Review

Resilience in Complex Catchment Systems

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Abstract: In this paper we explore how we can use catchment resilience as a unifying concept to manage and regulate catchments, using structured reviews to support our perspective. River catchments are physical boundaries which delineate where all surface water (e.g. precipitation, snow, meltwater) falling on a piece of land runs off or flows to a single point at a lower elevation, where the river meets a larger body of water (e.g. sea, lake). Catchments are complex systems with interrelated natural, social, and technical aspects. The exposure, vulnerability, and resilience of these aspects (separately and in combination) are the latent conditions which when triggered by a specific hazard, result in catchment impacts. In complex catchment systems, resilience is the ability to bounce-back, the ability to absorb, and the ability to transform. When all three abilities are accounted for, we are forced to consider the interactions of the catchment system. Six main complexity concepts can be used to frame how we approach evaluating catchment resilience. These concepts are: natural-social-technical aspects, interactions, spatial scales, time scales, multiple forms of evidence, and uncertainty. In analysing these complexity concepts we have found that there are several gaps in current practice. For example critical interactions which need further methodological study are the linkages between the natural-social-technical realms, as well as across spatial scales (e.g. households or communities) and time scales (e.g. days or years). Requirements for future methodological approaches are suggested. Central to these is (1) the study of interactions linking the short- to medium-term time scales (2) better integration of bottom-up and top-down approaches, to link local context with higher-level decision-making, and (3) developing 'hazard-agnostic' methods which can address the impacts of floods, droughts – even acknowledging dormant 'socio-technical hazards'. There is no 'one size fits all' approach to catchment resilience. Mixed method approaches are required and their selection will depend on contextual issues identified early in the process for specific catchments. Central to any effective approach is the incorporation of a linking systems or interaction analysis, which draws together the natural-social-technical system in a meaningful way. If our approaches do not begin to acknowledge the interdependencies and interactions, we may miss substantial opportunities to enhance catchment resilience

Keywords: resilience; complex systems; catchment

1. Introduction

River catchments supply resources such as water, food and energy, while being economically-tied to their urban areas through trade. Urban areas are the driver of regional, national and global economies. The complex inter-relationship between these urban areas and their supporting catchments is a vital aspect of a city's economic success. Cities offer opportunities for employment, culture and social interaction; this has resulted in the growth of the global urban population from 34% in 1960 to 55.7% in 2019 [1], with WHO projections suggesting growth to 68% by 2050 [2]. The speed at which cities are increasing their exposure needs to be matched by measures to reduce vulnerability. This rapid urban expansion is taking place against a background of climate change, the impact of which is uncertain. It is however clear that cities within the UK, aswell as internationally, are already impacted by hydrological extremes (floods and droughts: hydro-hazards) which cause economic damages year on year, affecting homes, businesses, food security and energy supplies; and increasing population vulnerability. These hazards are set to intensify (magnitude, frequency and duration) in the future due to the influence of climate change. One way in which the UK can manage the potential future impacts from increasing exposure to natural climate related hazards, is by improving river catchment resilience. This paper will explore the question:

How can we use catchment resilience as a unifying concept in catchment management and regulation – particularly in light of climate risks, population growth and other pressures?

This paper reviews current literature following the structured approach set out in our previously publsihed papers [3,4], these focus on flood management resilience, and climate change adaptation to hydro-hazards. We use these these reviews to develop our argument and identifies promising research or management gaps and directions. Specifically we will focus on catchment resilience for hydro-hazard management, where we define hydro-hazards as floods and droughts. Our recent published work, specifically two structured reviews of literature ([3,4]) on adaptation and resilience within the water domain, are used to formulate and inform our arguments. The first [3] systematically reviews literature for climate change adaptation to hydrohazards, and we explore available methods for their ability to address complexity. The second [4] systematically reviews the academic literature on flood resilience to explore how resileince is assessed, operationalised and implemented. These two structured reviews are used to develop our perspective on catchment resilience, and answer the question posed above.

The paper will introduce the concept of a catchment as a complex adaptive system at the nexus of the natural, social, and technical realms (Section 2). It will move on to discuss resilience and its concepts, characteristics and methods by which to explore it in a catchment context (Section 3); alongside a review of current methods capable of considering catchment resilience in the context of complex adaptive systems (Section 4). Finally we finish with identifying some promising research gaps and explore a future research agenda (Section 5).

2. The Catchment as a Complex Natural-Social-Technical (NST) System

Catchments are complex systems. Within one river catchment or basin, there will be a large diversity of land use, each of which presents a different pressure, exposure, driver or buffer in the system and fulfils a particular role. For example urban areas are economic and infrastructure hubs [5], and simultaneously resource users (water, energy and food), runoff and pollution sources (e.g. from impermeable land), and central points of vulnerability (due to their high population density).

Flood hazards result from excess water from one or multiple sources (e.g. coastal, fluvial, or surface water); while drought hazard arises from a deficit of flow (hydrological), soil moisture (agricultural) or precipitation (meteorological) over a period of time. A hazard acts as what we might perceive as an 'active' trigger for impacts within a catchment. However, impacts are a consequence not just of this active trigger, but also the latent conditions within the catchment – its exposure, vulnerability, and level of resilience. In this paper we consider exposure to 'include people, infrastructure, housing, production capacities and other tangible human assets located in a hazard-prone area', and vulnerability as the 'conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards' (following the definitions by UNISDR [6]).

