with asset operator data input via a standardised data format and set of cost-reporting templates. From here, CReDo combines these asset operator inputs with the simulation outputs to automatically calculate the economic costs for a selected flood scenario and level of resilience.

Asset operator inputs are defined at the asset level (e.g., customer counts), asset-class level (e.g., capital costs of resilience interventions and flood repair) or service level (e.g., customer willingness to pay from regulatory incentive or penalty rates). The cost-reporting template designed for this phase of work is flexible for application to a broader range of asset classes, resilience interventions and asset operators. Further detail on the inputs used for the economic impact evaluation is provided in Annex A.

2.3 ASSUMPTIONS ADOPTED WHEN IMPLEMENTING THE METHODOLOGY

Given the time available for this project, we adopted some simplifying assumptions when implementing the ideal methodology described in Section 2.1. These assumptions could be relaxed in a future phase of work. The assumptions we made are described in the following section.

THE FACTUAL SELECTION ALGORITHM

As a proof-of-concept, we produced a simplified algorithm designed to define the complete set of feasible intervention scenarios (so-called 'factual selection'). To do this, we narrowed the scope of the intervention scenarios to include only[13] (i) equipment-level flood protection,[14] and (ii) perimeter-level flood protection. We also implemented a simplified selection approach.

For a given flood scenario, this proof-of-concept selection algorithm does the following:

- First, it ranks all assets according to their criticality.
- Second, it considers the subset of X assets that are flooded in the 'do nothing' scenario.
- Third, it defines X intervention scenarios. In the first scenario, only the most critical asset is made resilient. In the second scenario, the top two most critical assets are made resilient, and so on. In the X^th^ scenario, the top X most critical assets are made resilient.

In other words, the set of intervention scenarios is defined with each scenario successively increasing the resilience of flooded assets in descending order of their system criticality. For example, the first scenario increases the resilience of the most critical asset that flooded, the second scenario increases the resilience of the top two most critical assets that flooded, and so on.

This algorithm is applied both at the system level (i.e., using the system-level view of criticality) and for each of the asset operators (i.e., using the asset operator-level view of criticality). This results in two sets of intervention scenarios:

- **System-view intervention scenarios**. These are the interventions identified by applying the system-level view of criticality.
- **Network-view intervention scenarios.** These are composites of each of the individual asset operator-view factual scenarios. For example, each asset operator has its own series of factual scenarios which it can implement independently of each another. This means that the total number of network-view factual scenarios consists of all possible combinations of scenarios across these three sets. To operationalise this, we restricted the composite set by assuming that asset operators make their top X scenarios resilient at the same time.[15]

This simplified proof-of-concept decision algorithm approach constrains CReDo's ability to identify optimal interventions as it will not consider the many thousands of combinations which fall outside of the rule. We consider this to be a development area for further work.

---

[13] We also worked with asset operators to populate a set of incremental containment measures, their tolerance characteristics and costs. However, due to time constraints, this information is not reflected in the set of interventions considered in this phase of work. We discuss this further in Section 4.

[14] This is a group of measures situated within the perimeter of the asset site which are targeted at particular critical components. This includes preventative measures such as stilted platforms, internal bunding and critical component elevation as well as all containment measures (as reported in Table 1).

[15] For example, the first UKPN scenario increases the resilience of the most critical flooded UKPN asset, the second UKPN scenario increases the resilience of the top two most critical flooded UKPN assets, and so on. This is repeated for AWG and BT. We then assume that each asset operator concurrently implements each scenario from its individual set. For example, the first composite scenario reflects UKPN, AWG and BT Group implementing their first scenarios, the second composite scenario reflects UKPN, AWG and BT Group implementing their second scenarios, and so on.

ASSET-LEVEL DATA

In this phase of work, we focused on a subset of each asset operator's most critical asset classes which are currently reflected in CReDo. For UKPN, this includes primary substations and secondary substations. For AWG, this includes sewage pumping stations, water recycling centres, ground water sources, water treatment works and water pumping stations. For BT, this includes tier 1 exchanges, mobile mast sites and cabinets.

For all asset operators, only a subset of 'do nothing' resilience measures are reflected within their existing asset register data (as summarised in Table 1). Other measures, most notably operational response measures which asset operators currently deploy to mitigate impacts of disruption (discussed further in 4.2), could be included in future work.

For UKPN and AWG, we associated each asset with the number of customers served by that asset. The number of customers varies by location and asset. For BT, we assumed an even distribution of customers across its fixed assets. The data agreement with BT Group did not allow for that information to be shared. Future data sharing architectures and technologies should enable operators to use all information at their disposal to make the best decisions. This could be considered in a future phase of work.

The current version of CReDo maps the interdependencies between UKPN, AWG and BT's fixed telecommunications network. Data on the connections from BT's mobile network assets to other networks (e.g., electricity distribution, water, etc.) was not available at the time this document was produced. We therefore omitted the BT Group mobile network from the current implementation.

FLOOD DATA

Flood data was provided by Fathom Global in the form of a set of flood hazard maps. These maps were parameterised by the return period (i.e., average time or an estimated average time between events), representative concentration pathway (i.e., the greenhouse gas concentration trajectory) and year of forecast.

Overall, these maps provide the probability that the flood depth exceeds a given value at 10m grid resolution, with the exceedance probability given by the return period. For example, the 1-in-100 year flood hazard map (for a given simulation year and representative concentration pathway) provides the maximum flood depth that is exceeded in only 1% (1/100) of simulated flood runs, for each point in space.

