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Reframing resilience to guide indicator identification for index-based coastal flood resilience assessments within the UK's nuclear decommissioning sites

Michael Landry[1*], Sarah Percival[1], Joshua Griffiths[2,3], Nicholas Smith[1,2,3]
1 Liverpool John Moores University
2 United Kingdom National Nuclear Laboratory
3 University of Liverpool
Email: M.W.Landry@2024.ljmu.ac.uk

ABSTRACT

There is a significant lack of research regarding the coastal flood resilience of nuclear decommissioning sites, an issue that necessitates continuous assessment. As climate change associated sea level rise (SLR) projections are fuelling concerns about the long-term safe management of radiological inventory, and efficient progression of decommissioning, emphasised by the growing number of facilities entering decommissioning phases globally. A significant collection of literature was reviewed to collectively inform the reframing of resilience, which also aims to guide the development of coastal flood resilience index assessments through identification of indicators. Within this paper, resilience was reframed as the ability of the decommissioning site to maintain continuous essential operations, respond effectively, incorporate adaptations, and retain essential objectives. This approach presented decommissioning sites as systems, highlighting elements within dimensions that strongly influence resilience capabilities, further informed by the widely recognised framework (seismic resilience) that identifies key qualities required for sufficient resilience within a system. Focus on requirements of maintaining continuous essential operations was underpinned by the need to represent operational degradation and responses required to understand when resilience is being lost, and when it is no longer resilient, represented through thresholds. Overall, the synthesis of these elements into a reconceptualised resilience ability applicable for decommissioning contexts is significantly beneficial. As it provides a foundation not only for future research towards resilience in decommissioning sites, but for practical application, particularly in aiding index-based assessments with indicator identification within nuclear decommissioning sites for coastal flood and general natural hazard resilience.

1 INTRODUCTION:

Flooding is understood as the UK's most frequent and detrimental natural hazard, with coastal flooding ranked as the second highest risk for causing civil emergency, posing increasing risk for the UKs coastal zones (Hendry et al 2019), a significant issue that has impacted the UK previously. Such as the 1953 'North Sea Flood' storm surge that impacted the UKs east coast, causing approximately £1.2bn in damage (current value) and 307 deaths (Haigh et al 2017). In December 2013, the UK was hit by Storm Xaver, where extreme storm conditions generated comparable water levels to 1953 measurements, impacting coastlines on the Southwest of England and West of Wales (Kendon and McCarthy 2015). Future climate change induced SLR projections and associated increases in the frequency and severity of storms linked to amplification of extreme water levels are fuelling concerns for the UKs coastal zones (Perks et al 2023). As these zones are home to 9 operational reactors at 4 sites (Heysham 1 and 2, Sizewell B, Hartlepool, and Torness), with new reactors proposed across coastal positions, and Hinkley Point C (Somerset coast) and Sizewell C (Suffolk) under construction (Web 1). Yet there are 17 former sites that have ceased operations and are undergoing decommissioning by the Nuclear Decommissioning Authority (NDA), with most on the coastline and projected to take decades to complete due to engineering challenges associated with ageing assets and radiological inventory (Foster et al 2021). Consequentially, their coastal positions will further risk safety, security, and existing challenges.

There is significant focus on improving the natural hazard resilience for current and planned nuclear plants globally (Portugal-Perreira et al 2024), but a significant gap regarding the assessment of hazard resilience at decommissioning sites. It is imperative to tackle this, not only for the UK but globally, as nuclear reactor fleets are continuously aging and reaching the end of their lifespans, soon coming offline and entering decommissioning phases at an increasing rate (Wimmers and Von Hirschhausen 2023). This trend will result in an increasing number of coastal nuclear decommissioning sites that must be equipped with the tools and knowledge to assess coastal flood resilience.