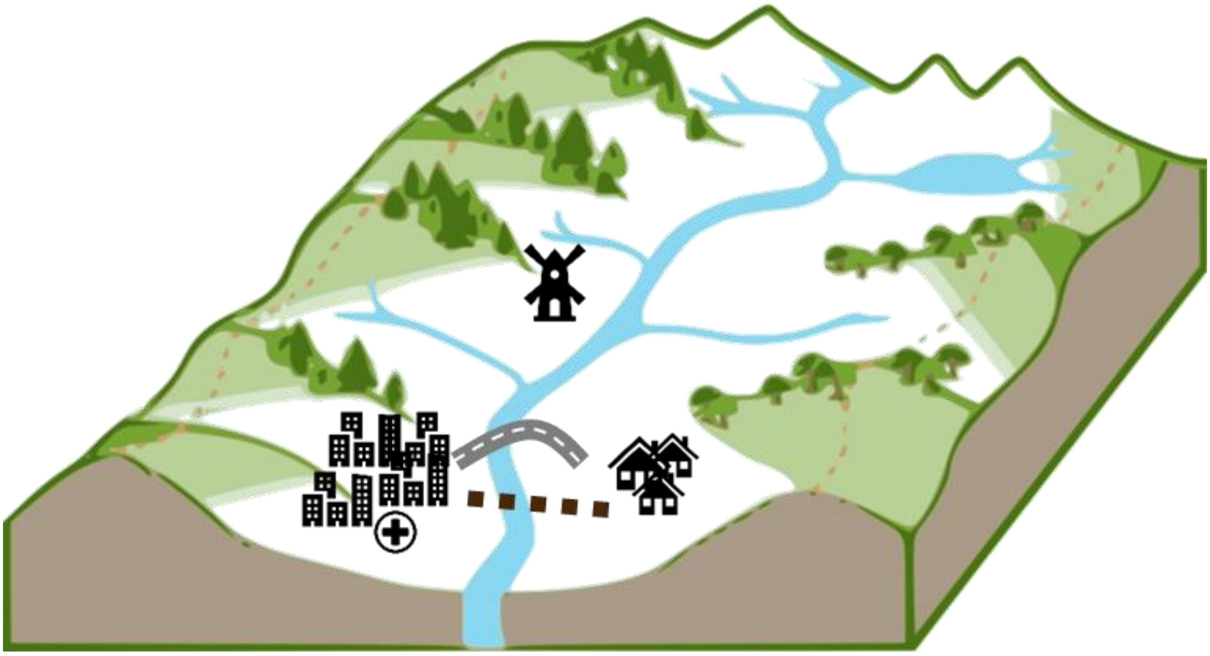

Figure 1: River catchment supporting natural, social, and technical systems

The combined exposure, vulnerability, and resilience of a catchment can result in impacts affecting: agriculture (e.g. [7]), infrastructure (e.g. [8]), human health (e.g. [9]), economic activity (e.g. [10), government and institutional practices (e.g. [11]), cultural heritage and community (e.g. [12]), and of course the environment (e.g. [13]). In the last five years (2014-2019), the UK has experienced several significant natural-hazard related disasters [14] affecting over 100,000 people and resulting in over £3.5Bn of direct economic damages. These disasters have been the result of different natural hazards including fluvial floods, convective or frontal storms and heatwaves. Each hazard has different characteristics, causing different impacts spatially and temporally across the country. Hydro-hazards are known to have devastating economic and social consequences for different sectors (e.g. transport, energy generation and supply, communications networks), and communities (e.g. rural, urban). In particular, understanding the vulnerability of exposed sectors or populations can shed light on disproportionately affected members of society, thereby informing more effective adaptation strategy development to improve resilience within a river catchment.

Natural hazards are also projected to increase in frequency and magnitude (15, 16. 17], and may occur concurrently or in close succession. This is why it is critical to begin characterising catchments as complex systems, rather than a set of neatly isolated parts. In so doing we can more effectively unpack the dynamics in each catchment that might lead to different types and degrees of impact. Recently established research threads in social-ecological systems and socio-hydrology [18] recognise the dynamic link between natural processes and social systems, which is particularly pertinent in the catchment context. In this vein, Tempels & Hartmann [19, p. 873] propose resilience as a "fluid frontier" to conceptualise the interdependencies of ecological and human systems.

We take this further to argue that the catchment system can be loosely characterised as consisting of three dynamically-linked sub-systems: natural (including physical processes e.g. hydrology, hydrogeology, geomorphology, sediment transport, nutrient cycles, ecosystem functions etc.), social (processes driven by intangible human values and priorities e.g. community cohesion, health, economic standing, etc.), and technical (physical infrastructure that is in some way human-made or –influenced, e.g. transport, energy provision, communications, etc.). Figure 2 shows these three sub-systems as mutually coupled in an inextricable way, whereby a change in one sub-system may trigger a feedback in another. We argue that to consider the true resilience of a catchment, the complexity of the system must be acknowledged, with feedbacks and interactions explicitly considered.

