Note

HaskoningDHV UK Ltd.
Water

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Subject: **Role of flood risk management assets in Flood Resilience**

Executive summary

This note explores how the role of flood defence assets in overall flood resilience could be captured by resilience metrics. The analysis was developed initially for 'passive' linear flood defence assets only, but it broadly also applies to other asset types such as operated assets and conveyance assets.

Literature review has confirmed that there are no existing mature approaches for explicitly measuring the role of assets in flood resilience. There is a wide range of definitions and concepts, and it is noted that this hampers operationalisation. This study therefore takes a pragmatic approach, by translating accepted broad resilience concepts toward practical defence characteristics.

Through comparison with existing infrastructure resilience definitions from Cabinet Office and National Infrastructure Commission, the study has grouped asset resilience features into three 'asset life stages':

1. Behaviour under loading (range of conditions; breach / damage behaviour)
2. Behaviour after damage / breach (residual performance; recoverability)
3. Adaptive capacity

For each of these three sets of features, there are three levels of approaches for setting performance metrics:

- Weighted scorecard / formula of basic asset characteristics (materials, structural principle, geometry) – relatively easy to develop and quantify, but poor proxy of actual resilience
- Performance indicators that take loading into account (e.g. adapted fragility curves, breach speed, residual performance, cost of future improvement) – medium effort to develop, will require modelling, good reflection of actual resilience
- Resilience indicators that take receptors into account (e.g. impact on risk to life, economic risk, health & social impacts) – high effort to develop and calculate, but with the strong benefit of enabling a direct link to overall flood resilience and its other 'capitals'. In practice, the receptors and consequences would be used to set target values for the metric, similar to the existing Target Condition Grade.

The analysis shows that the role of assets in resilience contains multiple dimensions, and there is no single parameter that captures all of these adequately. If the Environment Agency requires a Single Metric for the role of assets in flood resilience, then this would have to be a composite metric that combines those dimensions considered most important, including the potential for weighting to steer priorities (through an overarching weighted scorecard / formula, similar to e.g. the Partnership Funding calculator).

There is a possibility to relate this directly to the metrics for overall flood resilience to be developed from the FD2716 project. If that is the preferred way forward, then this is likely to require a 'level 3 approach' as outlined above: an approach that determines how the asset's (and system's) resilience features influence the impact of flooding on receptors (in all relevant dimensions) – this is likely to require flood impact modelling.

The interaction with the overall development by Defra and the Environment Agency of flood resilience policy needs to be managed carefully. The study recommends further progressing the thinking about this particular aspect of resilience because the more concrete and applied level of analysis will help to inform the development overall resilience policy.

Progressing the thinking in the short term will also help in working toward clarity from the Environment Agency about a number of high-level decisions about the role of assets in resilience as identified in this study:

- Is there a need for a Single Metric?
- Is there a need to link the asset metrics to overall resilience metrics?
- What is the right balance between effort and accuracy ('reflectiveness')?

1 Introduction

Royal HaskoningDHV is working on Defra project FD2716 Evidence Review of Flood Resilience, as part of a team led by Collingwood Environmental Planning (CEP). The FD2716 project aims to provide evidence to support Defra and the Environment Agency in understanding options for using flood resilience as a central concept in managing flood risk. The main scope addresses the full range of flood risk management, in terms of flood hazards, intervention types, receptors and actors.

The Environment Agency commissioned Royal HaskoningDHV (as a sub-consultant to CEP) to carry out a study on asset resilience. The envisaged scope is:

- how asset resilience fits into wider flood resilience
- the key documents on asset resilience and asset health
- what makes up asset resilience, with a particular focus on flood assets
- metrics used to measure asset resilience and the components of these

This Asset Study is delivered under project FD2716 so that it draws on the same background information.

The proposal and the start-up meeting further confirmed the approach, in particular:

- Focus is on the role of assets in resilience – 'resilience of assets' is only a means to that end
- Four defined features of asset resilience are used as a starting point (see Section 3).
- The study explores how these four resilience features link to Cabinet Office's 4Rs, and to flood risk (i.e. probability and consequence). This is then used to identify potential metrics that relate to the design and maintenance of flood defence assets
- Emphasis is on conceptual analysis; literature review serves to support this
- The study focuses primarily on raised 'passive' flood defences; other asset types (e.g. defences that need operation, water courses) are similar in many ways, but there are also differences which are not fully bottomed out in this study. The study primarily looks at individual assets, while considering how these function in an asset system; the role of asset systems in resilience is mentioned where relevant.