A commonly utilised technique to assess resilience are index-based tools, consisting of the identification of a context's elements and combination into a comprehensive index to quantify resilience, requiring indicator determination to represent these elements (Marzi et al 2019). Indicators are understood as *'inherent characteristics that quantitatively estimates the condition of a system; they usually focus on minor, feasible, palpable and telling piece of a system'* (Balica et al 2012). But a lack of past frameworks or research to assist index-based assessments for coastal flood resilience is absent. Hence, to support determination of potential indicators, this paper undertook the challenge of reframing resilience to aid guidance, repurposing previous definitions and approaches to resilience in literature to achieve this.

2 METHODOLOGY:

The requirement of reframing resilience for nuclear decommissioning sites requires the gathering of existing relevant research, encompassing the need for a literature review. This paper could not use a *'systematic'* approach for this paper due to the lack of literature surrounding the topic when the search string *'Nuclear Decommissioning'* AND *'Coastal Flooding'* AND *'Resilience'* produced minimal results with no eligibility. This paper utilised a '*narrative review'*, a more useful approach for researching topics with a lack of an extensive literature base, providing a comprehensive overview (Greenhalgh et al 2018). The narrative review provided an overview of links between associated resilience literature to synthesise knowledge across an array of research areas, providing a comprehensive understanding. This allowed a broad exploration of literature resulting from the combination of string searches that were utilised to infer applicable elements that can be utilised in conjunction to understand how resilience can be reframed for nuclear decommissioning sites. The array of existing literature was continuously refined and analysed that allowed categorisation into 4 stages in the discussion of findings, aiding reframing resilience for application into nuclear decommissioning sites, aiding guidance of index-based assessments.

3 DISCUSSION OF FINDINGS

Stage 3.1. Preliminary Review – Foundational resilience concepts relevant to nuclear decommissioning contexts:

There are many resilience definitions in literature, but the prominent theme remains the ability to withstand external disturbances and recover effectively (Haque and Doberstein 2021). But resilience is not an all-encompassing concept, and its effective application requires consideration of multiple context dependant factors (Jones 2019). Lack of relevant resilience research for decommissioning sites required an understanding of previous resilience approaches, to bolster how it can be reframed and effectively assist in indicator identification guidance. The most relevant identified resilience perspectives included engineering, ecological, social-ecological, adaptive capacity, and system resilience, presented below:

Engineering resilience entails the ability of a system to return to a singular equilibrium following disturbance, judging resilience capabilities by the speed of return to a singular stable state (Li et al 2020). The requirement to incorporate an ability of adaptation and preparedness implementation to reduce the likelihood of future failure is heavily present (Zevenbergen et al 2020). This perspective initially seems too simplistic for a heavily complex decommissioning site, but the aspect regarding recovery speed (i.e. operational restoration) was deemed highly applicable.

Ecological resilience was pioneered by *Holling (1973)*, focusing on the ability of ecosystems to withstand disturbance without changing self-organised structures and processes, where a system can exist in multiple stable states if essential structures are retained and resilience sufficient (Dakos and Kéfi 2022). Focus is on elements required to continuously support essential key processes, significant to consider in indicator identification guidance due to influence upon a system. However, despite relevant components, further review had to be undertaken to understand how related knowledge can be translated to aid reframing of resilience in decommissioning sites, leading to the social-ecological perspective.

The social-ecological resilience approach builds upon ecological and engineering perspectives to recognise resilience as a system's capacity to absorb disturbance, reorganise, and retain essential processes, recognising the interactions between human/engineered systems (e.g. decommissioning site) and natural systems (coastal zones) (Chaffin and Scown 2018). Focus on the need to re-organise to improve resilience links heavily to engineering and ecological approaches, reinforcing the importance of adaptation and reorganisation. Furthermore, this concept highlights the influence of the *'social'* dimension, underlining how social factors can influence resilience and adaptation ability through organisation, reflected across and supported by social, governance, or institutional domains (Hahn and Nykvist 2017), important to consider as the ability to incorporate adaptations in a system underpins the sufficiency of continuous resilience.

