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Flood resilience: consolidating knowledge between and within critical infrastructure sectors

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Abstract

Flood resilience has been rising up the political, economic and social agendas. Taking an integrated systems approach, using the right design guidance and tools and ensuring that education is in place for all stakeholders are three themes which are intrinsically linked to delivering flood resilience. This paper reviews these themes across the academic research, policy landscape and practitioner approaches, drawing conclusions on the way forward to increase our societies resilience to floods. The term ‘flood resilience’ is being increasingly used, 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. This review investigates how performance objectives & indicators are currently interpreted in guidance documents. It provides an in-depth exploration of the methods, that although developed through European and US expertise, can be used for worldwide application. Our analysis highlights that resilience is often embedded in engineering education and frequently linked to risk. This may however, mask the importance of resilience and where it differs from risk. With £2.6 billion to be spent in the UK over the next 6 years on strengthening the country’s flood and coastal defences, this is the opportunity to rethink resilience from a systems approach, and embed that learning into education and professional development of engineers. Our conclusions indicate how consolidating flood resilience knowledge between and within critical infrastructure sectors is the way forward to deliver flood resilience engineering.

Keywords Flood · Resilience · Risk · Performance · Systems · Education

1 The context

Our analysis reviewed resilience and risk management concepts and methodologies in research, practice and education and investigated how these have evolved in order to establish a baseline upon which to build. Whilst exploring the European context, we provide an in-depth exploration of the methods, that can also be used for worldwide application. This paper focusses on the following three themes from the Resilience Shift Programme:

- Integrated systems approaches as context for major engineering projects
- Dynamic performance-based design approaches for resilience
- Embedding systems-thinking and resilience into engineering education

This three-fold focus was chosen because we believe these themes are intrinsically linked and are key to delivering

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This research was undertaken for the Resilience Shift initiative to shift the approach to resilience in practice for critical infrastructure sectors. The programme aims to help practitioners involved in critical infrastructure to make decisions differently, contributing to a safer and better world.

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flood resilience; take an integrated systems approach, use the right design approaches and develop and deliver the education needed for all stakeholders so that best practice can be implemented. The first two topics (Sects. 2, 3) are essentially a review of literature, and current state-of-the-art, whilst the final topic gives a perspective on current engineering education (Sect. 4).

2 Integrated systems approaches as context for major engineering projects

Resilience has been defined in many different ways and contexts [See for example (Haimes 2009)]. While ecological resilience concentrates on the ability of species and ecosystems to survive extinction [see the seminal paper by Holling (1973), and more recently the work by Fei et al. (2017)], engineering resilience includes the concept of bouncing back (Hosseini et al. 2016; Nan and Sansavini 2017). Flood resilience sits in between engineering and community resilience, which concentrates on the ability of communities to thrive through and past hardship (UNISDR 2009). Flood resilience captures the ability to thrive through flood events and recover from the disruptions occurred to the engineering assets. As for urban resilience to flood this has been translated to how a city tolerates flooding and recovers from its physical and socioeconomic disruptions (Liao 2012).

An operative definition of resilience is predicated around 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. A circle diagram is often used to represent this approach, where sectors of the circle represents the phases of preparation for the incident, emergency and recovery, coming back to preparation [see for example (Sterbenz et al. 2010)].

Most of the resilience measures available in the literature are applicable only “a posteriori”, i.e. they provide a measure of resilience by evaluating the effects of a catastrophic event that has hit the system. The bouncing back concept makes no exception. By modelling a system through, for example, a network approach it is usually possible to spot the vulnerable nodes [see for example (Gao et al. 2016)] or modelling its recovery ability (Ganin et al. 2016; Mulowayi et al. 2015), providing an “a priori” measure. In this case however, as in any modelling, the nodes to include in the system are chosen by the modeller, as well as the type, magnitude and effects of shocks.

The problem of resilience is amplified in critical infrastructures, those networked systems supporting essential flows of goods and services (Marsh et al. 1997). These systems have networks of dependencies within them (e.g. the electrical distribution network) and interdependencies between them (e.g. the railway network dependence on the electrical distribution network). These links were classified according to their nature in the seminal work by Rinaldi (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 could be traced back to the policy defining the operations of the Wivenhoe Dam, the communication network in place and the human factors involved (Smith and McAlpine 2014; Honert and 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. The example of protection of delta cities [see for example (Dahm 2014); Thorne et al. 2018)] by tackling the conservation of the ecological environment appears to look at the system level, where the system is not the city but the whole ecosystem (river deltas and wetlands) which the city initially thrived in. 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. The 80/20 rule popular in the Pareto analysis shows that topics up to Business and Economics are relevant; yet these present similar publication counts to many that follow after (from Telecommunications to Science and Technology—Other Topics).