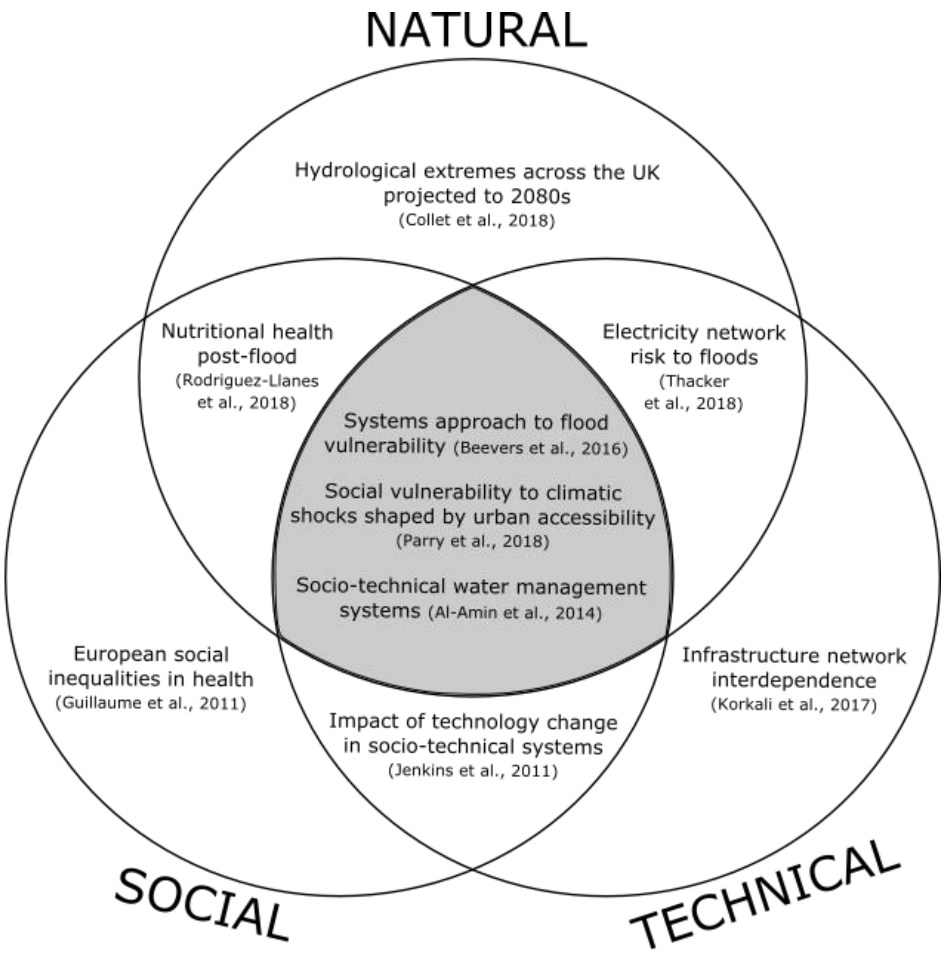

Figure 2: Interacting natural-social-technical sub-systems occurring within a catchment

For example, flooded communities may experience long-term health impacts arising from psychological impacts from the fear of repeat flooding [20]. Likewise, a person or community with poor health (e.g. retirement village) may be less able to invest time and resources in future flood adaptation measures, and as a result experience the impacts of the next flood to a greater degree [20]. Of course these are examples which are fairly straightforward in nature. In reality, there are an overwhelming number of feedbacks and interactions, and which of these will be key to a catchment's resilience is often elusive. Figure 2 depicts a handful of typical issues occurring within a catchment boundary. These exemplify current focus points for resilience research, and how these are situated within the three sub-systems and their overlaps. Traditional unidisciplinary research typically sits at the edges of the nexus [16, 21, 22], studying specific phenomena or known feedback loops, in order to explain and adjust the wider system from that perspective. Ideally, initial research on a catchment's resilience should be situated at the nexus [23, 24, 25], to acknowledge the importance of interactions between sub-systems. Currently, our research suggests only about 20% of hydro-hazards research addresses any type of interactions, despite the wider complexity literature pointing to these as an underlying source of emergence [3].

In conclusion, catchments are complex systems with interrelated natural, social, and technical aspects. The exposure, vulnerability, and resilience of these aspects (separately and in combination) are the latent conditions which when triggered by a specific hazard, result in catchment impacts. Interactions within the system are key to understanding its overall behaviour, but these are often not captured.

3. How to be resilient: Bounce-back, Absorb and Transform

There is an overwhelming body of literature which seeks to define and measure resilience. Originating in field of ecology [26], the resilience concept has developed over the intervening half century and pervades the discourse in many discipline [4]. Fundamentally, resilience relates to a system's ability to resume functionality in the wake of a perturbation. However, the recent popularity of the term resilience has led to ambiguity surrounding definitive application of the concept [4].

Our recent structured review[4] on resilience literature pertaining to the flood management field we observed that there are differences in definition across the discipline. For example in flood risk management, Restemeyer et al. [27] state that resilience centres on robustness, adaptability and transformability; Nguyen and James [28] point to speed of recovery, magnitude of disturbance relative to a threshold, and ability to learn/adapt/transform; Hegger et al. [29] define the capacity to resist, capacity to absorb/recover, and capacity to transform. The striking commonalities between these studies is the construction of resilience as a tripartite concept and the specific inclusion of transformation as a component of resilience [4]. These observations point towards resilience going beyond the mitigation of impacts and reducing probability of exposure, and exploring the opportunities which arise from a hazard (in this case floods) [4].

Martin-Breen and Anderies [30] reviewed 50 years of resilience research to produce a resilience spectrum of increasing complexity, and reflects the findings in [4]. The resulting spectrum reflects these different aspects and acknowledges the role of transformation. We recommend the use of this spectrum [4], which consists of three interdisciplinary frameworks: Engineering Resilience, Systems Resilience, and Complex Adaptive Systems Resilience.

