Environment Agency

Exploring the use of resilience concepts in catchment management

Chief Scientist's Group report

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Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

Further copies of this report are available from our publications catalogue: www.gov.uk/government/publications or our National Customer Contact Centre: 03708 506 506

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Keywords:
Catchment Resilience, Thresholds, Resilience Practice, Persistence, Adaptability, Transformability

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Citation:
Environment Agency (2023) Exploring the use of resilience concepts in catchment management. Environment Agency, Bristol.

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Dr Robert Bradburne
Chief Scientist

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Executive summary

The concept of resilience has been widely cited in environmental policy, plans and strategies in recent years; often connected to preparing for extreme events and climate change. Resilience can be defined as the capacity of a system to absorb disturbance and reorganize while undergoing change to retain essentially the same function, structure or identity. However, there are many definitions and ways of framing resilience. This presents a challenge for the Environment Agency, particularly in managing catchments, where we must balance competing objectives and demands and (by extension) diverse types of resilience.

This report describes an exploration of catchment resilience and how it is and could be used within the work of the Environment Agency. There were 3 main elements; what others say about resilience, how we currently use resilience and whether we could use it differently.

Despite a large literature few studies inform practical applications of resilience. But existing work indicates useful ways of framing resilience for use in practical management. The many definitions of resilience can be broadly categorised by whether they tend towards recovery (bounce-back) or evolution (bounce-forward), and whether resilience is seen as an inherent property or objective or an aspiration that may be a social construct. Definitions, measures and applications of resilience reflect its framing in a specific context, so they are not universally transferrable. Whilst ‘resilience’ and ‘catchment resilience’ specifically have some common currency and feel unifying some care is needed to be clear about intended outcomes and timescales.

We found wide recognition of resilience as a potentially useful concept across the Environment Agency, but general uncertainty and a range of views on what it means and how it can be used. We also found that there are many internal and external projects that are exploring or trialling resilience. The Environment Agency currently uses a mix of mostly bounce-back resilience approaches particularly in environmental protection although definitions are rarely clear. Where it is evident, we tend to assume that resilience is an inherent property of the system whereas in outcome we are usually trying to achieve a socio-political goal. Policy language tends towards a single definition and a single measure; practice tends towards measurable system characteristics.

We tested some of these ideas in three catchment studies working with operational colleagues to define the characteristics of resilient systems in a specific context and test catchment response to specific stresses. These were resilience thresholds for algal blooms, the way drought protection measures affect resilience and the nature of ecological community resilience in rivers. All highlighted the need to explain a system and exposed that eutrophication thresholds and system tipping points can be identified and managed. The effectiveness of drought measures can be identified with stress tests and in the ecology example we found that system dynamics are important, and stability is not always desirable.

The concept of resilience could facilitate a more complete understanding, assessment and management of catchment systems offering the potential to deliver environmental outcomes more effectively and be better prepared for the future. We suggest the following actions:

- The use of typologies of resilience. We propose a framework that includes values and outcomes, system description and pathways to resilience that might be persistent, adaptive or transformative.
- Further exploration of stress testing of our current resilience to climate change
- Continuing to share learning about how resilience fits with other ways to adapt to climate change.

Introduction

Resilience has become a widely used term in environmental management and policy in recent years, especially in considering how to manage extreme events and other effects of climate change (e.g., Berkes et al., 2003; Gunderson et al., 2010; Walker and Salt, 2006, 2012; Biggs et al., 2015; Newton, 2016). Whilst it offers the potential to deliver useful outcomes to protect and improve the environment there are many interpretations of resilience, its framing and definition, meaning that the term resilience is not always clear (Thorén, 2014; Vardy and Smith, 2017). Practical applications remain challenging, and frameworks aimed to inform practice can be hard to apply, particularly in managing catchments, where competing objectives and demands must be balanced.

Resilience as a guiding concept for environmental management and regulation, could help direct interventions to address existing pressures and be better prepared for the future. But there are questions that need answers to support practical implementation, for example:

- What is resilience?
- What are the useful components of the concept?
- Can we identify types, principles or approaches to using resilience in practice?
- How has the Environment Agency defined and used resilience, and how else could we use it?

Synthesizing this information presents more specific questions around catchment resilience including:

- What do we mean by catchment resilience?
- How can we achieve resilience now and in the future?
- When should we use resilience and when should we not?
- How should we use it? What benefit does it offer?
- Where, when and why does resilience occur?
- Can we measure resilience? What metrics can we use?
- Is it possible to increase resilience? Is doing so always helpful?
- What roles and responsibilities do we have in delivering catchment resilience?

This report describes the findings of a staff-led project to explore catchment resilience using a collaborative, shared learning approach to increase understanding and knowledge within the Environment Agency. We first developed a conceptual understanding of what resilience is, how it may be used in practice and applied to catchments, using literature review and commissioned reviews by experts. We then explored how the concept has been understood and used by the organisation, through staff interviews and a workshop. We then conducted 3 catchment-based studies to apply what we learned in practice. Finally, we reflect upon what the concept provides most usefully to the organisation in a practical sense and how we can use it going forward.

What is resilience?

This section provides an overview of the emergence of resilience as a concept in environmental policy and management and presents some of the practical challenges, based on a review of the literature. We establish a conceptual understanding of resilience both as a ‘property’ and an ‘approach’, including core concepts and principles, that could facilitate its use within the Environment Agency’s work. We then explore different perspectives on the concept of catchment resilience, presenting a summary of 8 solicited think pieces commissioned from experts.

Resilience in environmental management

Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change to retain essentially the same function, structure, identity and feedbacks (Walker et al., 2004; Walker and Salt, 2006, 2012). This definition and description of resilience is commonly used by scientists in many areas of inquiry (Walker and Salt, 2012) but has far-reaching consequences when applied to human and natural systems. This definition has emerged from several decades of research but it masks considerable complexity, consisting of several inter-related elements and principles. This ambiguity has presented challenges to the many attempts to clarify and apply it in practice.

A review of available literature identified an online repository of information on the understanding and practical application of resilience, adaptive capacity, and transformation of societies and ecosystems (see [Resilience Alliance - Home (resalliance.org)]), including a glossary and practical examples. We provide a brief background to the origins of the concept and the debates around definitions in Appendix 1 but in summary:

- Resilience has a long history and different meanings depending upon context
- Several typologies have been developed to understand the range of interpretations
- 3 primary conceptions can be identified in an environmental management context: engineering resilience, ecological resilience, and social-ecological resilience
- Resilience theory is the basis for adaptive management, which embraces uncertainty of complex resource systems (Gunderson and Allen, 2010).

Engineering, ecological and social-ecological resilience

Resilience can have multiple meanings so requires clear definition of the context in which it is being used. The primary distinction remains that between ecological and engineering resilience, identified by Holling (1996) and more recently socio-ecological systems (e.g., Folke et al., 2006). The latter underpins the three conceptions of resilience mostly used today (Table 1; see also Table A.1.1 for perspectives from other disciplines).

Table 1: Main characteristics of 3 different conceptions of resilience

Resilience	Details
Engineering	• Focuses on the resistance of a system to shocks and the speed of its return or 'bounce-back' to a pre-shock state or equilibrium (Kythreotis and Bristow, 2016). • Focuses on the return of structural and functional attributes of systems to pre-disturbance conditions following a disturbance; rapid return times (measured as time of recovery) reflecting high engineering resilience (Angeler and Allen, 2016).
Ecological	• Embraces a system's ability to withstand or absorb changes of state as well as its capacity to respond and recover quickly from a shock and thus to return to an equilibrium state after a temporary disturbance (Kythreotis and Bristow, 2016). • Accounts for the potential for regime shifts (alternative stable states after disturbance) of the same system (Angeler and Allen, 2016). • The 'state space' of a system is defined by the (state) variables that constitute the system – the state of the system at any one time is defined by their current values (Walker et al., 2004).
Social-Ecological	• Views humans as part of the biosphere, and assumes that social-ecological systems behave as complex adaptive systems (self-organize, characterised by emergent and non-linear behaviour and inherent uncertainty) (Biggs et al., 2015) • Aspires to be an integrated framework to be used across the boundaries of the natural and social sciences (Olsson et al., 2015)

There are different ways of conceptualising human-environment interactions (Biggs et al., 2015) with resilience being only one way of approaching assessing and managing the environment. Reconciling different perspectives and approaches may offer important ways of increasing environmental outcomes. For example, Wilby (2020) argues that all 3 of the related concepts of resilience, resistance, and reliability, should be embraced to broaden the range of options available and offer a more integrated conceptual framework. This aligns with incorporating resilience thinking and practice into an approach and framework for social-ecological resilience to address the sustainability challenge and provide practical guidance to decision-makers and practitioners (Biggs et al., 2015).

Policy and practice

The policy use of resilience is almost exclusively 'normative', treating resilience as something good (Olsson et al., 2015). Attempts to use the concept in practice emphasize that resilience is neither good nor bad (Walker at al., 2004) or 'neutral' in the Olsson et al.

(2015) typology. At a policy level, resilience has drifted towards being a perspective (e.g., Brand and Jax, 2007; Olsson et al., 2015) rather than the precise, practical meaning that would facilitate its use in environmental management. However, this perspective can be especially important for setting and guiding policy and strategic direction, behind which management ambitions may appear. Using more precise definitions of resilience and its core concepts and principles in context, paves the way for it to be useful in practice.

Core concepts of resilience

The concept of resilience has several essential elements i.e. the system, its equilibria, boundaries, thresholds and feedback mechanisms, its capacity for self-organisation and its function (Olsson et al., 2015). Drawing heavily on case studies and research undertaken through the Resilience Alliance, Walker and Salt (2006, 2012) provide an overview of resilience science and the development of their resilience thinking framework. They translate the concepts and framework into practical guidance for real-world application; the underpinning concepts are summarised in Table A.1.2.

Within their framework, the stability dynamics of all linked systems of humans and nature emerge from 3 complementary attributes (Walker et al., 2004): resilience, adaptability, and transformability (Table 2). There is a major distinction between resilience and adaptability, which relates to the dynamics of a particular system (or a closely related set of systems) and transformability (which refers to fundamentally altering the nature of a system) although the dividing line can be fuzzy and subject to interpretation (Walker et al., 2004).

