



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. 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 hydrohazard, 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. Requirements for future methodological approaches are suggested. 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 interrelationship 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, as well as internationally, are already impacted by hydrological extremes (floods and droughts: hydrohazards), 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 (in 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?

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses /by/4.0/). This paper summarises current literature following the findings of our previously published papers [3,4] — these are structured critical reviews focusing on climate change adaptation to hydrohazards, and flood management resilience. We use these reviews as a basis to develop and broaden our arguments; and relate these to the concept of catchment resilience in order to identify promising research and management gaps. Specifically, we will focus on catchment resilience for hydrohazard management, where we define hydrohazards as floods and droughts, thus we address both hydrological extremes.

The first paper [3] systematically reviews literature for climate change adaptation to hydrohazards, and we explore available methods for their ability to address complexity. The paper [3] identifies that research into climate change adaptation to hydrohazards suffers from a substantial lack of complexity-smart approaches. It highlights that complex climate change challenges are quickly outgrowing our 'classic' approaches, and thus there is a need to develop new methods. The second paper [4] systematically reviews the academic literature on flood resilience to explore how resilience is assessed, operationalised and implemented. The paper concludes [4] that resilience requires fluidity in concepts and recognition of context in order to recognise different ways to be resilient. The paper highlights gaps in current understanding of the importance of temporal and spatial scales when considering resilience and recommends a complex adaptive systems approach which accounts for the interdependencies between spatiotemporal scales, and couples human and physical systems to allow for new dynamics to emerge.

These two structured reviews are used as a basis to develop our perspective on catchment resilience. The first only focusses on existing methods for both floods and droughts, whilst the second is specific to floods. Within this paper, we expand on these findings in order to address catchment resilience, which necessarily requires consideration of both extremes of the hydrological cycle (floods and droughts), within the context of the water management unit (i.e., a catchment). Furthermore catchment resilience requires a forward-looking perspective in which critical external influences are considered (e.g., climate change and urbanisation). Thus, we use the findings of these papers as building blocks to expand our perspectives from floods to hydrohazards, within the context of a catchment, in order to answer the question posed above.

This 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). This paper 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'. For example, for flood exposure, this might be the assets located within an active floodplain area; and

for droughts, assets, goods, etc., which are directly at risk from short- or medium-term droughts. Vulnerability is defined 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]). Vulnerability to floods [7] can then be expanded to the extent to which a system [interacting human, social and technical components] is susceptible to flood exposure in combination with its ability to adapt. This can be expanded in a similar manner for droughts [8]. Resilience is defined as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, for example the preservation and restoration of its essential basic structures and functions" [6] p. 24. The water management policy context within Europe recognises the need to consider the catchment unit as the basis for assessment and management. For example, both the Water Framework Directive [Directive 2000/60/EC] and the Floods Directive [Directive 2007/60/EC] recognise the spatial unit of the catchment, and its interacting parts as a basis for understanding processes. There is, however, still an emphasis on the interaction of the natural catchment system more than the social and technical components.

The combined exposure, vulnerability, and resilience of a catchment can result in impacts affecting agriculture (e.g., [9]), infrastructure (e.g., [10]), human health (e.g., [11]), economic activity (e.g., [12], government and institutional practices (e.g., [13]), cultural heritage and community (e.g., [14]), and of course the environment (e.g., [15]). Despite the policy context mentioned earlier, in the last five years (2014–2019), the UK has experienced several significant natural hazard-related disasters [16], 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. Hydrohazards 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 [17–19], 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 sociohydrology [20] recognise the dynamic link between natural processes and social systems, which is particularly pertinent in the catchment context. In this vein, Tempels and Hartmann [21] 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 subsystems: natural (including physical processes, e.g., hydrology, hydrogeology, geomorphology, sediment transport, nutrient cycles, and ecosystem functions), social (processes driven by intangible human values and priorities, e.g., community cohesion, health, and economic standing), and technical (physical infrastructure that is in some way human made or human influenced, e.g., transport, energy provision, and communications). We specifically include the technical within this framework as the interactions between infrastructure and the natural environment and society are critical to their function. For example, building a flood wall may improve flood exposure for some, but have feedbacks on the natural environment whilst also acting to erode the perception of risk of those living directly behind them [22]. Figure 1 shows these three subsystems as mutually coupled in an inextricable way, whereby a change in one subsystem 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.