3.1. Engineering resilience

Engineering Resilience is to *"withstand a large disturbance without, in the end, changing, disintegrating, or becoming permanently damaged; to return to normal quickly; and to distort less in the face of such stresses"[30]*. It should be noted that Engineering Resilience is not constrained to this engineering discipline, rather it is a widely used conceptual framework. Therefore it is not exclusive to physical 'hard-engineered' infrastructure (e.g. road networks), rather it indicates the ability to bounce-back, and is associated with the emergency recovery stage of a shock event [4]. According to Martin-Breen and Anderies [30], resilience from this perspective is about decreasing a hazard-specific risk and restoring conditions to a pre-crisis state. A strength of framing resilience in this way, they argue, is that it makes the concept straightforward to understand, model, and measure. It also produces simple management strategies. However, its simplicity is also a major limitation when we focus on Engineering Resilience alone. By focusing on aspects such as 'withstand', 'bounce-back' 'return to normal quickly', it maintains the status quo, which has been argued to be detrimental to future resilience [30]. In other words, is returning to 'normal' conditions always advisable? Acknowledging additional aspects of resilience expands the space to consider whether future change is needed.

3.2. Systems resilience

Systems Resilience is *"maintaining system function in the event of a disturbance"[30]*, this framework increases the complexity of the engineering resilience by acknowledging that the "world is in flux", where the aim is to keep things functional as opposed to identical. When we consider the world to be in flux, we acknowledge that there are slower variables of resilience as a result of interacting parts within a system, which have an impact during a shock event [30].

As such it is necessary to couple Engineering Resilience and its focus on a relatively short and specific hazard event, with a Systems Resilience understanding of longer-term and wider-scoped system dynamics. The goal of Systems Resilience is to ensure that system components can still function during a crisis [30]. However, ensuring the catchment system can continue to operate as normal may not be enough. Similar to the limitations of seeking only engineering resilience, is maintaining the normal operating rules of the system always advisable? Does the ability of a catchment to absorb a shock today, mean that we are adequately prepared for the future? In the face of climate change, such an assumption becomes increasingly dubious.

3.3. Complex Adaptive Systems Resilience

Complex Adaptive Systems Resilience is the *"ability to withstand, recover from, and reorganise in response to crisis"* [30]. According to Martin-Breen and Anderies [30] this framework acknowledges not only adaptation in response to a shock event, but the ability of systems to generate new ways of operating to achieve longer-term resilience. Transformability is a key element of the complex adaptive framework, which is the ability of a system component to assume a new function [30]. As one would expect, acknowledging complexity makes operationalising more complex, which requires innovative methods to capture such dynamics and a truly interdisciplinary approach.

Whilst Martin-Breen and Anderies [30] give definitions for each framework, these are complementary and not mutually exclusive. We would argue against limiting the resilience concept to one specific framework [4]. In general, the literature which addresses all three resilience frameworks refutes the false of infrastructure vs. nature, or control vs. chaos. In reality, there are shades of grey between these black and white concepts. For example, [19, 29] both discuss the nuances of resistance vs. resilience, even arguing that resistance measures are an inherent part of resilience. Tempels & Hartmann [19] further discussed robustness vs. flexibility, and the need to take a balanced approach to these rather than prioritising one or the other, as they are not on opposite ends of a spectrum but instead overlap in many ways. Indeed, defining resilience is the source of much contention in the literature [31], perhaps because resilience is often linked to real-world complex adaptive systems, which are also notoriously context-dependent and difficult to define.

Instead, we would argue in favour of acknowledging the different aspects of resilience that align with each framework for a more holistic and complete understanding of catchments. All three frameworks (in isolation or combination) can be matched to different catchment issues. For example on the one hand, the Netherlands can be perceived to be resilient to flooding because they are highly advanced in their ability to control flooding, leading to less frequent flooding and lower flood damages compared to England [29]. On the other hand, England could be perceived to be more resilient to flooding due to its high capacity to absorb and adapt to flooding, allowing England to perform well in terms of response and recovery [29]. We argue [4] that one framework perspective is not 'more resilient' than another, but that these differences emphasise the fluidity of the concept, where certain aspects of resilience are prioritised depending on their relative importance. In other words, we consider that the concept of the "fluid frontier" [19] is only applicable to natural, social, and technical interactions but also to our operationalisation of true resilience. Whilst resilience is truly present in all three frameworks, which aspects are most applicable will depend on the context of how natural, social, and technical aspects are interlinked in a given catchment.

3.4 Resilience frameworks:

When all three resilience frameworks are accounted for, we are forced to consider the interactions, not only between natural, social, and technical aspects but also between spatial and temporal scales the system [32]. One framework of resilience cannot be considered in isolation without having a feedback to other aspects of resilience. However, the current state of play lacks this integrated conceptualisation. From our structured literature review [4], we found that only 15% of flood risk management papers accounted for all three frameworks in their definitions of resilience. The majority of papers consider engineering resilience alone; systems resilience alone; or engineering and systems aspects of resilience. This indicates that the majority of existing work in this area does not perceive resilience to be an iterative, adaptive process with the ability to transform. In other words, catchments are not yet widely understood as complex adaptive systems, limiting the instances in which the three resilience frameworks can be precisely applied.

4. Catchment Resilience

So far we have argued that catchments must be considered as complex adaptive systems comprising of interrelated natural, social and technical systems; and that resilience must acknowledge the context and the concept can be considered fluid to reflect this. If we now turn our attention to catchment resilience – we must consider a shock occuring within a catchment, e.g. a flood or a drought (hydro-hazard [3]), and we must recognise that these shocks are not stationary; i.e. the influnece of climate change is modifying the frequency, magnitude and duration of these shocks [15, 16] . The tripartite resilience concept alludes to some key considerations in applying this theoretical systems thinking to actually grappling with resilience in the real world.