Table 2: Complementary attributes of dynamic systems: resilience, adaptability and transformability (adapted from Walker et al., 2004)

Attribute	Details
Resilience	• The capacity of a system to absorb disturbance and reorganize while undergoing change to essentially retain the same function, structure, identity and feedbacks. There are 4 crucial aspects of resilience: • Latitude: the maximum amount a system can be changed before losing its ability to recover (i.e. before crossing a threshold which, if breached, makes recovery difficult or impossible). • Resistance: the ease or difficulty of changing the system; how much stress or pressure the system can withstand before it begins to change. • Precariousness: how close the current state of the system is to a limit or threshold. • Panarchy: the resilience of a system at a particular scale will depend on the influences from scales above and below, due to cross-scale interactions.

Adaptability	• The capacity of actors in a system to influence resilience
	• In socio-ecological systems this is the capacity of humans to manage resilience.
	• The collective capacity of individuals or groups to intentionally manage resilience, determines whether crossing into an undesirable system regime can be avoided or a return to a desirable state can be achieved. This can be done in the following ways:
	  ○ Move thresholds away from or closer to the current state of the system (by altering Latitude)
	  ○ Move the current state of the system away from or closer to the threshold (altering Precariousness)
	  ○ Make the threshold more difficult or easier to reach (altering resistance)
	  ○ Manage cross-scale interactions to avoid or generate loss of resilience at the largest and most catastrophic scales (altering panarchy).

Transformability	• The capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable. • Transformability means defining and creating an alternative, replacement system by introducing new components, changing the state variables and often the scale.

To address seemingly contradictory concepts, Folke et al. (2010) clarify some of the terminology, confirming that the resilience framework broadens the description of resilience beyond its meaning as a buffer for conserving and recovering. Beyond this persistence, resilience thinking incorporates the dynamic interplay of persistence, adaptability and transformability (PAT) across multiple scales (Folke et al., 2010). Several recent studies have followed this PAT framing; integrating different resilience concepts to suggest that these are the 3 capabilities that characterize a resilient system and that we can assess and manage for all 3 (see Rockström et al. (2014), Boltz et al. (2019) and Hall et al. (2019) for some examples of this approach in the water environment). Assessing these 3 attributes within the context of environmental outcomes moves us towards understanding system behaviour and how our response can be integrated into policy and practice.

Principles of resilience

The last few decades have seen intense activity around the development of theoretical frameworks and less on comparative, empirical studies to advance understanding of principles and practice (Schlüter et al., 2015). There are 2 related strands of activity: developing general principles and developing means to apply the theory more consistently in practice.

Principles of a resilient world include diversity, variability and modularity (see Walker and Salt (2012) and Table A.1.3). Policy-relevant principles for enhancing the resilience of desired ecosystem services in the face of disturbance and ongoing change in social-ecological systems (SES) include (Biggs et al., 2015):

- Maintain diversity and redundancy
- Manage connectivity
- Manage slow variables and feedbacks
- Foster complex adaptive systems thinking
- Encourage learning
- Broaden participation
- Promote polycentric governance systems (where multiple bodies interact to achieve collective action)

Biggs et al. (2012, 2015) note that in practice these principles often co-occur and are highly interdependent but often not well understood. They acknowledge that they are not definitive or universally beneficial in every system and will require interrogation, modification and refinement. For example, polycentric approaches facilitate achieving benefits at multiple scales as well as experimentation and learning from experience (Ostrom, 2010). However, currently there is a lack of understanding of how to use polycentricity in governance of social-ecological systems (Schoon et al., 2015).

From theory to practice

Walker and Salt (2012) suggest translating concepts into practice could be a 3-stage approach describing the system, assessing resilience by analysing system dynamics and what this means, and managing resilience by deciding what you are going to do about it

(Table A.1.4). This approach is flexible and scalable. The main elements are (Walker and Salt, 2012):

- Resilience is a dynamic property of a system, and managing it requires a dynamic and adaptive approach. There are many ways of putting resilience into practice.
- The basics of resilience thinking involve appreciating a system's thresholds, domains, and linked adaptive cycles.
- Resilience thinking is about understanding requisite simplicity (defined as 'attempting to discard some detail, while retaining conceptual clarity and scientific rigour' by Stirzaker et al. (2010)). What, essentially, do you need to know about your system to keep it sustainable?
- Specified resilience is how far the current state of a system is from a threshold. General resilience is the system's capacity to manage a disturbance and prevent the state of the system from reaching a threshold.

Measuring and managing resilience

The transition from theory to practice requires assessment or estimation of resilience (Carpenter et al., 2005). If we are unable to measure resilience in some way, it will be hard to assure ourselves and others that we are taking the right actions. Direct measurement of resilience is difficult because it requires measuring the thresholds or boundaries that separate alternate domains of dynamics (Carpenter et al., 2005). Likewise, measurement of progress in practice or at a policy level is difficult without defining what it is that you are measuring and why. Ecological resilience can be measured through an assessment of mutually non-exclusive attributes, including alternative states, feedbacks and scales (Angeler and Allen (2016). Carpenter et al. (2005) highlight that:

- resilience measures differ from traditional ecological indicators in several respects so it is better to use the term surrogates instead of indicators;
- resilience measures should correspond in specified ways to theoretical aspects of resilience;
- these aspects depend on the context and change over time, with spatial configuration, and among the constituent ecosystems and people;
- the relationship between resilience and any particular surrogate may be dynamic, complex, and multidimensional.
- the resilience of SES is not directly observable; surrogates may be created through stakeholder assessments, model explorations, historical profiling and case study comparison, for example.

Catchment resilience

Using the resilience perspective to analyse social-ecological systems (SES) emphasizes the need to understand and manage change, particularly unexpected change, moves beyond viewing humans as external drivers of ecosystem dynamics, and fundamentally assumes that SES behave as complex adaptive systems (Biggs et al., 2015). In application, resilience can be highly context specific; requiring definition of the system of interest and an understanding of outcomes.

An important early stage in the process ("describing the system", Table A.1.5) involves defining the appropriate scale for the system of interest and recognising that interactions at other scales are important in understanding resilience (Walker and Salt, 2012). Many of the most pressing climate change risks and impacts in the UK are water related (Garner et al., 2017). Although changing river flows and impacts on flooding, water resources, water quality and ecosystems are managed and understood at a range of scales, historically the river catchment has been the defining unit land and water resource management (see Knighton, 1998; Newson, 1992). As much of the Environment Agency's work is based on the catchment scale (for example River Basin Management Planning, Catchment Based Approaches), we aimed to understand how concepts of resilience may be used in a catchment context to improve environmental outcomes within our remit.

A literature search for catchment resilience found an increase in peer reviewed publications since the early 21st century, particularly in the last ten years, and especially in the environmental/ecological literature. Research on catchment resilience has been applied at a mix of scales, mostly defined according to hydrological thresholds but incorporating a mix of environmental and social-science based parameters. As many socio-hydrological systems have inherently ambiguous boundaries (scientific/political) this has emerged as a challenge for applying resilience concepts.

Given the limited published information on practical applications of catchment resilience in England we commissioned a range of perspectives from leading UK academics with different specialist areas. Each of the 8 separate reviews described the current state of understanding and the extent of practical use of resilience in the management of key components of the physical environment, including hydrology, agriculture, communities, ecology and the coast (summarised in Appendix 2). Some have also been further developed into journal papers: Fuller et al., 2019; Masselink and Lazarus, 2019; and Wilby, 2020.

Consistent with the broader resilience literature, the reviews found several common elements that highlight the practical barriers to applying the resilience concept at a catchment scale within the remit of the Environment Agency:

- a lack of examples of practical application
- confusion about what is meant by resilience
- resilience is likely to be best achieved through collaboration and a collective effort and sharing of resources to aid recovery
- considering the links between risks and where the resources that build resilience come from

Despite the diversity of topic areas, many of the perspectives highlight the common elements of resilience presented earlier that we need to consider:

- **Resilience is complicated.** Include natural, social and technical aspects**.**

- **Spatial and temporal scale**. For example, the UK is resilient to coastal flooding as there is plenty of higher ground, but this won't feel reassuring to those living in low lying coastal communities, or a community may recover from a single flood in a year but may not be resilient to more frequent flood events.
- **Thresholds, tipping or failure points and equilibrium states.** It might be wise to consider resistance (e.g., to flooding) and reliability (e.g., of water supply) alongside resilience, as these terms along with vulnerability are often used interchangeably.
- **Persistent and emerging threats.** The magnitude of influence of properties that determine resilience could change or vary.
- **Catchment characteristics** that favour recovery or support transformation. Catchments are naturally evolving complex systems, so resilience needs to be considered in this context.
- **Interactions**. Resilience may be found in the interactions of parts of a catchment system. We may be able to identify cascading effects or feedback pathways.
- **The ecosystem services people and the environment need.** Some of these may be very resilient in UK catchments so we can usefully focus on those most at risk.
- **Uncertainty.** Due to the complexity of a catchment, obtaining a complete understanding of the entire system is likely impossible. Therefore, we should identify particular mechanisms, pathways or variables that we understand (at least in part), are able to somewhat predict and we know play some role in determining the overall catchment resilience.
- **Lack of measures.** There are no readily available measures of catchment resilience, although there are studies that have attempted to develop them. Resilience could be assessed through a range of different indicators, metrics and surrogates that characterise a system and its behaviour. We may already record some during routine or ad hoc monitoring, others will need to be identified or measured. The right measures allow an assessment of resilience and how it may change under different conditions (changing climate, management practices) and could be used for measuring progress towards resilience.

Resilience in the Environment Agency

This section describes insights from informal discussions with staff across the organisation and a structured workshop to understand how the concept has been used in the Environment Agency to date.

Interviews with staff

An important component of this project was to capture the understanding and use of the concept of resilience in Environment Agency work. We talked to 20 Head Office colleagues and leadership teams about what resilience means to them and how we, as an organisation, are engaging with this idea, formally and informally, in relation to catchments. Conversations were summarised (Appendix 3) under the questions asked and responses broadly reflect the issues raised in the Expert Review papers and the Literature Review described earlier.