The consistent mention of *systems* within these resilience perspectives is significant to consider, as it illustrates a decommissioning site as composed of a range of elements responsible for the continuity of essential operations (Mentges et al 2023). Resilience within systems is understood as the ability to withstand disturbance, recover, and adapt, underpinned by the capability to maintain vital functions, where understanding internal actions are crucial to comprehend resilience (Hosseini et al 2016). Thus, decommissioning sites could be perceived as *systems,* encompassing a significant array of internal interconnected and interacting components responsible for continuous essential operations, influenced by internal actions. Therefore, approaching decommissioning sites as systems could reduce the complexity of understanding what elements are responsible for resilience and operating capabilities, simplifying identification of elements that can be translated to indicators for index-based resilience assessments.

Preliminary Review findings summary:

When applicable aspects identified were combined, resilience for a decommissioning site is reframed as the ability to maintain continuous essential operations, respond effectively and efficiently, continuously incorporate adaptations, and retain original objectives. Further review simplified this approach by portraying nuclear decommissioning sites as engineered/human systems with an array of interacting elements responsible for the systems resilience capabilities, where the interaction with the natural system (coastal zone) must be recognised. Furthermore, this section presented the significance of considering the engineering, natural, and social aspects due to understood influence upon resilience capabilities, reflected within the organisational, environmental, and human dimensions. These findings provide guidance on what areas should be considered within indicator identification, signifying the importance of focusing on elements that influence the presented resilience capabilities and dimensions (organisation, environmental, human) that underpin its effectiveness. But these findings that have aided reframing resilience had to be deemed practical for real-life examples and synergise with literature regarding resilience in nuclear contexts, to reinforce applicability.

Stage 3.2. Applicability of preliminary review findings within nuclear context literature:

This section refines the preliminary review's findings through application of the reframed resilience capability to real-life examples, aiming to reinforce applicability. These examples revolve around the 2011 tsunami that impacted the Northeastern coast of Japan, specifically, the Fukushima Daiichi Plant, Tokai No.2, Onagawa, and Fukushima Daini plants. In 2011, Fukushima Daiichi was subject to the 2011 earthquake and induced tsunami, interrupting operations, causing failure in reactor cooling processes and triggering a chain reaction resulting in eventual explosions within reactor buildings and release of significant radiological material (Hasegawa et al 2014). Impacts were significant, resulting in the widespread contamination of the surrounding area that caused mass evacuations, leading to the plant's shutdown and decommissioning (Ono 2021). This practical example was found to link heavily to preliminary review findings, as the plant was unable to **maintain continuous essential operations, respond effectively** to operational loss, and **essential objectives were lost**. The other 3 plants were also impacted and operations interrupted, but these plants were able to **maintain continuous essential operations** to **respond effectively** and safely reach reactor shutdown (Ibrion et al 2020), reinforcing preliminary review findings. But only Onagawa unit 2 (a reactor within the site) is in active operation since restart in 2024, and the rest are either undergoing decommissioning or awaiting restart (Web 2), reinforcing the requirement of retaining essential objectives to remain sufficiently resilient.

Maintaining continuous operation as a key resilience capability is furthered by the requirement of safe long-term management of radiological inventory to prevent consequence (Jenkins et al 2020). Focus can be directed to elements that influence safe-management, aiding identification of associated elements translation to indicators for index-based assessments. These concerns can be further fuelled by challenges associated with decommissioning sites, regarding engineering complexities management alongside radioactive inventory and secondary waste generated by decommissioning (Ngulimi 2025; Foster et al 2021). But despite this prominent concern, another significant consideration revolves around the ensuring of continuously efficient decommissioning progression (Wimmers and von Hirschhausen 2023), both this concern and inventory management identified the influence of organisation from the preliminary review.