To consider resilience in these complex systems we need to move towards a complex adaptive systems approach which recognises the systems' ability to transform in the face of a shock (hydro-hazard). Due to their nature as complex adaptive systems, catchments are under constant reorganisation, and evaluative measures will need to be applied in an ongoing fashion to account for this changing context. Consequently we undertook a structured review of the state of the art methods which deal with adaptation within catchments.

4.1. Complexity challenges for catchment resilience: a review

In oder to inform our review of the state of the art in systems research within climate change adaptation [3] we identified six complexity challenges [3]; these challenges apply directly to the assessment of catchment resilience. These six challenges are informed by key literature in complexity, sustainability, and transformations [3, 33, 34, 35, 36], frame the critical considerations to be addressed in this section, and include:

1. Natural-social-technical aspects: Acknowledging and accounting for the influence and feedback arising from human values, behaviour, culture, infrastructure and institutions;
2. Interactions: Accounting for multiple interactions across natural, social, and technical systems; connecting global scale dynamics to local realities and vice versa;
3. Spatial scales: Coverage of multiple spatial scales; connecting contextual, place-based understandings (bottom-up) with theoretical and systemic knowledge (top-down);
4. Time scales: Coverage of multiple temporal scales;
5. Multiple forms of evidence, and
6. Uncertainty: Recognitions of the uncertainty in future projections.

Using the six complexity concepts identified we recently reviewed 910 papers on climate change adaptation to hydro-hazards [3] in a structured manner. These papers were analysed to understand the degree to which they incorporated the six complexity concepts, and which methods were used to do so. Straightaway 173 (19%) of these papers addressed *none* of the six complextity concepts, even in a cursory search for these concepts within titles, abstracts and keywords. From this it is clear that the journey to truly 'doing systems research' has just begun.

A the forefront of operationalising these initial two concepts (natural-social-technical sub-systems, and their interactions) is the need to address different spatial and temporal scales. McClymont et al. [4] found that few existing studies adopt a systems-thinking perspective which allows all interactions to be taken into account across multiple spatial scales by focusing on interrelationships and feedback loops. When this is done, it is typically with heavy emphasis on social aspects [e.g. [37, 38]]. Only rarely do papers attempt to combine the social and technical interactions across different spatial scales for a more holisitic understanding of catchment resilience (e.g. [24, 39]).

In our structured review [3] we found that most studies tended to focus on assessint medium-term time scale impacts (i.e. taking months or years), without strong connections to the study of short-term time scales (i.e. taking hours, days, or weeks). This focus on the Medium-term is somewhat expected because the impacts of a hazard, such as a flood or drought, can take more than hours, days, or weeks to be fully realised, for example, the impacts of a flood on a city's wider healthcare system. However, without a robust understanding of how short-term dynamics lead to medium- or long-term effects (e.g. stressors) being realised, it will be difficult to create effective interventions and transformative adaptation. We also found [3] that the medium-term time scale studies are significantly correlated to the study of ecological, economic, and social impacts. Economic and social impacts are currently studied in a primarily top-down fashion (e.g. using census data) which could be a barrier to the unpicking of system dynamics and interactions. A challenge in this area is that the study of interactions at multiple time scales is an inherently data-intensive exercise, so it is often only done in the short-term time scale, to minimise data requirements. Emphasis is needed on methodological development to study interactions in general, but particularly in linking the short- to medium-term timescales, and ideally in a way that minimises data requirements.

Interlinked with the consideration of multiple spatial and temporal scales is the need to connect 'top-down' (from a large and broad spatial scale, e.g. prescribed by institutions at the national level) and 'bottom-up' (from a local context, e.g. agreed and proposed by the neighbourhood or community scale) solutions. These two approaches also typically require different forms of evidence and models. Bottom-up approaches are considered to be the most relevant to resilience, particularly in understanding the interplay of institutions, flood risk communication, and flood modelling tools [40]. However, results from our comprehensive methods review on climate change adaptation to floods and droughts [3] show that 'bottom-up' data is often physical or natural (e.g. rainfall measurement), and is often only integrated with 'top-down' social data (e.g. census datasets, indicators). Often when participatory methods (e.g. focus group) are used, these are combined only with qualitative data collection (e.g. survey) and corresponding statistical analysis. Thus, when multi-method, multi-scale approaches are used, these are often top-down decision-making tools with quantitative analysis. These approaches continue to be extremely data- and time-intensive, requiring multiple sophisticated models. What is missing – and what could arguably alleviate the data-hunger of higher-level policy- and decision-making analyses – is the 'end user' and their insights into local context. To fulfil the recommendation of O'Sulliven et al. [40], we must seek fuller integration of 'bottom-up' social methods (e.g. participatory) with higher level policy and practice processes, to inform more effective and equitable outcomes. This suggests a move away from exclusively top-down, technocratic approaches. Indeed, the allowance of small manageable floods enables community adjustment and learning over time, increasing resilience capacity to cope with larger, unpredictable flood events [39, 41, 42]. However care should be taken in balancing bottom-up and top-down approaches. Consideration of the collective, distributed responsibilities for catchment resilience is needed, as rescaling of resilience to be the exclusive responsibility of the community or household level risks neglect of the state's accountability [43]. Rather than "failure becom[ing] a property of those who fall victim" {43, 2015, p. 1083], each catchment should collectively consider how to distribute responsibility for its resilience amongst government, regulatory, and community organisations based on local context, to ensure an equitable and ultimately more effective strategy for resilience.