What is resilience?

Staff recognized the broad range of uses of the concept: one or several of the interpretations identified in the literature applied to their thinking, depending on their individual perspective and application. In addition, related terminology was used in varying ways, e.g., “bounce-back”, “static”, “bounce-forward” and “transform”. There was no consensus definition or concept of resilience and some interviewees noted that a common description of what we as an organisation mean by resilience would be welcome. Others broadly defined resilience in line with the ecological definition (presented earlier in the ‘What is Resilience?’ section) but observed that this overarching definition needs to be clearly specified within the context of the system of interest. Some see resilience as protection (from flooding, for example), while others see it as something akin to sustainability.

Generally, staff view the concept through the lens of their particular interest, with the term used in relation to a specific stress and receptor: the resilience of x to y. Different actors and parts of the business have different x’s and y’s making a standard description or definition challenging. This is in part because such a specific focus may obscure the broader definition, giving the impression of a lack of consensus. It also reflects the broad scope of Environment Agency responsibilities. For example, historically flood defence and water resources tended to be largely engineering focussed. In contrast other parts of the business, such as water quality, tend to consider wider systems with greater interactions.

Staff with a greater policy focus tended to view resilience as a more vague term and desired a single organisation-wide view. Others, focused more on practice, used the term in a more specified manner. The majority of those interviewed fell somewhere in between.

How does the Environment Agency use resilience?

The term resilience is widely used across the organisation, particularly in policy documents (e.g., 25-year Environment Plan (HM Government, 2018) and the new National Flood and Coastal Erosion Risk Management Strategy for England - GOV.UK (www.gov.uk) (Environment Agency, 2020)). It is also used in a mixture of senses (sometimes broadly and colloquially; sometimes in a more specified way) at a practical level. This can cause a disconnect between what is meant at a policy level and how it translates to in practice. This discourse is consistent with the review of literature and remains a constant theme running through environmental management more generally.

Interviewees were interested in what resilience could do for them as a concept and in practice. They were particularly interested to know: is it worth doing, how can we operationalise it, where is it most useful and what are its limits?

What are the work areas where the Environment Agency already uses, or could use resilience?

Our interviews found that the concept of resilience is widely used (or proposed) by the Environment Agency and our partners, in catchment and other areas primarily: water resource management; natural capital; community resilience to flooding; resilience metrics. It was also identified as being a useful concept for specific work streams, including Water Land and Biodiversity's Better Planning for Environment initiative, the Draft River Basin Management Plans consultation and Abstraction reform planning.

What questions do colleagues have that research could help with?

There are some areas around which interviewees indicated a desire to improve their understanding of resilience, including around governance and practical applications, the economic, practical or other limits or tipping points to resilience; and balancing potential trade-offs between resilience to different hazards within and between different components of a system. Some of the research questions identified are included in Appendix 3. Other areas of interest concerned how we might use existing or emerging assessment approaches (for example, mixed modelling approaches or stress testing) to assess and manage resilience, how we might measure and apply resilience, and how we might effectively investigate interacting components of related systems. Several staff expressed a strong desire to explore how stress testing could help identify thresholds, as they felt other measures of resilience were harder to control.

Summary

These conversations suggested that a set of principles that capture the core concepts of resilience that can be transferred across the wide range of applications could be more helpful than a single definition that meets some needs but not others. The conceptual understanding presented from the literature and expert reviews can help develop a shared foundation going forward.

Workshop with staff

The interview responses underlined the importance of organisational learning of resilience and helped shape an internal workshop held in July 2019. The workshop aimed to share knowledge from the literature and expert reviews, to outline and test out conceptual understandings with colleagues and to gather further insights into the existing use of resilience within the Environment Agency. We also explored ways to do things differently and got ideas for some practical tests of catchment resilience within the organisation's work.

Understanding resilience-related activities in the Environment Agency

The first objective was to build upon the conceptual understanding of resilience identified in both the literature and expert reviews and assess how different perspectives or concepts of resilience have been used across the Environment Agency. The intention was to identify where we can be more rigorous in applying resilience concepts.

To do this a draft typology based on the earlier reviews and staff interviews was developed. In an interactive session, promoting open discussion, attendees were asked to assign how activities in their work areas may match the descriptions. This was challenging because individual projects or measures did not always align strictly with the definitions, with some displaying elements of more than one. Furthermore, there was confusion around terminology (particularly inconsistent use of similar terms). Examples from a post-it note session were loosely transcribed placing examples on a continuum from persistence to transformability (Table 3 and Appendix 4).

Table 3: Output from the workshop with Environment Agency staff; self-reported examples of existing Agency work placed within a resilience framework

Persistence		Adaptability	Transformability	
Repair of Wainfleet flood embankment.	Flood uplift values: flood protection by updating guidance with best available science.	Thermal resilience goal: ‘preventing excess warming of rivers’ by planting trees.	FCRM strategy and adaptive pathways – using the idea on any new capital schemes.	Redefining Estuaries and Coasts across government. System = Estuaries and Coasts governance/policy framework. Goal=integrated Estuaries and Coasts regulation with a move towards self-regulation.
Assessing suitability of spreading waste to land: would soil systems still function or would resilience be compromised?	Making sure communities are more. resilient to flooding.	Water supply planning: climate change and changing population/demand – identify options to maintain levels of service.	Resilient fisheries system. Goal is maintaining sustainable fish stocks (Although species may change).	Land use change project: multiple objective mapping and decision support tools (national and local outcome support). Using water quality, food, biodiversity, forestry and climate change data and mapping.
Water Framework Directive (WFD achieving Good Ecological Status GES).		Catchment Based Approach (CaBA) partnerships working together to develop vision and joint action to WFD.	Change a damaging abstraction licence to make abstraction more sustainable.	25 Year Environment Plan using natural capital and system thinking in planning.
Capacity and capability of Permitting and Compliance resource		Resilience of drainage and water systems: infrastructure, reduced risk of	Climate resilient strategies project: how resilient are EA	System recovery after Phosphate (P) removal at Water Treatment Works (reduced P in river, achieved

system is technical management, goal is to deliver Estuaries and Coasts duties.		flooding and pollution after intense rainfall events.	strategies and plans?	Environmental Quality Standards (EQS) but ecological system disturbed leading to algal bloom and revised goals.
Building headroom into single functional permits e.g., for water quality and water resource.		Restoring our estuaries and coast systems = naturally functioning estuarine and coastal ecosystem.		
Recovery from flooding following Storm Desmond.		Rapid water trading: system agricultural purpose: produce food without damaging rivers.		
		Creating flood communication tools.		

Staff identified a lot of work that seeks to enhance resilience and several examples that were considered to represent the 3 basic capabilities (persistence, adaptability and transformability). The tension between policy and practice use of resilience is clear. Many of the work areas identified are future intentions rather than current operational practice and many are stated ambitions in policy visions like the 25 Year Environment Plan, rather than practical examples of a resilience approach. This matches findings from the staff interviews where we found that environment protection for example is largely designed around quantitative standards. Most of these are regimes based on environmental standards e.g. Environmental Quality Standards (EQS), Nitrate Vulnerable Zones (NVZ), bathing waters, Environmental Permitting Regulations (EPR) intended to maintain the environment at a particular biological or geochemical composition. Our approach to fisheries management also tacitly assumes that populations will return by themselves if pressures are removed.

The changing distributions of plants, animals, fish and diseases are recognised in policy positions but are not yet explicitly embedded in terms of resilience in permitting where-targets are often species based. Addressing this disconnect is an important step. The

Catchment Based Approach includes Natural Flood Management and other interventions to alter physical components of the catchment system to improve resilience of the system to cope with flooding, water demands or other pressures. This includes an assumption that resilience is an objective property of the catchment system, i.e., altering one component will automatically change capacity of the catchment system to cope with a given stress. For example, planting trees benefits flood resilience.

The periodic Price Review that dictates water company planning indicates two framings - resilience of supply and environmental protection. For example, abstraction reform seeks to change the way in which water allocations are managed to ensure water availability under changing environmental and demand pressures. In flood risk management, climate change flood uplift allowances for planners acknowledge the changing risks and build in a value that aims to prevent a threshold breach. What emerged from the workshop discussions was a growing awareness of how resilience framings can be helpful in thinking through how we approach future challenges. It is also clear that management approaches exist on a continuum with regards the resilience framework. What matters is ensuring that the chosen options have been evaluated within the context of the desired environmental outcomes.

Generic policy terms dominate specific resilience terminology. It is, for example, not clear that any of the activities relating to transformability consider changing to a new system because the current one is untenable. Many of the actions under adaptability largely represent actions to maintain or return the system to its current state, rather than managing the change within it. Many of the actions also appear to adopt the policy-framing of resilience rather than the practice-oriented framing. This suggests that to bridge this gap we need to be more explicit about using resilience in practice, streamlining assessments that specifically identify and manage for resilience.

Workshop focus groups

Based on the literature reviews, staff interviews and first part of the workshop, a series of focus groups were used to explore some of the practical issues in more detail and to identify some potential catchment trials to collaboratively test aspects of resilience in practice (Table 4).

Table 4: Summary of the workshop focus groups

Focus group	Background	Questions	Proposed
Building on existing work	Throughout the day we had demonstrations of work on resilience around rural diffuse pollution, the Flood Strategy and community flood resilience.	Are there elements of this work that we could replicate elsewhere? How could we go about this?	A clearly defined systems and goals approach, linking top-down (theoretical) and bottom-up (contextual) evidence would be most effective in future work.
Stress Test	Based on the 2008 financial crisis, the Bank of England (2020) now applies stress tests to the financial system to understand points of weakness and prevent the same issues reoccurring.	By applying a number of theoretical "shocks" to catchments, can we improve resilience by understanding points of success and failure?	Undertake pilot studies in a number of areas, including: Effect of Section 57 restrictions (limiting spray irrigation during severe drought) on abstractors. Requests for variances in abstraction licences during prolonged dry weather.
Pilot projects	Catchment resilience concepts could be tested through local catchment pilot studies.	Questions remain over whether a local study could be scaled up to give national outcomes, or whether a top-down approach would be more suitable, but metrics for success in either event would need to be generic enough to allow for comparison across catchments.	Assess integrated water resource and water quality issues in test catchments to understand how to assess and manage for resilience.
Policy and practice	Catchment resilience is part of a wider policy shift towards whole catchment permitting, local decision-making and increased	What activities would lead to greater alignment between systems thinking, 25 Year Environment Plan, Natural capital, River Basin and Flood Risk Management Plans and spatial planning?	No specific recommendation but agreement that more alignment is needed

	regulatory flexibility.		