For example, flooded communities may experience long-term health impacts arising from psychological impacts from the fear of repeat flooding [23]. 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 [23]. Of course these are examples which are fairly straightforward in nature. In reality, there is an overwhelming number of feedbacks and interactions, and which of these will be key to a catchment's resilience is often elusive. Figure 1 suggests 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 subsystems and their overlaps. Traditional unidisciplinary research typically sits at the edges of the nexus [18,24,25], studying specific phenomena or known feedback loops, in order to explain and adjust the wider system from that perspective. Research exists which addresses the intersection of two domains (e.g socio-technical studies [26,27]. Ideally, initial research on a catchment's resilience should be situated at the nexus [7,28,29], to acknowledge the importance of interactions between subsystems. Currently, our research suggests that only approximately 20% of hydrohazards research addresses any type of interaction, despite the wider complexity literature pointing to these as an underlying source of emergence [3].

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Figure 1. Interacting natural-social-technical subsystems occurring within a catchment [7,10,11,18,24–29].

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. Figure 2 illustrates our conceptual framework for catchment resilience as a unifying concept for hydrohazard management. The framework presents our view of 'what' catchment resilience is, situated at the nexus of the natural-social-technical system. Within this nexus, we can explore the 'how' of catchment resilience by considering the feedbacks between exposure, vulnerability and resilience. The different aspects of resilience outlined in Section 3 help to consider the interactions within a catchment. Section 4 considers the methods capable of accounting for this complexity. These interactions within the system are key to understanding its overall behaviour, but these are often not captured. By considering the different aspects of resilience, we can start to think of the 'why' of catchment resilience, in particular the interaction between short-term exposure and longer-term objectives [30], which are explored in Section 5.



What of catchment resilience

Why of catchment resilience

Figure 2. Conceptual framework for utilising catchment resilience as a unifying concept in hydrohazard management.

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 [31], the resilience concept has developed over the intervening half century and pervades the discourse in many disciplines [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 risk management field observed that there are differences in definition across the discipline. For example, Restemeyer et al. [32] state that resilience centres on robustness, adaptability and transformability; Nguyen and James [33] point to speed of recovery, magnitude of disturbance relative to a threshold, and ability to learn/adapt/transform; Hegger et al. [34] 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 [35] reviewed 50 years of resilience research to produce a resilience spectrum of increasing complexity, which consists of three interdisciplinary frameworks—engineering resilience, systems resilience, and complex adaptive systems resilience—reflecting the different aspects of resilience. This resilience spectrum was used in [4] to inform the review and to match the flood resilience definitions to the resilience aspects of each framework in order to identify where flood resilience studies are currently situated along this spectrum. Martin-Breen and Anderies [35] provide case studies for each framework in the broader resilience literature, and Philip et al. [36] have used the engineering and complex adaptive systems framework to inform their research on assessing long-term impacts of flooding.

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" [35]. 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 [35], resilience from this perspective is about decreasing a hazardspecific risk and restoring conditions to a precrisis state. A strength of framing resilience in this way, they argue, is that it makes the concept straightforward to understand, model, measure and manage. However, its simplicity is also a major limitation when we focus on engineering resilience alone. By focusing on aspects such as 'withstand' and 'bounce back' 'return to normal quickly', it maintains the status quo, which has been argued to be detrimental to future resilience [35]. 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" [35], and this framework increases the complexity of the engineering resilience, where the aim is to keep things functional as opposed to identical. When we consider that the "world is 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 [35]. 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 [35]. System resilience includes aspects such as 'absorb', 'maintain', 'cope' and 'function' [4]. However, ensuring that 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 al-ways 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" [35]. According to Martin-Breen and Anderies [35], 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 [35]. Key aspects from this framework include 'transform', 'adapt', and 'learn' [4]. 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 [35] 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 dichotomy of infrastructure vs. nature, or control vs. chaos. In reality, there are shades of grey between these black and white concepts. For example, [21,34] both discuss the nuances of resistance vs. resilience, even arguing that resistance measures are an inherent part of resilience. Tempels and Hartmann [21] 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 [37], 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 [34]. 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" [21] is not 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 [38]. 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 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 occurring within a catchment, e.g., a flood or a drought (hydrohazard [3]), and we must recognise that these shocks are not stationary, i.e., the influence of climate change is modifying the frequency, magnitude and duration of these shocks [17,18]. 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 (hydrohazard). 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 order 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 [3,39–42], 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;
- Spatial scales: Coverage of multiple spatial scales; connecting contextual, placebased understandings (bottom-up) with theoretical and systemic knowledge (topdown);
- 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 hydrohazards [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 complexity 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.