We understand from the CPC that flood hazard maps may not be optimal for the current use case. This is because the flood hazard data is aggregated over a set of simulated flood runs and, as a result, the dynamics (i.e., time component) of each individual run are lost. Instead, the maximum flood depth per run is aggregated at each point in space.

As a consequence, we understand that this aggregation loses the spatial correlation of the flood depth at each run, although some residual correlation is believed to be retained. We do not have a good quantification of the error introduced by this process. By losing the dynamics of the flood, it is difficult to approximate the expected duration of future flooding events.

REFLECTING TIME DURATIONS OF FLOODS AND OUTAGES

In the current phase of work, an outage caused by a flood or cascading effect is assumed to last for 48 hours for each asset operator. This is a simplifying assumption adopted in lieu of an explicit time dimension modelled within CReDo, based on the primary restoration targets for asset outages as defined in the relevant standards of performance and codes of practice.[16] We assume that asset operators meet this 48-hour target on average and, therefore, a typical outage incident involves a service disruption of this duration.

In future phases of work, we recommend that the dynamics of the flood and operational responses to the event are captured within the modelling of service disruption duration.

Aside from this, it should be noted that we did not model how the duration properties of asset-level containment measures themselves would propagate throughout the network as part of a cascading outage event.

---

[16] In particular, 48 hours represents the threshold duration beyond which penalties apply for customer disruptions. This is set out in the Guaranteed Standards of Performance targets from Regulation EGS11B (R7) from ED1 (electricity distribution) 17F and 9 from PR19 (water supply) and the industry voluntary code of practice for fixed telecommunications services. We note that this threshold (48 hours) can vary depending on the circumstances of the interruption as defined by the relevant regulation, and may be greater or lower in practice.

3 IMPLEMENTATION OUTPUTS FROM PHASE 2

As described in Section 2, we developed a methodology to support the development of CReDo as a decision-support tool for asset operators. This methodology was implemented in CReDo and a range of outputs were produced to illustrate how CReDo could be of value to asset operators. In this section, we present two high-level outputs:

1. **Comparing asset criticality between a system perspective and an individual asset operator perspective**. Asset operators could use this information to complement their own assessments of the criticality of their assets by comparing the impact of flooded assets from a system perspective and a network perspective. In the future, this information could help to decide how to allocate resources to deliver the highest benefits to the system.

2. **Comparison of benefits from resilience interventions that are selected from a system perspective versus an individual asset operator perspective**. Asset operators could use this information to complement their assessment of the costs and benefits of different resilience interventions by comparing the economic benefits under a 'CReDo' approach with those under a 'siloed' digital twin approach. This could also be used in future to leverage investments across sector boundaries.

The current version of CReDo also produces a range of other outputs which decision-makers might find helpful. These include: (i) the origination points and transmission pathways of the cascading asset outages; (ii) the share of an investment's benefits that are attributable to different customer and stakeholder groups (and therefore implications for cost recovery); and (iii) the choice of resilience investments themselves and their budget implications. We do not present these outputs in this report for confidentiality reasons.

3.1 HOW TO INTERPRET THESE OUTPUTS

The outputs presented in this section represent an illustrative case study for a selected flood with a simplified and stylised set of resilience intervention scenarios. The objective of this case study is to illustrate how CReDo can evaluate different courses of action from different perspectives of asset criticality based on the asset and resilience measure data made available by AOs during this phase of work. Whilst the outputs themselves are not intended to represent quantification of the benefits of CReDo, they demonstrate circumstances where a system measure of criticality can lead to different outcomes.

The case study is based on a 1-in-500 year coastal flood scenario simulation, which is assumed to take place in a given year after a resilience intervention has taken place.[17] This flood scenario has been selected as an illustrative example based on the balance of directly flooded assets and cascading asset outages that result from the simulation. The intervention selection strategy (discussed in Section 2.3), shows a subset of the total intervention scenarios which asset operators could take across either a system perspective or network perspective but not necessarily those which maximise net economic benefits.

---

[17] A 1-in-500 year flood can be interpreted as having a probability of 0.02% that a flood as severe as this takes place in a given year. We understand that the impact of flood scenarios with large return periods have greater uncertainty due to the lack of historic data informing them. The selection of flood scenario is therefore for illustrative purposes rather than intended to be representative.

3.2 COMPARISON OF CRITICALITY

For the flood scenario considered, CReDo simulates that, without any additional intervention, 79 assets fail as a consequence of flooding, with a further 230 experiencing failures due to cascading outage effects. This is estimated to generate £26.7m of total economic costs to the system under the 'do nothing' scenario.

The assets that are flooded have different levels of criticality for the system and the asset operators. This is shown in Table 2 below. The table compares the top 12 most critical assets for the system with the assessment of criticality that CReDo assigns to these assets from an asset operator perspective. The most critical assets have a ranking of 1, the second most critical assets have a ranking of 2, etc.

The table shows that the assessment of criticality can change according to whether the system view or network view is considered. For example:

- From UKPN's view, primary substation 02 is more critical than secondary substation 01. However, from a system's view, secondary substation 02 is more critical as it provides power to critical assets of AWG and BT.
- From AWG's view, water pumping station 01 is the second most critical asset in its network, but, from a system's view, that sewage pumping station is the top fourth most critical asset.

