Catchment management as a systemic socioecological challenge: developing cross-scale approaches to critical pressures

Harrie Mort

Submitted in accordance with the requirements for the degree of Doctor of Philosophy

The University of Leeds

School of Earth and Environment

September 2025

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly authored manuscripts has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Chapter 3: Bridging scales for systemic eutrophication management: principles, challenges and the role of participation

CRediT authorship contribution statement

Harrie Mort: Conceptualisation, methodology, investigation, formal analysis, writing – original draft, visualisation. Geneviève S. Metson: Conceptualisation, methodology, investigation, writing – review & editing. Tina-Simone Neset: Methodology, writing – review & editing. Carolina Rodriguez: Methodology, investigation. Julia Martin-Ortega: Writing – review & editing, supervision. Pippa J. Chapman: Writing – review & editing, supervision. Marc Stutter: Writing – review & editing, supervision.

Chapter 4: Navigating scales in collaborative catchment management : the dual role of catchment partnerships in managing catchments as coupled human and natural systems

CRediT authorship contribution statement

Harrie Mort: Conceptualisation, methodology, investigation, formal analysis, writing – original draft, visualisation. Marc Stutter: investigation, writing – review & editing, supervision. Julia Martin-Ortega: Writing – review & editing, supervision. Pippa J. Chapman: Writing – review & editing, supervision.

Chapter 5: Bridging scales for systemic eutrophication management: principles, challenges and the role of participation

CRediT authorship contribution statement

Harrie Mort: Conceptualisation, methodology, investigation, formal analysis, writing – original draft, visualisation. Julia Martin-Ortega: Writing – review & editing, supervision. Pippa J. Chapman: Writing – review & editing, supervision. Marc Stutter: Writing – review & editing, supervision.

Acknowledgements

The first thanks go to my supervisors Julia, Marc and Pippa, whose support, guidance and, let's be honest, unwavering patience has been invaluable to the completion of this work. Their positivity, strength as a team and obvious care for the wellbeing of their colleagues was a large part of why I chose to do this PhD. I'm pleased to say that I was not mistaken in my first impressions these qualities are a large part of why I can look back on my PhD with fondness.

Further thanks go to my co-authors Gen, Tina and Carolina and other members of the Linköping team. Thank you for your generosity in opening up opportunities for me and the instrumental role you played in the evolution of this thesis. I also want to say a big thanks to the team at the James Hutton Institute who supported my research and made me feel incredibly welcome.

To Martina, Emmanuel and Teodor I offer a special thanks as my first and most enduring friends in Leeds. Martina, you are a wise and insightful friend who helped me make my way through the mire of the philosophy of scale (ew) and PhD life more times than I can count. Emmanuel, you are the kind of rock steady and positive presence that could get basically anyone through their PhD. You'll be pleased to know that I can now officially run 5k. Teodor, what can I say? Thanks for adding a measure of pure insanity, which certainly kept things from getting stale. I'm sorry I never made it to any techno clubs.

Dad, thanks for your encouragement and your unwavering belief in me. Let's hope you pre-emptively calling me "Harrie PhD" does not turn out to be a horrible, terrible, jinx -**ERROR thesis not found**-

Just kidding.

To Mum, I owe you a great deal of gratitude for listening to me ramble and rant over my PhD and, arguably, since I first learned to speak. Thank you for putting things firmly into perspective when I was having a PhD meltdown by pointing out the identical meltdowns I had over my bachelors, both my master's degrees and Cameron eating my leftover curry. Thank you for tolerating me and I hope that while the projects have gotten bigger, the meltdowns have become less frequent and dramatic.

I want to thank the members of RecaP and particularly Jake, Kaspar and, most especially, all of the RecaP ESRs for turning my PhD into an adventure.

I want to thank the crew at 10 Wood Lane: Will, Imogen, Zoë and Sadie. I already miss my kitchen debriefs.

Thank you to all the rest of my friends and family who have made the last four years a truly lovely period of my life and supported me in so many different ways.

Last but not least, I extend my sincere thanks to all of the participants in this research, not only for your generosity in offering me your time but also being a source of inspiration throughout my PhD.

Abstract

Policies aimed at improving the ecological status Europe's waters have proliferated over the last few decades, and evolved significantly as the 'wickedness' of critical pressures like eutrophication became increasingly apparent. Most noteworthy is the evolution towards integrative and participatory approaches based on hydrological boundaries, an approach that is the foundation of the EU's Water Framework Directive. While there have been some improvements, including reductions in nutrient inputs to Europe's waterbodies, 60% of Europe's waterbodies still fail to reach good ecological status. Clearly, there is a need to understand how the integrative and participatory approaches that have emerged in the last ~20 years can be strengthened to realise water quality goals. This thesis contributes to this goal by investigating how ambitions for catchment management to be (i) systemic, (ii) multi-scalar and (iii) participatory, can be realised in practice, with a focus on mitigating eutrophication. These three aspects are often held up as pillars of good catchment management; however, there is little work that explicitly looks at the significance of scale and how to approach 'cross-scale' management when addressing eutrophication as a systemic socioecological problem. Equally, the role of participation in supporting systemic cross-scale management is under-explored despite its potential value in water management. To address these critical gaps, this thesis presents three pieces of interdisciplinary and participatory research: (i) a case study in Stockholm, Sweden that shows the value of integrating systemic perspectives on scale into management, supported by participation, (ii) a case study in Scotland that demonstrates the value, challenges and limitations of collaborative catchment partnerships in supporting cross-scale management, and highlights how their role may be evolving, and (iii) a conceptual paper that suggests principles for approaching systemic cross-scale management of eutrophication and realising the value of participation for achieving this goal. Together, these pieces of work make strides towards establishing how socioecological cross-scale management can be implemented in practice to strengthen mitigation efforts, and how participation can support these efforts. By doing so it adds to the literature that demonstrates the value of participation in water management and environmental management more broadly. Overall, this thesis represents an important step forward in response to oft-repeated calls for managing eutrophication systemically and collaboratively 'across scales' that have yet to be answered.

Contents

List of Tables

List of Figures

1 Introduction

1.1 Research background and literature review

1.1.1 Integrated approaches for 'wicked' water problems

Over the last few decades, growing recognition of the 'wickedness' of human pressures on water systems has driven a step change in how the mitigation of critical issues like eutrophication are approached. Increasingly, management efforts are based on 'integrated' catchment-scale approaches that address water pressures as interconnected systemic problems, resulting from interacting ecological, social and technological drivers across the land-water continuum (Benson et al., 2013; Giakoumis & Voulvoulis, 2018; Pahl-Wostl et al., 2012). By acknowledging the systemic nature of water challenges and the relevance of hydrological boundaries, 'Integrated' catchment management[i] aims to reflect the fundamental features of water systems rather than disciplinary, sectoral or administrative silos (Pahl-Wostl *et al.*, 2012). The need to effectively manage interactions between land and water-based systems has also driven a shift towards more participatory and collaborative forms of water governance to facilitate coordination across governance levels and sectors (often termed vertical and horizontal coordination.) Engaging a variety of actors in governance is seen as an important means to develop management strategies that are effective, context specific and that have high public buy-in (Bilalova, Newig and Villamayor-Tomas, 2025).

'Integrated' approaches to catchment management have been embedded in water policies across the Globe since the 1990s (Allouche, 2017). Notably, implementing "integrated water resources management at all levels" by 2030 is target 6.5 of the UN's Sustainable Development Goal (SDG) 6, "Ensure availability and sustainable management of water and sanitation for all" (Allouche, 2017; Carlsen & Bruggemann, 2022; Collins et al., 2020; Moss et al., 2020). Integrated River Basin Management (IRBM) is also the founding principle of the EU's Water Framework Directive (WFD), and has driven a proliferation of management strategies across scales that aim to manage water resources according to 'integrated' principles (Moss et al., 2020; Water Framework Directive 2000/60/EC).

