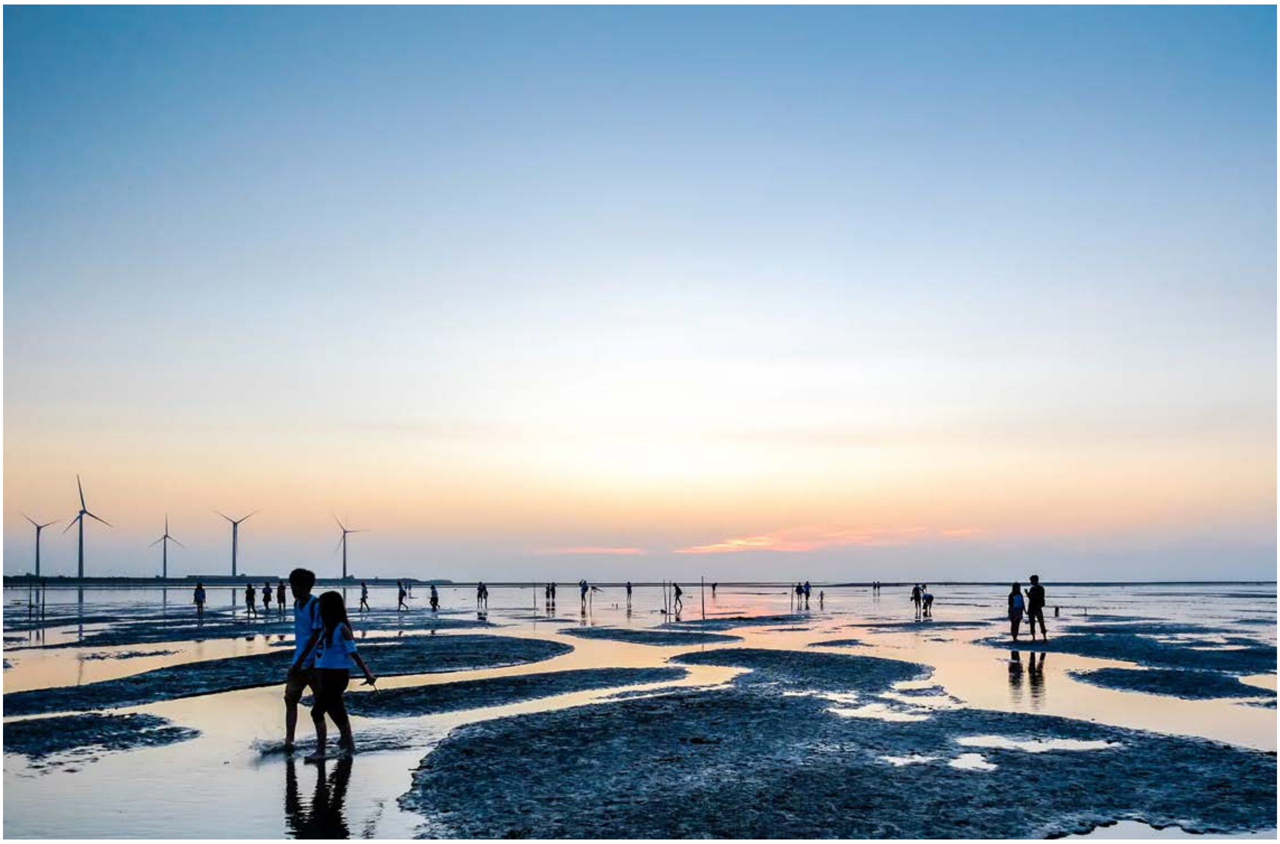
THE RESILIENCE SHIFT

Flood Resilience: Consolidating Knowledge Between and Within Critical Infrastructure Sectors

Agenda Setting Scoping Studies Summary Report



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Acknowledgements

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Whilst the inputs of all stakeholders have influenced this review, not all suggested changes have been included and the authors alone are responsible for its content.

Summary

Flood resilience has been rising up the political, economic and social agenda's over the last 12+ years with events such as Hurricanes Katrina and Sandy, and repeat flooding in the UK hitting the headlines. The UNDP estimates that the global cost of natural disasters (earthquakes, tsunamis and weather) in 2011 was more than $380 Billion [UNDP, 2012]. Even this figure understates the human costs in lives lost and millions losing their homes.

This report is a summary of a more detailed scoping study, which has been carried out to review current practice in flood resilience and make recommendations for further work in delivering the Resilience Shift needed by global society. Whilst focussing on the UK context, the consortium's international experience in flood resilience engineering, international research and teaching collaborations is reflected in the key findings. Desk based literature reviews and engagement with key stakeholders, have focussed on the following three themes from the Resilience Shift programme:

- Integrated systems approaches as context for major engineering projects (Sheffield)
- Dynamic performance based design approaches for resilience (Warwick).
- Embedding systems-thinking and resilience into engineering education (Brunel & ICE Blue)

The purpose of this is to review the current state-of-the-art (SOTA) of resilience and risk management concepts and methodologies in research, practice and education and investigate how these have evolved in order to establish a baseline upon which to build improved processes and methods that will enhance the SOTA and best practice. We have chosen this focus because we believe these themes are intrinsically linked and are key to delivering flood resilience; take an integrated systems approach, use the right design approaches and ensure the education is in place for all stakeholders so that best practice can be implemented.