Given the intervention scenarios considered, this implies that UKPN will prioritise primary substation 02 in its allocation of resilience resource despite the system benefiting relatively more from secondary substation 01. This is because, from the perspective of UKPN, the economic costs associated with an outage of primary substation 02 are larger than for secondary substation 01, despite the economic costs of the latter being larger for the system (i.e., after reflecting the impacts this has on AWG and BT). AWG, on the other hand, will prioritise investment in water pumping station 01 despite the system benefiting relatively more if this resource had been allocated to UKPN's most critical secondary substations.

CReDo produces tables similar to the one below for a range of different flood scenarios. A future version of CReDo could produce this table taking account of the aggregated impact of a range of likely scenarios over a given time horizon.

TABLE 2 CRITICALITY RANKINGS OF FLOODED ASSETS

Asset	System	UKPN	AWG	BT
Primary substation 01	1	1		
Secondary substation 01	2	3		
Primary substation 02	3	2		
Water pumping station 01	4		1	
Secondary substation 02	5	4		
Secondary substation 03	6	5		
Secondary substation 04	7	6		
Secondary substation 05	8	7		
Secondary substation 06	9	8		
Secondary substation 07	10	9		

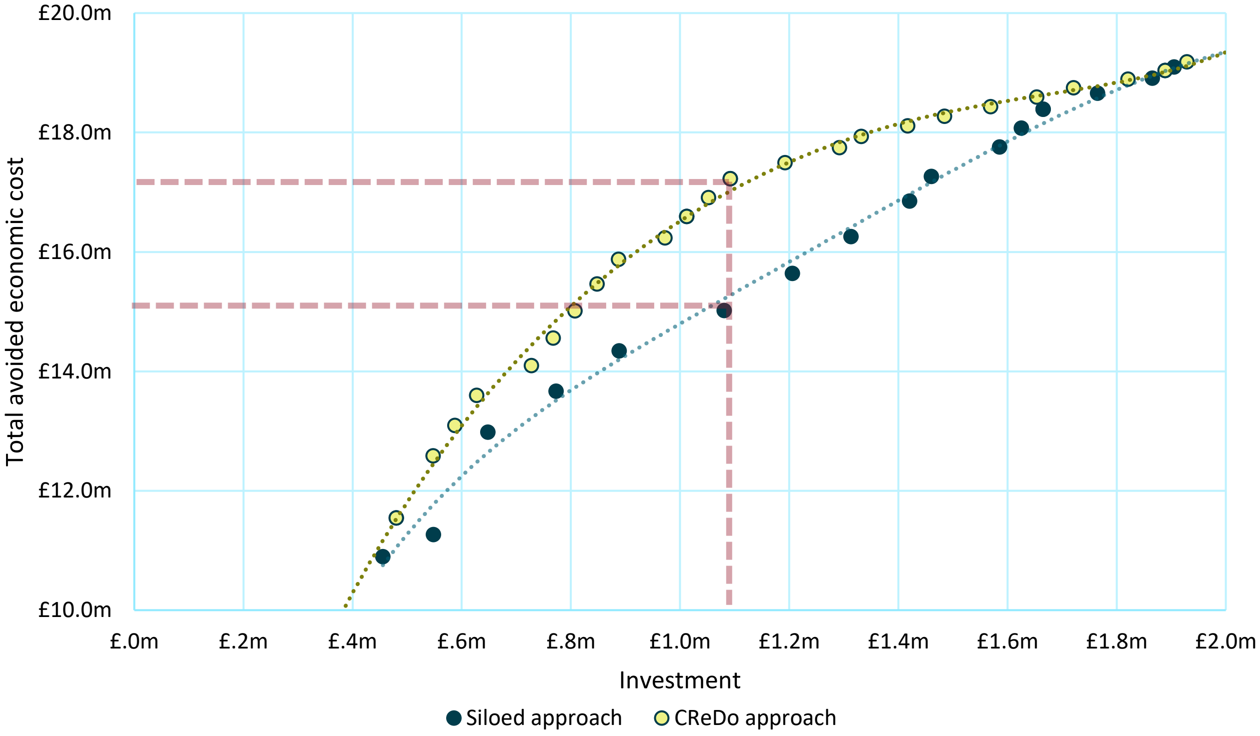
Source: Frontier Economics

3.3 ILLUSTRATION OF INVESTMENT BENEFITS

For the illustrative flood scenario considered, we compared the intervention outcomes that can be achieved for a given level of investment according to a system view of criticality compared to a network view of criticality.

Figure 6 below plots the total economic benefits associated with each intervention scenario against the investment made in that scenario. The set of investments undertaken in each scenario is informed by the criticality ratings presented in Table 2 . For example, under the CReDo approach, each data point (in yellow) represents an intervention scenario characterised by a set of investments in the most critical assets from a system view.[18] Under the siloed approach, each data point (in blue) represents an intervention scenario characterised by an investment by each individual asset operator in its own most critical assets.

FIGURE 6 CASE STUDY OF A 1-IN-500 YEAR COASTAL FLOOD WITH STYLISED RESILIENCE INTERVENTION STRATEGY, FROM A SYSTEM VERSUS SILOED VIEW OF NETWORK CRITICALITY



Source: Frontier Economics

In this illustrative example, we find that different assessments of criticality may lead to different priorities for a given amount of investment. For example, with total economic costs of £27.6m in the 'do nothing' scenario, we estimate that an investment of £1.1m would mitigate £15.0m of these costs if each individual asset operator pursued its independent intervention scenarios (i.e., 'siloed approach'), whilst £17.2m of these costs would be mitigated if this investment was based on the system intervention strategy (i.e., 'CReDo approach').