The National Infrastructure System Model (NISMOD) allows for modelling infrastructures, their interdependencies and the reciprocal impact with the surrounding environment for the UK, with a system of systems approach (Hall et al. 2016). This has recently been applied for analysing 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).

The timescale of infrastructure realisation and upgrade does not 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 service and their efficiency [that can diverge from resilience (Madni and Jackson 2009; Ganin et al. 2017)]. In the case of flood resilience, this means protection from climate change consequences and increased urbanisation. Over-engineering the system, by providing extra robustness and redundancy can be in this case just an apparent solution, as it is in general not known what to reinforce, when, and against which threats.

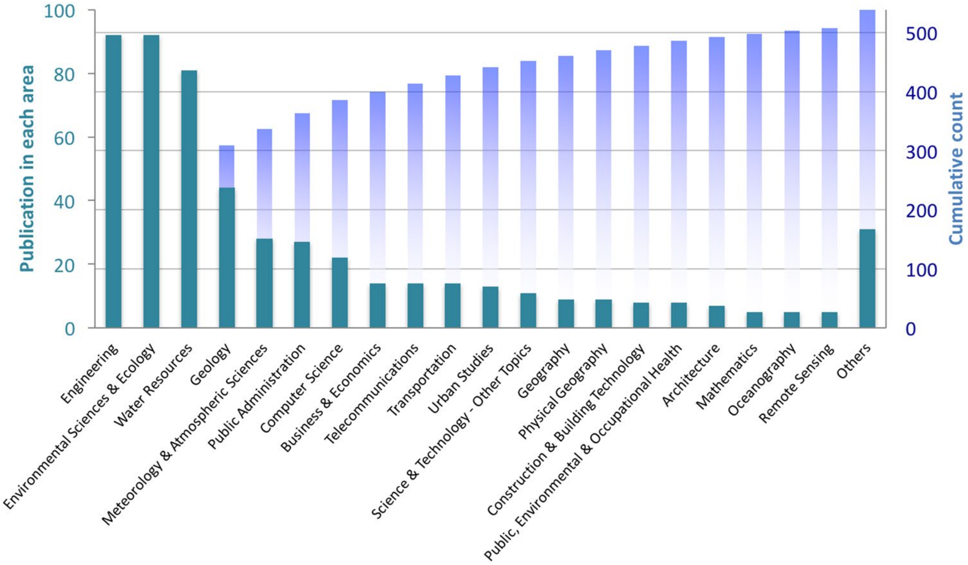


Fig. 1 Subject categories for the scientific works listed in the Web of Science core collection (SC field), published in the last 50 years, and responding at the same time to the search keys "resilien*", "infrastructur*" and "flood*" as topics, where the '*' is a wild character

A step change in resilience can be achieved through the building of 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 organising it in logical relation through causal loops [see for example the "bow-tie", in Fig. 2, and the "circle analysis" tools in the INTACT project (INTACT 2017)]. 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.

The INTACT project cited above identified the Bow-Tie method as well suited to be used in the risk identification and risk estimation steps as it captures the whole system risk, from hazard to consequence and is flexible enough to be improved through threat barriers and recovery measures added to the diagram. In this, as in any other method aimed at building resilience, and flood resilience in particular, the availability of information is a key aspect. An outlook into the future to remain resilient is the last (but not least) of the principles for resilience to extreme weather events according to de Bruijn et al. (2017), where the adoption of a system approach is the first.

Unravelling the complexity, seeing clearly the future risks and anticipating the evolution of the infrastructure environment requires 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. A relevant example of system level visualisation is the Shoothill work in mapping electricity substations and NHS hospital premises, against Environment Agency (EA) Flood Risk data. A snapshot is shown in Fig. 3 with the visualisation for the whole country available on the web (Shoothill 2017): the blue pins represent the substations within a flood risk zone and the red pins mark the position of hospitals within a flood risk zone. Medium- and high-flood risk areas are also highlighted.