Resilience and the Environment Agency

Taken together the interviews and workshops indicate a wide variety of interpretations of the concept of resilience, which are both consistent with some of the literature and present a barrier to its use in practice. However, it is clear that many of the concepts of resilience theory are embedded in our environmental management practices and we are doing practical work to manage the resilience of relevant systems, although this is rarely formalised or recognised.

Some themes emerged:

- Definitions tend to split along the lines of different framings. These are either topic specific (ecological and engineering) or focussed on policy and practice. Some emphasize the value of incorporating both topic and policy/practice into a flexible approach.
- The broad concept of resilience is highly context specific, giving the impression of multiple, potentially contradictory versions of resilience.
- Policy language tends towards a single definition and a single measure; practice tends towards the potential for using measurable system characteristics. A general sense that resilience is not measurable was pervasive.
- Environment Agency work tends to use policy-based framing of resilience rather than the more practice-based framing. This makes it hard to assess if any the activities we take are enhancing or managing for resilience. This indicates that the detailed work around assessing and evaluating resilience at a practical level needs to be streamlined into our practice.
- Approaches to characterising system responses and interpretations can be useful for understanding how and why the concept is being used and for guiding and monitoring overall ambitions. However, these have less utility in designing on the ground interventions unless incorporated into assessments in some way.
- Resilience is a helpful concept but must always be considered and understood in context of the specific system of interest and in the time and spatial scales under consideration. The diversity of system contexts can give the impression that interpretations of resilience are too varied to be useful in practice
- Resilience can change as the pressure/stress vary with time. We must be willing to revisit our understanding of current and future resilience on a regular basis.

Catchment Trials

We conducted 3 studies to explore and demonstrate how we could use resilience in a climate change context across different areas of the Environment Agency's remit:

1. Exploring catchment resilience to drought and whether an intervention to protect the environment during low flows (spray irrigation restrictions) increases resilience. It included a vulnerability assessment to understand how a particular management method may fare under current and future conditions and what this may tell us about resilience.
2. Looking at the functional dynamics of different macroinvertebrate communities and how variability in the composition relates to the resilience of the wider ecological system. It assessed ecological resilience using trait-based measures of biodiversity to help understand response to disturbance.
3. Appling the principles of resilience practice to assess and manage water quality risks relating to excessive growth of algae (algal blooms). It used a mixture of methods to identify thresholds and model changes in the main drivers of algal bloom dynamics under current and future conditions and explored how different management options may reduce the occurrence and persistence of algal blooms.

The following sections provide an overview of the catchment trials.

1. Catchment resilience to drought

Drought is expected to become an increasing risk with climate change although there is uncertainty around changes in the severity, duration and location of such events (Garner et al., 2017). One drought management tool available to the Environment Agency is the implementation of restrictions under Section 57 of the Water Resources Act 1991, commonly known as Section 57s. As a result, the Environment Agency can vary licences for spray irrigation during periods of low flow or other emergencies. The aim is to reduce agricultural consumption of water, ensuring it is available for other uses. From a resilience perspective they aim to aid recovery and prevent drought impacts worsening.

The aim of this trial was to assess whether, and how, the use of Section 57 restrictions contributes to resilience in different catchments (Environment Agency, 2023). We did this by assessing the impact of restrictions on a catchment's response to drought and considering whether the drought management action is an effective tool for managing the risk of drought under a changing climate in three English catchments.

A scenario neutral approach was used to identify system performance under different lengths of drought and rainfall conditions. Compared with scenario-led impact studies the approach is based on sensitivity analyses of catchment responses to a plausible range of climate changes (rather than the time-varying outcome of individual scenarios), making it 'scenario-neutral' (Prudhomme et al., 2010). The approach involves systematically exploring how changes in different variables can result in changes in other variables that respond to them. This response relationahip can then be visualsed graphically as a response surface. In the example shown in Figure 1, the response surfaces show the amount of demand for water that is not met in 3 different water supply systems (Sussex North, Swindon and Oxfordshire (SWOX) and Wimbleball) with systematic changes in the duration of a drought and the magintude of the rainfall deficit. This example is taken from an Environment Agency project to explore the impacts of mild to extreme droughts on water supply systems, but it has also been used by the Environment Agency to estimate the impact of climate change on flood flows (DEFRA and Environment Agency, 2009, 2010, 2023; Environment Agency, 2015, Kay et al. 2021). Such a “bottom-up” approach (see also Charlton and Arnell, 2014) is beneficial to system managers (Brown and Wilby, 2012) in helping them understand the risks they face and whether they may need to intervene to make the system perform differently. It is therefore sometimes referred to as a stress test.

Three metrics were chosen to understand the effectiveness of S57s. Crossing thresholds in Q95 flow (a low flow indicator where the flow is equalled or exceeded 95% of the time) define the system change of interest, whilst additional days above Q95 threshold and additional flow volume (Ml/d) above the threshold represent the benefit of restrictions. Response surfaces were produced representing drought duration (months), % of long-term average rainfall, and the metric of interest on the x, y, and z axes, respectively (Figure 1). Climate change scenarios can then be imposed on the surface.

This trial tested the ability S57s to return river flow volumes to a pre-disturbance state (above the Q95 flow threshold) as quickly as possible and avoid any further impact. To some extent this project takes an engineering resilience perspective in attempting to understand the performance limits under given conditions on a particular set of drivers and responses. The results suggested that for these catchments, Section 57s are not an effective way to ensure catchment resilience by preserving low flow volumes in the present day or under future climate change. Their implementation provided only marginal benefit to influence or maintain flow volumes during different drought conditions: thus they will not be effective in enhancing resilience at these locations. This is an important finding highlighting that other ways of managing drought should be implemented in these catchments to create resilience. This is likely to be because the S57 restrictions are appropriate for catchments with high agricultural abstractions, which these are not. The current assessment could be applied in additional catchments to identify when and where S57 measures are effective in improving resilience. It highlights that drought management needs to be adapted to be more effective in different locations.

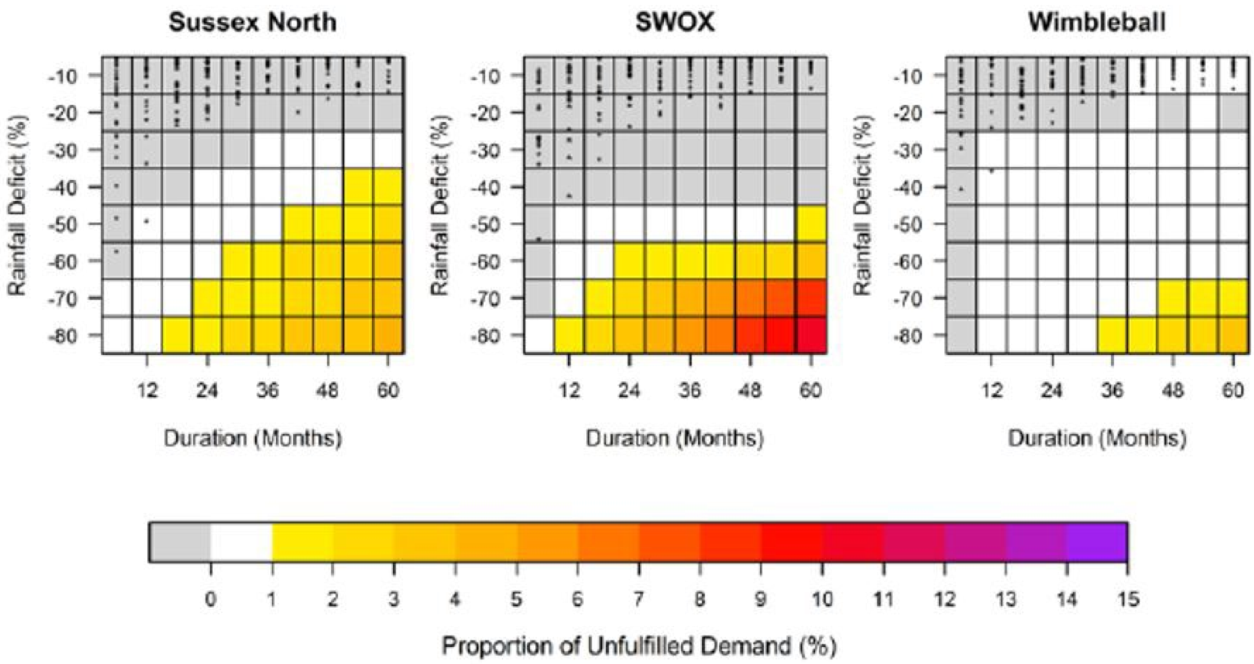


Figure 1: Example drought response surfaces for 3 reservoir systems (adapted from Environment Agency, 2015).

The approach used in this trial could be used on different types of system to:

- Summarise system response to varying pressures (whether the same pressure or different characteristics or different pressures).
- Identify thresholds and tipping points in a system's response to changing pressure. Identifying thresholds is the basis for understanding resilience.
- Facilitate a multi-disciplinary conversation to define the metrics of key importance to assess the resilience of a particular system.

Section 57 interventions may provide additional benefits to river biota or water quality that were not captured in this analysis. This highlights the need for a more holistic (complete) analysis for understanding resilience and deciding what are the important metrics and outcomes for a particular catchment. The current form may not work well under multiple stressors but could be expanded to develop a framework for stress testing different systems within the Environment Agency's remit by for example:

- An empirical assessment, literature review or expert elicitation to define critical thresholds and desirable outcomes, then identify changes that stretch the system even further than the existing historical record.
- By representing system performance (as well as management benefit) the critical thresholds can be mapped onto the response surface to indicate current system state relative to the critical threshold.
- Change under different conditions can then be mapped to infer more about the benefits for system resilience and allow comparisons between different catchments.