While the implementation of integrated water management approaches has been tentatively linked with positive outcomes for water, widespread improvements in catchment ecological health remain out of reach (Bilalova *et al.*, 2023). As of 2024, none of the SDG 6 targets for water and sanitation

---

[i] I use the term 'integrative water management approaches' as an umbrella term which includes 'watershed management', 'catchment-based management', 'Integrated River Basin Management' (IRBM) and 'Integrated Water Resources Management' (IWRM) (Surridge, Holt and Harris, 2009).

are on track to be met by 2030 and 50% of countries report the degradation of at least one water-related ecosystem type (Sachs, Lafortune and Fuller, 2024; United Nations Environment Programme, 2024). Pressures and impacts on ocean ecosystems are less well characterised; nevertheless, existing evidence shows that they are also undergoing increasing degradation. As a result, the targets in SGD 14 "Life Below Water" have seen some of the poorest progress of all the SDGs (Recuero Virto, 2018; United Nations, 2021; Andriamahefazafy *et al.*, 2022; Sachs, Lafortune and Fuller, 2024). At the European level, the picture also remains challenging. Progress against SDG 6, SDG 14 and the EU's own WFD have been mixed, and water quality continues to decline (Andriamahefazafy *et al.*, 2022; Eurostat, 2025). As of 2018, 60% of the EU + UK's surface waters failed to meet the standards needed to achieve good status according to the EU's WFD and are not expected to reach this standard ahead of its 2027 deadline (European Environmental Agency, 2018a)

Clearly, there is a need to understand why waterbodies across the world remain in poor ecological status despite decades of efforts and a perceived global shift in water management paradigm. Natural factors like recovery lag times are of fundamental importance; however, the shift towards integrated water governance approaches has failed to silence voices that point to ineffective governance as the critical factor (Pahl-Wostl *et al.*, 2012; Bilalova, Newig and Villamayor-Tomas, 2025). Instead, the attributes, operationalisation and implementation of integrated water governance approaches have received criticism since their inception (Biswas, 2008; Molle, 2008; Bertule *et al.*, 2018; Gain *et al.*, 2021). A key critique is that, despite being strongly influenced by socioecological systems theory, integrated water management approaches have failed to adequately incorporate some of its fundamental principles. Most notably, integrated management approaches do not adequately consider scale and cross-scale dynamics (Gain *et al.*, 2021; Whaley, 2022; Bennett and Reyers, 2024; Moore *et al.*, 2024)

1.1.2 Integrating socioecological systems scale concepts into integrated water management

Scale, cross-level and cross-scale dynamics are essential for understanding and addressing critical water issues as emergent properties of socioecological systems management (Cash *et al.*, 2006; Bennett and Reyers, 2024). (key scale terminology as used in this thesis is defined in (**Table 1.1**). Scales and the levels within them are conceptual frameworks that are used to analyse systems and their components according to certain dimensions (e.g. time, space, level of organisation or political power), which may be used alone or in some combination to define a scale (Vervoort *et al.*, 2012). It is expected that different drivers and processes may become visible or change when observing the system at different levels within a scale (Gibson, Ostrom and Ahn, 2000). For example, on a yearly timeframe (temporal level), fertiliser inputs to a catchment may be the primary anthropogenic driver of eutrophication. In contrast, on a multi-decadal timeframe, land-use change through the drainage of pre-existing swampland may be the most significant driver (Siman and Niewiarowski, 2023). Furthermore, cross-level interactions may occur between drivers and processes observed across different levels within a scale to contribute to overall system outcomes. Climate change, national agricultural policy and individual preference can be said to operate at different spatial levels but can interact with each other to deeply impact land use and water system health. The choice of analytical scales and levels, and attention paid to how they interact, can therefore have important implications for how systems are understood and subsequent management and policy decisions.

An added complexity is that different scales are often used to analyse the social and ecological 'sub-systems' of socioecological systems. Sociopolitical scales are frequently used to analyse the governance components of socioecological systems but have little relevance to ecological sub-systems. Equally the same type of scale can be applied to both social and ecological sub-systems but be broken down into very different relevant internal levels. The global spatial level may have relevance for both hydrological and social drivers. For example, atmospheric moisture flows and the UN SDGs can all be located at the global level. However, subsequent spatial levels like the river basin, river reach and riffle level lose their relevance for social drivers. Socioecological system theory recognises that the interactions between these components can nevertheless have important implications for system functioning and must be taken into account. Therefore, developing effective management strategies means identifying 'cross-scale' interactions that occur between the system drivers and processes that are analytically treated as existing across disparate scales and levels. (Gain *et al.*, 2021; Whaley, 2022; Bennett and Reyers, 2024; Moore *et al.*, 2024)

In integrated management approaches, the focus on the river basin as both the appropriate hydrological spatial level and governance level for management has often obscured the importance of multiple scales and levels for managing water (Benson, Gain and Giupponi, 2020; Moore *et al.*, 2024). As a result, integrated management practices have rarely achieved the alignment across sectors and levels of governance that were envisaged at their inception (de Loë and Patterson, 2017). The singular focus on the river basin level has been linked to a narrow application of the concept of spatial socioecological or institutional 'fit,' which proposes that the spatial extent of governance should match that of the ecological system to be governed. However, the concept does not prescribe a focus on a single scale or level and there is no one scale or level at which water must be managed in complex socioecological systems (M.-L. Moore et al., 2024; Moss, 2012; Young, 2002).

When considering the hydrological logic of the river basin spatial level alone, groundwater and infrastructures that facilitate inter-basin water transfers raise questions about the appropriateness of this boundary (Biswas, 2008; M.-L. Moore et al., 2024; Moss, 2012; Young, 2002). Researchers have also developed concepts like telecoupling and virtual water footprints, which are used to describe the impacts that activities in one location can have on distant water systems (Liu et al., 2013; M.-L. Moore et al., 2024). For example, telecoupling or virtual water footprints can be used to explain how meat consumption in Europe can drive the intensification of soya production, water use and water quality degradation in Brazil (Lun *et al.*, 2021).

Again, this challenges the focus on a single spatial level, as does the reality that river basin management must also be translated to spatial levels that are tangible and implementable by actors at multiple sociopolitical levels. This is demonstrated by the proliferation of plans and measures at increasingly small spatial levels after the development of WFD river basin management plans, down to the farm or field level that is of relevance for individual farmers (Moss, 2012; Newig, Schulz and Jager, 2016; Whaley, 2022). Management efforts formulated around hydrological spatial boundaries could therefore be strengthened by the better integration of scale concepts from socioecological systems theory. Paying greater attention to the significance of scale, cross-level and cross-scale interactions in water systems has the potential provide better insights into how disparate system components can be managed across scales to resolve critical water challenges (Bennett & Reyers, 2024; Gain et al., 2021; M.-L. Moore et al., 2024; Whaley, 2022)

Table 1.1: Definitions of terminology related to scale, as used in this paper. Many of these terms will be used in different ways across or even within different disciplines. However, in this work, the following definitions are used to avoid issues with conceptual conflation that continue to challenge discussions of scale in socioecological systems management

Term	Definition
Dimension	An aspect of an object of study like space, time or power etc. that can be structured using a particular scale e.g., space can be ordered using many different scales including hydrological (plot, catchment, river-basin) or jurisdictional scales (local, regional, national).[b]
Scale	A graduated reference system that is used to structure a particular dimension of an object of study for analysis e.g., a temporal scale. [ab]
Level	Differentiated units of analysis within a scale e.g., a jurisdictional scale may contain local, regional and national levels.[ab]
Scalar level	A unique level within a specific scale.
Extent	The proportion of a scale that an object or phenomenon occurs over e.g., the spatial extent of a river basin that experiences eutrophication.[b]
Resolution / grain	The smallest unit of change that is measured.[c]
Generalisation	The extrapolation of data, system analyses or solutions developed at one level to other levels.[d] Often referred to as upscaling or downscaling data.
'Right' scaling	Identifying the optimal scale level(s) for analysis, intervention or the magnitude of system throughputs.[d]
Upscaling / downscaling	The propagation of system change from one level to others e.g., P recovery as struvite is upscaled from a lab-based niche innovation to full-scale deployment in wastewater treatment plants (WWTPs).[e]
Outscaling	The extrapolation of data, system analyses or solutions developed for one system to another system[g]
Temporal scale and timeframe	Temporal scales are applied to break time into discrete increments, timeframes are the individual increments or levels within a temporal scale. E.g seconds, minute, hours. [b]
Spatial scale and spatial level	A spatial scale is applied to break the geographic extent of a phenomenon into spatial units or levels. E.g plot, farm, landscape. [b]
Organisation scale and organisational level	An organisational scale is applied to aggregates of individuals within networks and contains levels that are largely defined by the number of individuals. E.g individual, community and nation, or organism, population, biome.[f]
Sociopolitical scales and levels	A jurisdictional scale describes the organisation of governance structures into discrete units or levels that generally operate over a defined spatial extent and are often organised hierarchically. They can also be referred to as jurisdictional, governance or policy scales / levels.[a]

Sources: [a]Cash et al., 2006, [b]Vervoort et al., 2012, [c]Friis et al., 2023, [d]Gibson, Ostrom and Ahn, 2000, [e]Bögel et al., 2022, [f]Cumming et al., 2006, [g]Lam et al., 2020