Within Fukushima Daiichi, the Tokyo Electrical Power Company Holdings (TEPCO) and nuclear regulators organisational ineptitude hindered the ability to effectively respond and prepare, a result of inadequate emergency response training and lack of safeguards being implemented (Murata 2021). Technical issues also stemmed from organisational ineptitude, like locating many emergency generators underground resulting in their flooding and failure (Hollnagel and Fujita 2013). A relevant dimension as the technical dimension encompasses engineered components contributing to overall resilience capacity dependent on condition, a relevant concern in decommissioning sites due to deteriorating conditions. The influence of both the organisational and technical dimension is furthered by the example of the Kashiwazaki-Kariwa Nuclear Power Plant (KKNNP), Niigata Prefecture, Japan. Although only partially operating at the time, the Daiichi disaster sparked concerns, leading to reactors being shut down following the accident and the implementation of safety features within shutdown reactors, whereas unit 6 has been restarted with aims to return to operation in March 2026 (Web 3). Since previous damage from seismic events (2007), there has been positive organisational influence from TEPCO learning from the previous Fukushima Daiichi disaster, as enhanced safety measures have been mandated, leading to rigorous inspection and implementation of upgrades as of 2024 (Yamamoto and Yamamoto 2024). TEPCO implemented increasing safety investigations and upgrades like flood barriers to safeguard against tsunamis, whilst improving preparedness through response plans, training, and backup power systems (Web 3), highlighting positive organisational influence on resilience, alongside socio-economic and technical examples that can be taken to bolster resilience at nuclear sites.

This stage provides further evidence to the influence of dimensions and elements within, and when utilised in conjunction with previous findings, it provides further information regarding responsible components within a decommissioning site to further aid resilience indicator identification. However, further clarification to effectively guide indicator identification and reduce the complexity of reframing resilience ability was required, where further review found a plethora of aspects that could result in more specified and applicable aspects that must be considered (stage 3.3)

Stage 3.3: Further understanding the applicability of findings and influence on resilience capabilities:

Requirement of decommissioning sites to ensure safe long-term management of radiological inventories and efficient decommissioning progression led to evolution from systems to 'high risk' systems, an aspect linked to the critical infrastructure systems (CI). Like decommissioning sites, CI's require continuous operation to support economic growth, governmental functions, and essential tasks (Ouyang 2014), as failure generates serious consequences (like Fukushima Daiichi) (Comes and Van de Walle 2014). Focus on continuous operation is prominent, and further research within CI literature heavily cited the framework of Bruneau et al (2003), a highly regarded, and relevant framework paper. Bruneau et al's (2003) framework provides further understanding to disaster resilience, highlighting four properties, understood as qualities a system must possess to be resilient. Understood as **robustness** (strength of a system to endure disruption without functional degradation), **rapidity** (capacity or speed to recover and restore function if it falters), **resourcefulness** (ability to effectively apply resources to meet priorities), **redundancy** (extent to which systems components are substitutable).

Further highlighted are the idea of 4 dimensions, highlighting domains where resilience properties can be applied or expressed within a system, adding to the preliminary review's findings regarding dimensions. Within the framework they are understood as **technical** (covers an engineered system components ability to maintain acceptable essential operations during disturbance), **social** (represents human aspects and measures in place to less the extent of consequences for communities), **economic** (encompass financial aspects and the capacity to reduce economic losses), and **organisational** (capacity of managing organisations to take actions to enhance resilience properties effectiveness). These dimensions are evidently present and influential in real life examples, like the Fukushima Daiichi (2011) disaster, as resilience properties were impacted by organisational ineptitude, contributing to issues in the technical dimension, and inhibiting resilience capabilities of the site. In contrast, the influence of organisational dimension can have positive impacts on resilience, evident at the improved resilience capabilities of the KKNNP, improving the technical dimension. But dimensions have varying degrees of importance, dependent on the context they are applied to (Annarelli et al 2020), and based on previous findings, the technical and organisational dimensions are seemingly more important than social and economic dimensions within decommissioning sites. As the technical dimension can be linked to engineering domains, including infrastructure and technology responsible for continuous operations, and links to engineering concerns of ageing/deteriorating assets in decommissioning sites. Whereas the significance of the organisational dimension is supported by ineptitude at Fukushima Daiichi dampening resilience, whilst fostering resilience improvements at KKNNP. Evidently, the organisational dimension can be seen as the most influential upon resilience nuclear decommissioning sites, followed by the technical dimension, influencing resilience properties, and thus capabilities.