Integrated systems thinking

The term 'flood resilience' is being increasingly used in the professional flood risk management world, however it remains to be clearly defined and implemented. The UK, USA and Australia are leading the way in considering what flood resilience really means, but our review has found few examples of action underpinned by an understanding of systems and complexity. Furthermore, the goal of being flood resilient is some way off, and the UK Climate Change Risk Assessment 2017 (UK-CCRA-2017) [CCC, 2017] provides the evidence that flooding and coastal change risks to communities, businesses and infrastructure is a top priority. The risk assessment also states that the impacts are likely to increase and 'Risks to communities and local economies are closely linked to the resilience of local infrastructure, in particular energy, transportation and communications systems.'

The UK-CCRA-2017 has also identified urgent additional action required to reduce these risks in support of infrastructure resilience as:

- Risks to infrastructure services from coastal flooding & erosion and
- Risks to bridges and pipelines from high river flows and bank erosion has been ranked the most urgent priority, requiring vital research.

Reducing the likelihood and consequence of these impacts occurring is clearly a UK priority, but success will need integrated systems tools and approaches beyond what we have observed.

Dynamic Performance Based Design

The significant challenges above arise at a time where the greatest proportion of investment is targeted at new schemes addressing the highest flood risk, yet The State of the Nation: Infrastructure 2014 [ICE, 2014] reports that flood management infrastructure is infrequently maintained and requires attention. According to the National Flood Resilience Review [HM Government (UK), 2016], most attention to improve protection from and resilience to flooding has been focused on those sites within the UK's existing critical national infrastructure (CNI). Repair, maintenance, retrofit, or replacement and strengthening strategies need to be informed by clear analysis of why the infrastructure has failed, and an appreciation that some repairs can worsen other failure modes. As engineers struggle to maintain traditional 'hard' defences, such as rock walls, armour or embankments, 'soft' engineering solutions, including the recreation of foreshores and beaches, are rapidly finding favour, however design guidance notes for the practicing engineer for variable and softer natural defences are limited, requiring further research. Consolidating knowledge between and within critical infrastructure sectors is clearly needed to deliver flood resilience engineering.

Education

Resilience is 'implicitly' taught in engineering design and assessment of 'failure'. However, engineers experience failures and understand the concept of resilience when practicing in the workplace. The 2016 NCE Industry Report, 'Skills: Meeting Demand' challenges universities and industry to enhance student's professional development using industry-led expertise as a key element of the programmes.

Our review has identified that resilience is often implicit in engineering education and frequently linked to, and perhaps masked by, learning around the theme of 'risk'. The focus is likely to be on individual assets at a fixed point in time rather than considering the whole evolving flood system which could limit graduate's capabilities or confidence when faced with complex and developing scenarios.

Stakeholders have referred to 'resilience' as being the new 'sustainability'. While this highlights the importance of the topic, it is clear that even now, 25 years after the Rio Summit, sustainability needs further embedding into education at all levels. There are questions around institutions' ability or willingness to adopt new approaches to teaching and learning.

With £2.3 billion to be spent in the next 6 years by the Environment Agency on strengthening the country's flood and coastal defences (and on other significant UK infrastructure programmes), this is the opportunity to rethink resilience from a systems approach, and embed that learning into education and professional development of engineers. Educating engineers is not enough though, we suggest that flood resilience can only truly be delivered through working collaboratively with, and therefore educating, a range of non-engineering organisations, and players that are not themselves engineers.

Recommendations

Our study details key gaps within current approaches to the rapidly evolving areas of research, policy development and practice. In detailing these emergent 'gaps', we further identify a range of knowledge, assessment and operational barriers which currently restrict the extent to which critical infrastructure operations can transition from a modus operandi focussed on protection, to one which embodies the principles of resilience. We finally present these in a list of desired recommendation outcomes from this study to support the Resilience Shift needed.

Integrated systems approaches as context for major engineering projects

There is not a single definition for resilience due to the variety of scientific fields that have investigated this aspect of a number of systems. While ecological resilience is the ability of species to survive evolutionary pressure, engineering has often looked at the ability of a system to “bounce back” and regain its functionalities after being struck by an event [Hosseini et al. 2016]. In the case of flood resilience, as in many natural disasters, it is arguable that a well-suited concept is the one of community resilience, that is the ability of communities to sustain long period of distress and continue thriving once these are over. The breadth of definitions hence ranges from the ability to bounce back (see [Nan and Sansavini, 2017] for example) to the ability of thriving through and past hardship (e.g. [UNISDR, 2009]).

The way resilience is put into practice is rooted in the cyclical application of risk assessment techniques [Clarke et al., 2016] that continuously increase the knowledge of the operators about the system helping prevent catastrophic events, and responding timely when these occur. This is often represented as a circle diagram where the system passes through phases in which it prepares for the incident, progressing through phases of emergency and recovery that lead again to preparation (see for example [Sterbenz et al. 2010]).

Measuring resilience is a challenge. The idea of “bouncing back” provides an immediate measure through the quantification of the essential functionalities lost through an event, and the time the system needs to recover. However, this, as most of the other measures available in the literature, seem to be applicable only “a posteriori”, i.e. they need a catastrophic event to happen to return a resilience measure.

The problem or resilience in infrastructure is amplified in critical infrastructures, those networked systems producing essential flows of goods and services [Marsh et al. 1997]. These systems have networks within them (e.g. the electrical distribution network) and between them (e.g. the railway network dependence on the electrical distribution network). These dependences were classified according to their nature in the seminal work by Rinaldi et al. [2001]. In this scenario, defining resilience is even more problematic as the problem starts with defining the boundary of the system to which the definition applies and for which the resilience thinking (i.e. the cyclical application of risk assessment practices) applies. The Brisbane flood of 2011 is an example of this, where the causes had to be traced back to the policy behind the operations of the Wivenhoe Dam, the communication network in place and the human factors involved [Smith & McAlpine, 2014, Honert & McAneney, 2011].