Careful consideration of the system and the design of test is crucial for the approach used in this trial (Environment Agency, 2023). The initial step of assessing system performance and identifying critical thresholds can be resource intensive but ensures that resilience can be identified in terms of where the system is in relation to the critical performance threshold; especially in situations in which the outcome is to maintain a particular level of performance. Exploring ways of representing changes in multiple stressors is important if the approach is to be able to help us understand resilience beyond single measures. This approach is likely best suited as part of a broader suite of assessment methods.

2. Ecologically resilient catchments

The health of freshwater environments can be considered degraded “when the ecosystem’s ability to absorb a stress has been exceeded’ (Loeb and Spacie, 1994). The stress experienced can be physical, chemical or biological. The effects of stressors are not mutually exclusive, and can occur in combination leading to faster, and prolonged, environmental degradation. A resilient ecosystem is considered one that can resist regime shifts into alternative states. Regime shifts (abrupt and persistent changes in ecosystem structure and/or function) may be caused by a stress and affect the services that the ecosystem provides (Folke et al., 2004). Thus, the likelihood of the regime shifts occurring increases when resilience is low.

Research on ecological resilience of river systems highlights how trait-based measures of biodiversity (e.g., body size, diet) can aid understanding of river ecosystems response to, and recovery from, disturbance (i.e., quantifying resilience) (Southwood, 1977; Townsend and Hildrew, 1994; Winemiller et al., 2015; Brown et al., 2018). Immediately after exposure to a stress, species possessing traits that aid resistance (able to withstand stress in-situ) will be favoured, whereas those with resilient traits will recover most rapidly following the stress.

This study (McKenzie et al., 2022) assessed ecological resilience through taxonomic and functional trait-based analysis of macroinvertebrate assemblages in three English catchments. Using an analysis-led approach, the macroinvertebrate communities were analysed and the results ‘ground-truthed’ against the knowledge of local experts. The investigation found that large changes in taxonomic and functional indicators were common across most sites assessed. Evidence of clear regime shifts between alternate stable states were found at many sites but lacked long-term (e.g., >2 years) persistence. Change was more commonly associated with random environmental variation, or stochasticity, reflecting the dynamic nature of rivers (Yang et al., 2019). There was high variability (i.e., low resilience and the community is less stable over time) in the more natural sites in lowland chalk streams (less modified, heterogeneous flow patterns, good connectivity to the floodplain, and well-developed riparian zone). By contrast, results suggest there is low variability (e.g., high resilience and the community is more stable over time) in natural sites with hard geology.

The frequency of abrupt structural and functional changes observed in this study raises the question as to whether stable states exist in English rivers. Ecological stability may be more likely to occur in impacted sites rather than more natural sites. At impacted sites the system may be locked in a state that prevents the community from increasing in structural and/or functional complexity as a stress changes (Heiri, et. al, 2001). This is known as 'undesirable resilience', and recovery or change to its previous state can only be achieved through large, costly interventions (Oliver et al., 2015). However, high variability (reduced stability) can also be indicative of ecosystem stress (Cottingham et al., 2001), where such stochasticity can be indicative of closeness to a tipping point leading to sudden changes and a new equilibrium (Dai et al., 2012). This study demonstrated that combining functional and taxonomic responses together provided richer insights than analysing the taxonomic outcomes alone. Further work is needed to understand the frequency of regime shifts in other rivers and how this reflects ecosystem resilience.

This trial highlights the importance of identifying appropriate metrics to describe resilience, the 'natural' variability of ecological systems and where ecosystem structure and function may be near to change. It also demonstrates how large data sets can contribute to understanding ecological resilience. By identifying appropriate metrics we will have a better understanding of current ecological resilience in catchments that can be used to inform management actions to preserve the current regime or respond to a regime shift. This trial also demonstrated that, depending on context and perspective, not all resilience is desirable.

3. Eutrophication thresholds in lowland rivers

Rivers in East Suffolk periodically suffer from excessive growth of algae (phytoplankton blooms) leading to falling oxygen levels in slow flowing channels, especially in dry periods. This can affect the quality of the water, the availability of water for public supply and ecosystem health. We applied resilience principles to understand if they may help us manage water quality problems in practice by exploring resilience to algal blooms and their consequences (Environment Agency, 2023b). We began by understanding the risks to the rivers in the area. We defined metrics of resilience, metrics that influence resilience and identified management solutions that have potential to improve resilience to algal blooms. Local stakeholders helped to describe and understand the river system. For three rivers in the area (Deben, Gipping and Stour), site-specific metrics for assessing resilience were defined for: water temperature, flow and residence time, nutrient concentration, phytoplankton biomass (chlorophyll-a concentration), global solar radiation, dissolved oxygen content and a measure of algal bloom risk days.

Threshold analysis and analytical models were used to assess system resilience (under current pressures and future climate change) and options for management (focusing either on preventative action or treatment). Three methods of increasing complexity were used: a load apportionment model, a multi-criteria threshold-based assessment for algal blooms, and a process-based water quality model (QUESTOR). The approaches were applied in a proportionate and scalable way allowing more focused analysis at specific sites where issues with resilience had been identified.

The multi-site analyses suggested that rivers become less resilient to algal blooms with increasing distance from source and that residence time was the primary factor influencing eutrophication risk in these rivers. Specifically:

- The risk of algal blooms was greater in the longer study rivers with increasing observation of algal biomass (chlorophyll concentration) downstream
- The water temperature range in which blooms can occur increased downstream.
- In the upper catchments, blooms only occurred during the lowest flow conditions. Downstream, blooms occurred at low flow, but at the very lowest flows there were very low chlorophyll concentrations (less blooms).

Assessing the changing risk of algal blooms under climate change for 2 rivers showed how resilience varies due to residence time in the longer river stretch, the timing of changes in solar radiation and water temperature, and how coincident critical thresholds in these were. Analysis of management options suggested:

- Reducing phosphorus concentrations by 50% through improvements at wastewater treatment plants had no impact on risk in either catchment.
- A small, temporary increase in flow could stop a developing algal bloom in one river.
- A simulated increase in riparian shading reduced risk for both rivers by lowering solar radiation exposure. This would also reduce water temperature effects.

QUESTOR modelling was used to increase understanding of resilience on the Deben using additional metrics. It showed:

- a river largely resilient to phytoplankton blooms, especially upstream.
- phytoplankton blooms were unlikely in themselves to have caused prolonged oxygen sags in the past.
- decreases in flow seem unlikely to deteriorate water quality.
- the slow-flowing nature of the river in conjunction with biotic respiration suggests vulnerability to prolonged summer oxygen sags.
- water quality conditions were worse downstream: the higher frequency of increased chlorophyll and lower dissolved oxygen shows the downstream site to be more vulnerable to blooms and less resilient.

Using QUESTOR, a detailed assessment of management options (individually and in combination) to understand their effectiveness in reducing problems associated with algal blooms showed:

- On their own removal of weirs made no difference to dissolved oxygen response.
- Increased discharge at low flow (flow augmentation), increased shading (riparian tree planting), and reduced flow resistance (for example by some weed cutting) to reduce residence times, were all substantially beneficial in terms of dissolved oxygen, chlorophyll and temperature.
- Benefits were seen to varying degrees along the river but are most apparent downstream.

Combining local knowledge and a range of modelling approaches can indicate more or less resilience to algal blooms and enable an assessment of the benefit of a range of practical interventions. Residence time, shading and water temperature are the main factors that influence eutrophication risk in the East Suffolk rivers. All methods are consistent in suggesting decreasing resilience downstream and successful mitigation of risk by increasing shading and decreasing residence time. A suite of management options is beneficial; prioritised in specific vulnerable river stretches or where greatest benefit can be achieved and used in a responsive way when conditions are vulnerable. Finally, this trial demonstrated that it is possible to use the principles of resilience practice to carefully design collaborative management actions using a mixture of methods to assess resilience, understand dynamics and explore management options across multiple drivers and scales, within a flexible and scalable framework.

Important messages from the catchment trials

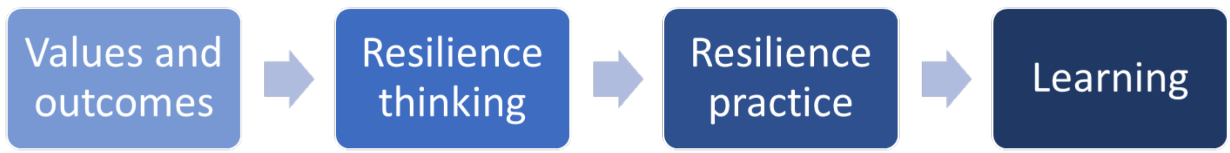
- All 3 trials demonstrate the need to understand the system in question and design an appropriate assessment. There is no one-size-fits all approach.
- Focusing on identifying thresholds and measurable characteristics can help identify where a catchment is in relation to a desired system performance or a particular environmental risk.
- Each trial suggests a broader consideration of management options becomes necessary and requires an understanding of the complexity and dynamics of systems now and under changing conditions in both the short- and longer-terms.
- Different approaches can highlight the timing and magnitude of failure points, thresholds, rates of change and alterations in behaviour of systems. They have also demonstrated the ability to assess management options in theory. None of the trials evaluated management solutions that have already been implemented.

What we learnt about resilience

This project has highlighted the need to develop a clearer framing of what is meant by resilience, and how it can be assessed, and guidance to facilitate its use. Below we propose a framework to understand and manage resilience in a flexible and proportionate way. It draws together the elements, principles and approaches discussed throughout this report and integrates them with the organisational learning to help identify pathway choices for policy and practice. It is organised it in a hierarchy to support different levels of application.

Developing a practical resilience framework

At the highest level a 4-component framework is a guide to thinking about what we want to achieve (values and outcomes), considering the system we are working with and the likely response to available options that informs a pathway towards resilience (resilience thinking), through an ongoing process of assessment and evaluation (practice and learning) (Figure 2). Questions in Figure 2 act as prompts to work through the components which overlap. The outcome of one stage will shape the next but may also require a return to the previous one. At all stages the process involves different actors (for example, stakeholders, decision-makers, scientists) working together to define, design and test the system under different conditions. Once designed, the bulk of the activity is in the iterative assessment stage, which informs choices for implementation and further analysis.