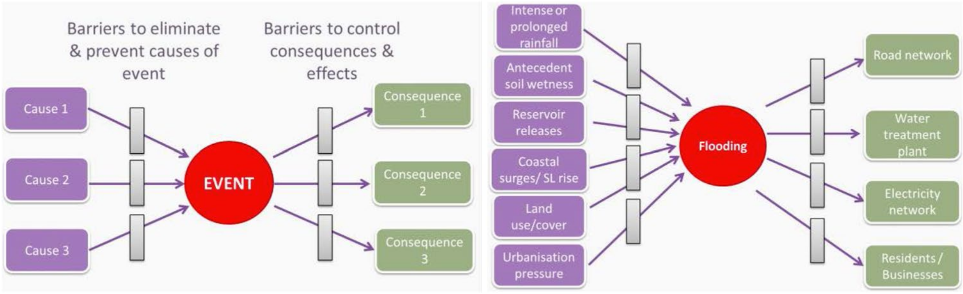
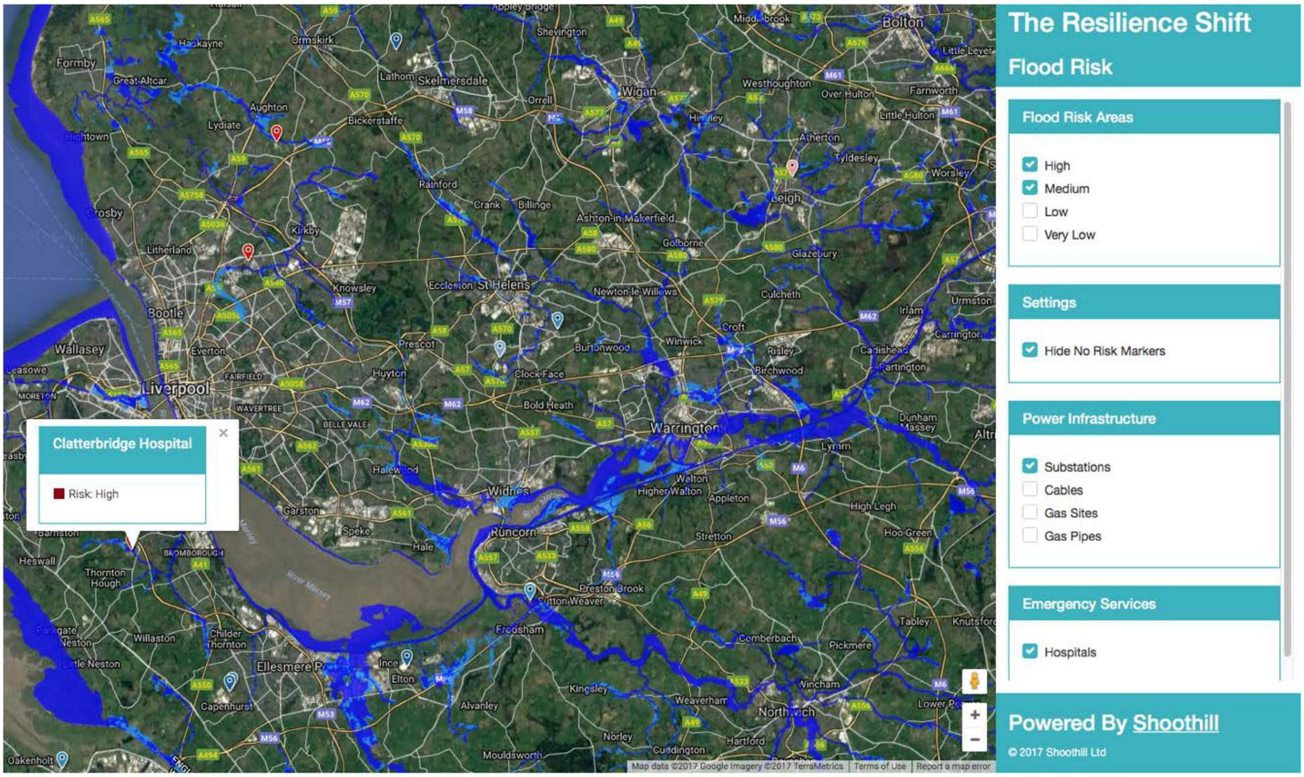


Fig. 2 The Bow-Tie concept. A visualisation tool for presenting the causal relationships involved between a particular hazard, the associated threats and consequences, and the potential mitigation measures that could be used to control the threats (INTACT 2017)