---

[18] In particular, each data point is characterised by an investment in the top n assets where n [1,10] leads to 10 data points.

As discussed further in Section 4, CReDo does not currently reflect a number of factors such as the potential benefit that making this investment could deliver across a broader range of floods and the likelihood of these outcomes occurring. A further relevant consideration could also be the budget constraints of the asset operators.

4 DEVELOPMENT AREAS FOR FUTURE PHASES OF WORK

In this section, we summarise two key areas of development that could enhance CReDo as a decision-support tool and that could be investigated in future phases of work:

- Estimating the impact of interventions over time and across flood scenarios; and
- Scope of resilience measures considered.

We describe these areas below.

4.1 AGGREGATING ACROSS FLOOD SCENARIOS AND OVER TIME

In Phase 2, the economic impact evaluation set out to calculate the costs associated with the damages caused by a particular flood. This would allow asset operators to compare the avoided costs across a range of interventions for that flood.

In principle, a profit-maximising asset operator would evaluate whether to undertake an investment by weighing up ex ante (i) the upfront cost of that investment, and (ii) the stream of probability-weighted benefits (or avoided costs) that an investment is expected to deliver across the economic lifetime of that asset.[19] This can be achieved by calculating the expected net present value (ENPV) of benefits accrued across a particular time horizon (e.g., 2023 to 2050).

An ENPV calculation allows decision-makers to compare and aggregate uncertain streams of present and future costs and benefits by adjusting for the probability of their expected to occurrence and their relative time value. The probability that these costs and benefits will occur depends on the probability of a particular flooding outcome,[20] whilst time value is based on the preference that decision-makers give to present benefits over future benefits.[21]

The probability of occurrence is, however, complex to estimate as a number of different events could lead to a particular outcome, but we only observe the probability associated with one event (i.e., a 1-in-500 year flood). However, the probability of occurrence of this event (i.e., 1/500 or 0.2%) may be a poor proxy for the probability of occurrence of the resulting outcome. For example, some of the damages caused by a 1-in-100 year flood (which has a probability of occurrence of 1%) are likely to also be caused by a 1-in-250 year flood (which has a probability of occurrence of 0.4%) (and so on).

In the longer term, it may be possible to run very large numbers of flood scenarios but, for the more immediate future, decision-support systems are likely to need to be more pragmatic and based on a limited

---

[19] In practice, an asset operator's investment business case may include broader strategic objectives beyond the direct net economic benefit (e.g., reputational impacts, distributional considerations, etc.)

[20] A flooding outcome is defined by the set of physical attributes of a flood scenario which affect the states of assets in the system at a point in time, including the services they receive and provide and level of flood damage. Scenarios result in different flooding outcomes which in turn are associated with different asset states and economic costs.

[21] As an example, the policy appraisal and evaluation guidelines prescribed by *HMT Green Book* indicate that future costs and benefits should have a 'discount factor' of 3.5% applied for each year into the future that they are expected to occur.

number of flood scenarios.[22] A report commissioned by Ofgem[23] provides thoughts on how this might work in practice, particularly on how to proceed when only a limited number of scenarios can be run. For the purposes of this project, we instead focused on calculating the net benefits for a given flood scenario assuming that that flood scenario takes place.

4.2 EXTENDING THE SCOPE OF RESILIENCE MEASURES CONSIDERED

Asset operators emphasised that resilience planning includes both strategic capital investments and operating response measures. This can include the deployment of mobile resources (e.g., electricity generators) to those affected by an incident or rediverting network flows to bypass areas of the network where there are problems.

For example, UKPN can isolate a faulty substation by reconfiguring the surrounding network via transformer switching and ‘back-feeding’ unaffected substations located downstream to maintain their power supply. AWG can also re-direct water flows by adjusting the configuration of valves at the borders of neighbouring distribution zones (so-called ‘re-zoning’) or can even transport water by vehicle to bypass faulty in-line pumping stations (so-called ‘tankering’). Similarly, for BT, the flow of communications data can be diverted around exchanges experiencing faults through alternative network pathways (so-called ‘dual-backhauling’).

In all of these cases, operating measures are deployed by skilled technicians who evaluate the specific network context, determine access routes to affected assets and evaluate actions that can mitigate service interruptions. To accurately model the impact of these measures, it would be necessary to consider a number of factors such as response times, site access and other operational considerations which affect the decision-making processes. Within the time available for this project, we were not able to collect realistic data to support this. This is an important area of development for future phases of work

---

[22] We understand that a 1-in-X year flood for a particular location does not alone define a single scenario, which also depends on temporal and geographical factors. It is also possible that, as more and less probable scenarios are added, the sum defining an expected ENPV may converge very slowly if the damage costs grow rapidly as events become rarer.

[23] Zachary, C.J. Dent and S. French, ‘Decision making for future energy systems’, Section 5.2 and Endnote 12.

ANNEX A: TECHNICAL APPENDIX

This is a technical appendix to the 'CReDo Phase 2: Developing decision support use cases', a report prepared for the Connected Places Catapult by Frontier Economics. This technical appendix includes a description of the economic cost calculations (A1) and the data templates used to populate the inputs to these calculations (A2).