At the forefront of operationalising these initial two concepts (natural-social-technical subsystems, 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 performed, it is typically with heavy emphasis on social aspects (e.g., [43,44]). Only rarely do papers attempt to combine the social and technical interactions across different spatial scales for a more holistic understanding of catchment resilience (e.g., [7,45]).

In our structured review [3], we found that most studies tended to focus on assessing medium-term time-scale impacts (i.e., taking months or years [46–48]), without strong connections to the study of short-term time scales (i.e., taking hours, days, or weeks). The full database of studies on climate change adaptation to hydrohazards is available for reference [49]. 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 health care system. However, without a robust understanding of how short-term dynamics lead to medium- or longterm 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 [47,48]. 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 performed in the shortterm 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 time scales, 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 [22]. However, results from our methods review [3] show that 'bottom-up' data are often physical or natural (e.g., rainfall measurement), and are often only integrated with 'top-down' social data (e.g., census datasets, indicators) [50]. Often when participatory methods (e.g., focus groups) are used, these are combined only with qualitative data collection (e.g., survey) and corresponding statistical analysis. Thus, when multimethod, multiscale approaches are used, these are often top-down decision-making tools with quantitative analysis [51]. 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. [22], 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 [45,52,53]. 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 [54]. Rather than "failure becom[ing] a property of those who fall victim" [54] 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 hydrohazards effectively within the concept of catchment resilience, it will become increasingly important to address both ends of the hydrological spectrum in a comprehensive way [18,19,55,56]. While floods and droughts are covered equally overall, floods and droughts are considered together only in approximately 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 and Hartmann's [21] 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 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 and McGuinness [57] integrate dynamics between national social policy and micro-level mitigation measures, covering a range of spatial and temporal scales. Beevers et al. [7] and Adeyeye and Emmitt [45] 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 away from the technical (except [58]) toward the social, and use predominantly qualitative methods such as interviews, desk study, or new conceptual frameworks (e.g., [21,34,43]). 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].

	Concept	Current State of the Art	Future Next Steps
1	Natural-So- cial-Technical Dimensions	This was the most frequently mentioned challenge	More dimensions should be considered systematically within
		to address;	methods-this should become routine in assessments.
		In particular, papers referred to infrastructure, eco-	Specifically, future assessments should consider community
		logical and economic aspects as critical challenges	impacts and post-hazard infrastructure aspects.
2	Interactions	Only 1/5 [19%] studies claim to address interac- tions 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 interac- tions across time scales.

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

3	Spatial Scale	Research has tended to have a strong emphasis on regional and community scale analysis; Most research which considered spatial scales ex- plicitly had a physical emphasis, i.e., social dynam ics and considerations less covered	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 incorporate social, behav- ioural, 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 o 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 Evi- dence	Most approaches used within recent research still relied on classic quantitative methods (e.g., physi- cal measurement and statistical analysis) and simu lations	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 ef- ficiently.
6	Uncertainty	Only 22% of research accounts for uncertainty;	Future research must include greater consideration of multi- ple possible futures. Methods must also consider and quantify how uncertainty cascades through different time scales, and across different spatial scales.
0	VERALL	 So far, there is no 'one right way' to study catchment resilience; 1 in 5 papers reviewed does not cover any of the six complexity concepts, even at a broad level; Three-quarters of all reviewed papers ad- dressed only 1 or 2 complexity concepts; None of the 910 papers addressed all six com plexity 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 hydrohazards, how might this be achieved? 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 we link our understanding and modelling of these interactions across temporal and spatial scales? An example here is to consider how could we link short-term impacts resulting from a shock to the longer-term outcomes that might be monitored for catchment resilience? This would require understanding of the interactions and feedbacks, as well as quantification of the system outcomes which should be tracked through time. Using existing methods employed in the community, exploring and understanding this complexity is difficult, if not impossible. Case studies are emerging which explore flood resilience in NTS systems, giving support to catchment resilience as a unifying concept [59,60]. However, there remains a significant scientific gap which requires catchments to be considered as complex, interacting NTS systems, with consideration of long-term outcomes which are desirable, 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. The How of Future Catchment Resilience