As the Wivenhoe Dam case suggests, the scenario for flood resilience is extremely complex. Yet it is rare to find examples of systems-thinking that exploit complexity-related concepts to address the problem. Figure 1 below demonstrates the breadth of topics linked to research on resilience, infrastructure and flood, showing that sector-focused approaches are not practicable within a strategy to deliver flood resilience.

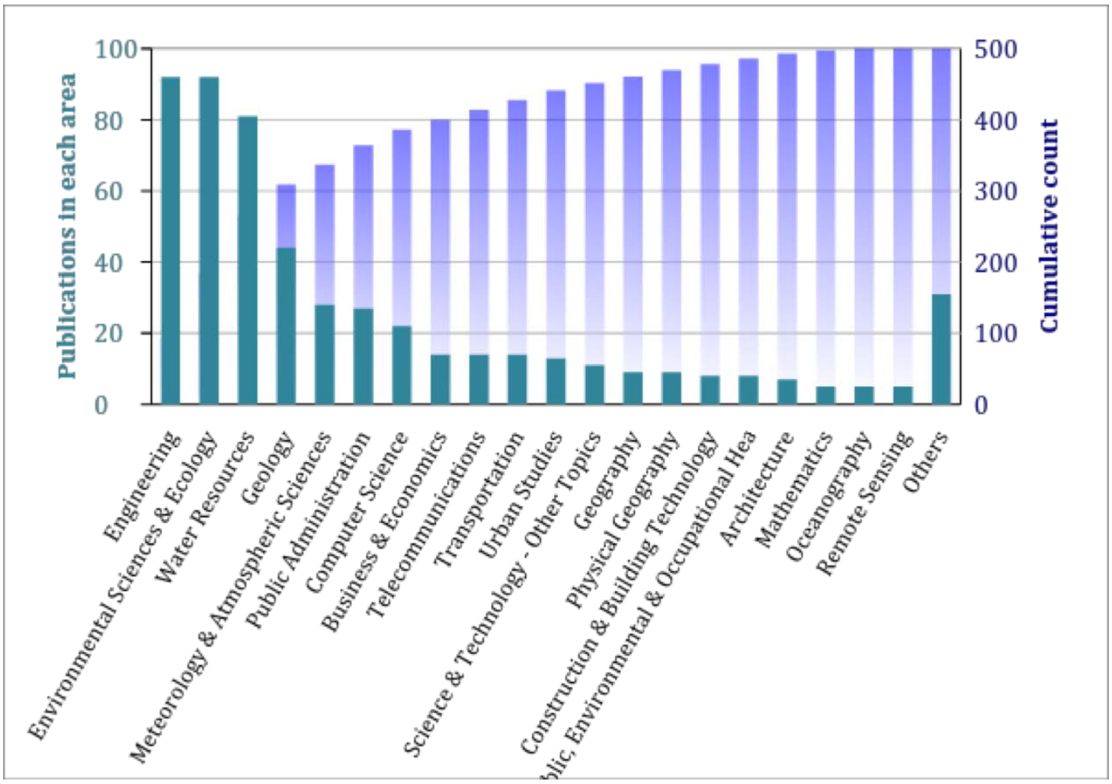


Figure 1: Subject categories for the scientific works listed in the Web of Science core collection (SC field), published in the last 50 years, and responding at the same time to the search keys “resilien*”, “infrastructur*” and “flood*” as topics, where the ‘*’ is a wild character.

One of the most significant contributions to systems thinking for resilient infrastructure is the National Infrastructure System Model (NISMOD) allowing for modeling infrastructures, their interdependencies and the reciprocal impact with the surrounding environment for the UK infrastructure systems. This has recently been applied for analyzing the impact of climate change, flood risk and climate policies on infrastructures and how these can work in these new, evolving scenarios, that is their resilience [Ives 2017, Pant et al. 2017, Oughton et al 2017, Caparros-Midwood et al. 2016]. Through the long-term modelling NISMOD is also highlighting an ongoing problem of infrastructure resilience: the need for a proactive approach as opposed to a reactive one. The timescale of infrastructure realization and upgrade doesn’t allow for fast reaction and is comparable with the time scale over which the environmental scenario changes. For this reason, infrastructure design and its associated resilience thinking has to evolve faster than the actual needs for services. In the case of flood resilience, this means protection from climate change consequences and increased urbanization. Note however, that this does not coincide with over-engineering the system, given the lack of information on what to reinforce.

Growth in resilience has to be achieved through the building of the awareness of the interdependencies in the system, using today's technology to envisage tomorrow's threats and problems. At the same time this awareness has to be constructed ahead of the shock impacting the system. The current way of doing so is exploiting expert knowledge and organizing it in logical relation through causal loops (see for example the "bowtie" and the "circle analysis" tools in the INTACT project). As highlighted, however, these are the first steps in the direction of a system-wide approach and presently it looks far from offering quantitative results or models able to measure the relative importance of causes and effects.