When applied to aid the guidance of indicator identification for index-based resilience assessments, the resilience properties provide further understanding of the influence of elements, as they can be recognised based on contribution to redundancy, robustness, resourcefulness, and rapidity. This is the same for the dimensions, presenting areas influencing resilience where elements are expressed, further reducing complexity and grouping them on a basic level to further aid potential indicator identification. But continued focus has been on retaining essential operations, resulting from the system composed of dimensions and components. This led to stage 3.4, as focus on operations highlights the need to understand when a decommissioning site is no longer resilient, and to understand periods of operational loss that require differing responses before critical loss, as highlighted in stage 3.2's examples.

Stage 3.4: Understanding operational degradation, response, and point of failure:

Focus on reframing resilience capability within decommissioning sites centres upon maintaining essential operations. Failure will result in consequence, thus operational loss and response required must be appropriately understood to effectively supplement practical application for guiding identification of indicators within index-based resilience assessments to reduce its complexity.

To represent operational loss effectively, the concept of *thresholds* is utilised, commonly present in resilience literature, and understood as the point a system can no longer withstand disturbance, transforming to an unrecognisable state (Forzieri et al 2022). Prominent aspects that must be understood for sufficient application revolve around the point disturbance can no longer be withstood, recovery, and state of the system post threshold crossing (Dakos et al 2015). Suggesting that threshold application can highlight resilience levels required for differing coastal flood scenarios, signifying its performance against hazard and the importance of adaptation incorporation to improve resilience. This is an imperative aspect to incorporate, due to climate change and associated increasing risk of coastal flood hazards (Portugal-Pereira et al 2024), necessitating a need for higher resilience to lower the possibility of threshold crossing during coastal flood hazards. However, focus on response effectiveness to restore operations signifies a single threshold representation does not accommodate the importance of restoration through rapidity of response, a key capability in reframing resilience within this paper. This led to considering multiple thresholds for appropriate representation of progressive periods of functional loss. As this bettered understanding of response requirements to highlight resilience at each threshold needed for operational restoration before critical failure is reached within a system (Liu et al 2019), significantly relevant for this paper's focus on coastal flood hazard resilience, and its reframing for decommissioning sites.

Incorporation of multiple thresholds highlights the sufficiency of resilience within a decommissioning site based upon how quickly thresholds are crossed and effectiveness of restoration. This would aid indicator identification by magnifying focus to elements that influence operational degradation and thus response, signifying early warning signs, and suggesting improvements within the organisational and technical dimension. It is integral to map the potential stages of operational degradation across thresholds in coastal flood scenarios at nuclear decommissioning sites, highlighting response required and overall sufficiency of resilience, which can be translated into possible indicators.