Values and outcomes: What policy or practice outcome is needed and why? What world do we want to see?

Resilience thinking: The theoretical underpinning, knowledge and capacity. What do you need to understand about the complexity and dynamics of your system? For example, do you know how close it is to important thresholds?

Resilience practice: The elements of designing, implementing an assessment and management options. How are you going to describe your system, design your assessment and implement and evaluate your management options?

Learning: What are the outcomes of each part of the assessment, implementation and evaluation. *System Response:* Can you achieve resilience with no intervention, with intervention or will transformation be required? *Pathways to change:* How will resilience be managed and have the intended outcomes been realised?

Figure 2 High level framework for considering resilience

Further description behind the 4 components involved in exploring resilience (Figure 2) are:

1. **Values and outcomes** requires defining what are we trying to achieve and why? These determine boundaries, scales and actions relating to system response and management. These may exist as high-level policy or may emerge from knowledge of existing risks or the system description. Once high-level aspirations have been identified specific outcomes and decisions can be defined.
2. **Resilience thinking** provides the theoretical underpinning for resilience practice and entails preparing for the assessment and developing the appropriate conceptual understandings of the social-ecological system (SES) its thresholds, scales and areas of interests. Whilst the river catchment is a useful scale for the work of the Environment Agency, considering what might happen at a smaller scale (e.g., a water resource zone, or local water quality hotspot) and at larger scales (e.g., at a regional, river basin district or national scale) helps ensure that activities to manage resilience in one location or at one scale do not result in a loss of resilience in/at another. Consideration should be given to:
    a. understanding if the system is inherently resilient or not, and whether we can, or should, preserve the existing system or determine how to guide an appropriate transformation.
    b. considering interactions where increasing resilience of particular parts of the system to specific disturbances may cause the system to lose resilience in other ways.
    c. consider multiple timescales. A reactive response such as to short-term responses to extreme weather events may be at the expense of longer-term adaptation to climate change.
    d. consider uncertainty. There are emerging approaches that help with decision-making under deep uncertainty. Applying some of these frameworks alongside resilience concepts will facilitate a more complete understanding of the risks we face and how to manage them in a rapidly changing world.
3. **Resilience practice** integrates values and outcomes and resilience thinking into a description of the particular resilience problem and provides the analytical and management framework for designing and conducting appropriate assessments of resilience. Using the clearly defined system, appropriate analysis and iterative evaluation of potential solutions that match stated outcomes can be developed. There is no one-size-fits-all approach. Assessments need to remain flexible, robust and proportionate for the task at hand. This step of the process is highly iterative and should ensure that appropriate risks, scales and levels of resilience under different scenarios are understood and managed.
4. **Learning**. Throughout the process the aim is to ensure that we are meeting our outcomes in an evolving and adaptable way by understanding system response, resilience capabilities (persistence, adaptability, transferability) and pathways to change. Once chosen options are implemented, they need to be monitored and re-assessed to understand their effectiveness. This can then inform an ongoing re-assessment of resilience and consideration of additional/alternative management actions. The *Manage, Monitor, Adapt* approach is helpful for long-term decision-

making in face of deep uncertainty to achieve multiple objectives for a long-term future (Marchau et al., 2019). Developing effective ways of monitoring and reporting progress will ensure ongoing adjustment of understanding and management in the face of evolving environmental dynamics. A third element of learning involves reflection and re-design and re-assessment where appropriate (for example, if values and outcomes change).

A more detail visualisation of the 4- component framework expands how an analysis of system response and behaviour can be used to understand resilience capabilities and inform choices around pathways to change (Figure 3).

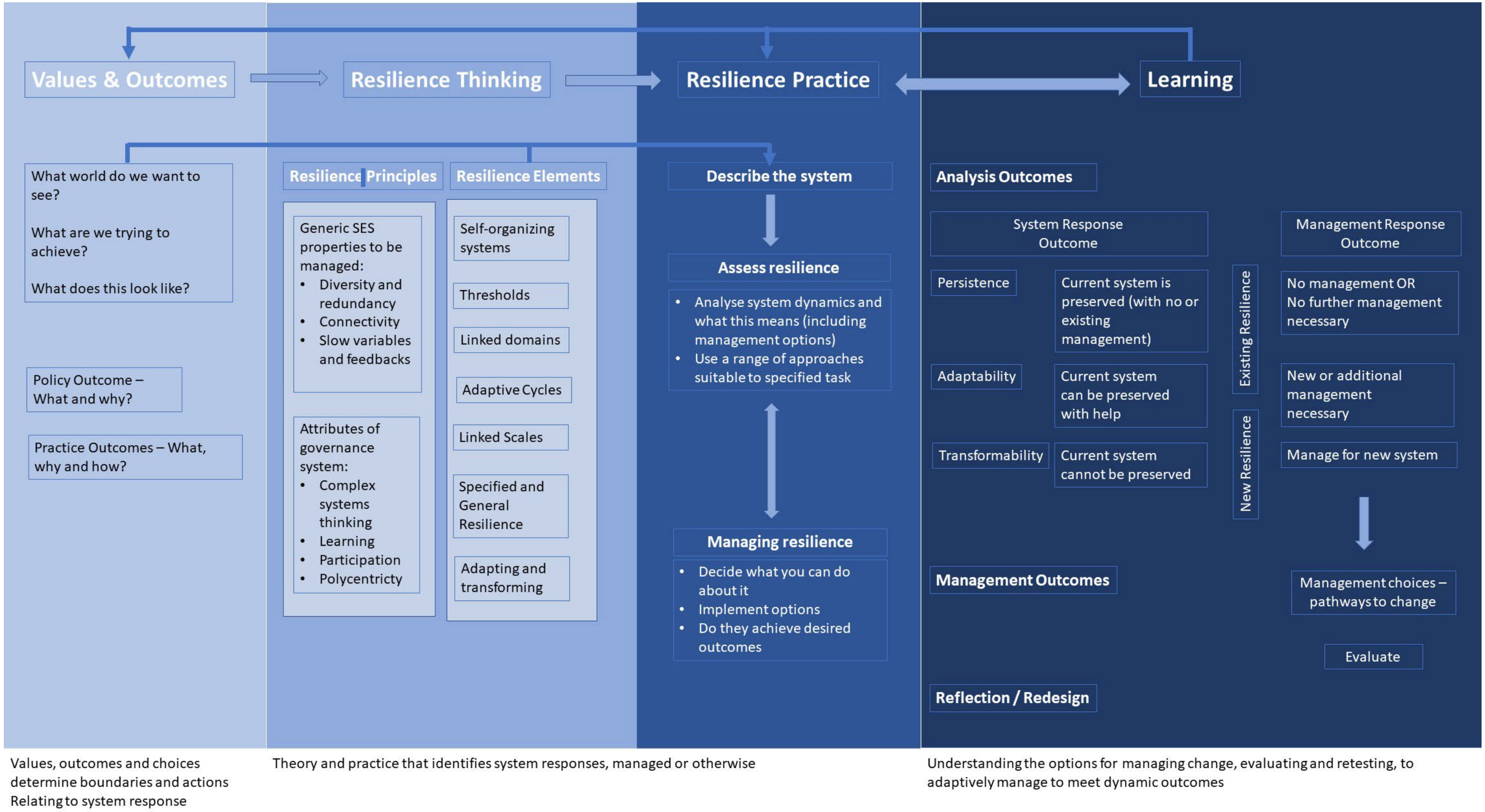


Figure 3: Flexible Resilience Framework with greater detail on the different components.

Challenges and limitations of resilience in practice

To use concepts of resilience most effectively in practice requires us to think across multiple scales, focus on thresholds and to embrace change and uncertainty (Walker and Salt, 2012). A full analysis of resilience is resource intensive at every stage and requires considerable organisational capacity. It relies on many different stakeholders and the availability of appropriate tools for parts of the assessment to be conducted. Its clear that solving problems in a narrower way is tempting and tractable but may have driven loss of resilience in socio-ecological systems.

Processes for the design and delivery of resilience assessments that include the large range of existing types of assessment we currently undertake (but framed slightly differently) and solutions to meet desired outcomes at different levels are necessary. As with any existing assessment the initial conceptualisation and selection of appropriate assessment methods and management options is necessary to ensure environmental outcomes are met successfully. Many of these approaches are already being used throughout the Environment Agency. However, much of our management now is about trying to maintain the way we do things or the systems we have in a changing world. Resilience challenges us to do something different.

There are significant risks to viewing resilience as a panacea. Resilience, applied indiscriminately to all circumstances, risks becoming synonymous with "business as usual" (Vardy and Smith, 2017). The resilience approach has been criticised for applying physical science concepts to social systems (see Olsson et al, 2015). It has been used to present narratives that exclude the 'messiness' of the world (Vardy and Smith, 2017). It risks striving towards being a unified concept at the expense of other conceptions of the environment and can be used as a cover for maintaining the status quo (Olsson et al., 2015; Vardy and Smith, 2017). However, we have found that the multi-faceted character of resilience is part of its appeal. If applied within a flexible framework, it facilitates a more complete understanding, assessment and management of catchment systems offering the potential to deliver environmental outcomes more effectively.

Conclusions

Resilience is a common language that we talk about across the Environment Agency, it feels holistic and thus could be an enabling concept. However, whilst resilience is already embedded conceptually in environmental management policy, it is largely aspirational rather than practical.

Much of the work the Environment Agency has done on resilience is set within an engineering resilience framing trying to ensure protection and recovery. This is beginning to change with increasing acceptance of the need to consider social ecological resilience behaviours more fully and to consider resilience thresholds and transformative change. For much of the work done by the Environment Agency a more expansive definition of resilience and the adoption of flexible approaches, suited to the specific context within an overall framework, will reduce the chance improvements in one area come at the expense of other areas.