The Resilience Shift

Flood Risk

Flood Risk Areas

☑ High
☑ Medium
☐ Low
☐ Very Low

Settings

☑ Hide No Risk Markers

Power Infrastructure

☑ Substations
☐ Cables
☐ Gas Sites
☐ Gas Pipes

Emergency Services

☑ Hospitals

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Clatterbridge Hospital

■ Risk: High

Fig. 3 Shoothill's visualistion of electricity substations and NHS hospital premises, against Environment Agency Flood Risk data around the River Mersey (Shoothill 2017)

3 Dynamic performance-based design approaches for resilience

3.1 How performance objectives & indicators are currently interpreted and assessed in guidance documents

Until recently, management of flooding in the UK has been static or undergoing slowly evolving, incremental change rather than revolution (Johnson et al. 2005). According to Thorne et al. (2007), government policy in 1970s & 1980s, was dominated by reliance on the construction of hard defences. However, by the early 1990s, increasing credence was being given to the concept that mitigating or avoiding flood losses has a role to play. This aim was to be achieved by (a) encouraging the provision of adequate and cost-effective flood warning systems; (b) encouraging the provision of adequate, technically, environmentally and economically sound and sustainable flood and coastal defence measures and (c) discouraging inappropriate development in areas at risk from flooding or coastal erosion.

Dadson et al. (2017) reports that national monitoring networks are revolutionising the availability of real-time information on water levels and water quality. They report that 'data can and will support the development of more complex models, and be used to constrain model uncertainty'. Importantly, long-term monitoring is necessary, as major floods are rare events. This will facilitate the further development of models, with places acting as agents for the assimilation of hard and soft data by models which will act as a focus for learning about places. In terms of current resilience thinking, the UK National Flood Resilience Review (2016) has highlighted the following challenges; (a) understand the risks of river and coastal flooding from extreme weather over the next 10 years (using revised meteorological predictions, and modelling outputs), (b) assess the resilience of key local infrastructure (such as energy, water, transport and communications) and (c) identify ways to protect it better and improve response to flood incidents, including through new temporary flood defences.

In the UK, the meteorological driver of fluvial flooding is predominantly through precipitation. The UK National Flood Resilience Review (2016), undertook modelling projections using well established models based on the available physical principles (using the Flood Estimation Handbook—FEH) and the three components (extreme precipitation, tidal surge, and river flow/flood extent); the results of bringing these together being a set of 'stress test' case studies (i.e. uplifting current rainfall forecasts for a range of scenarios). In a separate study, analysis of the spatially average annual precipitation levels, has shown that there has been no detectable long-term change since the eighteenth century (Dadson et al. 2017), although the UK has experienced a statistically significant increase in winter precipitation, and a reduction in summer precipitation. Lavers et al. (2011), suggests that winter floods in Britain are connected to atmospheric rivers, but that this doesn't explain UK Summer Extreme Rainfall (Champion et al. 2015).

Coastal flooding can occur due to four physical elements either acting on their own or in combination with each other; predicted astronomical tide, storm surge residual, wave effects and local bathymetric effects. The accepted design standard in the UK, for deriving predicted coastal flood levels is through the application of the Coastal Flood Boundary (CFB) method (Environment Agency/DEFRA Flood and Coastal Erosion Risk Management R & D project SC060064 Coastal flood boundary conditions for UK mainland and islands). The Coastal Flood Boundary method provides an up-to-date, scientifically robust national evidence base and practical guidance on appropriate design sea level and swell wave conditions around the country and how to use them (SEPA 2015). Although the prediction of the astronomical tidal cycle is incredibly reliable, the uncertainty of swell and wave conditions can cause challenges for the practicing designer. However, by far the biggest challenge is considering the allowances for future sea-level changes. Scientific estimates on sea-level rise have increased considerably since their last projection in 2007. The Intergovernmental Panel on Climate Change (IPCC) now estimates sea levels will rise between 260 and 820 millimetres during the twenty-first century. It is therefore no surprise that coastal flooding is one of the most significant issues in the world today, especially as human populations continue to grow and occupy the coastal zone.