4 COMPREHENSIVE SUMMARY:

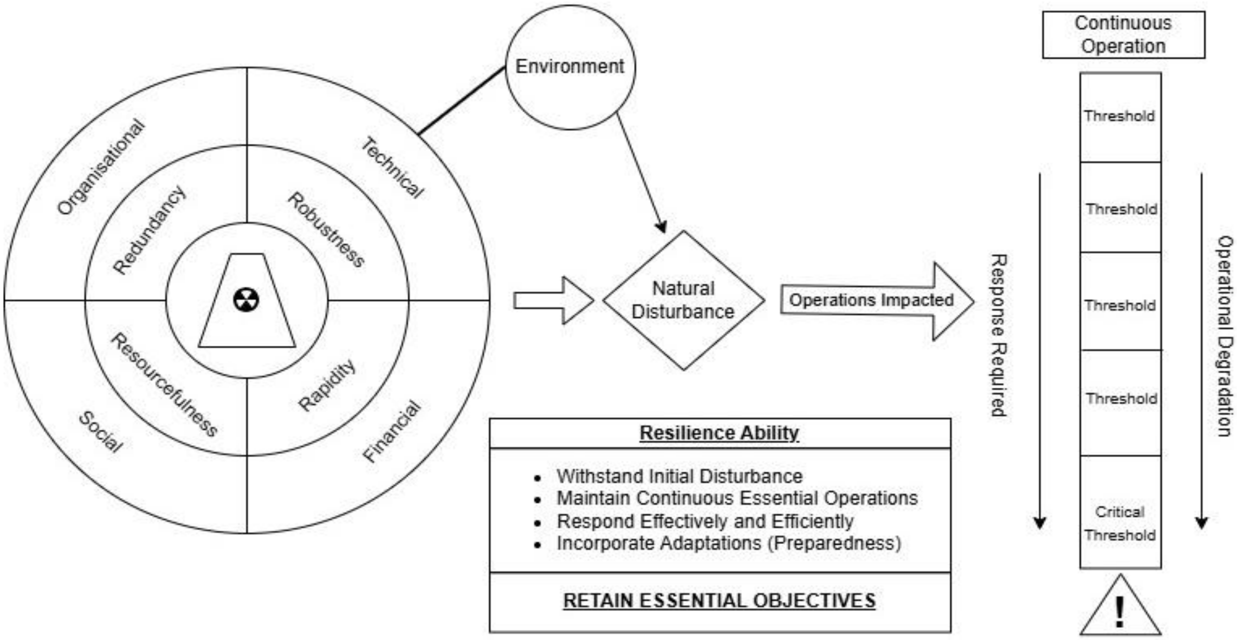

Figure 1, comprehensive illustrated representation of the reframed resilience ability.

Within figure 1 resilience capability is reframed as the ability to withstand initial disturbance, and failing that, maintain continuous essential operations, respond effectively, incorporate adaptations to improve preparedness, and **retain original essential objectives**. The capabilities to express this ability are dependent on the state of the system and resilience qualities/properties it possesses across elements, which are located within multiple dimensions that collectively shape the operational performance; organizational dimension is the most influential upon these properties. These *'systems'* (decommissioning sites) interact with the surrounding environment and if a coastal flood disturbance occurs it could interrupt essential operations. Operational loss or degradation will be represented through thresholds when applied to a site (figure 1), and dependent on the severity of the coastal flood disturbance, will result in the crossing of further thresholds and advancing operational degradation, requiring higher levels of response before a critical threshold (consequence) is reached. When this comprehensive reframed ability (figure 1) is applied within a nuclear decommissioning site, it will heavily aid the guidance of indicator selection for index-based resilience assessments, by reducing the complexity that exists within these vastly engineered sites. This will signify locations within a decommissioning site where indicators can be identified when this reframed resilience ability is applied. Providing a foundation of relevant knowledge for further reframing of resilience for nuclear decommissioning contexts to guide indicator selection in index-based coastal flood resilience assessments for decommissioning sites.

5 CONCLUSION:

To appropriately reframe resilience ability for nuclear decommissioning sites, concerns were understood through requirements of maintaining the long-term safety of radiological inventory and continuously progressing decommissioning operations without delay, underpinned by the capacity to maintain continuous levels of operation and respond to disturbances. Collectively the repurposed aspects when encompassed into application at nuclear decommissioning sites highlight a range of dimensions, elements, and components that contribute towards resilience as the ability to maintain continuous essential operations, respond effectively, adapt, and retain original objectives. This will provide a beneficial structure within indicator identification and evaluation due to the structure it provides to seek out indicators across these areas, effectively establishing how resilience can be approached and how this influences the types of indicators that should be utilised to represent this. Further research should be undertaken to build on this foundation, encompassing further levels of research to understand in-depth how resilience can be more effectively approached to guide possible indicator identification for index-based resilience assessments with nuclear decommissioning sites. This could lead to the eventual practical execution of these findings which will ultimately assess the resilience of nuclear decommissioning sites to understand its current level and how that may cope with coastal flooding disturbances within the future.

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