A1: CALCULATION OF TOTAL ECONOMIC COST

In this section, we set out how the avoided total economic costs are calculated for a given year and flood simulation. The calculations of costs are applicable to the factual and counterfactual scenarios and are also the basis for the calculation of the asset-level criticality measures.

TOTAL ECONOMIC COSTS

For a given year and flood event, the expected total economic cost is calculated as follows:

$$C_{flood^{total}} = \mathrm{c}_{\mathrm{surplus}^{\mathrm{p}}} + \mathrm{c}_{\mathrm{surplus}^{C}} + \mathrm{c}_{\mathrm{externalities}} + \mathrm{c}_{\mathrm{business}}$$

Where;

i. $\mathrm{c}_{\mathrm{surplus}^{\mathrm{p}}}$ is the value of lost producer surplus;
ii. $\mathrm{c}_{\mathrm{surplus}^{C}}$ is the value of lost consumer surplus;
iii. $\mathrm{c}_{\mathrm{externalities}}$ is the societal cost of negative externalities; and
iv. $\mathrm{c}_{\mathrm{business}}$ is the private cost to asset operators (AOs) of maintaining service provision.

We specify in more detail below how each of the above terms is calculated.

LOST ECONOMIC SURPLUS (SUM OF PRODUCER AND CONSUMER SURPLUS)

We proxy the total cost of lost economic surplus (i.e., combining both consumer and producer surplus) based on customers' willingness to pay (WtP) per unit multiplied by the volume of lost output. We note that this approach is expected to overestimate total welfare loss by assuming that the marginal cost of lost output is zero.[24]

To estimate this, we multiply an asset-level 'output' variable by its respective economic benefit. In practice, we use asset-level data on the number of customer connections per asset ID (i.e., the output) and the average value that each customer places on one hour of that service (i.e., the benefit), multiplied by the duration of the simulated service disruption

---

[24] In practice, marginal cost data is not available (and often not observable). However, we note that in the context of the current asset operators, marginal costs constitute a relatively low share of total costs, with the majority being fixed. By adopting this simplifying assumption, we can calculate the value of the economic surplus.

(i.e., 48 hours, by assumption). The number of customers may also depend on the year under consideration and could be simulated to increase as the population grows over time.

The cost of lost economic surplus is calculated by:

$$c_{surplus,t} = \sum_{k}^{K}\{outage_{k,t} \cdot customers_{k,t} \cdot wtp_{k} \cdot \mathrm{duration_{k}} \cdot (\mathrm{duration_{k}} > \mathrm{tolerance_{prevent,k}})\}$$

Where;

i. $\boldsymbol{outage_{k,t}}$ is a binary variable generated as an output from the flood simulation, which is equal to 1 if asset k experiences an outage caused by on-site flooding or a cascading service outage effect, and zero otherwise;
ii. $\mathbf{customers_{k,t}}$ is the number of customers of asset k in the year considered;[25]
iii. $\mathbf{wtp_{k}}$ is the average customer's WtP for an hour of the services delivered by asset k (i.e., £/customer/hour).
iv. $\mathbf{duration_{k,t}}$ is the asset-level outage duration which is assumed to be 48 hours;[26] and
v. $\mathbf{duration_{k}} > \mathbf{tolerance_{prevent,k}}$ is a binary variable for each asset, which is equal to 1 where the flood duration (in hours) at the site of asset k exceeds that asset's containment tolerance level, and 0 otherwise;

The key parameter in this calculation is $\mathbf{wtp_{k}}$ as this enables us to compare and aggregate the costs of different types of service disruption across different groups of customers. WtP estimates are taken from industry and regulatory research which is used to inform financial incentive mechanisms (output delivery incentives, or ODIs) that reward/penalise AOs for over/underperformance across a range of outcome measures.

Financial incentives are transmitted through 'incentive rates', which aim to proxy the marginal (dis)benefit of a defined outcome based on customers' WtP (or to avoid) this outcome. There are a number of potential outcomes which are relevant for outcomes related to service disruption. In the current phase of CReDo, we focus on a subset of these as defined in the prevailing regulatory frameworks for each sector.

For UKPN, these outputs and accompanying incentive rates are defined by the RIIO-ED1 regulatory framework and include a measure of 'customer minutes lost'. For UKPN's EPN licence area, the relevant incentive rate is £1.29m per average customer minute lost,[27] which

---

[25] Customers in year t can be calculated by scaling up the customer counts recorded in 2022/23 by expected regional population growth estimates for future periods. For AWG and UKPN, this is based on actual customer number counts assigned to each asset. As comparable data was not available for BT, we instead distributed customers across assets such that (i) each asset within a particular asset class had an equal number of connections and (ii) each asset class had an equal number of connections.

[26] This assumption is discussed in Section 2.3

[27] UKPN ED1 Business Plan Annex 2F, available at: https://library.ukpowernetworks.co.uk/Library/GetPdf?pdfUrl=Main_Business_Plan_Documents_and_Annexes%2FUKPN_Quality_of_Supply_Strategy.pdf

amounts to a WtP of £20.92 per hour of outage per property.[28] As the original incentive rate figure was published in 2014 and is due to be renewed in May 2023, we apply inflation (CPIH) over the period until 2022 resulting in a value of £25.21.

For AWG, the PR19 regulatory framework includes ‘water supply interruptions’. For AWG, the relevant incentive rate is £1.146m per average customer minute lost[29] which amounts to a WtP of £32.51 per hour per property[30].