However, even if significant emission decreases are achieved, sea levels will continue to rise into the future. The most obvious consequence of sea-level rise is reduced freeboard levels at our coastal defences, and hence the increased likelihood of coastal flooding. However, our changing climate is also causing additional problems with potential increases in the intensity, severity and frequency of coastal storms and surges occurring, which will allow larger waves to reach our defences due to increased water depths (overtopping), and direct inundation or breaching from greater storm surges. The tsunamis in Indonesia in Dec 2004, and Japan in March 2011 clearly illustrate the devastation coastal flooding can cause, which is further hampered by debris entrainment. According to the latest available best practice guidance the Scottish Environment Protection Agency would recommend a minimum allowance of 600 mm be made for coastal freeboard. This may be required to be more depending on local circumstances and/or the provision of specific guidance on this matter by local authority flood protection staff' (SEPA 2015). Similar evidence is emerging in the USA, (USGCRP 2014).

The Pitt Review (recommendation 27) recommended that the EA and others should collaborate to achieve greater working with natural processes to manage flood and coastal erosion risk. Pitt also recognised that working more with natural processes does not mean that traditional hard defences will not be needed, but that more sustainable approaches should work alongside them (EA, 2010). In terms of current guidance notes for overtopping of a barrier (e.g. Levee Handbook, CIRIA C731 & Overtopping Manual, EurOtop 2016), guidance predominantly focuses on simple geometric hard defence configurations. In the absence of detailed numerical or physical models, currently, for complex geometries or softer natural defence configurations, practitioners have to make rudimentary assumptions from current guidance, which leads to large levels of uncertainty of where, when, and how much overtopping flow volume occurs.

Additionally, many man-made coastal structures are designed to limit overtopping, in which predictions are derived from general empirical formulae fitted to laboratory measurements. Whilst these structures may be efficient in overtopping, they may be subject to impulsive wave breaking giving sudden and violent overtopping flows, and very large wave impact pressures, the interactions of which are currently difficult to describe with any degree of certainty. A further limitation is that experimentalists have biased their studies to cases where overtopping has been recorded, thereby limiting the usefulness of neural network models for cases of zero or low overtopping volumes.

3.2 Towards performance-based design

Performance-based design approaches are more commonly used in North America (Caverzan and Solomos 2014). According to FEMA 543 (2007), performance-based design seeks to augment current code approaches rather than replacing them. However, there is a significant drive to introduce performance-based codes and, particularly in the field of fire safety, performance-based codes are now used for many applications. In the natural hazards area, although performance-based design is well developed for seismic design, prescriptive approaches are still typical for floods. A sound multi-hazard design approach should provide an impetus to adopt a performance-based philosophy for design against risk (FEMA 424 2010). Performance-based design requires a quantitative measure of risk (FEMA 2007). It also establishes the basis for evaluating acceptable losses and selecting appropriate designs. While specific performance objectives can vary for each project, the notion of acceptable performance level generally follows a trend ranging from; little or no damage for small, frequently occurring events to significant damage for very large, very rare events.

The Levee Handbook provides guidance on risk management (CIRIA C731 2013). There are a variety of preventative measures which can help mitigate the effects of flooding, either through non-structural mechanisms (urban development planning, building regulation, insurance risk spreading, coastal hazard zoning, increased public awareness) or structural mechanisms ranging from hard engineered (man-made) defence solutions to soft natural defences (sand-dunes, salt marshes, managed retreat). A cost-effective approach to flood risk management often involves programmes of different types of measures for reducing the overall risk. The management of a levee throughout its serviceable life follows a similar approach to other physical assets, the levee Handbook provides a framework based around the life cycle of a defence, new defences enter from an upper level, whereas existing enter from routine operational cycle changes to policy or event revolve around the outer loop, the inner loop ‘an emergency’ is triggered from a severe event, in this situation, the defence is not likely to perform as expected.

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 and Meadowcroft 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:

Source: of flooding
Pathway: that influences the propagation of flood waters
Receptor: of inundation damage
Consequence of damage

In terms of coastal flood defence response, particular emphasis is focussed on the Pathway element. The concept of fragility curves was initially postulated for use on flood risk management in the USA by the US Army Corps of Engineers (1984), but it was not until the RASP study that it was first implemented in risk assessments in Europe and the United Kingdom (Sayers and Meadowcroft 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.

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 2010). 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 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. Mockett and Simm (2002) reported that risk management approaches in the design and the setting of risk levels in coastal and fluvial engineering varies depending on the perspective of the individual, organisation and design culture of the project. They reported that approaches to management of risk in design, ranged from heavily codified procedures to extensive use of best practice, the three main design disciplines generically involved in the design of coastal and fluvial structures, together with their typical design approach, are:

Structures—heavily codified, the use of partial safety factors
Geotechnics—often empirical design codes, limited use of partial safety factors
Hydraulics—limited codes, largely dependent on design notes.