Finally, uncertainty – particularly surrounding the natural hazards we might expect in the future – is a key consideration. To address climate change adaptation to hydro-hazards effectively within the concept of catchment resilience, it will become increasingly important to address both ends of the hydrological spectrum in a comprehensive way [16, 17, 44, 45]. While floods and droughts are covered equally overall, floods and droughts are considered *together* only in about 23% of cases. In other words, consideration of the entire hydrological cycle is essential, possible, and often unaddressed. The inverse of this finding is the possibility that approaches capturing interactions and using multiple forms of evidence have greater potential to be extended across hazard types (i.e. from application of floods to application of forest fires). Thus, a high priority for future catchment resilience research is to develop and apply methods which are in some ways 'hazard-agnostic', in their capability to consider not just floods and droughts together, but any combination of multiple, interacting, or compound hazards. In general, this might also include the characterisation of latent social or technical vulnerabilities as dormant hazards.

4.2. Studying catchment resilience

In the previous sections we used Tempels & Hartmann's [19] concept of a "fluid frontier" between ecological and human systems, to apply the same sort of "fluid frontier" to the tripartite resilience concept. We propose to extend this again [3. 4] to the conceptualisation of bottom-up and top-down approaches to catchments, including the blended use of qualitative and quantitative methods at all spatial and temporal scales.

Some studies are venturing into these fluid frontiers. For instance Johnson & McGuinness [46] integrate dynamics between national social policy and micro-level mitigation measures, covering a range of spatial and temporal scales. Beevers et al. [24] and Adeyeye & Emmitt [39] attempt to combine technical and social systems across different spatial scales within their methodologies. However in general, even cutting-edge studies which cover all three resilience frameworks tend toward covering only a large (often city) scale, tend away from the technical toward the social, and use predominantly qualitative methods such as interviews, desk study, or new conceptual frameworks. In general, there are no significant patterns in methods currently applied to different catchment hazards, impacts, floods, droughts, time scales, spatial scales, or natural-social-technical dimensions [3]. One size does not fit all, and no single solution exists. As a result catchments are a fertile ground for testing new approaches to resilience.

Table 1 summarises our suggested next steps for studying catchment resilience in general, respective to the six complexity concepts and is based on the findings of our recent structured review [3].

Table 1. Next steps for studying complex catchment systems, respective to key complexity concepts.

#	Concept	Current state of the art	Future Next Steps
1	Natural-Social-Technical Dimensions	This was most frequently mentioned challenge to address; In particular papers referred to infrastructure, ecological and economic aspects as critical challenges	More dimensions should be considered systematically within methods – this should become routine in assessments; Specifically future assessments should consider community impacts & post-hazard infrastructure aspects
2	Interactions	Only 1/5 [19%] studies claim to address interactions of any kind; Where interactions are considered these tend to be in studies which consider short-term (hours or days or weeks) shocks.	Future work must link short-term shocks and long-term stressors in assessments. This requires new methods which can explicitly link interactions across timescales.
3	Spatial Scale	Research has tended to have a strong emphasis on regional and community scale analysis; Most research which considered spatial scales explicitly had a physical emphasis i.e. social dynamics and considerations less	Next steps must consider a finer level of scale (e.g. household-level) to determine what scale of critical complexity dynamics are necessary to incorporate; Additionally research is needed to

		covered	incorporate social, behavioural, cognitive, and/or cultural aspects across spatial scales within assessments.
4	Time Scale	Most research reviewed focused (90% occurrence) on medium-term impacts; rather than short-term or long-term impacts;	In the future more focus is needed on short-term (hours or days or weeks) and linking this to medium-term (months or years) as well as longer term considerations (impacts and interactions).
5	Multiple Forms of Evidence	Most approaches used within recent research still relied on classic quantitative methods (e.g. physical measurement & statistical analysis) and simulations	Future work will require the research community to develop methods which integrate participatory methods (bottom-up) and decision-making analyses (top-down) better and more efficiently
6	Uncertainty	Only 22% of research accounts for uncertainty;	Future research must include greater consideration of multiple possible futures; Methods must also consider and quantify how uncertainty cascades through different time scales, and across different spatial scales
OVERALL		1. So far there is no 'one right way' to study catchment resilience; 2. 1 in 5 papers reviewed does not cover any of the six complexity concepts, even at a broad level; 3. Three quarters of all reviewed papers addressed only 1 or 2 complexity concepts; 4. None of the 910 papers addressed all six complexity concepts	Future work: 1. We must include more systematic consideration of the six complexity concepts in research design; and 2. We need look to other disciplines for complexity-smart methods – and adapt them to catchment resilience needs.

5. Future Catchment Resilience

If we are to understand catchment resilience as a unifying concept for the purpose of enhancing resilience to hydro-hazards, how might this be done? How can we study the suite of interactions we allude to, and address the complexity concepts above in order to manage catchments? Additionally how can link our understanding and modelling of these interactions across temporal and spatial scales? An example here is to consider is how could we link short-term impacts resulting from a shock to the longer term outcomes that catchment resilience might require to be monitored? This would required understanding of the interactions and feedbacks, as well as quantification of the outcomes which should be tracked. Using existing methods employed in the community, exploring and understanding this complexity is difficult, if not impossible. Thus there is a significant scientific gap which requires catchments to be considered as complex, interacting systems (natural-social-technological systems), consideration of the long-term outcomes which are desireable, alongside methods capable of exploring catchment resilience properties and vulnerabilities in specific contexts. Their complex adaptive nature indicates that there is no 'destination resilience' [4] on the horizon, or any single method to produce a perfect 'resilience score' at which point we will have finally achieved resilience.