For BT, as there are no relevant regulatory incentive payments for service outputs, we instead adopt the industry voluntary code of practice compensation payments for interruptions to fixed broadband and voice services as a proxy for marginal benefit. This amounts to £8 per hour per customer connection.[31]

EXTERNALITIES

In the current context, externalities are defined as costs which arise as a consequence of market activity and which affect stakeholders who are not party to the transaction. In this phase of work, we focus only on the externality costs generated by failure of wastewater assets in the AWG network, particularly pollution incidents caused by wastewater treatment facilities.[32]

Unlike the calculation of lost consumer surplus, the failure of a wastewater asset does not necessarily transmit a particular detriment to the group of customer premises receiving a service from that asset. Instead, externality costs affect any stakeholders (including those connected or not connected to the asset) who are either physically disrupted or mentally distressed by an externality incident.

As part of the regulatory and business planning processes, AWG uses a set of ‘consequence costs’ that proxy society’s WtP to avoid different types of externality impacts from potential wastewater asset failures. These unit costs are specified on a per-incident rather than on an hour-per-customer basis.

The cost of externalities is calculated by

$$c^{i}_{\text{externalities},t} = \sum_{k}^{K} p_{k}^{e} \cdot (\text{outage}_{k,t} \cdot \text{wtp}^{e})$$

---

[28] £1.29 divided by 3.70m customer connections in EPN licence area, multiplied by 60 minutes.

[29] Anglian Water annex, PR19 Final Determinations, available at: https://www.ofwat.gov.uk/wp-content/uploads/2019/12/PR19-final-determinations-Anglian-Water-%E2%80%93-Outcomes-performance-commitment-appendix.pdf

[30] £1.146m divided by 2.115m total household and non-household water connections, multiplied by 60 minutes.

[31] https://www.ofcom.org.uk/__data/assets/pdf_file/0026/216962/Industry-Code-of-Practice-for-Automatic-Compensation.pdf

[32] Other externality effects which could be considered in further work include compliance failures caused by water treatment facilities and sewage overflows (internal and external) caused by sewage pumping stations.

Where;

i. p_k^e is the probability that the failure of asset k results in externality e;
ii. $outage_{k,t}$ is equal to 1 in period t if asset k experiences an outage; and
iii. wtp_k^e is the WtP of society to avoid an externality incident e.

BUSINESS COSTS

Incremental business costs include (i) repair and restoration of assets, and (ii) costs of resilience measures. Within each of these cost categories there are up to four sub-components: fixed capital costs (e.g., construction of assets), variable capital costs (e.g., maintenance of assets), fixed operating costs (e.g., overhead labour costs) and variable operating costs (e.g., fuel costs).[33]

To simplify, we assume that repair and restoration costs only include the fixed capital costs associated with repairing flood-damaged assets, whilst resilience measures incur variable operating costs in the counterfactual (i.e., assuming investments are already sunk) and both fixed capital and variable operate in the factual.[34] Unit cost data is taken directly from each AO's own cost assessments.

The business costs are calculated by:

$$
\begin{aligned}
c_{business} = \; & \textstyle\sum_k^K \{capex_{repair,k} \cdot (flood_k > tolerance_{prevent,k}) \\
& opex_{contain,t} \cdot duration_k \cdot (duration_k > tolerance_{prevent,k})\} \\
& + capex_{prevent,t} \cdot
\end{aligned}
$$

Where;

i. $Capex^i_{repair,k,t}$ is the capital cost of replacing asset k in period t;
ii. $flood_k > tolerance_{prevent,k}$ is a binary variable for each asset, which is equal to 1 where the flood depth (in metres) at the site of asset k exceeds that asset's preventative tolerance level, and 0 otherwise;
iii. $duration_k > tolerance_{prevent,k}$ is a binary variable for each asset, which is equal to 1 where the flood duration (in hours) at the site of asset k exceeds that asset's containment tolerance level, and 0 otherwise;
iv. $opex^i_{contain,t}$ is the operating cost per hour of containment provided by containment measures installed at asset k in period t;
v. $duration^i_k$ is the hours of flooding event or upstream outage event impacting asset k in period t; and

---

[33] In this context, 'variable' is defined with respect to an additional unit (e.g., hour) of a resilience measure's use case.

[34] In this phase of work, we do not consider the costs associated with restoring services outside of a flood-induced fault but note that, in some circumstances, there are also costs associated with reactivating an asset following a cascading outage.

vi. $\text{capex}_{\text{prevent},t}$ is the capital cost of incremental preventative resilience measures installed in the factual scenario.

A2: DATA REPORTING TEMPLATES

In this section, we set out the templates used to populate the inputs for the calculation of total economic costs, with the value field header assigned the name of the term from the relevant formula described in A1. We have redacted the values derived from data submitted by individual asset operators due to commercial sensitivity of this information. All other values are derived from publicly available information, as explained in A1.

TABLE 3 WILLINGNESS TO PAY ESTIMATES

Asset Operator	Asset Class	Disruption	wtp_k	Unit
UKPN	Secondary Substation	Power outage	25.73	£/property/hour
AWG	Water Pumping Station	Water supply outage	32.51	£/property/hour
BT	Tier 1 Exchange (MSAN)	Loss of fixed and mobile service	8.06	£/customer/day
BT	Cabinet	Loss of fixed copper service	8.06	£/customer/day

Source: Figures based on publicly available inputs from UKPN Business Plan (2015 to 2023) Annex 6: Quality of Supply Strategy (link) for UKPN, PR19 Customer Facing ODI Rates and Company Statistics (link) for AWG and Ofcom Industry Code of Practice for Automatic Compensation (link) for BT.