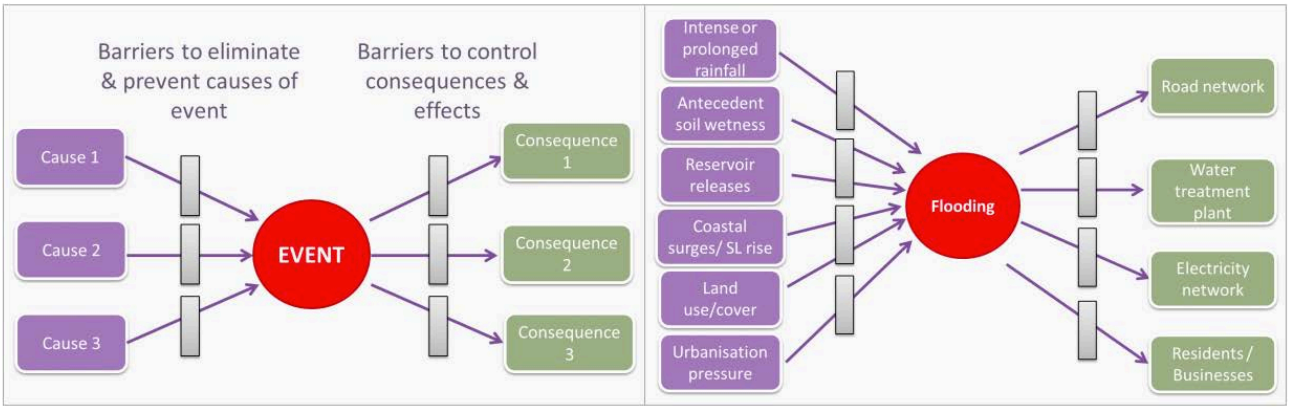


Figure 2: The Bow-Tie concept. A visualisation tool for presenting the causal relationships involved between a particular hazard, the associated threats and consequences, and the potential mitigation measures that could be used to control the threats [INTACT, 2017].

Because the Bow-Tie method captures the whole risk system from hazard to consequence, it can be used in the risk identification and risk estimation steps. Moreover, threat barriers and recovery measures can be added to the diagram, so it assists in identifying the most appropriate mitigation measures to use against the main threats. In this, as in any other method aimed at building resilience, and flood resilience in particular, the availability of information is a key aspect.

Unravelling the complexity, seeing clearly the future risks and anticipating the evolution of the infrastructure environment requires a better exploitation of the data and information than is current practice. This includes making the information available not just to infrastructure operators, but also using this to raise awareness in the public, influence policies and consolidate the notions that will form the educational background of future stakeholders. As an initial demonstration of system level visualisation, Shoothill have obtained open data from a range of sources and mapped electricity substations and NHS hospital premises, against Environment Agency Flood Risk data. This data has been visualised and is available at URL: http://jpre.shoothill.com/ (Username: jpre, Password: fastorangetank). Figure 3 below shows a snapshot of this visualisation, with the blue pins being the substations within a flood risk zone and the red pins being the hospitals within a flood risk zone. Medium and high flood risk areas are also highlighted.

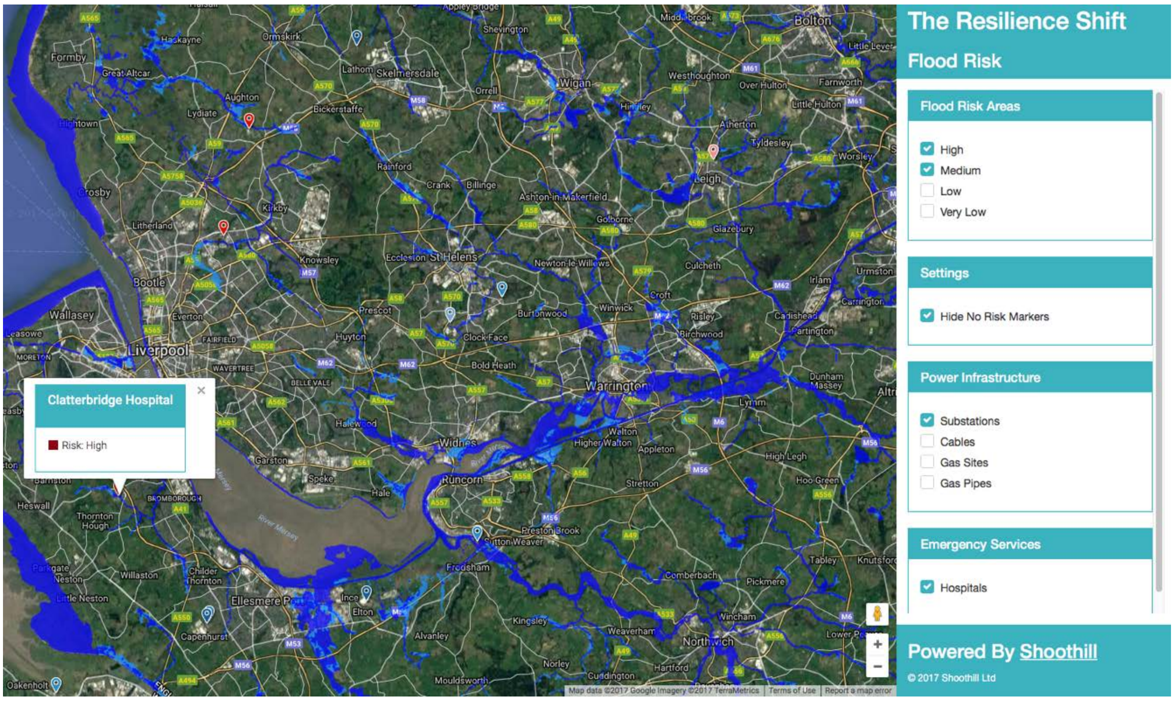


Figure 3: Shoothill’s visualistion of electricity substation and NHS hospital premises, against Environment Agency Flood Risk data around the River Mersey.