Practical applications of resilience require a clear description of the system of interest and the desired outcomes. Methods and tools are available to help assess catchment resilience. Some focus on single aspects of resilience, whilst others consider more far-reaching elements. No one-size-fits-all approach exists or should be aimed for.

We have proposed a 4-component framework to help define, think about and implement resilience in practice. This includes being clear about required outcomes, the proximity of critical thresholds and assessing whether a system can be maintained with or without additional management or whether transition to a new system will be needed.

To further support practical use of resilience we suggest:

- Developing a shared understanding and awareness of resilience and how it can be used across policy and practice to help meet our environmental objectives.
- Applying and refining the framework through in-practice examples thus developing approaches that allow resilience to be assessed, managed and monitored within diverse contexts.
- Developing the necessary analytical approaches to conduct resilience assessments and to evaluate the success of implemented management measures.

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Acknowledgements

We gratefully acknowledge Jens Evans (Climate Change and Energy, Environment and Business) for initially leading this project and the rest of the Climate Change and Resource Efficiency Research team for their contributions. We also acknowledge all those colleagues involved in workshops and who shared their knowledge and experience in interviews.

Appendix 1

Origins, definitions, and typologies of resilience

Resilience has a long history. Detailed accounts (e.g., Hellige, 2019) trace it from its linguistic origins through several transfers between the disciplines of physics, applied mechanics and materials sciences as well as physiology, psychology, biology and ecology, developing into a multidisciplinary universal concept over the last few decades. Development of ecological resilience theory began in the 1960s with attempts to mathematically model dynamic ecosystems and the term was first introduced by Holling in 1973 (Gunderson and Allen, 2010). It emerged in ecosystem science to explain surprising and nonlinear dynamics of complex adaptive systems, forming the basis for adaptive management, which embraces uncertainty of complex resource systems (Gunderson and Allen, 2010).

Resilience can have different meanings depending on context. The concept of resilience has evolved since Holling's (1973) paper but different interpretations of what is meant by resilience cause confusion (Walker et al., 2004). It has been viewed and defined in multiple ways, each based on different assumptions, both within ecology and as the concept has been adopted in many other fields (Gunderson and Allen, 2010). Each has interpreted it to reflect their needs and frames of reference (Table A1 summarises the 4 main origins). The specific meaning has been diluted and it has been used ambiguously as divergent conceptions are proposed related to specific interests (Brand and Jax, 2007).

Consequently, several typologies have been developed to understand these diverse meanings and how they relate to the specific contexts and perspectives. Some of these focus on the different definitions, whilst some focus on their meanings or application. For example, Handmer and Dovers (1996) developed a 3-class typology of resilience (resistance to change; change at the margins; openness and adaptation) to identify where and how the creation of decision-making and management approaches that could operate in the face of pervasive risk and uncertainty has been addressed. Brand and Jax (2007) identified a variety of definitions across 3 broad categories and a tension between the original, descriptive concept (ecology) and the more recent, vague boundary object in which it is increasingly conceived of as a perspective, rather than a clear and well-defined concept. Thorén (2014) further summarises these 13 definitions into global and local but suggests that the various uses of the concept are more closely related than previously suggested. Olsson et al. (2015) considered a typology around 2 conceptual meanings on one axis and 2 attributes on the other. The first conceptual meaning refers to the ability of a system to cope with stress and "bounce back"; the second refers to the ability of the system to "bounce-back" and "transform". The first attribute is descriptive implying that resilience is "neutral" (neither good nor bad), contrasted by a prescriptive attribute implying that resilience is desirable and "good".

Some have suggested that the potential for wide interpretation is a strength and makes resilience more inclusive as a concept while others are less confident about its utility (e.g., Newton, 2016; Kythreotis and Bristow, 2016). Typologies can be useful for understanding and classifying different perspectives and uses of the concept, but they do not necessarily facilitate using the resilience concept in practice, and can themselves contribute to further confusion, which may act as a barrier to the use of the concept in practical application. To enable its use in practice requires understanding more about the underlying and interrelated concepts and identifying where and how the concept has been used in practice.

Table A.1.1: Four main origins of resilience (adapted from Walker and Salt, 2012)

Discipline	Understanding
Psychology	Marked differences exist in the resilience of individuals (and societies) confronted with traumatic and disastrous circumstances
Ecology	Either focus on the speed of return following a disturbance or whether the system can recover
Disaster relief / military	Incorporate both aspects (speed and ability to recover). Much commonality in the understanding of resilience with Psychology and Ecology.
Engineering	Robustness and “designed resilience”. Differs from the other 3, assuming bounded uncertainty (kinds and ranges of disturbances and shocks are known). System is designed to be robust in the face of these shocks.

Table A.1.2: Summary of core concepts of resilience (see Walker and Salt (2012, p3-24) for more detail)

Concept	Details
Self-Organizing Systems	• The systems we depend upon are complex adaptive systems. • You can change bits of the system, but it will self-organize around this change. • Sometimes you have a good idea about how the system will respond to your actions, sometimes it's difficult to predict, and other times the response comes as a surprise. • Most of the time the system can handle (absorb disturbance and reorganizes and keeps performing as it did) the changes it experiences. • Sometimes it cannot and starts behaving in some other (often undesirable) way.
Thresholds	• There are limits to how much a system can be changed and still recover. • Beyond those limits the system functions differently because some critical feedback process has changed. • Beyond these thresholds the system crosses into another regime and behaves differently. • In social systems thresholds are often referred to as tipping points. • Thresholds are not always easy to identify, discovering where they might lie is not easy, and not all threshold behaviours are the same. • The pathway back from crossing the threshold may be different from the pathway that took you over the threshold in the first place. • Thresholds define the safe operating space of your system. • Thresholds can move because of other changes in the system (resilience can increase or decrease).
Domains are Linked	• Changes in one domain will often lead to changes in another, and these can feedback to cause further changes in the first domain. • Linkages are most important when thresholds are crossed, because crossing one threshold can cause the crossing of other thresholds in other domains. • Understanding the interplay between thresholds and the linkages between domains is critical to understanding the behaviour and resilience of self-organising systems.
Adaptive Cycles	• The behaviour of self-organising systems changes over time through internal processes. • The way components of a system interact can cause the system to go through cycles.

	• As this happens, resilience changes, as does the potential for people managing the system to make changes. • There are times in the cycle when there is greater leverage to change things. • The kinds of policy and management interventions appropriate in one phase don't (necessarily) work in others.
Scales Are Linked	• Systems operate over a range of different scales of space and time (and each scale goes through its own adaptive cycle). • You cannot understand the focal scale (that which you are interested in) without appreciating the influence from the scales above and below and at larger and finer scales. • Linkages across scales play a major role in determining how the system at another scale is behaving.
Specified and General Resilience	• Resilience thinking: capacity to envisage your system as a self-organising system with thresholds, linked domains, and cycles. • Resilience practice is the capacity to work with the system to apply resilience thinking, to manage its resilience. • Specified resilience: resilience of some specified part of the system to a specified shock. • General resilience is the capacity of a system that allows it to absorb disturbances of all kinds. • There is a trade-off between the two: preparing a system for a specific disturbance optimises capacity for a specific threat but may reduce your system's general capacity to absorb other kinds of disturbance.
Adapting and Transforming	• Resilience by itself is not good or bad. • Assuming resilience as a good thing, assumes that the economies, communities, and landscapes being discussed are in a desirable state that you want to maintain. • Undesirable states can be very resilient. • Managing resilience to maintain the identity of your system by adapting and building up resilience of the current state. • If the current state is undesirable, you can try and get back into the desirable state by reducing the resilience of the undesirable state. • If not possible, you can aim not to adapt but to reimagine your system as something else: transform: become a different system. • Any tension between adapting and transforming can be resolved when considering the system at multiple scales – making the system resilient at the regional scale may require transforming it at lower scales. • Complementary processes: adaptability and transformability are complementary attributes of a resilient system. • If transformation is necessary, it is better to do so sooner rather than later. • It has 3 ingredients: the preparedness for change, having the options for change, and the capacity for change.

Resilience Comes at a Cost	• Direct costs of the actions you take and the indirect costs of the opportunities lost by not using resources in some other way. • Enhancing the resilience of a system usually involves reducing the efficiency, staying away from maximum yield states, maintaining reserves, etc.
Not Everything Is Important	• Requisite simplicity: Identify the minimum but sufficient information to manage your system for the values that you hold important.
It's not about not changing	• Sometimes the definition of resilience provided above is interpreted as 'staying the same'. • However, being resilient requires changing within limits. • Staying the same is a prescription for the loss of resilience because the system loses its capacity to deal with change and disturbance.

Table A.1.3: Principles of a resilient world (see Walker and Salt (2012, p193-1944) for more detail)

Principle	Description
Diversity	• a resilient world would promote and sustain diversity in all forms (biological, landscape, social, and economic)
Ecological variability	• embracing and working with, rather than attempting to control and reduce it
Modularity	• resilient systems consist of modular components
Acknowledging slow variables	• there needs to be a focus on the controlling variables associated with thresholds
Tight feedbacks	
Social capital	• this is about promoting trust, well-developed social networks, and effective leadership
Innovation	• resilience places an emphasis on learning, experimentation, locally developed rules, and embracing change
Overlap in governance	• institutions that include “redundancy” in their governance structures
Ecosystem services	• a resilient world includes all the unpriced ecosystem services in development proposals and assessments
Fairness / equity	
Humility	

Table A.1.4: Resilience in practice (adapted from Walker and Salt, 2012)

Stage	Details
Describing the system	• A good description brings together the insights of the key stakeholders in the system. • Good resilience practice is not so much about producing a single “best” system description as it is about creating a process whereby the system description is constantly revisited, reiterated, and fed into adaptive management. • It’s about the balance between including all the critical information and requisite simplicity (as simple as possible, but not too simple). • Understanding what’s important in your system in terms of valued goods and services and the stocks that underpin them, and the interactions among these bundles of systems goods and services, is a good way to begin coming to grips with the “resilience of what”. • Drivers cause change in the controlling variables; as a controlling variable approaches a threshold level, a shock to a fast variable (goods/services), or a directional change in a driver, can push a system across a threshold into an alternate stability regime.
Assessing Resilience	Analysing system dynamics and what this means • Resilience is not a single number or a result. It’s an emergent property that applies in different ways to the different scales, domains and cycles (and their interplay) that make up your system. It’s relative and contextual. • Assessing resilience involves understanding specified resilience, general resilience, and transformability. • You assess specified resilience by identifying alternate states and associated thresholds. This might be approached by considering known thresholds, thresholds of potential concern, conceptual models and analytical models. • Diversity, modularity, the tightness of feedbacks, openness, reserves, and high levels of all types of capital (including social capital) are important system attributes conferring general resilience. • The attributes of general resilience interact. It is not possible to determine one level or amount of any attribute that marks a critical level. The most appropriate approach is to try and identify trends and changes and examine them in terms of effects. • Transformability depends on three main attributes: getting beyond the state of denial, creating options for transformational change, and having the capacity for transformational change.
Managing Resilience	Deciding what you can do about it • Appropriate actions / policies depend on the phase of the adaptive cycle the focal scale is in (as well as the phases that the higher and lower scales are in). • Consider all kinds of interventions – management, financial, governance, and education – not just the easiest or most obvious options. • Consider how to best sequence the interventions you select. • Ask yourself if your system is in a trap. If so, is transformation needed? • How can interventions be implemented in an adaptive-management framework? • How can adaptive governance be introduced?