TABLE 4 EXTERNALITIES

Asset Operator	Asset Class	Disruption	wtp^e	Unit
AWG	Sewage Pumping Station	Sewage overflows (internal)	46,157	£/property/incident
AWG	Sewage Pumping Station	Sewage overflows (external)	4,770	£/asset/incident
AWG	Water Recycling Centre	Pollution incident (Cat 3) – first time offence	38,310	£/asset/incident

Source: Figures based on publicly available inputs from PR19 Customer Facing ODI Rates and Company Statistics (link)

TABLE 5 REPAIR COSTS

Asset Operator	Asset Class	Sample statistic	$\mathrm{capex}_{\mathrm{repair},k}$	Notes
UKPN	Primary Substation	Mean	[REDACTED]	Average replacement cost specified at asset class level
UKPN	Secondary Substation	Mean	[REDACTED]	Average replacement cost specified at asset class level
AWG	Sewage Pumping Station	Min	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Sewage Pumping Station	Mean	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Sewage Pumping Station	Max	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Recycling Centre	Min	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Recycling Centre	Mean	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Recycling Centre	Max	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Ground Water Source	Min	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Ground Water Source	Mean	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Ground Water Source	Max	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Treatment Works	Min	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Treatment Works	Mean	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Treatment Works	Max	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Pumping Station	Min	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Pumping Station	Mean	[REDACTED]	Use asset-level data provided by AWG where available
AWG	Water Pumping Station	Max	[REDACTED]	Use asset-level data provided by AWG where available
BT	Tier 1 Exchange (MSAN)	Mean	[REDACTED]	Average total reinstatement cost specified at asset class level
BT	Cabinet	Mean	[REDACTED]	Average historic flood repair for cabinets, excluding civils
BT	Mobile mast site	Mean	[REDACTED]	Average cost of flood damage to ground-level equipment at mast base

Source: Frontier calculations based on asset operators confidential data

TABLE 6 PREVENTATIVE MEASURES

Asset Operator	Asset Class	Preventative measure	$\text{tolerance}_{\text{prevent},k}$	$\text{capex}_{\text{prevent},t}$	Notes
UKPN	Primary Substation	Standard structural characteristics	[REDACTED]	[REDACTED]	Buildings' door threshold or minimum air-brick level (counterfactual only)
UKPN	Primary Substation	Equipment level flood protection	[REDACTED]	[REDACTED]	Any measure targeting components within the substation, including; localised bunding, compound assets, limited switch house bunding, half metre wall around the switch
UKPN	Primary Substation	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with steel flood gates
UKPN	Secondary Substation	Standard structural characteristics	[REDACTED]	[REDACTED]	Buildings' door threshold (only applicable for counterfactual scenario)
UKPN	Secondary Substation	Transformer pole mounts	[REDACTED]	[REDACTED]	Wooden/steel towers with sunken foundations (only applicable to counterfactual)
UKPN	Secondary Substation	Equipment level flood protection	[REDACTED]	[REDACTED]	Any measure targeting components within the substation, including; localised bunding, compound assets, limited switch house bunding, half metre wall around the switch
UKPN	Secondary Substation	Site relocation	[REDACTED]	[REDACTED]	Includes stilted platforms
AWG	Sewage Pumping Station	Standard structural characteristics	[REDACTED]	[REDACTED]	Buildings' door threshold or minimum air-brick level (counterfactual only)
AWG	Sewage Pumping Station	Equipment level flood protection	[REDACTED]	[REDACTED]	Elevation of electrical components for wastewater pumps and telemetry
AWG	Sewage Pumping Station	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with flood gates
AWG	Water Recycling Centre	Standard structural characteristics	[REDACTED]	[REDACTED]	Buildings' door threshold or minimum air-brick level (counterfactual only)
AWG	Water Recycling Centre	Equipment level flood protection	[REDACTED]	[REDACTED]	Elevation of electrical components within the interior of the site
AWG	Water Recycling Centre	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with steel flood gates
AWG	Ground Water Source	Standard structural characteristics	[REDACTED]	[REDACTED]	Protruding steel or concrete borehole chamber casing (counterfactual only)
AWG	Ground Water Source	Equipment level flood protection	[REDACTED]	[REDACTED]	Elevation of transformer bays and switchgear within the interior of the site
AWG	Ground Water Source	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with steel flood gates
AWG	Water Treatment Works	Standard structural characteristics	[REDACTED]	[REDACTED]	Buildings' door threshold or minimum air-brick level (counterfactual only)
AWG	Water Treatment Works	Equipment level flood protection	[REDACTED]	[REDACTED]	Elevation of electrical components
AWG	Water Treatment Works	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with steel flood gates
AWG	Water Pumping Station	Standard structural characteristics	[REDACTED]	[REDACTED]	Buildings' door threshold or minimum air-brick level (counterfactual only)
AWG	Water Pumping Station	Equipment level flood protection	[REDACTED]	[REDACTED]	Elevation of electrical components for pumps
AWG	Water Pumping Station	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with steel flood gates
BT	Tier 1 Exchange	Standard structural characteristics	[REDACTED]	[REDACTED]	Buildings' door threshold or minimum air-brick level (counterfactual only)
BT	Tier 1 Exchange	Equipment level flood protection	[REDACTED]	[REDACTED]	Includes multiple interior interventions; pumps, elevation etc.
BT	Tier 1 Exchange	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with flood gates
BT	Cabinet	Standard structural characteristics	[REDACTED]	[REDACTED]	Cabinet door threshold or wind inlet level (counterfactual only)