Dynamic performance based design approaches for resilience

This section has reviewed how performance objectives & indicators are currently interpreted and assessed in guidance documents (e.g. Levee Handbook, CIRIA C731, EurOtop: The overtopping Manual, The Flood Estimation Handbook, & RASP: Risk assessment for flood and coastal defence systems for strategic planning). It has provided an in-depth exploration of the methods, largely based on European & US expertise, but can be used for worldwide application. The credibility of existing approaches against what is needed for flood resilience of critical infrastructures has been considered with a particular focus in fluvial and coastal environment. The primary goal of sustainable flood management is the avoidance of flood risk in the first instance. Policy has looked towards solutions that seek to mitigate risk at flood prone sites through targeted interventions, sometimes using techniques which involve working with natural processes. In recent years, there has been a shift in the desirability to move from critical infrastructure protection (CIP) towards critical infrastructure resilience (CIR), the review concludes, highlighting the need for a more integrated and holistic appreciation of risk and resilience frameworks.

A typical flood risk study involves assessment of a) the sources of flooding; b) the potential pathways (or barriers) that influence the propagation of flood waters, and c) the receptors of inundation damage. The Source-Pathway-Receptor conceptual model is widely used to assess and inform the management of environmental risks across Government [Sayers et al, 2005], and in the past decade has become the central framework for risk assessment and management. Further advances in the ‘Risk Assessment of Flood and Coastal Defences for Strategic Planning (RASP)' study applied a methodological conceptual framework [Hall et al., 2003], which introduced the notion of systems analyses at progressive scales using the SPRC approach:

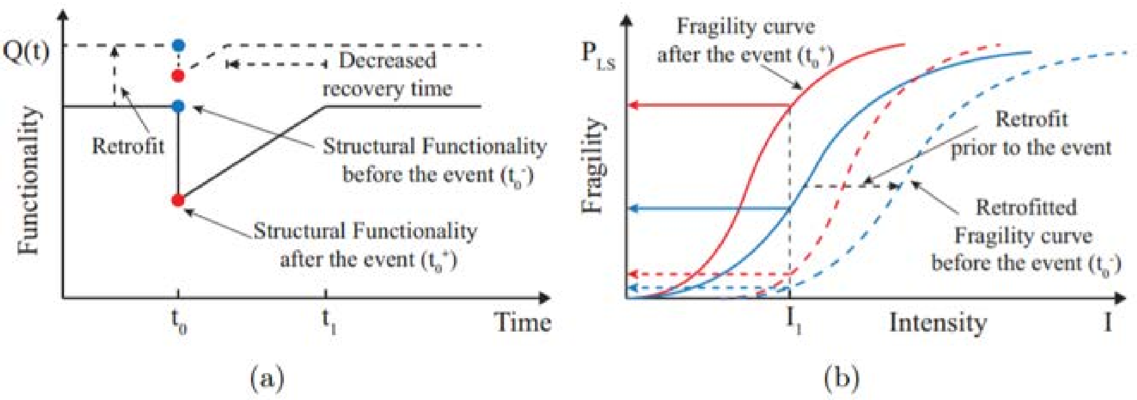
- **S**ource: of flooding
- **P**athway: that influence the propagation of flood waters
- **R**eceptor: of inundation damage
- **C**onsequence of damage.

The concept of fragility curves was initially postulated for use on flood risk management in the USA by the US Army Corps of Engineers (1993), but it was not until the RASP study that it was first implemented in risk assessments in Europe and the United Kingdom [Sayers et al, 2005]. Fragility curves define the relationship between the magnitude of a loading event (i.e. water level) and the probability of failure of an individual component. Probabilistic analysis evaluates the statistical likelihood that a specific event will occur and what losses and consequences will result. This approach may use both statistics and historical information, whereby in terms of fragility, the curves enable the performance of defences to be taken into account in a system-wide flood risk analysis [Sayers et al, 2002]. A recent in-depth review and further analysis of Source-Pathway-Receptor concepts can be found in Narayan, 2014.

Risk analysis incorporates the likelihood of a specific event and the severity of the outcome. This process combines both the severity and the probability of all relevant hazard loss scenarios [FEMA 424]. It is the intent of a performance-based design to establish the acceptable or tolerable level of risk. The overall analysis must consider not only the frequency of an events' occurrence, but the effectiveness and reliability of the design as a system. Risk analysis provides a quantitative measure of the risk [FEMA 543] and it can also establish the basis for evaluating acceptable losses and selecting appropriate designs. Risk managers use two different evaluative methods in risk and hazard analysis: deterministic and probabilistic.

Current approaches to management of risk in coastal and river engineering design, range from heavily codified procedures in structures, through to use of best practice in hydraulics with limited design codes, largely dependent on guidance notes and user expertise. Guidance notes predominantly focus on simple geometric hard or engineered defence configurations. In the absence of detailed numerical or physical models, currently, for complex geometries or softer natural defence (green infrastructure) configurations, practitioners have to make rudimentary assumptions, which leads to large levels of uncertainty of where, when, and how much overtopping flow volume occurs. There is a further need for designers in coastal and river engineering to consider a more systems based approach to develop an acceptable risk level for the overall system rather than the same level of risk for each element, allowing flexibility managing the design through its own (arbitrary) lifetime and beyond [Mockett & Simm, HR Wallingford – 2002]. Fragility curves are commonly adopted in seismic design. Research (e.g. Sayers et al., 2005, Simm et al. 2008, Wojciechowska et al. 2015) has demonstrated that the use of fragility curves are a viable methodology for probabilistic, process-based assessment of flood risk management, although there is still a need to improve the link with developed risk assessments and practitioner approaches.