1.1.3 Investigating the role of participation in facilitating systemic cross-scale management

Navigating multiple scales, cross-level and cross-scale dynamics is an essential feature of institutional fitness for water governance (Bennett & Reyers, 2024; Gain et al., 2021; M.-L. Moore et al., 2024; Whaley, 2022; Young, 2002). An important question to address is what role can participation play in achieving this ambition? Participation has increasingly been regarded as an important mechanism for democratising environmental management (Lawrence, Daniels and Stankey, 1997), as well as improving systems knowledge, developing more effective management strategies and increasing the social acceptance of measures. Consequently, participation is a fundamental feature of good governance in both socioecological systems theory and integrated water resource management (Han et al., 2024; Stringer et al., 2006; von Korff et al., 2012). Consequently, there has been an explosion of participatory and collaborative water governance organisations, not least of which are river basin organisations that have been initiated in response to the WFD. As these organisations and other more grassroots collaborative management organisations play an increasing role in water management, there is a need for them to successfully navigate socioecological cross scale dynamics as hubs for not only the development and implementation of on-the-ground measures, but also for social and political engagement (Amblard & Mann, 2021; Surridge et al., 2009). Participatory governance can be resource intensive and challenging to do well. While there are many successful examples of collaborative water management (Freak et al., 2023; Hasan et al., 2023), there are also many examples of participatory processes that failed to have meaningful outcomes. In many cases, these failures have been attributed to the unseriousness of participatory processes that exclude or marginalise non-powerful actors, were poorly designed, and/or had no real pathways for the outcomes to influence water management (Aleu et al., 2022; Benson et al., 2013, 2020; Moss et al., 2020; Seigerman et al., 2023). Therefore, as expectations for participatory processes and governance to navigate scales grow, it is essential to clarify whether and how participation can add value and how it can be done well.

1.1.4 Eutrophication: a case for participatory, systemic, cross-scale management?

Eutrophication offers an important focus for exploring issues of systemic cross-scale management of critical water challenges as an issue that is widespread, hugely damaging and remained intractable despite decades of policy effort.

Eutrophication occurs through the over-enrichment of water systems with phosphorus and nitrogen, and is a critical problem that impacts freshwaters, groundwaters and coastal regions worldwide (Luijendijk, Gleeson and Moosdorf, 2020; McDowell *et al.*, 2020; de Raús Maúre *et al.*, 2021). Different types of aquatic ecosystems vary in terms of whether nitrogen or phosphorus is typically their 'limiting nutrient', or the nutrient that determines the ceiling for maximum biomass production in that type of ecosystem. Freshwaters are typically phosphorus limited, while nitrogen is more commonly the limiting nutrient in estuaries and coastal systems. However, the limiting nutrient cannot be assumed for individual systems and may change over time; for example, in response to an emerging imbalance in one nutrient over the other (Howarth and Marino, 2006; Wilkinson, 2017).

The over-enrichment of aquatic ecosystems with nutrients, most notably nitrogen and phosphorus, can lead to a cascade of damaging environmental and social effects. The overgrowth of algae, including toxic cyanobacteria, which can impede the use of surface waters for both leisure and drinking water, cause illness and death in humans and other animals and have extremely detrimental impacts on aquatic ecosystems. A critical concern is the development of hypoxic conditions as algae die and decompose, consuming oxygen in the water and generating dead zones where other aquatic species are unable to survive (Carpenter *et al.*, 1998; Diaz and Rosenberg, 2008; Wurtsbaugh, Paerl and Dodds, 2019)

At European level, policy efforts aimed at mitigating eutrophication have been ongoing for over fifty years. Initial policy efforts targeted phosphorus from wastewater point sources, or nitrate from diffuse agricultural sources that both caused eutrophication and threatened human health. However, in the 1990s, the complexity and intractability of particularly diffuse contributors[ii] to eutrophication was the key impetus for the emergence of the 'integrated' water management, which have become embedded in policies across the world (Benson, Jordan and Smith, 2013; Allouche, 2017; Giakoumis and Voulvoulis, 2018).

Despite inspiring and being a central focus of integrated water resource management efforts, eutrophication has remained intractable and even intensified across the globe (Luijendijk, Gleeson and Moosdorf, 2020; McDowell *et al.*, 2020; de Raús Maúre *et al.*, 2021). The scope of the problem is global, hugely damaging, long-term and overwhelmingly human-driven (V. H. Smith & Schindler, 2009). Major inputs of both nitrogen and phosphorus come from human wastewater, agriculture and, in the case of nitrogen, the burning of fossil fuels (Morée *et al.*, 2013; Malone and Newton, 2020). In their global assessment of large river catchments McDowell et al., (2020) estimated that 31% are likely to affected by severe eutrophication, while Tigli et al., 2025 estimated that 44% of global lakes were eutrophic as of 2010. Over 700 eutrophic and/or hypoxic coastal zones have been identified around the world (World Resources Institute, 2011), and a recent assessment approximates that around 1.15 million km^2 of coastal zones are likely to be eutrophic (de Raús Maúre *et al.*, 2021). Holistic assessments of the impacts of eutrophication on ecosystem services are limited, but nevertheless demonstrate the significance of the impacts of eutrophication (Del Rossi *et al.*, 2023). Eutrophication of freshwaters is estimated to cost the US $2.2 billion yr^{-1} (Dodds *et al.*, 2009) and England and Wales $105−160 million yr^{-1} (Pretty *et al.*, 2003). A single harmful algal bloom (AB) in Chile in 2016 generated $800 million of US export losses through farmed fish deaths (Armijo *et al.*, 2020; Carias *et al.*, 2024), while the costs of eutrophication-driven lake methane emissions are predicted to cost $7.5–$81 trillion globally between 2015 and 2050 (J. A. Downing et al., 2021).

In response, there have been frequent calls for eutrophication to be treated as a multi-scalar, systemic problem and for management to be aligned across scales, which have yet to be answered

---

[ii] Diffuse sources of nutrients refer to losses to water that occur over a wide area like run-off and leaching from across the landscape. They are held in contrast to and harder to manage than point sources, which are concentrated sources that can be readily pinpointed like outlet pipes from wastewater treatment plants.

(Haygarth *et al.*, 2005; Chowdhury *et al.*, 2014; Metson *et al.*, 2015a; Rosemarin and Ekane, 2016a; Carlsen and Bruggemann, 2022). Developing an understanding of what this could look like in practice could therefore be extremely valuable for developing more effective management strategies for this intractable management problem. Furthermore, it could also contribute valuable insights into how scale and cross-level and cross-scale dynamics can be approached from a socioecological systems perspective and enrich integrated water resource management more broadly. At present, analyses of cross-scale interactions in 'integrated' and socioecological systems approaches to water management are often criticised for neglecting either the social or the ecological aspects of the system (Bennett and Reyers, 2024), and there is limited understanding of the relationships between system components across scales needed to support decision-making (Elsawah *et al.*, 2020; Dressler *et al.*, 2022). Therefore, there remains a need for further conceptual development and insights into how socioecological concepts of scale and cross-scale interactions can be applied in practice to support management efforts (Bennett & Reyers, 2024; M.-L. Moore et al., 2024; Whaley, 2022).

1.2 Research rationale, aim and objectives

In summary, integrated water management approaches have made significant steps forward in the management of water challenges as systemic socioecological problems. However, they have yet to deliver the hoped-for improvements in chemical and ecological status in water systems across the globe. A key problem has been the failure to embed socioecological systems principles that treat water systems as multi-scalar and multi-level, and critical water challenges like eutrophication as emerging from interactions across these levels and scales. There is a need for further conceptual development regarding the importance of scale(s) and how calls for 'cross-scale' management of catchments and water challenges can be meaningfully addressed as systemic socioecological problems. Naturally, the limited integration of systemic perspectives on scale and cross-scale interactions into integrated water management approaches mean that perspectives on how participation can contribute to cross-scale management are also missing. Expectations for water governance to be participatory have become increasingly mainstreamed; however, these processes are still often critiqued for being poorly designed, resource intensive and un-serious. Therefore, it is important to understand whether and how participatory approaches can best contribute to effective cross-scale governance of water.

To begin addressing these gaps, this thesis will explore how ambitions for catchment management to be (i) systemic, (ii) multi-scale and (iii) participatory can be realised in practice, with a focus on the mitigation of eutrophication. To explore this issue, I take two focuses. The first is the role of participation in the cross-scale analysis and management of eutrophication. This is explored through a case study of a eutrophic lake in Stockholm, Sweden and a conceptual paper based on a qualitative evidence synthesis literature review. The second is the role of collaborative catchment organisations and their potential to strengthen cross-scale management of water systems. This is investigated through a case study of four collaborative catchment partnerships in Scotland.