The structure of this note is as follows:

- Section 2: Literature review

- Section 3: Role of assets in flood resilience: link with existing paradigms; role in flood risk; role in design & asset management
- Section 4: Options for metrics
- Section 5: Conclusions, recommendations, next steps

2 Literature review

CEP carried out a rapid and focused literature review to support this study, building on the wider review carried out for the FD2716 project. The asset-focused review used relevant parts of the same research questions, drawing out asset-specific topics from the FD2716 review, and adding some additional documents with specific relevance to asset resilience. The full literature review is provided in Appendix A to this note. The main conclusions are summarised here.

The literature review has confirmed that there are no existing mature approaches for explicitly measuring the role of assets in flood resilience. There is a wide range of definitions and concepts for resilience and for asset resilience, and various sources note that this hampers operationalisation (i.e. management on the basis of resilience indicators).

The FD2716 study has identified three existing frameworks which could be useful in developing a flood resilience framework for England. The review in Appendix A explores the role that assets play in these frameworks. They typically address the role of infrastructure as a 'receptor', but there is also mention of the protective role of infrastructure. This however remains rather superficial, largely reflecting flood defence assets' typically used performance objectives of reducing change and impact of failure; there is however also mention of concepts such as bounce-back and adaptive capacity.

3 Role of assets in flood resilience

As identified in the proposal and confirmed in the Start-up telecom, this study started out with a focus on <u>four key features</u> of asset resilience. In the course of the work, a fifth feature emerged and was added to the list, namely Adaptive Capacity. This results in the following list of five features of asset resilience:

1. Chance of breach under the full range of loading conditions (in particular more extreme than design conditions);
2. Breach / damage behaviour ('graceful' or catastrophic), at design loading but also below and above;
3. Continued partial performance after breach / damage;
4. Recoverability – speed of repair or replacement;
5. Adaptive capacity - ability to change in order to maintain function in a new environment.

For each of these five features, the following three sub-sections elaborate the following three <u>technical aspects</u>:

- How do they relate / can they be related to existing resilience paradigms;
- How can they influence flood risk (in terms of chance and impact, including depth, velocity, duration, warning lead time, etc.);
- How can they be influenced in design and asset management?

3.1 How the Asset Resilience Features relate to established definitions of Infrastructure Resilience

The Environment Agency's emerging definition of flood resilience (as provided through comments on the draft report of the overall FD2716 study) encompasses the whole of flood risk (chance and impact), and appears to relate to the Cabinet Office's '4Rs' of Infrastructure Resilience: Resistance, Reliability, Redundancy and Response & Recovery. Another relevant resilience paradigm is provided by the National Infrastructure Commission's recent Resilience Scoping Study.

This section explores what these two existing paradigms can mean for flood defence assets, always relating this back to the ultimate aim of reducing the impact of flooding on receptors.

3.1.1 Cabinet Office

The 'Four Rs' of Infrastructure Resilience (Keeping the Country Running: natural Hazards and Infrastructure, Cabinet Office, October 2011)

The **Resistance** element of resilience is focused on providing protection. The objective is to prevent damage or disruption by providing the strength or protection to resist the hazard or its primary impact.

The **Reliability** component is concerned with ensuring that the infrastructure components are inherently designed to operate under a range of conditions and hence mitigate damage or loss from an event.

The **Redundancy** element is concerned with the design and capacity of the network or system. The availability of backup installations or spare capacity will enable operations to be switched or diverted to alternative parts of the network in the event of disruptions to ensure continuity of services.

The **Response and Recovery** element aims to enable a fast and effective response to and recovery from disruptive events.

Feature of asset resilience	Resistance	Reliability	Redundancy	Response & Recovery	Comments
Chance of breach under the full range of loading conditions					reliability' by definition
Failure behaviour ('graceful' or catastrophic)					mixture
Continued partial performance after failure					mixture
Recoverability – speed of repair.					clear link to R&R

Notes:

- Redundancy is defined as being about the asset system; it could however be argued that components within an individual asset also form a system and can provide redundancy – for example a cohesive embankment core providing continued partial performance after failure. Redundancy is already inherent in the application of operated assets (MEICA, temporary defences), through the use of back-up components and operational procedures.