The recovery time is the period necessary to restore the functionality of a structure, and infrastructure system to a desired level that can operate or function the same, close to, or better than the original



one [Cimellaro et al., 2009, 2010]. Caverzan & Solomos (2014), undertook a comprehensive study on structural resilience, which introduced losses and loss recovery in time by applying loss functions in engineering and economical terms and functionality functions, before, during and after an extreme event. This considered the relationship between long-term structure degradation - event - recovery function (including building back better), resourcefulness and time. They provided an in-depth analysis and discussion on the effects of response, recovery and retrofit in the aftermath of an exceptional event (Figure 4).

Figure 4: Effects of retrofitting on the fragility curve and structural functionality: a) functionality; b) fragility curves [Caverzan & Solomos, 2014]

Ongoing research (EU-RESILENS) has highlighted that there has been a shift from critical infrastructure protection (CIP) towards critical infrastructure Resilience (CIR) which includes the need for a more integrated and holistic appreciation of risk and resilience. The key theme that is emerging from the RESILENS project is around 'the uneasy relationship between risk and resilience, and how different understandings of this relationship impact upon the policy and practice of resilience, and its adoption by CI providers'. They emphasise the need for a coherent multi-sector understanding of resilience, which was conceptualised by four 'perspectives' on the relationship: Perspective 1 contended that resilience is the outcome of risk management, Perspective 2 that resilience is a component of risk management, Perspective 3 argues that resilience is an extension to conventional risk management and Perspective 4 that resilience is entirely independent of risk management practices. It was concluded that for the RESILENS project, Perspective 3 offered the best way to transition from a narrow risk management led approach to a more holistic resilience paradigm within the sector.

Table 1 illustrates the transition in Critical Infrastructure Resilience, which provides some key terms that articulate the differences in approach (note: these are presented as binary oppositions for clarity but in reality the picture is more complicated).

	Traditional	**Transformational**
Aim	Equilibrist Existing normality Preserve Stability	Adaptive New normality Transformative Flexible
Focus	Endogenous Short term Reactive	Exogenous Long-term Proactive
CI Approaches	Techno-rational Homogeneity Robustness Recovery Fail-safe Protection Optimisation Single-sector focus	Complex adaptive Heterogeneity Malleable Realign Safe-to-fail Predictive Greater redundancy/diversity Dependencies

Table 1: Transition in CIR (adapted from the RESILENS project)

It has been reported [Linkov et al. 2014] that that there is a lack of framework to adopt resilience-based approaches amongst technical specialists in CI, but there is increasingly wider consensus that resilience offers a necessary frame for considering unknown or unforeseeable events [Baum, 2015]. According to the RESILENS project, ‘there are fundamental limitations to probabilistic forecasting methods implicit in traditional risk assessment, which are based upon earlier events and are often inaccurate at determining event occurrences or predicting new threats [Linkov et al, 2014; Davies, 2015]. Resilience is also more open ended than risk management and as such is potentially a more helpful approach for considering unknown events.

Embedding systems-thinking and resilience into engineering education

This section presents the findings of a review into how engineering education is addressing the need for systems thinking and resilience. The review focuses on the needs and challenges, and builds from sections 2 and 3, identifying the actions needed to:

- Integrate systems thinking and resilience into engineering education programmes.
- Maintain and enhance the skills of professionals to deliver resilient systems.
- Set out ‘resilience’ best practice for academic institutions, and professional development training providers.

Our assessment for ‘needs’ begins with those who are the key players in delivering resilience from flooding, their roles, responsibilities and operating environment. Then, to focus on what they need to know in order to operate and communicate, so that the information is built into an effective, adaptive, and collaborative ‘learning and development environment’ for their careers.

Engineers are placed at the heart of creating and managing resilience. As a community, they are responsible for the *risk assessment,* and then the *planning*, *construction* and *maintenance* of fixed and moving assets, and other systems, that:

- protect against flooding;
- are resistant to flooding impacts;
- warn professional partners, stakeholders and communities
- drive the emergency management, contingency planning and exercising
- support recovery and return to normality following major flooding and related weather impacts

The wide range of components and systems involved in flood risk assessment and management presents a significant challenge for engineers delivering and assessing resilience to flooding. They need to work intelligently and creatively across a range of disciplines within ‘engineering’ and consider the interdependence of, and redundancy across those disciplines. Competence in resilience of systems therefore has to be about how engineers evaluate and communicate risk across their disciplines, working as a coherent team, rather than seeking to be technical experts in all specialist areas.

Most engineers responsible for managing flood risk are employed by public authorities or are in their supply chain. To operate effectively and avoid ‘silo thinking’ across (and within larger) organisations therefore requires engineers to apply wider systems thinking, and have strong networking and partnership working skills.

Engineers also need to assess the risk of third-parties not maintaining or changing the operation of their flood assets as a critical element in securing flood resilient systems. The complexity of the political and organisational operation of flood risk, coupled with mixed ownership of assets, leads ‘responsible’ engineers to face significant challenges in synthesising a comprehensive overview of flood ‘systems’, and being clear on system ‘resilience’.

Community resilience is a key part of overall system resilience in flood situations. Flood professionals clearly advocate that the public funding and response cannot provide the protection of all communities, and that they need to work in partnership.

Working ahead of flooding events with community groups, engineers can assess ‘success’ in resilience planning, and determine the key outcomes desired by the communities and their inhabitants. In approaching the educational development of engineers, we also need to generate learning interventions that deliver awareness, understanding and partnership working across the professional (private and public) sector and civil society.