By taking these two focuses and using a mixed case study and literature-based conceptual approach, I aim to fulfil the following objectives and sub-objectives:

Objective 1 - Contribute to an interdisciplinary, systemic perspective on the significance of scale for the development of 'cross-scale' management of eutrophication as a critical water challenge:

- **1.1 –** Identify what 'scales' emerge as most relevant in the management of eutrophication as a socioecological problem. (**Chapter 2** and **3**)
- **1.2 –** Explore what can be gained from integrating multiple scale perspectives to understand eutrophic systems and their management. (**Chapter 3**)
- **1.3 -** Develop some key principles for cross-scale management of eutrophication from a socioecological perspective. (**Chapter 2**)

Objective 2 – Identify key contributions that participatory approaches can make to systemic cross-level and cross-scale management, by:

- **2.1** – Understand whether and how current collaborative efforts at the catchment level contribute to bridging scales in efforts to implement catchment management. (**Chapter 4**)
- **2.2 –** Assess whether and how participatory approaches can support the application of the key principles established in sub-objective **1.3** (**Chapter 2, 3** and **4**)

By achieving these objectives, the aim of this PhD is to generate insights on what it means to manage eutrophication across 'levels' or 'scales' when eutrophication is approached as a systemic socioecological problem. It also aims to establish the potential of participatory approaches to contribute to the understanding of scale, cross-level and cross-scalar dynamics and the successful establishment of systemic cross-scale eutrophication management. The conclusions drawn from this research will focus on the management of eutrophication and be necessarily place-based. However, the insights developed here will have relevance to systemic approaches to water resource management more widely.

1.3 Contribution of the research

Through achieving these objectives this thesis aims to make three types of contribution: (i) conceptual developments that are relevant to academic literature, (ii) the development of policy-relevant insights into participatory cross-scale management of eutrophication and, to a lesser extent, other critical water issues, and (iii) place-based, stakeholder relevant empirical insights as embedded participatory research.

This research contributes to the conceptual development of cross-scale management of eutrophication, and critical water issues more broadly, as systemic socioecological problems. This includes developing some fundamental principles for approaching the cross-level and cross-scalar management of eutrophication as a socioecological problem that are tangible and practicable. A key aspect of this acknowledging cross-level and cross-scale management as a dual issue for water management practitioners who must both develop 'scale sensitive' on the ground management strategies and address the 'scale challenges' of being embedded in a multi-level governance system. By doing so, the aim is to provide some guidelines to support the development of collaborative management organisations that are able to both develop management strategies that are aligned across relevant levels and scales, and are able to operate effectively in their given sociopolitical context. In addition, this thesis makes a conceptual contribution to the role of participation in water and socioecological systems governance by developing guidelines for how participation can meaningfully contribute to cross-scale governance of water challenges.

As well as constituting a theoretical contribution to academic literature on water governance, the principles for cross-scale management developed in this thesis may also prove useful to practitioners and policy-makers engaged in water management. However, this thesis also contributes place-specific, policy-relevant empirical insights into the cross-scale management of eutrophication. Namely, through the use of a case study approach, I developed place-based insights on the current status of management eutrophication and catchment health in Sweden and Scotland in both urban, rural and mixed contexts. I also developed recommendations for how collaborative cross-scalar governance of eutrophication can be done more effectively in these contexts.

Finally, as embedded participatory research, this research aimed to make a contribution that had value to the participants themselves. In the Swedish context, the research was initiated by an allotment garden association that were concerned about the links between allotment gardens and nutrient pollution in nearby lakes. Therefore, I conducted soil sampling and surveyed allotment gardener practices, to give them insights into their own practices and characteristics of their soils. This was useful for providing insights into the implications of the biogeophysical characteristics of the allotment sites and their management practices for nutrient losses. However, it was also useful information from a gardening perspective. By organising and facilitating workshops I also aimed to foster connections between stakeholders across sociopolitical levels to increase engagement around the role of allotment gardens in urban sustainability. Finally, I provided stakeholder-relevant reporting to provide on the ground insights into nutrient issues and management efforts. Similarly, in the Scottish context, I contributed to the characterisation of nutrient issues in catchment through water sampling, catchment characterisation and run-off risk evaluation. This research will also result in stakeholder-relevant reporting of interview results on the strengths and weaknesses of current catchment partnerships and potential next steps from the perspective of participants.

1.4 Timeliness of the research

After ~35 years of integrated water management and relatively little to show for it, some authors perceive a sense of 'integration fatigue' and advocate for a change in approach (Giordano and Shah, 2014; Allouche, 2017; Gain *et al.*, 2021; Whaley, 2022). They point to practical challenges involved in operationalising and implementing integrated water management, echoing early critics that referred to it as a 'nirvana concept' that presents an idealised management paradigm that is impossible to realise in practice (Biswas, 2008; Molle, 2008). They suggest newer concepts like the water-food-energy nexus and adaptive governance as possible alternatives that may offer a way forward (Giordano and Shah, 2014; Benson, Gain and Rouillard, 2015). However, at this juncture, there are several reasons to instead make efforts to address some of the underlying conceptual issues of integrated water management and how it treats scale specifically.

The first are its usefulness as a socially and politically embedded boundary object (Molle, 2008) and its conceptual fuzziness. 'Integrated' management drove an important break from the reductive water management paradigms that came before. It has since become an important shared touchstone or 'boundary object' that has mobilised researchers and practitioners and been deeply embedded in policy worldwide (Molle, 2008; Pahl-Wostl *et al.*, 2011; Bilalova, Newig and Villamayor-Tomas, 2025). A core critique of integrated water management is that its conceptual 'fuzziness' allows it to be co-opted and acts as barrier to its implementation (Molle, 2008; Benson, Gain and Giupponi, 2020). However, the same fuzziness may offer scope for addressing its underlying conceptual issues, including inadequate conceptualisations of scale, cross-level and cross-scale dynamics. The final reason is that many of the alternative systemic approaches also suffer from weak conceptualisations of scale, cross-level and cross-scale dynamics. Therefore, they are likely to suffer from some of the same challenges if these conceptual problems are not addressed (Benson, Gain and Rouillard, 2015; Whaley, 2022).

Furthermore, many of these other 'holistic' or 'systemic' water management approaches, including Nexus approaches and adaptive management, have their roots in socioecological systems thinking and have a commitment to participatory water governance. Consequently, they may also benefit from stronger perspectives on the systemic, participatory cross-scale governance of eutrophication. Achieving the better integration of scale concerns into the management of eutrophication and water resources more broadly may help to break the stalemate that characterises water management at all levels (Syed, Choudhury and Islam, 2020).

1.5 Thesis structure

Chapter 1 has established the rationale, aims and objectives of this research, rooted in a review of the literature. The remainder of this thesis is structured as follows. **Chapter 1** outlines the research paradigm this work is situated in, the research approach, methodology and ethical considerations. **Chapter 1** conducts an interdisciplinary integrative literature review to develop a framework for the systemic, participatory cross-scale management of eutrophication drawn from a literature-based synthesis. The next two chapters present case studies that offer empirical insights into the how participation can contribute to the systemic cross-scale management of eutrophication and catchments more broadly. **Chapter 3** presents a case study of eutrophication management as part of the implementation of the WFD in Stockholm, Sweden. It conducts a participatory analysis to identify the significance of scale, cross-level and cross-scale dynamics for eutrophication management from the perspective of practitioners. **Chapter 4** consists of a case study of four catchment partnerships in Scotland, UK. This case instead applies the concepts developed in **Chapter 1** to explore the role of participatory catchment partnerships in supporting the cross-scale management of catchment challenges more broadly. **Chapter 4** concludes the thesis, drawing together the key findings of the research and outlining some of its broader implications for theory, policy and practice. This chapter also outlines some research limitations and suggests some future research directions.

2 Research paradigm, approach and methods

In this chapter I give an overview of the critical realist research paradigm this thesis is aligned with (**Chapter 2.1**), and how this informed the primarily qualitative research approach based on a participatory case study methodology (**Chapter 2.3, 2.4, 2.5**). It then discusses the ethical considerations relevant to this research and how they were addressed (**Chapter 2.6**). A detailed description of the application of the different methods can be found in the individual empirical chapters (**Chapter 3.3, 4.3, 5.4**).

2.1 Research paradigm

This research is situated in the critical realist paradigm. Critical realism has not been extensively applied to human-environmental systems research. However, several authors have argued that it has value as an ontological and empirical framework for interdisciplinary research at the interface between people and the environment (Bhaskar *et al.*, 2010; Price, 2014; Danermark, 2019; Cockburn, 2022; Longo, Isgren and Carolan, 2025). The fundamental perspective of critical realism is that there exists a reality that is independent of human perceptions of it (ontological realism), and that while human knowledge of reality cannot be separated from my own perceptions and experience (epistemological constructivism), this knowledge can be more or less close to the underlying 'truth' of reality (Bhaskar, 2013).