3.1.2 National Infrastructure Commission

NIC Resilience Scoping Study, September 2019:
There are a wide range of definitions of resilience. Some of the terms most commonly used to define resilience in infrastructure systems are:

- plan (anticipation or design)
- resist – the ability to withstand possible hazards
- absorb – the capacity of the system to limit the damage incurred during an event
- recover – the ability for the system to return to its original state following an event
- adapt – the system's ability to change to maintain its function in a new environment.
- transform (dynamic improvement; transformation or growth)

Feature of asset resilience	Plan	Resist	Absorb	Recover	Adapt	Transform	Comments
Chance of breach under the full range of loading conditions							focus on 'chance of hazard'
Failure behaviour ('graceful' or catastrophic)							focus on 'impact of hazard'
Continued partial performance after failure							focus on 'impact of hazard'
Recoverability – speed of repair.							strong focus on recovery

Notes:

- 'Plan' and 'Transform' are not part of the core NIC definition. They do apply to asset management, even if not directly to assets themselves.
- With regard to 'Plan': The quality and effectiveness of asset plans (emergency response plans, but also operational plans, strategic plans, exceedance plans) enhance the role of assets in resilience. The extent to which the assets are formally designed also comes under this item and informs resilience.
- 'Adapt' has some link with some of the four originally defined features, but its essence of 'ability to change' is missing and has therefore been added as a fifth asset resilience feature (Adaptive capacity).

3.2 How the Asset Resilience Features influence flood risk

This section explores how the five asset resilience features can influence flood risk. This has been broken down in terms of chance and impact, including depth, velocity, duration and warning time.

Feature of asset resilience	chance	depth	velocity	duration	warning time	comments
Chance of breach under the full range of loading conditions						
Failure behaviour ('graceful' or catastrophic)						
Continued partial performance after failure						duration within the event
Recoverability – speed of repair.						duration after the event
Adaptive capacity						reduces future risk only; can increase present day cost and decrease future cost

3.3 How the asset resilience features can be influenced in design and asset management

This section explores for each of the five resilience features how they can be influenced in flood defence design and in flood defence asset management. This is where the conceptual thinking from the tables above is translated to the practicalities of the Environment Agency's asset related business processes. This translation is needed to work toward resilience metrics to support asset-related decision making.

3.3.1 Chance of breach under the full range of loading conditions (in particular more extreme than design conditions

Design

- Reinforced crest and landward slope (hard or vegetated) for embankments; reverse T-wall instead of I-wall
- Check for tipping points when loading exceeds design value (e.g. for piping: not just gradual reduction of Factor of Safety but also for opening up of new seepage pathways; seepage along edge of components of hard structures)
- Check for non-standard loading conditions (e.g. drought-induced cracking; long-duration hydrographs; traffic)

For water courses / conveyance assets, this resilience feature is relevant for events lower than design conditions: e.g. risk of blockage causing flooding, which already influences design of channels, thrash screens etc.

Asset management (Inspect – assess – improve cycle)
This concerns asset management activities to ensure that 'transient' aspects such as deterioration and damage by third parties and animals are kept under control:

- Ensure crest and landward slope are adequate (e.g. vegetation management for embankments, material condition for walls)
- Check for features sensitive to exceedance tipping points (e.g. burrows causing piping, anchors)
- Check for features sensitive to non-standard loading (e.g. inspect and repair cracking)
- Prevent localised weaknesses and irregularities (e.g. third party damage, burrowing)

For water courses / conveyance assets, asset management is needed to manage risk of blockage below extreme events.

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Other activities (incident management)
Organisation set up to deal with breach / damage even if it happens below design loading, including asset-related emergency planning and asset exceedance plans.

3.3.2 Breach / damage behaviour ('graceful' or catastrophic)

Design
Design with 'plastic' rather than 'brittle' components:

- Erosion resistant (e.g. clay) core
- Reliant on mass rather than friction (e.g. for revetments loose rock better than interlock blocks, which is again better than concrete slabs; for walls, gravity may be preferable to cantilevered)

At asset system level, secondary defence elements can also reduce the catastrophic impact of a flood event.

For operated ('on demand') assets, including MEICA, the speed of failure could be slowed down by back-up equipment and emergency arrangements.

Asset management
Ensure the asset remains 'plastic'; in relation to gradual deterioration (e.g. prevent cracking as this could reduce cohesion of clay core) or damage (e.g. human intervention that changes the structure, removes key components etc).

Operated ('on demand') assets require management to ensure continued performance of back-up equipment and emergency arrangements.

Other activities (incident management)
Early warning based on monitoring of performance during an event, including how this is incorporated in asset emergency response plans and asset exceedance plans.