Deterministic analysis relies on the laws of physics and chemistry, or on correlations developed through experience or testing, to predict the outcome of a particular hazard scenario. In the deterministic approach, one or more possible designs can be developed that represent the worst possible credible events in a specific setting. In this approach, the frequency of possible occurrences need not be evaluated, hence the defence would be considered safe up to a given loading limit, identified as a single step function to represent the defence fragility and considered to have surely failed once that limit is exceeded (Simm et al. 2008).

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).

Mockett and Simm (2002) highlighted a real need to move towards the use of similar terminology (i.e. lifetime probabilities rather than factors of safety or return periods), and provided guidance on how the practice based designer can move towards a more systems oriented design approach. The development of these different approaches has resulted in very little formal understanding of how individual safety levels in one design culture can be communicated with other cultures (Mockett and Simm 2002). Further limitations are that typical design approaches are focussed towards hard design configurations, with less emphasis on softer natural solutions, although recent evidence based studies focussing on natural science (Dadson et al. 2017; SEPA 2016) clearly demonstrate the benefits of a holistic approach to flood risk management.

The EU-RESILENS (2015–2018) project, entitled "Realising European Resilience for Critical Infrastructure", is aiming to 'further significant advancements in the resilience of critical infrastructure through practically applied research'. The RESILENS project has identified that there is a 'lack of engagement with resilience, ISO 31000 is increasingly the standard risk assessment methodology utilised across a range of sectors and extensively by Critical Infrastructure (CI) providers; it is thus important to reflect upon its advocated approach'. As with many resilience approaches, ISO 31000 begins by 'establishing the context', including factors such as local and national policy, and using this as a baseline for assessment and management. The next stage is 'risk assessment', which also includes 'risk identification', 'risk analysis' and 'risk evaluation', and often involves a variety of quantitative approaches. This can then be translated into physical or organisational methods through 'risk treatment', whist the final stages of the approach are 'monitoring and overview' and 'communication and consultation'.

3.3 From critical infrastructure protection to critical infrastructure resilience

A review of critical infrastructure providers by the RESILENS project team suggested that providers are increasingly moving towards an approach based on resilience principles rather than one fundamentally focused on protection. UK Government policy also recognises the need, and defines Critical Infrastructure Resilience (CIR) as encompassing activity to prevent, protect and prepare for natural hazards [Cabinet Office (UK), 2010]. This policy symbolises a shift in practice from critical infrastructure protection (CIP) towards critical infrastructure resilience (CIR). Combining these approaches, the RESILENS project team see CIR as reflecting a wider journey from the traditional, techno-rational approaches with prescriptive, rigid methodologies, to a more transformative understanding of CI resilience. The definition of CIR from the RESILENS project is framed 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'.

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'. The authors emphasise the need for a coherent multi-sector understanding of resilience, which was conceptualised by a number of 'perspectives' on the relationship (adapted after Suter 2011). They report that the best way to transition from a narrow risk management led approach to a more holistic resilience paradigm within the sector was through what was identified as 'Perspective 3, An extension of risk management':

This transitionary perspective recognises the importance of risk management to CI operation, but proposes that these practices need to be extended to encompass resilience practice that integrates social and organisational factors, as well as building capacity to change.

It has been reported (Linkov et al. 2014) that that there is a lack of a 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.

4 Embedding systems-thinking and resilience into engineering education

The dominant paradigm of risk assessment has seen significant steps forward in addressing the challenges posed by flooding (Environment Agency 2009). However, the need for increased engagement with resilience as highlighted through the RESILENS project (Sect. 3.2) requires considering the issue as a function of system characteristics, with the flood system consisting of an interacting suite of physical, environmental and socio-political components. Within this large-scale system are more focussed systems, such as spatial sets of engineering interventions. This more holistic approach potentially helps generate a more sophisticated understanding of what is vulnerable to flood, and an appreciation of whether this vulnerability is of significance in terms of 'value'. It also provides a framework for producing a mitigation response that is flexible to changing degrees of risk and more effective in using finite economic, material and human resources. The challenge of adopting this resilient systems-type approach is that it requires a deeper understanding of the system by a range of governmental and non-governmental organisations and leading individuals, and by other people in a range of roles in society who have typically been receivers of information and advice, and passive in terms of being able to implement change. This lack of knowledge was emphasised by engineers from across a range of UK sectors completing a survey carried out by CIRIA on Flood Resilience for Critical Infrastructure (CIRIA 2010). Here then, we consider the role of education and training in enabling engineers, a group with a significant role to play, to implement flood resilience.