5.1. How could we approach future catchment resilience?

Gaining a full understanding of catchment resilience will thus require, understanding desireable long-term outcomes and the development of a mix of methods to understand and quanitify it.

Dealing first with long-term outcomes, there has been significant bodies of work which explore and map urban resilience, such intiatives recognise urban areas as complex systems. For example the Rockefellar Foundation 100 Resilient Cities Program [48] or the World Health Organization's Healthy Cities initiative [49] through to recognising the nexus among these goals in the United Nation's Sustainable Development Goals [50]. Each of these spearate components of resilience into different sections under which indicators can be developed to map on to different outcomes. The expectation is that progress is monitored against these outcomes over the long-term in order to understand and ultimately improve resilience [51, 52]. For example the 100 Resilient Cities Framework uses the City Resilience Index, which is separated into four dimensions: Health and wellbeing, Economy and society, Infrastructure and environment, and Leadership and strategy. Each dimension has three individual goals and the Index has 52 indicators which allows tracking of urban resilience. Deceloping a similar framework for catchment resilience, which recognises the complexity of the system across natural, social and technical systems represents a research gap which could move the domain forward.

Next, turing our attention to methods, there are few patterns in how we currently address catchment resilience. In general, there is a need to combine quantitative and qualitative methods. Simulations combined with classic quantitative methods are most popular when studying hydrological extremes. However many existing simulations cover only natural processes, or in rare cases, very fine-scale human behavioural processes. These are not yet capable of studying the complex nature of resilience, particularly at a catchment scale. Classic quantitative methods combined with classic qualitative methods which might better account for systems resilience are used one fourth as often [3]. When adding participatory methods – which are perhaps more likely to capture deep contextual insights about system interdependencies – to the mix this is even less frequent. Real-world practice continues to be heavily reliant on indicators to account for the social (and sometimes also technical) spheres, as these provide quantifiable measures wherever simulations cannot be constructed. Increasingly, new conceptual frameworks are being developed in the academic sphere [47] arguably to shift emphasis from indicators which are 'snapshots' of system states, (i.e. proxies for system behaviour), to interrelationships or system structures (i.e. system behaviour itself).

Embracing more mixed methods approaches in the interdisciplinary space is necessary. These could use the catchment as the physical boundary, whilst recognising that administrative and political boundaries rarely match these. This can be used to build the context and understand the different networks in play within any given catchment. The interactions and feedback can then be mapped and connected on top of this [24, 32, 47]; and potentially linked to the long-term outcomes or goals identified for catchment resilience (identified as a gap above).

The below serves as just one example of what may be included in such a combined approach; future research is needed in order to develop this area in order to assess, understand and improve future catchment resilience.

- *Strategic overview of the contextual issues for a specific catchment;* to include the natural, social and technical components. This would set the framework for the understanding the catchment an estimate where in the natural-social-technical Venn diagram those identified issues reside, which can inform the latter stages of a deeper analysis. This could be completed using:
  - Indicator methods which are top-down may be useful at this broad exploratory stage (e.g. communication capacity as in [53]; or Multiple livelihood sources [54]. However indicators can miss deeper issues that could be picked up by also using community workshops or other participatory methods (i.e. bottom-up approaches).
- *Natural aspects* might be analysed (bearing in mind temporal and spatial scales of assessment) using:
  - Hazard models to estimate flood and drought frequency, magnitude and duration

- Methods to map and characterise ecological impacts, knock-on effects and feedbacks from within the natural catchment system
- Methods to explore the efficacy, and feedbacks from building with nature for increasing resilience

- *Technical aspects* might be analysed (bearing in mind temporal and spatial scales of assessment) using:
    - Network analysis of physical infrastructure networks and their potential interactions
    - Numerical analysis of the performance of flood alleviations schemes, both hydraulically and structurally; similarly water resource networks and interactions with withdrawals and users.
- *Social aspects* might be analysed (bearing in mind temporal and spatial scales of assessment) using:
    - Human factors methods such as the Event Analysis of Systemic Teamwork method, to study team operations within governance, or critical services like emergency response)
    - Capabilities Approach framework [55] to study what capacities are required for local neighbourhood-scale resilience
    - Agent-based modelling to study household-level decision-making around the uptake of adaptation measures
- *Interaction analysis*: this area would use the domain information from above, however it needs method development in order to recognise and build interactions. Methods may include
    - Systems analysis [47] – where are the functional pinch points, risks, and high level vulnerabilities within the existing inter-connected system structure?

Using interaction analysis, the system's functional structure can be explored. Several system design questions can be posed around this topic. For instance, to enhance catchment resilience, are more interactions better for the system? Or should we explore 'smarter' interactions, strengthening particular links or dependencies and prioritising them over others? Would additional redundancies within the catchment (i.e. several different aspects undertaking similar functions) added in specific parts of the system enhance its overall resilience? If the answer to any of these questions is 'yes', an interaction analysis can also experiment with new system structures before large investments are made, without the risks of real-world trial and error.