In the critical realist paradigm, reality is conceptualised as consisting of three 'domains': the empirical, the actual and the real. Real events occur (the actual domain) as a result of underlying laws or mechanisms (the real domain) independently of human perception. Humans can experience and investigate these events and their underlying mechanisms to generate knowledge that is more or less reflective of their reality. However, my knowledge of events and underlying laws in the empirical domain is fundamentally and irrevocably shaped by my characteristics as both an individual and an agent embedded in a broader social system. Consequently, my knowledge of the object of study falls somewhere between the objective and the subjective and is a conversation between the features of the object of study and the characteristics of the subject or observer (Bhaskar *et al.*, 2010; Price, 2014; Danermark, 2019; Cockburn, 2022; Longo, Isgren and Carolan, 2025). Knowledge is always partial and is considered 'true' when it is believed to adequately reflect reality, based on whether it seems to be logically coherent and whether it stands the test of practice and experience over time (Proctor, 1998; Bhaskar, 2013).

Under critical realism, multi-scalar socioecological systems theory attempts to describe real underlying mechanisms of phenomena like the emergence of eutrophication. This is essential to provide a basis for developing tangible measures for addressing problems. However, it also provides the scope for acknowledging that any systems descriptions are always filtered through a social lens (Longo, Isgren and Carolan, 2025). Consequently, they are only partial models that are generated as a conversation between the reality being represented and social factors that include human cognition, their needs and even political goals. This is extremely important to recognise when moving from theory to practice, particularly in participatory research, as there may be many different perspectives on what is 'legitimate' systems knowledge. I can see this challenge reflected in the formulation of so-called 'wicked' challenges, which are not just defined by their perceived complexity. Their 'wickedness' also arises from the multiple stakeholders that must be involved to address them, all of whom may have different perspectives on the problem, its causes or its potential solutions (Danermark, 2019; L. Price & Lotz-Sisitka, 2015). Consequently, as a researcher working under the critical realist paradigm, while I aim to produce knowledge about real underlying causal mechanisms, I acknowledge that my production and interpretations of research data will be constitutive of both my positionality and that of my research participants. Therefore, I will strive to be reflexive and evaluate how characteristics like my personal history, disciplinary background and normative commitment to environmental goals may impact my research (Moore and Kelly, 2024).

2.1.1 Scale in critical realism and coupled human-environmental systems

In critical realism, scale has been an important focus in core writings by Roy Bhaskar, Leigh Price and Berth Danermark on interdisciplinary research on human-environmental systems (Bhaskar *et al.*, 2010; Price, 2014; Danermark, 2019). In addition to its division into three 'domains', reality is further understood as 'stratified' or divided into 'levels' according to their distinct characteristics. For example, an organism is made of cells, which are made of molecules, which are made of atoms and so on. In this stratified system, dynamics at higher order levels emerge from, but also influence lower order levels. Critical realism therefore offers us an ontological and epistemological framework that can accommodate centuries of socioecological systems knowledge that has developed and used scale(s) as an organising principle. Critically, it does so while leaving room to acknowledge that the construction and application of scales can (1) be uncritical and unsuitable for understanding and addressing systemic socioecological challenges, and (2) be strongly influenced by aspects other than the system itself, including the desire to achieve other social goals including the redistribution of responsibility or power (Moss and Newig, 2010; Newig and Moss, 2017). It therefore offers us a powerful bridge between two essential aspects of the socioecological systems literature on scale: (1) the use of scale as an important framework for understanding socioecological system dynamics (the actual and real domains) and (2) the critique of how scale concepts are applied in society why, including how they are used for political ends (the empirical domain).

This thesis therefore draws on critical realism as a valuable framework for the interdisciplinary integration that has been called for in socioecological systems research on scale (Manson, 2008; Friis *et al.*, 2023). In line with the tenets of critical realism and socioecological systems theory, the definition of relevant scales and levels for systems analysis, key drivers and their interactions across levels and scales can be more or less strongly linked to underlying system properties. Their definition can be significantly influenced by social factors; for example, resource constraints can define the temporal or spatial resolutions of monitoring rather than what would ideally suit the characteristics of the system (Enloe, Schulte and Tyndall, 2017). However, they can be more closely reflect underlying system properties (in the real domain) through the appropriate application of scientific methods (Bhaskar, 2013; Järvinen and Mik-Meyer, 2020). This means that I have to take seriously the different approaches to and types of scale that have been used across disciplines to study and explain system properties. However, I also need to approach them critically and not assume that particular scales or levels are best used to analyse and develop strategies for addressing socioecological problems a priori. A key challenge of conducting this kind of interdisciplinary integration has been diverse and unclear understandings of scale and use of scale terminology (**Table 2.1**).

In the literature, terms like 'scale' and 'level' are often used interchangeably, however, they are conceptually different (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Vervoort *et al.*, 2012). In this study, I draw on the conceptual understanding outlined by Vervoort et al., (2012), to define a scale as a conceptual framework that is used to structure analysis of objects of study according to certain dimensions (e.g time, space, power or interconnectedness), which may be used alone or in some combination to define a scale. Levels within a scale are then used to demarcate where there is expected to be a significant change in observed characteristics (Gibson, Ostrom and Ahn, 2000; Vervoort *et al.*, 2012). For example, the use of cover crops over the winter months may be a significant driver in reducing nutrient losses over the timeframe or temporal level of a year. However, over a timeframe of decades or centuries the conversion of forest to arable land can dominate as a driver of nutrient losses in a watershed. Consequently, the choice of applied scale and level of focus means deciding which dimensions and dynamics to analyse and which to exclude (Gibson, Ostrom and Ahn, 2000). This is a necessary process to a certain extent. However, when analysing multi-faceted, complex systems it is important to recognise that the delineation of a scale, or levels within a scale for the purpose of analysis neither implies that these are the only possible scales and levels that could be important, nor that they are isolated from each other (Cash *et al.*, 2006; Buizer, Arts and Kok, 2011; Vervoort *et al.*, 2012).

Therefore, when developing eutrophication management strategies, it is necessary to consider interactions across and between the applied scales that contribute to the behaviour of the system overall (Hewett *et al.*, 2009; Moss and Newig, 2010; Chowdhury *et al.*, 2014; Hüesker and Moss, 2015; Rosemarin and Ekane, 2016b). For example, cross-level interactions mean dynamics at lower levels can contribute to those at higher scales, as I can see from critical source areas that contribute disproportionately to the eutrophication of a larger catchment in a hydrological scale (Pionke, Gburek and Sharpley, 2000; Doody *et al.*, 2012). Equally, cross-scale interactions mean that disruptions to global trade in mined phosphorus or industrially produced nitrogen fertilisers (typically observed at a global sociopolitical level) can contribute to lower nutrient losses at the hydrological level of the field, by driving lower applications of mineral fertiliser by an individual farmer (Zou, Zhang and Davidson, 2022).

Table 2.1: Definitions of terminology related to scale, as used in this thesis. Many of these terms will be used in different ways across or even within different disciplines. However, in this work, the following definitions are used to avoid issues with conceptual conflation that continue to challenge discussions of scale in socioecological systems management

Term	Definition
Dimension	An aspect of an object of study like space, time or power etc. that can be structured using a particular scale e.g., space can be ordered using many different scales including hydrological (plot, catchment, river-basin) or jurisdictional scales (local, regional, national).[b]
Scale	A graduated reference system that is used to structure a particular dimension of an object of study for analysis e.g., a temporal scale. [ab]
Level	Differentiated units of analysis within a scale e.g., a jurisdictional scale may contain local, regional and national levels.[ab]
Scalar level	A unique level within a specific scale.
Extent	The proportion of a scale that an object or phenomenon occurs over e.g., the spatial extent of a river basin that experiences eutrophication.[b]
Resolution / grain	The smallest unit of change that is measured.[c]
Generalisation	The extrapolation of data, system analyses or solutions developed at one level to other levels.[d] Often referred to as upscaling or downscaling data.
'Right' scaling	Identifying the optimal scale level(s) for analysis, intervention or the magnitude of system throughputs.[d]
Upscaling / downscaling	The propagation of system change from one level to others e.g., P recovery as struvite is upscaled from a lab-based niche innovation to full-scale deployment in wastewater treatment plants (WWTPs).[e]
Outscaling	The extrapolation of data, system analyses or solutions developed for one system to another system[g]
Temporal scale and timeframe	Temporal scales are applied to break time into discrete increments, timeframes are the individual increments or levels within a temporal scale. E.g seconds, minute, hours. [b]
Spatial scale and spatial level	A spatial scale is applied to break the geographic extent of a phenomenon into spatial units or levels. E.g plot, farm, landscape. [b]
Organisation scale and organisational level	An organisational scale is applied to aggregates of individuals within networks. Contains levels that are defined by the number of individuals. E.g individual, community and nation, or organism, population.[f]
Sociopolitical scales and levels	A jurisdictional scale describes the organisation of governance structures into discrete units or levels that generally operate over a defined spatial extent and are often organised hierarchically. They can also be referred to as jurisdictional, governance or policy scales / levels.[a]