3.3.3 Continued partial performance after breach / damage

Design
Similar to 'graceful breach / damage': design with 'plastic' rather than 'brittle' components, which also incorporates an element of redundancy within the asset.

At asset system level, this also includes the role of secondary defences lines in influencing flood propagation, including features with other primary functions (e.g. road embankments) and natural features.

For conveyance assets: at catchment level, alternative flow routes can provide continued performance after blockage.

Asset management
Similar to 'graceful breach / damage': ensure the asset remains 'plastic' rather than 'brittle'.

At asset system level, manage the role of secondary elements in flood propagation.

Other activities (incident management)
This could be related to the asset management organisation's ability to carry out initial temporary, possibly partial repairs (big bags etc), including how this is incorporated in emergency plans.

3.3.4 Recoverability – speed of repair

There is a link with 'partial performance', which will typically make repair easier too.

Design
In addition to 'partial performance':

- Presence of a working platform for repair works
- Access for repair plant

Asset management
In addition to 'partial performance':

- Maintain working platform and access

Other activities (incident management)

- Availability of materials and plant for repair, relevant to the asset's structure, likely failure modes and location (access etc). (e.g. big bags from Chinooks); and how this is incorporated in emergency response plans.
- Skills of operational staff to manage and execute an adequate response

3.3.5 Adaptive capacity

Design

- Low regret solutions
- Foundation for future raising / strengthening
- Room for future raising / strengthening (also considering access and wider impacts)

Asset management
Ensure that room for raising / strengthening remains or is increased as required.

Other activities (incident management)
Not relevant for this feature.

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4 Options for metrics and operational use

The analysis indicates that the features can be grouped into features relevant for three 'stages' in the asset performance cycle:

1. Behaviour under loading (1 - range of conditions; 2 - breach / damage behaviour)
2. Behaviour after breach / damage (3 – residual performance; 4 - recoverability)
3. Adaptive capacity

This section first explores options for a single metric for each of these lifecycle stages. It then explores how these could be combined into a single metric for the role of assets in flood resilience.

4.1 Behaviour under loading (range of conditions, graceful breach / damage)

Asset behaviour under loading depends on the following structural characteristics:

- Materials (e.g. a cohesive clay core slows down breach / damage more than a sandy core)
- Structural principle (e.g. a gravity-based structure is less likely to fail catastrophically than a structure that relies on friction or complex details)
- Design (overdesign of relevant elements will typically slow down breach / damage, e.g. excess defence width)
- At system level, redundancy influences how the hazard reaches the receptors (e.g. secondary defence elements, bypass channels)

These are primarily determined in an asset's design stage, and then maintained (through inspection and improvement) in the asset management stage. In practice, asset management only influences the more 'transient' aspects (ongoing deterioration, damage by third parties or by hydraulic loading). Any inherent weaknesses require capital improvements, which relates back to design.
It is difficult to see how structural characteristics could be used directly for defining resilience metrics, unless through some form of weighted scorecard or formula. Once clearly defined, this could be relatively easy to calculate based on available data and local knowledge, but it will be a relatively poor proxy for actual behaviour under loading.

It is possible to translate these aspects to technical performance indicators, as follows:

- Performance under a range of loading conditions is already routinely captured by fragility curves (available at a generic level, but work is ongoing to enable creation of asset-specific curves). It could be possible to use fragility curves as a metric by defining points on the curve that indicate asset performance below and above 'design level'. For example, for linear fluvial defences, assume water level at crest level minus 0.3m as the 'design level', and take a water level at crest level + 0.2m as the 'exceedance loading'. The ratio of the two probabilities of breach can be an indicator / metric for 'performance under exceedance'.
- Breach / damage behaviour could conceptually be captured as the time from initiation to full breach. This will require a choice of loading level (e.g. design loading) and a definition of 'initiation' and 'full breach'. There is significant research literature on breach formation and breach process modelling which could form a basis for this indicator / metric. It may also be possible to relate a 'breach speed metric' to monitoring and to flood warning processes (breach speed being related to warning time).

Metrics based on these technical performance indicators would require a medium level of effort: once clearly defined, it would require production of fragility curves (or at least calculation of probability of breach at selected loading levels), but it will then be very easy to quantify and use. If a single metric is desired, the two indicators (excess loading; breach/damage behaviour) could be combined through a weighted scorecard or formula. This could be a technically accurate metric for asset resilience; however not directly linked to overall flood resilience.