Education and learning needs to support what engineers need to ‘do’, and how they need to ‘act’, to oversee and enable resilience in their systems. This requires engineers to have both a *Strategic* and *Operational* foci:

- *Strategic*: considers their system(s), the influences and dependencies, and based on flood risk assessments (strategic and local) consider the elements in their system, and the connectivity between the system components. They must also consider what is defended by the system, the effectiveness of how critical and other infrastructure is defended, and whether other ‘mitigations’ are necessary to deliver resilience outcomes successfully.

- *Operational:* build and maintain assets as components within an overall system so that the asset compliments the system and doesn’t exacerbate risks. Crucially, working with stakeholders across sectors to create a shared ‘learning environment’ within their system is essential - an agile approach to systems management.

From this approach, we have identified a range of ‘learning outcomes’ for resilience engineers:

- engineering knowledge;

- conceptual understanding;

- ‘directed’ information for example, regulation, new standards or best practice; as well as,

- the ability to take a very wide view of the 'functioning system' including stakeholders - collaborators, partners and 'customers'.

All these elements underpin the academic learning and continuous professional development for engineers and the stakeholders who they work with to deliver flood resilience, including:

- **Learning from failure** – Engineers need to be aware of what failures have happened, and importantly, why, so that they can apply that learning to the maintenance of assets, and the construction of new ones.

- **Learning from success -** understanding why structures are successful is also of great value since the asset performance will have validated the design and operation under 'stress'.

- **Resilience to future risks** – following on from learning from failure and success, understanding how the stresses on systems and assets are to change over time is critical to flood resilience.

- **Evaluating, managing and communicating risk and vulnerability** - Engineers need to be appraised of the most relevant concepts around assessing risk since this will ensure they are able to apply their best judgement on the options for solutions, and to communicate risk (and risk appetite) with stakeholders.

- **Cost, and cost avoidance** - Capturing the costs of 'loss' as well as the projected rebuild/repair costs are key to ensure that future business cases are appraised.

- **Awareness of relevant 'infrastructure' protected by flood risk management systems** - infrastructure supports normal functioning of a broad range of systems - transport, energy, water, community etc., so engineers must be appraised of not just the assets but also their significance.

- **Wider commercial considerations –** businesses, industry and their supply chains are dependent on access to their consumers/customers. Engineers could be more aware of how the 'supply-side' of the economy operates so that risks can be communicated both to those businesses and the communities that they serve.

- **Who engineers will depend on, and need to engage with, on flood risk** - ensuring systems thinking is not undermined by weaknesses in asset management, operation and wider stakeholder relations at the time when the systems themselves will be under the most stress.

Given the breadth of knowledge and understanding, we need to focus on what principles can be delivered, and at what stage of education, to engineers to ensure they are focused on 'resilience'. This will help us define the key outcomes at each stage of learning, sustain continual learning and develop the community of resilience practice that brings together all the key 'actors'.

Current higher education engineering provision is successful in producing technically-competent graduates who can work in teams. But there are challenges about how ready many graduates are to address more complex challenges, particularly in atypical contexts such as flood systems, or to work independently. As guardians of their future professional standards and practice, professional institutions can also play a leading role in setting ambitions for a holistic view across engineering disciplines, and the many stakeholders, including challenging academic institutions to innovate and change their provision, as part of the academic accreditation review process.

It is clear that future graduates must be equipped with an updated skillset ready to address the challenges of a changing world, working in partnership, and to be able to exploit new and emerging technologies. Delivering this opportunity requires a refinement of exactly what resilience means and a reconfiguration of engineering curricula to reflect the systems approach required to enable resilience. There will also need to be changes in the teaching delivery model to develop students' critical thinking so that they can effectively provide resilient solutions for the future, moving away from relatively passive learning towards more critical, interactive classes, for example using team-based and problem-based learning strategies.

Our assessment suggests that the richest opportunity to build resilience capabilities in future undergraduate and post graduate engineers, however, is through the professional working environment. The 2016 NCE Industry Report, 'Skills: Meeting Demand' challenges universities and industry to enhance student's professional development using industry-led expertise as a key element of taught programmes, then through to continual professional development 'providers' following graduation. The fundamental step change is that resilience education should be considered to be a continuum from foundations laid at the Level 1 academic stage, through professional development ultimately to Chartership, using well-described and examined case studies as the backdrop to progressing 'real' experiential learning.

Conclusions, gaps and recommendations

It is clear from this review that delivering the shift needed to be resilient to current and future flood risks requires a whole system view of infrastructure including the physical environment, the users, the overarching markets, policies and stakeholders. It is also critical to consider infrastructure design and operation, and cascading impacts, as well as taking a more strategic view of system resilience in the face of extreme ("black swan") type events. Educating to provide the skills and knowledge for this shift is essential to avoid the simple, and potentially unhelpful, 're-badging' of flood risk management as flood resilience.

Given the three themes our study has focussed on, it is perhaps unsurprising that we see resilience knowledge, education and guidance as the fundamental foundations for designing, operating and functioning within, flood resilient integrated systems (or systems of systems). The literature we have examined indicates that there are significant gaps in all elements of delivering this hypothesis.

There are a range of definitions for resilience, each with their own strengths and weaknesses. Effort needs to move beyond the definition debate, accepting that resilience has a broad set of elements. We do favour the definition of resilience offered by the RESILENS project because of its breadth and inclusion of transformation, where critical infrastructure resilience has been defined as:

"a transformative, cyclical process, building capacities in technical, social and organisational resources, so as to mitigate as far as possible impacts of disruptive events, and based upon new forms of risk management, adaptability and the assessment of potential trade-offs between parts of a system"

Recommendation 1

There is a need to invest in the broadest possible understanding of resilience and the integrated systems approaches required. Organisational resilience and organisational learning are key parts of this and the first priority should be to work with critical infrastructure owners and operators.