Some potential interventions arising from these analyses might include: nature based solutions for hydro-hazard management in the upper reaches of a catchment, changes to land use further down the catchment (away from heavily managed agricultural land towards encouraging greater infiltration into groundwater reserves), large scale water management infrastructure, or water sensitive urban design (incorporating the ideas from blue/green cities or sponge cities) where assets are connected across cities to increase water absorption in the catchment can then be tested within the larger system model to explore the response of the catchment. Additionally, mechanisms to increase social cohesion or inclusion, and strengthen environmental policy can be tested in the same way to understand how the system responds, whether its effects are experienced positively or negatively by local communities, and what responses might arise as a result. Some of these examples are illustrated in Figure 3. These interventions, whilst not new, do not always consider all of the interactions in their design, thus missing the unintended impacts across the system which can hamper their efficacy.

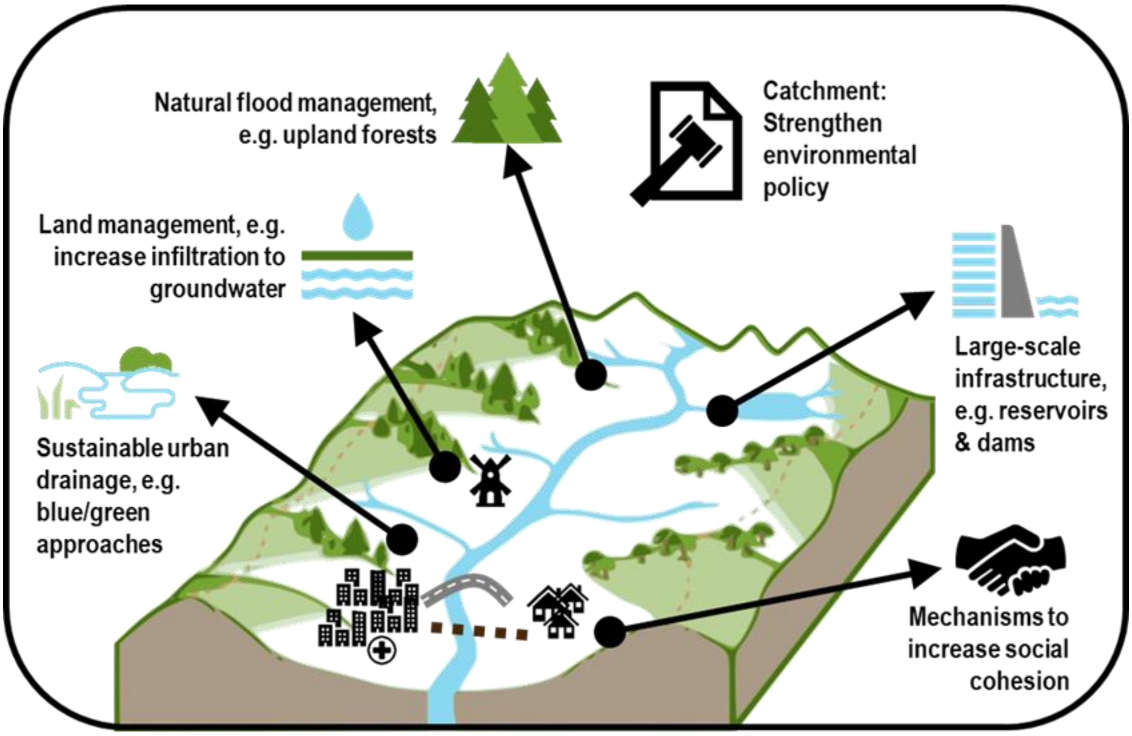

Figure 3: Examples of possible resilience-enhancing measures in a river catchment

Anticipating future changes is not simple, however understanding catchment resilience would require us to understanding how future change may impact the interacting system. Work is ongoing in anticipating the potential changes that the world may face in terms of climate perturbed hydro-hazards[15, 16, 17]. In the UK ITRC-MISTRAL researches multi-infrastructure vulnerabilities and as part of this project projected future changes of network. While in Scotland recent work on flood disadvantage has projected potential social changes [56]. Thus there is clear progress. What is needed is now a way to bring these together to explore the system – not just its parts – in order to enhance resilience. If we continue to resist considering the catchment as a complex adaptive system (with interactions between these natural, technical, and social aspects), the catchment system may self-organise in ways we cannot understand or track, resulting in unanticipated effects in the future. Thus we argue that is better to acknowledge complexity now so we might develop a more holistic way of understanding the catchment system, and be able to effectively 'co-evolve' with it.

There is no 'one size fits all' approach to catchment resilience. We need a framework in which to track long-term desired outcomes for catchment resilience. In order to undertake a deeper understanding, mixed method approaches are required and their selection will depend on contextual issues identified early in the process for specific catchments. Central to any effective approach is the incorporation of a linking systems or interaction analysis, which draws together the natural-social-technical system in a meaningful way.

6. Conclusions

In returning to our original question:

> *How can we use catchment resilience as a unifying concept in catchment management and regulation – particularly in light of climate risks, population growth and other pressures?*

we have argued for catchments to be considered as complex adaptive systems, consisting of interacting sub-systems (natural, social, and technical), which are able to adapt and transform in response to shocks (such as hydro-hazards).

Our reviews suggest that the research from this perspective is in its infancy. If our approaches do not begin to acknowledge the "fluid frontiers" and interactions between the natural-social-technical realms, spatial and temporal scales, and bottom-up and top-down approaches, then we may miss substantial opportunities to enhance catchment resilience. Understanding where parts of the system need to be strengthened or where redundancy may enhance or inhibit catchment resilience is critical to maximising its potential for managing climate risks, population growth and other pressures.

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