An alternative approach for Behaviour under loading could be to relate this more directly to the receptors of flood risk and therefore to overall flood resilience. This could be related to the metrics being developed in the overall FD2716 project. However at this stage, this note explores specifically how Behaviour under loading could be linked to the concept of Risk to life (which is likely to be part of any resilience metric in some form). Various hazard indices exist which combine flood depth, flood velocity and speed of onset, and these can be compared to receptor vulnerability to determine the chance of casualties. Hazard indices are often used qualitatively (e.g. through traffic light matrices). However, in the Netherlands a quantitative approach was used for setting statutory flood defence standards, driven by the (politically determined) principle that the chance of any individual dying from flooding has to be less than 1:100,000 per year. The behaviour of assets under loading is particularly relevant for Risk to life, because catastrophic flooding is known to be an important factor (less warning time, higher local flow velocities). In practice, a metric based on overall flood resilience will require a more complex analysis because it has to take account of the consequences of flooding and the state of the receptors. It will therefore require research to determine agreed modelling approaches, and then significant modelling to determine how each asset's characteristics influence risk to life. A key benefit is that this approach also captures system effects. However, this approach may not be realistic in the short term, but could be an ambition for the longer term (making best use of experiences in the Netherlands).

4.2 Behaviour after breach / damage (residual performance, speed of repair)

Asset behaviour after breach / damage depends on the following structural characteristics:

- Materials (e.g. a cohesive clay core slows down breach / damage more than a sandy core)
- Structural principle (e.g. a gravity-based structure is more likely to remain partly in place than a structure that relies on friction or complex details)
- Geometry (overdesign of relevant elements will typically leave more of the structure in place after breach, e.g. excess width)
- In addition to these, the speed of repair is strongly determined by access for plant and availability of materials for repair. This relates to the quality of emergency response plans and how well these are embedded.

Similarly to Behaviour under loading (section 4.1), a combined metric could be developed through some form of weighted scorecard or formula, which (once defined) would be relatively easy to calculate, but would be a relatively poor proxy for actual performance.

Even though the structural characteristics are very similar to those listed for Behaviour under loading (section 4.1), there are no obvious existing technical performance indicators that could be used as metrics. In theory, an agreed modelling approach could be used to estimate a residual asset profile after breach, which can then be analysed for its remaining flood risk reduction, and possibly also for its repairability (potentially incorporating the asset management organisation's preparedness). This is highly uncertain and seems unpractical. A pragmatic approach could be to use an estimated cost of repair – however this would still require methods for estimating residual asset profiles.

Behaviour after breach / damage could be linked more directly to the receptors of flood risk and therefore to overall flood resilience. For this feature, this could possibly be linked directly to flood damages (high residual performance and rapid repair will reduce flood levels and duration). This would require enhanced flood modelling, but less challenging that outlined in Section 4.1 for Behaviour under loading.

This may be realistic as a medium-term ambition. Other aspects to consider are the health and social impact of long-duration flooding.

4.3 Adaptive capacity

Adaptive capacity depends on the following structural characteristics:

- Geometry: Overdesign of relevant elements is likely to help meet future risk reduction requirements.
- Structure: is the existing structure strong enough to support the loading from potential future raising or strengthening
- Is there sufficient space alongside the asset reserved for potential future raising or strengthening (also considering access and wider impacts).

In themselves, these characteristics are very difficult to measure directly or use as a direct metric.

It is possible to consider technical performance indicators that could be used as metrics for adaptive capacity, although this would require some development work. This could be based on an agreed assumed future loading condition (for example, based on the year 2120 under a 2C scenario), and the metric could be the cost of the works required to sustain the defence asset's current performance level. Once agreed, this quantification could require labour intensive analysis at individual asset level, but there could be ways to use existing data for a simplified approach.
It is possible to take a more advanced approach than a single future scenario by using the probabilistic 'real options' methods developed in SC110001 (Accounting for adaptive capacity); however, this is likely to be unpractical for the purpose of resilience metrics.

It is not straightforward to relate adaptive capacity of assets directly to receptors and wider flood resilience. This would require a complex narrative to consider the lower chance that a low-adaptive asset will be improved if a high climate change scenario materialises. This is unlikely to be practical for resilience metrics.

4.4 Combined single metric for the role of assets in resilience

For each of the three groups of Asset Resilience features, different options exist for setting performance metrics:

- Weighted scorecard / formula of basic asset characteristics (materials, structural principle, geometry) – relatively easy to develop and quantify, but poor proxy of actual resilience
- Performance indicators that take loading into account (e.g. adapted fragility curves, breach speed, residual performance, cost of future improvement) – medium effort to develop, will require modelling, good reflection of actual resilience)
- Resilience indicators that take receptors into account (e.g. impact on risk to life, economic risk, health & social impacts) – high effort to develop and calculate, but with the strong benefit of enabling a direct link to overall flood resilience and its other 'capitals'. In practice, the receptors and consequences would be used to set target values for the metric, similar to the existing Target Condition Grade.