Sources: [a]Cash et al., 2006, [b]Vervoort et al., 2012, [c]Friis et al., 2023, [d]Gibson, Ostrom and Ahn, 2000, [e]Bögel et al., 2022, [f]Cumming et al., 2006, [g]Lam et al., 2020

2.2 Research approach and methodology

In critical realism, both quantitative and qualitative research methods have value for unfolding causal mechanisms of phenomena. Quantitative methods can be useful for identifying regularities that persist across cases. However, quantitative methods alone are considered insufficient for explaining phenomena that are deeply dependent on contextual factors that are usually excluded in experimental research. Qualitative methods are then essential for developing causal explanations of systems dynamics that understands them as inseparable from a given context (Maxwell and Mittapalli, 2010; Zachariadis, Scott and Barrett, 2013). This thesis therefore takes a mixed-methods approach, primarily based in qualitative methods. Further, I take participation as a fundamental component of my research approach. This is in line with the principles of both critical realism and socioecological systems theory, which both support participation as a legitimate and valuable method for both understanding and governing systems. In both critical realism and socioecological systems research, human experience and reflexivity means that their perceptions of socioecological systems can be an important piece of evidence in identifying underlying system mechanisms. Furthermore, both perspectives hold that, from a practical and normative standpoint, participation can lead to governance approaches that are both more effective and more socially just (Rollason *et al.*, 2018; Järvinen and Mik-Meyer, 2020).

I use two complimentary approaches to address my research objectives. The first is a participatory case study approach, used in **Chapter 3** and **Chapter 4,** which is appropriate for identifying context-specific causal mechanisms underlying challenges to cross-scalar management (Maxwell and Mittapalli, 2010; Zachariadis, Scott and Barrett, 2013; Yin, 2018). The case studies were based on interviews (**Chapter 3** and **4**), workshops (**Chapter 3**), document analysis (**Chapter 3** and **4**) and some quantitative characterisation of catchment challenges (**Chapter 3** and **4**) as boundary objects for stimulating discussions (Star, 1989). The second is a literature-based qualitative evidence synthesis to facilitate the identification of more general principles for improving cross-scale management as a systemic socioecological problem. The explanation of causal mechanisms in critical realism relies on a combination of deductive, inductive, abductive and retroductive reasoning (**Table 2.2**). These forms of reasoning inform the thematic analysis approach used to analyse qualitative data across **Chapters 3**,**4** and **4**.

Table 2.2: The types of reasoning used to explain underlying contextually dependent causal mechanisms in critical realism.

Deductive reasoning	Formulating a hypothesis about a relationship or pattern and generating observations to test the hypothesis.
Inductive reasoning	Identifying patterns and relationships based on observations.
Abductive reasoning	Generating provisional causal theories to explain patterns and relationships based on incomplete observational data
Retroductive reasoning	Incorporates deductive, inductive and abductive reasoning to refine causal theories that incorporate their contextual contingency. This can enable their transposition to other appropriate contexts.

Derived from Mukumbang et al., (2021) and Gilmore et al., (2019).

2.3 Qualitative evidence synthesis

This thesis aimed to propose some general principles for approaching the cross-scale management of eutrophication from a systemic (**Objective 1**), participatory perspective (**Objective 2**). I conducted an integrative literature review in **Chapter 1** to synthesise evidence from across highly interdisciplinary literature to identify what 'scales' emerge as most relevant in the management of eutrophication as a socioecological problem (**Objective 1.1**), suggest some key principles for cross-scale management of eutrophication from a socioecological perspective (**Objective 1.3**), and assess whether and how participatory approaches can support the application of the principles for cross-scale management (**Objective 2.2**). This synthesis was conducted based on the recognition that different methods and disciplinary perspectives may be appropriate for studying different aspects of socioecological systems (Danermark, 2019). However, these require integration to address cross-scale systemic management as more than the sum of its parts (Liu *et al.*, 2016; Danermark, 2019). As a first step, there is value in identifying and integrating fragmented insights across disciplines that can contribute to the development of a systemic perspective on cross scale management (Torraco, 2005; Bandara and Syed, 2023).

Literature selection proceeded according to the principles of integrative reviews, I (i) included relevant empirical, theoretical and review literature across disciplines (ii) used consistent and transparent Boolean search terms, (iii) applied explicit eligibility criteria in title, abstract and full text screening, and (iv) systematically coded relevant themes in the literature to improve the traceability of derived insights. These principles are also importance for reducing bias in literature selection and improves the transparency and reproducibility of the insights generated in the research (Torraco, 2005; Bandara and Syed, 2023).

2.4 Participatory qualitative case-study

In addition to using qualitative evidence synthesis approach to develop a framework for participatory cross-scale management, two participatory qualitative case studies were conducted in **Chapter 3** and **4**. **Chapter 3** involved a case study of the management of eutrophication in Stockholm, Sweden. **Chapter 4** focused on participatory catchment management organisations in Scotland, UK. Case study approaches are appropriate when attempting to understand real life causal dynamics where it is not necessarily possible or desirable to attempt to isolate the phenomena of interest from its context. The in-depth empirical insights provided by case study approaches can be highly useful to that specific context. Furthermore, case studies can be useful for testing and refining concepts and theories (Maxwell and Mittapalli, 2010; Zachariadis, Scott and Barrett, 2013; Yin, 2018). A qualitive case study approach was therefore highly appropriate for developing an interdisciplinary, systemic perspectives on the participatory ‘cross-scale’ management of eutrophication as a critical water challenge (**Objective 1** and **2**). This is because a case study approach allows the development of useful, context-specific empirical insights into the importance of scale (**Objective 1.1**), the impacts of cross-scale dynamics (**Objective 1.2**) and the contribution of participation to management in the case study contexts (**Objective 2.1** and **2.2.**). These empirical insights could then be used to support the evaluation of the heuristics developed in **Chapter 1** for understanding the underlying mechanics of the development of eutrophication and other catchment challenges (Mukumbang, Kabongo and Eastwood, 2021). In the case of these two case studies, this means evaluating how taking an integrative approach to cross-scale dynamics can contribute to improved systems understandings and management (**Objective 1.2**), as well as how participation can contribute to cross-scale management (**Objective 2.1** and **2.2.**). Insights can be drawn from the case studies in **Chapter 3** and **4** themselves. These insights can then be enriched by discussing the results of the two case studies alongside those developed through the qualitative evidence synthesis presented in **Chapter 1** (Gilmore *et al.*, 2019).

Water quality challenges and eutrophication are fairly ubiquitous, meaning that a wide variety of case studies could have reasonably been selected. The cases selected in this thesis were chosen partially due to the research interests and connections of the partners involved in the HO2020 Marie Skłodowska-Curie Actions Doctoral Network that funded this PhD. However, both the case studies were further selected due to (1) ongoing efforts to translate WFD river basin management plans to management efforts targeting smaller spatial levels, and (2) the significant stakeholder engagement around the issue of catchment management across sociopolitical levels in the case study context. This offered a unique opportunity to look at the issue of eutrophication management from a multi-scalar and participatory perspective. In Stockholm, the participatory aspect was convened by the researchers to gain insights into cross-level and cross-scale system dynamics. In the context of Scotland, the case studies were selected to gain insights into more formal collaborative / participatory water governance organisations and their role in cross-level and cross-scale management. Catchment partnerships were selected that varied in their characteristics and local contexts, while operating under the same national political system. This was done to better identify the commonalities and variations in the ways that the catchment partnerships functioned (or failed to function) as participatory bridging organisations for the systemic cross-scale management of catchments.