It is clear that the more an infrastructure is embedded in the fabric of society, the more its role becomes central, hence critical. From this perspective critical infrastructures present levels of interdependency, emergence and, overall, complexity that make their analysis through static techniques and the modelling of their evolution unfeasible at the present time.

Recommendation 2

Collaborative and cross discipline research is needed to inform a coherent multi-sector understanding of systems for flood resilience.

Current design approaches to management of risk in coastal and river engineering design, range from heavily codified procedures in structures, through to use of best practice in hydraulics with limited design codes, largely dependent on guidance notes and user or practitioner expertise. Guidance notes (e.g. Levee Handbook, CIRIA C731 & EurOtop, 2016) predominantly focus on simple geometric hard or engineered defence configurations. A key objective is to ensure that flood assets that protect other infrastructure networks are being made resilient to future extreme climatic events, which can be challenging for practitioners, given the reliance on user expertise, which also requires the continual assessment, monitoring & re-evaluation of our flood defence systems.

Recommendation 3

Fundamental research is required on softer natural defences (configurations)

Natural defences can be preferable to hard flood defences as they allow coastal zones to adapt to natural processes and reduce the need for long-term intervention. Traditional design approaches are focussed towards hard or engineered design configurations, with less emphasis on softer natural solutions. Recent evidence based studies focussing on natural science [Dadson, 2017] & [SEPA, 2016], demonstrate the benefits of a holistic approach to flood risk management, and that there is a clear appetite for natural flood risk management. It is still the case that practitioners have to make rudimentary assumptions for softer natural defences, which leads to large levels of uncertainty of where, when, and how much flooding flow volume occurs.

Recommendation 4

A practitioner toolkit should be developed to share practical experience, with particular focus on appropriate design criteria. This may comprise a set of documents outlining best practices, drawing on well-studied examples.

Fragility curves are commonly adopted in seismic design. Research (e.g. Sayers et al., 2005, Simm et al. 2008, Wojciechowska et al. 2015) has demonstrated that the use of fragility curves are a viable methodology for probabilistic, process-based assessment of flood risk management, although there is still a need to improve the link with developed risk assessments and practitioner approaches. Despite the significant development within the field and some coalescence of ideas around measures of critical system function, flexibility and adaptability, no multi-sector standards have emerged.

Recommendation 5

There is a need for more robust quantification, evidence and methods for inclusive metrics of resilience from post-event measures to pre-event indicators of capacity.

The wide range of components and systems involved in flood risk assessment and management presents a significant challenge for engineers delivering and assessing resilience to flooding. They need to work intelligently and creatively across a range of disciplines within ‘engineering’, and be competent across these engineering disciplines requires a breadth of not only awareness, but technical understanding. Competence in resilience of systems therefore is about how engineers evaluate and communicate risk across their disciplines, working as a coherent team, rather than seeking to be technical experts in all specialist areas.

Most engineers responsible for managing flood risk are employed by public authorities or are in their supply chain. The complexity of the political and organisational operation of flood risk, coupled with mixed ownership of assets, leads 'responsible' engineers to face significant challenges in synthesising a comprehensive overview of flood 'systems', and being clear on system 'resilience'.

Recommendation 6

To operate effectively and avoid 'silo thinking' across (and within larger) organisations engineers engaged with resilience need to develop their wider systems thinking, and have strong networking and partnership working skills. Professional Institutes should consider how this could be reflected in development standards.

Community resilience is a key part of overall system resilience in any incident scenario including flood situations. Indeed, investment to build community resilience will deliver benefits against a range of challenges.

Education and learning should support what engineers need to 'do', and how they need to 'act'. To oversee and enable resilience in their systems, this requires engineers to have both *Strategic* and *Operational* foci, with each providing a feedback for the other and generate an agile approach to flood risk systems management.

Given the breadth of knowledge and understanding, we need to focus on what can be delivered at specific stages of education to engineers to ensure they are focused more on 'resilience', building on their skills and expertise. This will help define the key outcomes at each stage of learning, sustain continual learning and develop the community of resilience practice that brings together all the key stakeholders in flood resilience. We have identified the following initial 'learning outcomes' for flood resilience engineers:

- engineering knowledge;
- conceptual understanding;
- 'directed' information for example, regulation, new standards or best practice; as well as
- the ability to take a very wide view of the 'functioning system' within which they operate, including stakeholders - collaborators, partners and 'customers'.

Recommendation 7

Learning interventions should be developed that deliver resilience awareness, understanding and partnership working across the professional (private and public) sector and civil society with clear indicators for increasing flood resilience and capability.

Our review has highlighted the need for a range of stakeholder interactions to support and deliver flood resilience. Shoothill have demonstrated a data visualisation map which could be developed used to increase stakeholder engagement and awareness of complex integrated systems. Given Shoothill's capability and track record in flood alerting, tools like this could be developed to introduce increasingly more complex information, e.g. using visualised trends in weather patterns to inform food supply chain managers.

Recommendation 8

The Resilience Shift programme should support pilot scale projects to bring together a range of the data sets informing flood resilience systems, and to create visualisation tools for stakeholder engagement and awareness.

This report is a summary of a more detailed scoping study, which has been carried out to review current practice in flood resilience. The above recommendations for further work have been developed taking on board stakeholder needs and the gaps identified through our literature review.

Our consortium is well placed to contribute to the Resilience Shift needed by global society and will be actively supporting this agenda.

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