The analysis shows that the role of assets in resilience contains multiple dimensions, and there is no single parameter that captures all of these adequately. If the Environment Agency requires a Single Metric for the role of assets in flood resilience, then this would have to be a composite metric that combines those dimensions considered most important, including weighting which can be used to steer priorities. Ultimately, it would be preferable if this was related directly to the metrics for overall flood resilience to be developed from the FD2716 project.

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5 Conclusions, recommendations, next steps

5.1 Conclusions

The overall conclusion is that the role of flood defence assets in resilience can be captured in metrics. A choice needs to be made between various possible approaches, based on the preferred balance between on the one hand the level of effort in developing and working with the metric, on the other hand the level at which the metric reflects the subtleties of the issue (a basic proxy versus a true reflection).

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There is a wide range of definitions and concepts, and it is noted that this hampers operationalisation.

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The study has grouped asset resilience features into three 'asset life stages':

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The role of assets in resilience contains multiple dimensions, and there is no single parameter that captures all of these adequately. If the Environment Agency requires a Single Metric for the role of assets in flood resilience, then this would have to be a composite metric that combines those dimensions considered most important, including the potential for weighting to steer priorities (through an overarching weighted scorecard / formula, similar to e.g. the Partnership Funding calculator). There is a possibility to relate this directly to the metrics for overall flood resilience to be developed from the FD2716 project. If that is the preferred way forward, then this is likely to require a 'level 3 approach' as outlined above: an approach that determines how the asset (and system) features influence the impact of flooding on receptors (in all relevant dimensions) – this is likely to require flood impact modelling.

5.2 Recommendations

The interaction with the overall development by Defra and the Environment Agency of flood resilience policy needs to be managed carefully. There is value in further progressing the thinking about this particular aspect of resilience, even if it runs ahead of the wider development, because the more concrete and applied level of analysis can inform wider development.

There is a need to work toward clarity from the Environment Agency about a number of high-level aspects:

- Is there a need for a Single Metric?
- Is there a need to link the asset metrics to overall resilience metrics?
- What is the right balance between effort and accuracy ('reflectiveness')?

To an extent this will emerge over time. However, it is possible to develop the conceptual approaches developed in this study further. This could start to provide the required information (benefits, impacts, costs) to support decisions.

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Appendix A: Asset resilience literature review FD27217

Short review of relevant literature
This review draws on the comprehensive review of literature on flood resilience conducted as part of related project FD2716, identifying and exploring asset specific topics. Some additional documents with specific relevance to asset resilience have also been included.

Approach and methodology
The literature review conducted for project FD2716 used four different sources to identify papers and documents relevant to flood resilience: expert knowledge of team members, expert knowledge of project steering group members, evidence provided in stakeholder responses to Defra's Call for Evidence (July - August 2019) and interviews with experts not directly involved in the project. These sources generated 67 new papers.

All the documents from all sources (1,2,3 and 4) were logged in an Excel spreadsheet, with basic information to identify the document: Author, Date, Title, Journal (if relevant), Access route (e.g. whether the document was provided by a Steering Group member, a team member or was identified through another route), along with additional information about relevance to the project, for example in relation to Resilience concept, Research approach and Robustness, based on standard criteria (after Collins et al, 2015).
This list was reviewed to identify documents and papers relevant to asset resilience. A total of 11 papers were considered to be relevant. A further four documents were provided by members of the project team and steering group. The Excel spreadsheet facilitated clustering and comparison of the documents included in the analysis. Of the three research questions for project FD2716 (see Annex 1), only the first two questions were included; the third question was not the explored considered relevant to this research. These were reformulated to bring out the aspects of relevance to flood asset resilience:

- To what extent and how has the contribution of flood asset resilience to overall flood resilience been conceptualised or operationalised?
- What metrics, indicators or standards have been used to describe, measure, assess or set targets for flood asset resilience? What are the challenges for developing such metrics?