Data collection in the case studies occurred through three methods: interviews (Chapter 3 and 4), documentary analysis (Chapter 3 and 4), and workshops (Chapter 3),. In each case, these sources were seen as key evidence that could be used in tandem to understand underlying system dynamics (Maxwell, 2012; Yin, 2018). Documentary analysis was used to improve familiarity with the case study contexts. This included identifying key actors, existing analyses of catchment issues and their drivers, and current management efforts. Documentary sources included legislation, policy statements, and organisational strategy documents, described in detail in Chapter 3 and Chapter 4. However, the lived experiences and expertise of actors involved in implementing eutrophication and catchment management were seen as fundamental to developing the grounded and practical insights and recommendations that are the ambition of this thesis. Consequently, Interviews and workshops provided the foundations of this research. Participant selection followed the selection criteria outlined in Chapter 3 and Chapter 4; however, participants can be broadly described as those engaged in the management efforts under investigation. In Chapter 3, this meant actors engaged in management activities relevant to eutrophication, while in Chapter 4, the focus was on actors participating in collaborative catchment management. These types of practitioners were selected in anticipation that they will have wider insights into relevant dynamics as active participants in management (Manzano, 2016; Pawson & Tilley, 2001).

Semi-structured interviews were used in both cases to gain participants individual experiences and perspectives to synthesise insights in-line with the research objectives. In both case studies, this involved eliciting participants' understandings of problems, drivers and challenges to successful management in the given context. However, in Chapter 4 interview questions ultimately focused in on these issues in relation to catchment partnerships. Workshops were then used in Chapter 3 to explore the cross-scale and cross-level dynamics that emerged in-situ during active discussions of a novel case for the management of eutrophication.

2.5 Thematic analysis

Data from interviews (Chapter 3 and Chapter 4), workshops (Chapter 3) and literature (Chapter 1) were all analysed using a thematic analysis approach (Braun and Clarke, 2022). Thematic analysis was selected because it supports both deductive and inductive approaches to data while also encouraging the development of overarching themes and theory development informed by existing concepts, frameworks and heuristics. Consequently, thematic analysis is highly compatible with a critical realist approach to systems analysis (Mukumbang, Kabongo and Eastwood, 2021; Proudfoot, 2023)

The thematic analysis was guided by both my overarching research aims and the objectives pursued by the individual chapters. The thematic analysis process followed the six-phase method outlined by Braun and Clarke (2022): (i) familiarising myself with the data through processes like transcription and initial reading, (ii) conducting initial coding of the data to systematically capture meaningful features of the data, (iii) grouping initial codes into overarching themes according to patterns of meaning, (iv) reviewing and editing themes and codes, (v) defining the final themes, and (vi) synthesising the developed themes into a coherent narrative that addressed the overarching research questions (Braun and Clarke, 2022). Coding and the development of themes was conducted both inductively (developed from the data) and deductively (applied according to externally developed conceptual frameworks). These two approaches were combined to ensure that the data analysis addressed the research objectives and made best use of previous conceptual work (deductive), while also allowing codes and themes to emerge naturally from the data that might challenge preconceptions (inductive). The use of this hybrid type approach to thematic analysis can also contribute to more robust analyses (Proudfoot, 2023).

2.6 Research ethics

Chapter 3 and **Chapter 4** both involved human participants; therefore, it was necessary to conduct a risk assessment, develop a data management plan and conduct an ethical review. The ethical review was conducted in-line with the requirements of the Environment and LUBS (AREA) Faculty Research Ethics Committee, and was approved (application reference: AREA 19-118). The project was designated as very low sensitivity; therefore, the primary concerns were participant consent, pseudonymisation and the handling of personal data.

The project involved the use of participant personal data for their identification and contact for research purposes. Participant personal data was store only on password protected and encrypted computers or locked offices in the appropriate research institution, according to the relevant data protection laws. For UK-based participants this was the University Leeds, UK according to the standards in the Data Protection Act. For Swedish participants, this was the University of Linköping, Sweden according to GDPR standards. Participants were pseudonymised during their participation in workshops and in any research data, which was stored separately to personal data.

Voluntary, informed consent was obtained from all participants prior to research activities via the provision of a participant information sheet and consent form. It was made clear to participants that participation was entirely voluntary, and that had the right to withdraw consent for their personal data to be stored at any point, and for their research data to be destroyed up until a named date, 30 days after it was collected. Furthermore, I explained that while there were not anticipated to be any major risks involved in participating in the project, there was a small chance that they will be identifiable by others during workshop participation or from their pseudonymised research data. No concerns were raised by participants; however, this would have led to changes in research reporting. Consent was further confirmed verbally ahead of any interviews after a verbal explanation of the project and their rights regarding their personal and research data.

3 Bridging scales for systemic eutrophication management: principles, challenges and the role of participation

3.1 Abstract

Eutrophication remains an intractable problem despite decades of management efforts and a significant evolution in management towards systemic, and participatory approaches to water governance. A critical factor is that it remains unclear how ambitions to manage eutrophication 'across scales' can be achieved in practice. This paper takes a step towards this goal by developing a framework for the participatory 'cross-scale' management of eutrophication as a systemic socioecological challenge. Through an interdisciplinary integrative literature review I develop a purpose-driven approach that conceptualises cross-scale eutrophication management as the management of interacting multi-level and multi-scale sub-systems of direct and indirect social, ecological and technological drivers. Based on this conceptualisation, I define three cross-scale management concerns: (i) developing on-the-ground management strategies that are coordinated across spatial and temporal scales to mitigate eutrophication across these scales, (ii) aligning indirect social, political and economic drivers across levels and scales to favour implementation and (iii) ensuring that these cross-scale indirect drivers are responsive to conditions in the eutrophic water system and contribute to positive ecological outcomes across scales. I finally outline tangible principles for how these cross-scale management goals can be approached and the role that participation can play in their successful implementation. This paper therefore provides a roadmap for achieving the systemic, participatory management of eutrophication across scales that is frequently advocated for, but has yet to be accomplished.

3.2 Introduction

The use of synthetic inorganic nitrogen and mined phosphorus fertilisers was foundational to the green revolution that transformed my agricultural systems and supported rising populations (Ashley, Cordell and Mavinic, 2011). However, it has also driven widespread ecological damage and negative social and economic impacts through eutrophication. Eutrophication has been the focus of research and policy efforts for several decades; however, despite significant reductions in phosphorus and nitrogen inputs from wastewater sources, the eutrophication of surface waters remains widespread across the globe (Richardson *et al.*, 2023). The key question is therefore, why have management efforts largely failed and how can they be improved?

To explore this problem, I approach eutrophication as an emergent property of a socioecological system and focus on two key claims of what 'good' management of eutrophication as a systemic socioecological problem should look like (Hillman, 2009; Thornton *et al.*, 2013). The first is the claim that eutrophication must be managed collaboratively and that participatory approaches to governance should be prioritised. This is foundational to integrated catchment management approaches and has been embedded in policy instruments across the world (Ferrier and Jenkins, 2009; Donoso and Bosch, 2015; Giakoumis and Voulvoulis, 2018; Vieira *et al.*, 2020), including as a fundamental part of Sustainable Development Goal (SDG) 6, "Ensure availability and sustainable management of water and sanitation for all" (Carlsen and Bruggemann, 2022). The second claim is that management efforts need to be implemented and aligned across spatial, temporal and governance 'scales' to achieve the systemic transformations necessary to address eutrophication (key scale terminology given in **Table 3.1**.) Again, this principle is embedded in the SDGs as SDG target 6.5, "By 2030, implement integrated water resources management at all levels" (Haygarth *et al.*, 2005; Chowdhury *et al.*, 2014; Metson *et al.*, 2015a; Rosemarin and Ekane, 2016a; Carlsen and Bruggemann, 2022). Participation and multi-scalarity therefore appear frequently as pillars of successful mitigation of eutrophication; however, there is limited work that explicitly looks at (i) what cross-scale management means from a systemic socioecological perspective and (ii) whether and how participation can support cross-scale management of eutrophication in practice (Brils *et al.*, 2014; Royer *et al.*, 2020). Addressing this gap can be an essential step forward for developing effective strategies for mitigating the ubiquitous eutrophication of surface waters.

I aim to develop a framework for participatory cross-scale management of eutrophication from socioecological perspective by conducting a synthesis of existing interdisciplinary approaches to the cross-level or cross-scale management of eutrophication. Despite a lack of explicit perspectives on their interplay in eutrophication management, participation and scale have been important themes in mitigating nutrient losses for many years. Therefore, reviewing the current state of knowledge is an appropriate first step towards developing participatory, cross-scale approaches to eutrophication management. Using a qualitative evidence synthesis approach, I first develop some key principles for the cross-scale management of eutrophication based on scale sensitive systemic understandings. Drawing on this literature, I then formulate recommendations for where participation can play an important role in implementing these principles for successful cross-scale management. I ultimately aim to lay the foundations for the development of systemic integrated perspectives on cross-scale and participatory management that can support practitioners in managing eutrophication effectively.