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, maintenance, and potential removal of fixed and moving assets, and other systems, that protect against flooding and are resistant to flooding impacts. Programmes driven by the EA such as the Long Term Investment Strategy (LTIS) (Environment Agency 2014) and the National Assessment of Flood Risk (Environment Agency 2009) have helped to create considerable knowledge and continue to represent leading international practice in 'flood risk' for engineers, at the system level. Our review included semi-structured interviews with a range of front line flood risk and resilience engineers who highlighted their expanding role in warning professional partners, stakeholders and communities and advocating emergency management, contingency planning and exercising. But, the view of these consultees is that these skills are not consciously taught, but are being 'learnt' on the job. Setting out 'resilience' best practice for academic institutions, and professional development training providers is therefore a key priority if we are able to accelerate the knowledge and skills development of future flood engineers. 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. However, the Royal Academy of Engineering predicted in 2012 that we need 830,000 new engineers by 2020 to meet the UK infrastructure targets.

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 requires engineers to apply wider systems-thinking, and have strong networking and partnership working skills. These skills are critical to ensure that a common picture of the issues within a flood-affected area is identified, and that all stakeholders, their needs and assets (such as utility infrastructure) and interdependencies are also understood.

Critical assets, however, may not be in the ownership of public bodies for example, ports and harbours, and so 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'.

Engineers also have a role in contingency planning for the sensitive receptors affected by flood risk. Community resilience is a key part of overall system resilience in flood situations. Flood professionals clearly advocate that public funding and response cannot provide protection for all communities, from all flood risks, and that they need to work in partnership (Dinnis 2018). 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 build their understanding and partnership working across the professional sector (private and public) and civil society.

Education and professional training therefore 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 an 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 engineered 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 does not 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.

Our interviews with front line flood risk and resilience engineers identified an initial range of 'learning outcomes' for resilience engineers involving conceptual understanding, knowledge and 'directed' information, for example, the regulatory framework, new standards or best practice, as well as the ability to take a wide view of the ‘functioning system’ including stakeholders—collaborators, partners and ‘customers’. The breadth of learning outcomes are being tested and developed through the Centre for Flood Risk and Resilience, established at Brunel University London, which has been set up to deliver a pipeline of skills and capability in tackling global flood risk and resilience challenges.

Current higher education engineering provision is successful in producing technically-competent graduates. However, 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. Frequently, graduates have studied largely idealised systems and lack experience of messy real world contexts. 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.

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

- Learning from failure at a system scale—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 at a system scale—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 need to engage with, on flood risk—ensuring systems-thinking is not undermined by weaknesses in wider stakeholder relations at the time when the systems themselves will be under the most stress. Essentially, this is a recognition that the engineering system extends beyond physical structures into society.

Given the breadth of knowledge and understanding needed, it is important to focus on what principles can be delivered, and at what stage of engineering education, to ensure a focus on ‘resilience’. This will help define key outcomes for each stage of learning, sustain continual learning and develop the community of resilience practice that brings together all the key ‘actors’.

It is clear that future graduates must be equipped with an updated perspective and skillset ready to address the challenges of a changing world, working in partnership across systems, and to be able to exploit new and emerging technologies. Delivering this opportunity requires 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.

In considering resilience education, there are also opportunities through research. Action-focused research during and after flood events [e.g. Storm Desmond (PERC UK 2015)], or taking a strategic overview of catchment-level investment, provide an increasing opportunity for systems research. Whilst most would consider the product of that research to be the thesis, reports and academic papers, we should also recognise the training and development for the researcher conducting the investigation. Masters and doctoral-level training enables graduates to develop the advanced critical thinking skills for our engineering community. Whether they subsequently remain in academia, or become skilled resilience-aware professionals in the ‘flood’ sector, being able to work in both environments in a translation/transformer role will help them make the most significant contribution to the flood resilience sector.

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 start of a student's university experience, through professional development ultimately to Chartership, using well-described and considered case studies as the backdrop to progressing 'real' experiential learning.

5 Conclusions

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.

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