Findings
To what extent and how has the contribution of flood asset resilience to overall flood resilience been conceptualised or operationalised?
The use of the concept of resilience to shocks and stress in many different contexts has made it hard to arrive at a single definition. While this presents a challenge when trying to establish the essential elements of resilience, the multi-disciplinary approach to its use can also have advantages:

> *"Resilience is widely seen as a desirable system property in environmental management……giving it traction beyond the ecological field in complex human-related spheres. Resilience, if viewed holistically, can bring together different*

> *perspectives (economic, environmental, human, physical, and social)." (Ruszczyk, 2019 p.2)*

In relation flood asset resilience, Forrest et al. (2019) suggest a distinction between the engineering perspective which is *"more functionalist, focusing on resistance and a post-flood return to equilibrium (Liao, 2012; Matthews et al., 2014)"* (p.424) and an ecological and evolutionary perspective characterised as "*more dynamic, focusing on adaptability and transformability of a system, emphasising notions such as flood-ability and reorganisation (Liao, 2012; Matthews et al., 2014)"* (p.424).

Approaches to the resilience of physical structures can be found in the literature on resilience to other natural disasters. Bruneau et al. (2003) proposed a framework to quantify measures of resilience to earthquakes for various types of physical and organizational systems. The conceptualisation of resilience is essentially one of minimising the impacts of the earthquake and bounce-back to the pre-existing situation. The community's infrastructure is seen as a key part of this resilience, alongside emergency response:

> *The objectives of enhancing seismic resilience are to ... minimize any reduction in quality of life due to earthquakes. Seismic resilience can be achieved by enhancing the ability of a community's infrastructure (e.g., lifelines, structures) to perform during and after an earthquake, as well as through emergency response and strategies that effectively cope with and contain losses and recovery strategies that enable communities to return to levels of predisaster functioning (or other acceptable levels) as rapidly as possible.* (Bruneau et al., 2003, p.735)

The measures proposed are 'reduced failure probabilities', 'reduced consequences from failures' (in terms of lives lost, damage and negative economic and social consequences) and 'reduced time to recovery' (restoration of a system or set of systems to their 'normal' level of performance) (Bruneau et al., 2003, p.736). The framework also proposes quantitative measures of robustness and rapidity (the 'ends' or objectives of resilience) as well as resourcefulness and redundancy (seen as means to achieve resilience) and integrates these measures into four dimensions of community resilience - technical, organizational, social, and economic. An example of this integration would be to consider the technical / physical and the organisational dimensions of critical services such as water supply and electricity and develop ways of measuring both.

Cutter et al. (2010) challenge this critical-infrastructure focussed approach to resilience because

> "*the operational framework ignores the dynamic social nature of communities and the process of enhancing and fostering resilience within and between communities*" (Cutter et al., 2010, p.2).

Physical infrastructure is of course widely recognised as a capacity or capital for community resilience (Cutter et al, 2015, Burton, 2015, Orr et al., 2016). In developing an approach to the assessment of resilience, it is important to start from the purpose of the assessment as this will influence both design and content (Parsons et al., 2016, p.4).

For example, the Australian Natural Disaster Resilience Index (ANDRI) was developed after the adoption of a National Strategy for Disaster Resilience in 2011. The ANDRI was not designed with any one natural hazard in mind and does not make specific mention of flood resilience assets.

> *The purpose of the ANDRI assessment is to audit the state of disaster resilience in Australia at one point in time. The ANDRI is not designed to assess regulated performance criteria*. (Parsons et al, 2016, p.5)

The index does include ‘infrastructure and planning’ as one of its coping capacities. This is measured by the indicators: dwelling type, building codes and local government land use (Parsons et al, 2016, p.8).

In the case of the City Resilience Index which was created as a result of collaboration between the Rockefeller Foundation and Arup and involved engagement and testing in cities around the world, the focus is once again on wider system resilience rather than resilience to any specific hazard such as flooding. The City Resilience Index measures relative performance over time rather than comparing cities and is intended to provide a common basis of measurement and assessment to better facilitate dialogue and knowledge sharing (Rockefeller Foundation and Arup, 2019).