BT	Cabinet	Equipment level flood protection	[REDACTED]	[REDACTED]	Raising of mounting structures within cabinet interior
BT	Mobile Mast Site	Standard structural characteristics	[REDACTED]	[REDACTED]	Cabinet door threshold or wind inlet level (counterfactual only)
BT	Mobile Mast Site	Equipment level flood protection	[REDACTED]	[REDACTED]	Raising of mounting structures within cabinet interior
BT	Mobile Mast Site	Perimeter level flood protection	[REDACTED]	[REDACTED]	Permanent concrete boundary with flood gates

Source: Frontier calculations based on asset operators confidential data

TABLE 7 CONTAINMENT MEASURES

Asset Operator	Asset Class	Measure	Containment	duration_k	$\text{opex}_{\text{contain},t}$	Notes
UKPN	Primary Substation	Back-up generation	Power outage	[REDACTED]	[REDACTED]	300kVA towable diesel generators
UKPN	Secondary Substation	Back-up generation	Power outage	[REDACTED]	[REDACTED]	300kVA towable diesel generators
AWG	Sewage Pumping Station	Standby generation	Power outage	[REDACTED]	[REDACTED]	Onsite diesel generator, duration is specified at the asset level
AWG	Sewage Pumping Station	Back-up generation	Power outage	[REDACTED]	[REDACTED]	Electrical input sockets installed on-site to enable deployment of existing portfolio of towable diesel generators
AWG	Sewage Pumping Station	Wet well retention	Flood	[REDACTED]	[REDACTED]	Retention of wet well overflow into storage-detention tanks or basins
AWG	Sewage Pumping Station	Tankering	Flood	[REDACTED]	[REDACTED]	Pumping out storm and wastewater from wet wells via existing portfolio of emergency vacuum tanker vehicles
AWG	Water Recycling Centre	Standby generation	Power outage	[REDACTED]	[REDACTED]	Onsite diesel generator
AWG	Water Recycling Centre	Back-up generation	Power outage	[REDACTED]	[REDACTED]	Electrical input sockets installed on-site to enable deployment of existing portfolio of towable diesel generators
AWG	Water Recycling Centre	Tankering	Flood	[REDACTED]	[REDACTED]	Pumping out storm and wastewater from wet wells via existing portfolio of emergency vacuum tanker vehicles
AWG	Ground Water Source	Standby water towers	Flood	[REDACTED]	[REDACTED]	Elevated water towers installed within network deliver standby water using existing gravitational potential energy of stored water
AWG	Ground Water Source	Tankering	Flood	[REDACTED]	[REDACTED]	Pumping out storm and wastewater from wet wells via existing portfolio of emergency vacuum tanker vehicles
AWG	Ground Water Source	Back-up generation	Power outage	[REDACTED]	[REDACTED]	Electrical input sockets installed on-site to enable deployment of existing portfolio of towable diesel generators
AWG	Ground Water Source	Standby generation	Power outage	[REDACTED]	[REDACTED]	Onsite diesel generator, duration is specified at the asset level
AWG	Water Treatment Works	Standby generation	Power outage	[REDACTED]	[REDACTED]	Onsite diesel generator, duration is specified at the asset level
AWG	Water Treatment Works	Back-up generation	Power outage	[REDACTED]	[REDACTED]	Electrical input sockets installed on-site to enable deployment of existing portfolio of towable diesel generators
AWG	Water Pumping Station	Re-zoning	Flood	[REDACTED]	[REDACTED]	Reconfiguration of interconnection valves across the water district to bypass affected assets
AWG	Water Pumping Station	Re-zoning	Power outage	[REDACTED]	[REDACTED]	Reconfiguration of interconnection valves across the water district to bypass affected assets
AWG	Water Pumping Station	Standby water towers	Power	[REDACTED]	[REDACTED]	Elevated water towers installed within network deliver standby water using existing gravitational potential energy of stored water
AWG	Water Pumping Station	Back-up generation	Power outage	[REDACTED]	[REDACTED]	Electrical input sockets installed on-site to enable deployment of existing portfolio of towable diesel generators
AWG	Water Pumping Station	Standby generation	Power outage	[REDACTED]	[REDACTED]	Onsite diesel generator, duration is specified at the asset level
BT	Tier 1 Exchange (MSAN)	Standby generation	Power outage	[REDACTED]	[REDACTED]	Onsite diesel generator, duration is specified at the asset level
BT	Cabinet	Standby battery	Power outage	[REDACTED]	[REDACTED]	As described, a standard contingency measure installed to maintain usual operations
BT	Mobile mast site	Overlapping coverage areas	Flood	[REDACTED]	[REDACTED]	Overlapping mobile cell site coverage areas in urban areas provide contingency service level in the event of a single site outage
BT	Mobile mast site	Overlapping coverage areas	Power outage	[REDACTED]	[REDACTED]	Overlapping mobile cell site coverage areas in urban areas provide contingency service level in the event of a single site outage

BT	Mobile mast site	Back-up generation	Power outage	[REDACTED]	[REDACTED]	300kVA towable diesel generators

Source: Frontier calculations based on asset operators confidential data

WWW.FRONTIER-ECONOMICS.COM