Appendix 2

Perspectives on Catchment Resilience

Catchment resilience viewed through the lens of climate change (Wilby, 2019)

Ten years ago, barely 50 papers a year were published on catchment resilience; now more than 10 times that number are published every year. However, the science community is more concerned with exposing vulnerability than advancing solutions. Practical examples for improving resilience are limited and interventions tend to be about returning systems to previous states or resisting further change. (See also Wilby, 2020).

Resilience in complex catchment systems (Beevers et al, 2019)

Catchments are social-technical-natural systems with complex interactions and subsequent vulnerabilities. If we are to use resilience as a unifying concept to manage catchments, then we need to embrace this complexity and develop methods that allow consideration of these interaction pathways. Interventions may be focussed upon improving the resilience of a given aspect of the complex catchment system, or instead on fostering and strengthening certain interactions or dependencies between such aspects (see also Beevers et al, 2021).

Catchment resilience: On-farm responses to water-related risks under a changing climate in England (Hess et al, 2019)

Most water-related risks to agriculture and food production cause an irreversible loss of production potential. If measures to reduce the probability of damaging events are prohibitively expensive, farmers are primarily concerned with strategies to build robustness or to reduce the impact of the shock through facilitated recovery. Most decisions about actions or investments to increase resilience are taken at the farm level and influenced by perceived costs and benefits of change. 'Working together', whether among farmers of between farmers and the regulator, allows for more optimal allocation of a resource during times of scarcity to increase headroom, e.g., by trading of water licences or to facilitate recovery (see also Hess et al., 2020).

Social-ecological dynamics of catchment resilience (Adger et al., 2019)

Community resilience concepts and function could be critical to understanding and achieving catchment resilience. Community resilience is not about the individuals but a collective ability to plan, recover and adapt to external pressures and events. Resilience is found in the interactions such as places attachment, community cohesion and leadership and networks as well as relational capital and belonging. (See also Adger et al., 2021).

Ecological resilience in catchments: from measurement to management (Oliver, 2019)

Identifying the underlying mechanisms to ecological resilience provides pro-active management opportunities. The relationship between ecological resilience and socio-economic resilience is important, and an interdisciplinary approach will help extend this concept to wider socio-economic systems, i.e., catchment resilience.

Managing Catchment Systems for Resilience (Watson, 2019)

Resilient catchments are given the goals of (1) remaining functional despite dynamic relationships and changes in drivers/pressures and (2) being able to avoid major disruptions/system collapse. Novel management strategies are suggested to assess, manage and enhance elements of catchment resilience. A combined, multi-organisational, collaborative and participatory approach incorporating all three strategies is expected to be most effective.

Building in Geomorphology into Understanding Catchment Resilience (Gilvear et al., 2019)

Rivers are, by definition, resilient features that adapt in the face of change. Rivers should therefore be allowed to follow their natural development through the incorporation of ‘freedom space’ which allows river mobility, riparian wetlands, and flooding across shorter timescales along with longer term free channel migration-avulsion and inundation by larger floods. (See also Fuller et al., 2019).

Think piece on coastal resilience (Masselink, G., 2019)

There is great disparity in the meaning of resilience in coastal literature with often competing interests, from ecological or natural resilience reliant on the free movement of sediment to socio-economic resilience more reliant on hard engineering solutions. Effective coastal management needs to balance socio-economic and natural drivers to increase overall system resilience (Masselink and Lazarus, 2019).

Appendix 3

How is the Environment Agency using resilience?

As part of this research project, we asked colleagues what resilience means to them and how as an organisation we are formally and informally engaging with this idea specifically around catchment resilience. The information below is a distillation of the notes from 20 interviews in response to some general questions. The responses helped shape a later workshop.

What is catchment resilience?

- There is no consensus on definitions or concepts of resilience

How does EA (Environment Agency) use resilience?

- We don't have a single, formal model and indeed mainly use resilience in a colloquial sense
- We should formally describe the implicit or explicit concepts of resilience used across EA to understand how it is used now and where it could be applied in the future

What are the work areas where the Environment Agency uses resilience?

- Abstraction Reform Plan will improve catchments through: Environmental Permit Review modernisation, Sustainable catchments, including working with catchment groups e.g., restoring unsustainable abstraction. Catchment based approaches; 4 trials underway including E Suffolk where drainage board is pumping water upstream rather than out to sea. Priority Catchments.
- Drought resilience – national drought group
- Natural Capital exploring resilience metrics and indicators
- FCRM (Flood and Coastal Risk Management) consider property resilience, incident resilience, natural flood management, LTIS (Long Term Investment Strategy), national flood strategy
- National Flood Resilience Review
- Net gain of natural capital
- Working with Infrastructure Operators Adaptation Forum on resilience. National Grid are surveying their stakeholders on resilience,
- National Resilience unit proposed by Green Finance Taskforce
- Regulated Industry could require operators to embed resilience in their management system.
- Ofwat reviewing PR19 water company plans. Government will impose duty on Ofwat for PR24 to ensure water companies are resilient. Ofwat already looked at resilient of water assets. Other EA, NE, Blueprint for Water Coalition want Ofwat to expand framing of resilience to include catchments as well as assets

What research questions do colleagues have about resilience?

Identifying resilience

- What is resilience worth?
- How do we develop pathways to resilience?
- How can resilience be framed in natural capital terms?
- Is resilience different in coastal vs inland catchments?
- Can we map the local factors that contribute to catchment resilience?
- Can we frame resilience according to organisational interests
- Do we identify when we need resilience or resistance?

Limits to resilience

- What are the economic, practical or other limits to resilience?
- Does resilience to one hazard imply trade-off with another?
- Resilience paradox, can we balance resilience and flexibility of systems?
- Is resilience a response to perceived fragility?
- Farmers are investing in on farm water storage to increase drought resilience, how can we encourage other users to improve their resilience?
- Can we develop resilience indicators/metrics to track our environmental performance?

Delivering resilience

- Where is resilience best delivered and by who? E.g., local authorities?
- Are catchments the right scale for resilience, what about groundwater?
- To what extent can EA control catchment resilience if we have limited influence over other actors?
- Can increased resilience exacerbate risk by increasing impacts in the event of catastrophic failure e.g., in flood defences?
- How do interventions contribute to catchment resilience?
- How do we determine Net Gain, and can resilience measures help?
- Should we focus on Natural Capital services or resilience instead of Good ecological Status?

Appendix 4

Draft typology of resilience

A draft typology was developed to guide discussions in the staff workshop in July 2019. This was based on the initial staff interviews and the expert reviews and reworked the Olsson et al. (2015) typology that attempts to classify different use definitions of resilience.

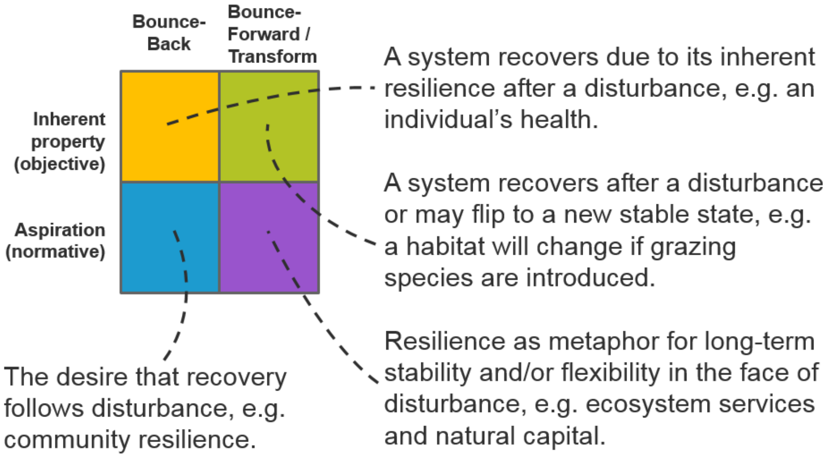

Figure A4.1: Typology of resilience

Clarifying resilience terms

Context is critical to the concept of resilience. It is easier to talk and think about resilience if we are more precise about what we mean. Each time we use resilience we should clarify how it is being defined in that occasion or circumstance. A variety of descriptive terms capturing system response or behaviour relating to management choices exist. In both the literature and staff engagement, several terms are used interchangeably, and others introduced. Terms that were popular in the interviews and workshops included static, bounce-back (BB), introduced in the draft typology, bounce-forward (BF).

Bounce-back (BB) refers explicitly to the capacity of a system to return to its initial state following disturbance and multiple equilibria are not considered and behaviour is more clearly termed return time, recovery and engineering resilience (Angeler and Allen, 2016). It most closely relates to persistence and is sometimes referred to as static, recovery can occur within the existing system.

In bounce-forward, sometimes referred to as adaptive, recovery can occur only if there are changes, or adaptations, made to the existing system that is some way leads to transformation in the system.

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