Like the ANDRI, the City Resilience Index does not have an indicator or measure of the resilience of flood assets. The Index sees ‘Ecosystems and Infrastructure’ as one of four dimensions of resilience. Within this dimension, a key goal is reduced exposure and fragility. One of the indicators for this goal is:

> *Integrated, forward-looking and robust network of protective infrastructure that reduces vulnerability and exposure of citizens and critical assets.* (Rockefeller Foundation & Arup, 2015, p.22)

Descriptions of the City Resilience Index approach provide more detail on the required qualities of this ‘protective infrastructure’:

> *The protective function of infrastructure relies on appropriate design and construction. This is as important for homes, offices and other day-to-day infrastructure as it is for specific defences, like flood barriers. .... In resilient cities, man-made infrastructure and buildings are well-conceived, well-constructed and safeguarded against known hazards. Building codes and standards promote long-term robustness, flexibility to adapt in the future and safe failure mechanisms in the event of a shock.* (Rockefeller Foundation and Arup, 2014, p.12)

Measures such as building codes and standards can be used as indicators of the resilience of protective infrastructure ((Rockefeller Foundation and Arup, 2014, p.12)
A third broad approach to flood resilience examined in the wider literature review is the Zurich Flood Resilience Alliance (ZFRA)’s Flood Resilience Measurement Framework and Tool (FRMT). This was created to test and validate a measure of community flood

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resilience. The approach measures a set of sources of community flood resilience to provide a baseline. When floods occur, it also measures resilient outcomes (level of loss and recovery time) (Campbell et al, 2018). The Framework is based on a conceptualisation of the socio-economic system as having five key community capitals: social, human, physical, financial and natural. The 88 sources of community resilience were drawn from across these capitals. Each of sources provides one or more of the 4 properties of a resilient system identified by Bruneau et al (2006): Robustness, Redundancy, Resourcefulness and Rapidity.

The research on the application of the FRMT found that the baseline grades for the different sources of resilience helped the NGO users and the community members to:

> *jointly identify areas that needed to be strengthened within the community. Interventions implemented across the communities (Campbell et al., 2018, p.15)*

A survey of the value attributed to each of the 88 sources of resilience found that sources assigned to human and physical capital (e.g. education and skills and infrastructure provision) are, in general, the highest graded (Campbell et al 2018, p12). Two of the physical capital resilience sources were flood assets:

- Communal Flood Protection (Flood Controls)
- Basin Level Controls

This is a generic description and the method for measuring the sources of resilience is based on a technical risk grading approach developed by Zurich Insurance Group. This provides a consistent benchmark for grading risks, based on quantitative and qualitative data. No information was available about the data that is used to assess flood assets.

The research on the application of the FRMT found that the baseline grades for the different sources of resilience helped the NGO users and the community members to jointly identify areas that needed to be strengthened within the community (Campbell et al., 2018, p.15)

Conclusions

The review indicates that there are no existing mature approaches for explicitly measuring the role of assets in flood resilience. There is a wide range of definitions and concepts of resilience. Physical infrastructure is widely recognised as one of the capacities or capitals for community resilience, however there is little work that looks at flood resilience assets as an element of physical resilience.

Three existing resilience frameworks that were explored in detail in the wider project provided some evidence on indicators used for the resilience of flood assets. These typically address the role of infrastructure as a ‘receptor’, but there is also mention of the protective role of infrastructure. This however remains rather superficial, largely reflecting flood defence assets’ typically used performance objectives of reducing change and the impact of failure; there is however also mention of concepts such as bounce-back and adaptive capacity.

Annex 1 Evidence Review of Flood Resilience FD2716 - Research Questions
Three research questions were identified for the Quick Scoping Review (QSR) undertaken as part of this project:

1. How has resilience been defined and conceptualised in regard to natural hazards generally and flooding in particular?
   1.1. To what extent have different aspects (e.g. social, technical etc) of resilience to natural hazards generally, and flooding in particular been conceptualised or operationalised as one “overall resilience” concept? What challenges, advantages and disadvantages of bringing these aspects together, conceptually, methodologically and practically are considered in the literature?
   1.2. How have definitions and conceptualisations of resilience generally and flooding/natural hazards in particular been expressed or reflected across government in England and Wales and specifically with respect to flood risk management policy?

2. What different metrics, indicators or standards have been used to describe, measure, assess or set targets for resilience to natural hazards, generally and flooding in particular? What are the challenges in developing metrics for different aspects of resilience to natural hazards generally and flooding in particular?
   2.1. What evidence is there around their implementability as tools for driving actions to support government policy?

3. How do the identified resilience frameworks (both concepts and metrics) perform in terms against the following flood risk management (FRM) criteria:
   - addressing a range of risks and impacts;
   - capable of being tailored to geographical area and local variation;
   - level of ambition to drive action;
   - appropriate distribution of costs and benefits;
   - meaningful to a range of audiences;
   - enables identification of timescales for implementation of measures:
   - short- to long-term;
   - appropriate and feasible allocation of roles and responsibilities;
   - and feasibility and affordability of data collection and verification).