Next, turning 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 [18,19]. However, many existing simulations cover only natural processes, or in rare cases, very fine-scale human behavioural processes [61]. 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 [62] 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 [7,38,62]; and potentially be linked to the long-term outcomes or goals identified for catchment resilience (identified as a gap above).

The suggestion 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 understanding the catchment and estimate where in the natural-social-technical Venn diagram those identified issues reside, which can then inform a deeper analysis and explore feedbacks between exposure, vulnerability and resilience (Figure 2). This could be completed using:
- Indicator methods, which are top-down approaches and may be useful at this broad exploratory stage (e.g., communication capacity as in [63]; or multiple livelihood sources [64]). 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 [18,19].
- Methods to map and characterise ecological impacts, knock-on effects and feedbacks from within the natural catchment system [65].
- 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 [7,38,58,66].
- Numerical analysis of the performance of flood alleviations schemes [50], 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 [67], to study team operations within governance, or critical services such as emergency response.

- Capabilities Approach framework [68] 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 [69].
- *Interaction analysis* would use the domain information from above. However, it needs method development in order to recognise and build interactions. Methods may include
- Systems analysis [62]—where are the functional pinch points, risks, and high-level vulnerabilities within the existing interconnected system structure?

Using interaction analysis, the system's functional structure can be explored. Several system design questions can be posed around this topic [38]. For instance, to enhance catchment resilience, are more interactions better for the system [38]? 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 hydrohazard management in the upper reaches of a catchment, changes to land use further down the catchment (away from heavily managed agricultural land to-wards 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.

5.2. The Why of Future Catchment Resilience

Gaining a full understanding of catchment resilience will thus require the development of a mix of methods, and a focus on desirable long-term outcomes.

There have been significant bodies of work which explore and map urban resilience outcomes, and such initiatives recognise urban areas as complex systems. For example, the Rockefeller Foundation 100 Resilient Cities Program [70] or the World Health Organisation's Healthy Cities initiative [71] through to recognising the nexus among these goals in the United Nation's Sustainable Development Goals [72]. Each of these separate components of resilience can be mapped to different outcomes of a system. The expectation is that progress is monitored against these outcomes over the long term in order to understand and ultimately improve resilience [5,73]. For example, the 100 Resilient Cities Framework uses the City Resilience Index, which is separated into four dimensions: health and well-being, 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. Another example includes the Ostrom [74] framework for analysing interactions and outcomes in social-ecological systems. Developing a similar framework for catchment resilience, which recognises and makes explicit the complexity of the system across natural, social and technical systems, represents a research gap which could move the domain forward. However, the practicality of this remains a challenge given the complexity of interactions which are not fully quantifiable yet.

Anticipating future changes is not simple. However, understanding catchment resilience would require us to understand 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 hydrohazards [17–19]. In the UK, ITRC-MISTRAL researches multi-infrastructure vulnerabilities and, as part of this project, projected future changes. Further, in Scotland, recent work on flood disadvantage has projected potential social changes [75]. Thus, there is clear progress. What is needed now is 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 selforganise in ways we cannot understand or track, resulting in unanticipated effects in the future. We must recognise that we do not yet have full understanding of the complexity of interactions, and as such we do not yet have the tools which will enable us to track future self-organisation. Blair and Buytaert [76] provide a comprehensive review of modelling tools to capture interactions between human and natural systems in the context of hydrohazards. The review states that rather than focusing on problem-solving, models "should be developed with a view to gaining new insight into these dynamics" [76] p. 443. Thus, we argue that it is better to acknowledge complexity now, so we might develop a more holistic way of understanding the catchment system, and be able to effectively 'coevolve' 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-methods 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 subsystems (natural, social, and technical), which are able to adapt and transform in response to shocks (such as hydrohazards). Our reviews suggest that research from this perspective is in its infancy. If 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 future assessments 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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