Table 3.1: Definitions of terminology related to scale, as used in this paper. Many of these terms will be used in different ways across or even within different disciplines. However, in this work, the following definitions are used to avoid issues with conceptual conflation that continue to challenge discussions of scale in socioecological systems management

Term	Definition
Dimension	An aspect of an object of study like space, time or power etc. that can be structured using a particular scale e.g., space can be ordered using many different scales including hydrological (plot, catchment, river-basin) or jurisdictional scales (local, regional, national).[b]
Scale	A graduated reference system that is used to structure a particular dimension of an object of study for analysis e.g., a temporal scale. [ab]
Level	Differentiated units of analysis within a scale e.g., a jurisdictional scale may contain local, regional and national levels.[ab]
Scalar level	A unique level within a specific scale.
Extent	The proportion of a scale that an object or phenomenon occurs over e.g., the spatial extent of a river basin that experiences eutrophication.[b]
Resolution / grain	The smallest unit of change that is measured.[c]
Generalisation	The extrapolation of data, system analyses or solutions developed at one level to other levels.[d] Often referred to as upscaling or downscaling data.
'Right' scaling	Identifying the optimal scale level(s) for analysis, intervention or the magnitude of system throughputs.[d]
Upscaling / downscaling	The propagation of system change from one level to others e.g., P recovery as struvite is upscaled from a lab-based niche innovation to full-scale deployment in wastewater treatment plants (WWTPs).[e]
Outscaling	The extrapolation of data, system analyses or solutions developed for one system to another system[g]
Temporal scale and timeframe	Temporal scales are applied to break time into discrete increments, timeframes are the individual increments or levels within a temporal scale. E.g seconds, minute, hours. [b]
Spatial scale and spatial level	A spatial scale is applied to break the geographic extent of a phenomenon into spatial units or levels. E.g plot, farm, landscape. [b]
Organisation scale and organisational level	An organisational scale is applied to aggregates of individuals within networks and contains levels that are largely defined by the number of individuals. E.g individual, community and nation, or organism, population, biome.[f]
Sociopolitical scales and levels	A jurisdictional scale describes the organisation of governance structures into discrete units or levels that generally operate over a defined spatial extent and are often organised hierarchically. They can also be referred to as jurisdictional, governance or policy scales / levels.[a]

Sources: [a]Cash et al., 2006, [b]Vervoort et al., 2012, [c]Friis et al., 2023, [d]Gibson, Ostrom and Ahn, 2000, [e]Bögel et al., 2022, [f]Cumming et al., 2006, [g]Lam et al., 2020

3.3 Methods

3.3.1 Literature selection

I conducted an integrative literature review to critically synthesise principles for integrating scale and participation in the management of eutrophication. In-line with the principles of integrative reviews, I (i) included relevant empirical, theoretical and review literature across disciplines (ii) used consistent and transparent Boolean search terms, (iii) applied explicit eligibility criteria in title, abstract and full text screening, and (iv) systematically coded relevant themes in the literature to improve the traceability of derived insights. This approach facilitates the integration of insights across disciplines relevant to systemic eutrophication management that are currently fragmented. Applying these principles also reduces bias in literature selection and improves the transparency and reproducibility of the insights generated in the research (Torraco, 2005; Bandara and Syed, 2023).

The literature search was performed in Scopus due to its broader coverage of social science literature than Web of Science, and better support of transparent and reproducible Boolean search terms in comparison to Google Scholar (Gusenbauer and Haddaway, 2020; Pranckutė, 2021). The search strings were constructed to capture 4 aspects: (1) a topic focus on addressing eutrophication in fresh waters, (2) a conceptualisation of water sustainability challenges as systemic, (3) a further conceptualisation of water sustainability challenges as cross-scale, and (4) a focus on participatory approaches to water management. For the first search string, key words (using the OR function) were chosen to capture relevant terms for water in the landscape, including both types of water body (e.g. lake) and hydrological boundary descriptors (e.g. lake). These were selected to include a broad range of research focused on mitigating eutrophication, while excluding research that did not focus on real-world management; for example, laboratory studies. This search string also included (using an AND function) a requirement to include eutrophication as a topic focus, including named nutrients to broaden the literature captured. The second search string was derived from a review of the literature of systemic perspectives on environmental problems, and included socioecological systems theory, the closely related coupled human and natural systems, sociotechnical systems and combined perspectives. The third search string was based on discussions of scale terminology in Cash et al., (2006) and Gibson et al., (2000), in recognition of the conceptual conflation between 'cross-level' and 'cross-scale' interactions that have been noted in research on human-environmental systems. The final search string used generic terms for participation, while also including some terms for management approaches from a preliminary review of the literature that had participation as a core feature. Wildcards and quotation marks were used where deemed appropriate to both ensure the inclusion of relevant literature and exclude spurious results.

Initial identification of the literature was conducted using the "participation and scale focused" search string (Table 3.2) to identify how these two aspects were currently being integrated in systemic eutrophication management literature. This search resulted in only 9 papers containing the required terms in their titles, abstracts or keywords, demonstrating that their integration is under-explored in this literature. This is a significant result in and of itself (i.e. there is extremely limited literature looking at the two aspects together); however, I developed two further search strings: "scale focused" and "participation focused" (Table 3.2) to broaden the body of literature identified, in order to (i) perform full text screening to identify further instances where participation and scale were addressed simultaneously and (ii) develop insights into how scale and participation can be integrated by critically evaluating how both scale and participation are currently approached separately. The Boolean searches using the search strings resulted in a total of **130** publications. Title, abstract and full text screening were then conducted to further exclude literature according to the criteria also outlined **Table 3.2.**

The retained literature totalled **50** publications. Full text screening led to the re-categorisation of 22 papers that were identified as solely concerned with scale in the initial literature search, as considering both scale and participatory approaches. In these cases, while participation may not have been focus of the study, it was nevertheless discussed as important to the process of managing eutrophication.

Table 3.2: Literature search strings, inclusion / exclusion criteria and resulting literature count before and after full text screening.

Literature group	Literature search strings	Inclusion criteria	Count Before	Count After
Participation and scale focused	(Catchment OR watershed OR "river basin" OR river OR lake OR stream OR "surface water" OR groundwater) AND (nutrient* OR phosphor* OR nitr* OR diffuse OR eutrophic*) AND (socioecological OR socioecological OR socialecological OR social-ecological OR social-technical-ecological OR socioecological-technical OR social-technical OR socio-technical) AND ("integrated catchment management" OR "catchment-based approach" OR participatory OR participation OR transdisciplinar* OR "engagement") AND (scales OR *scaling OR levels OR multilevel OR multiscale OR multi-level OR multi-scale OR multi-scalar OR "multiple levels" OR "multiple scales" OR cross-scal*)	Conceptual, theoretical, empirical or review paper. Acknowledges eutrophication as a systemic problem with heterogeneous elements. AND Uses a participatory and multi-level or multi-scalar approach. OR Discusses the role of participation in scale integration. OR Discusses the importance of scale in collaborative approaches to eutrophication management.	9	28
Scale focused	(Catchment OR watershed OR "river basin" OR river OR lake OR stream OR "surface water" OR groundwater) AND (nutrient* OR phosphor* OR nitr* OR diffuse OR eutrophic*) AND (socioecological OR socioecological OR socialecological OR social-ecological OR "coupled human and natural system" OR "CHANS" OR social-technical-ecological OR socioecological-technical OR social-technical OR socio-technical) AND (scales OR *scaling OR levels OR multilevel OR multiscale OR multi-level OR multi-scale OR multi-scalar OR "multiple levels" OR "multiple scales" OR cross-scal*)	Conceptual, theoretical, empirical or review paper. Acknowledges eutrophication as a systemic problem with heterogeneous elements. AND Uses a multi-level or multi-scalar approach. OR Discusses importance of scale(s) or levels in eutrophication management.	99	15
Participation focused	(Catchment OR watershed OR "river basin" OR river OR lake OR stream OR "surface water" OR groundwater) AND (nutrient* OR phosphor* OR nitr* OR diffuse OR eutrophic*) AND (socioecological OR socioecological OR socialecological OR social-ecological OR social-technical-ecological OR socioecological-technical OR social-technical OR socio-technical) AND ("integrated catchment management" OR "catchment-based approach" OR participatory OR participation OR transdisciplinar* OR "engagement")	Conceptual, theoretical, empirical or review paper. Acknowledges eutrophication as a systemic problem with heterogeneous elements. AND Uses participatory methods. OR Analyses a participatory or collaborative partnership. OR Discusses the role of participation and collaboration in eutrophication management.	22	7
			130 total	50 total

3.3.2 Thematic analysis

I then conducted a thematic analysis of the retained literature (Braun and Clarke, 2022), following the process in **Figure 3.1**, which had two distinct phases. The first phase derived key principles for the cross-scale management of eutrophication. The second phase, identified some ways that participation can support the application of these key principles for cross-scale management.

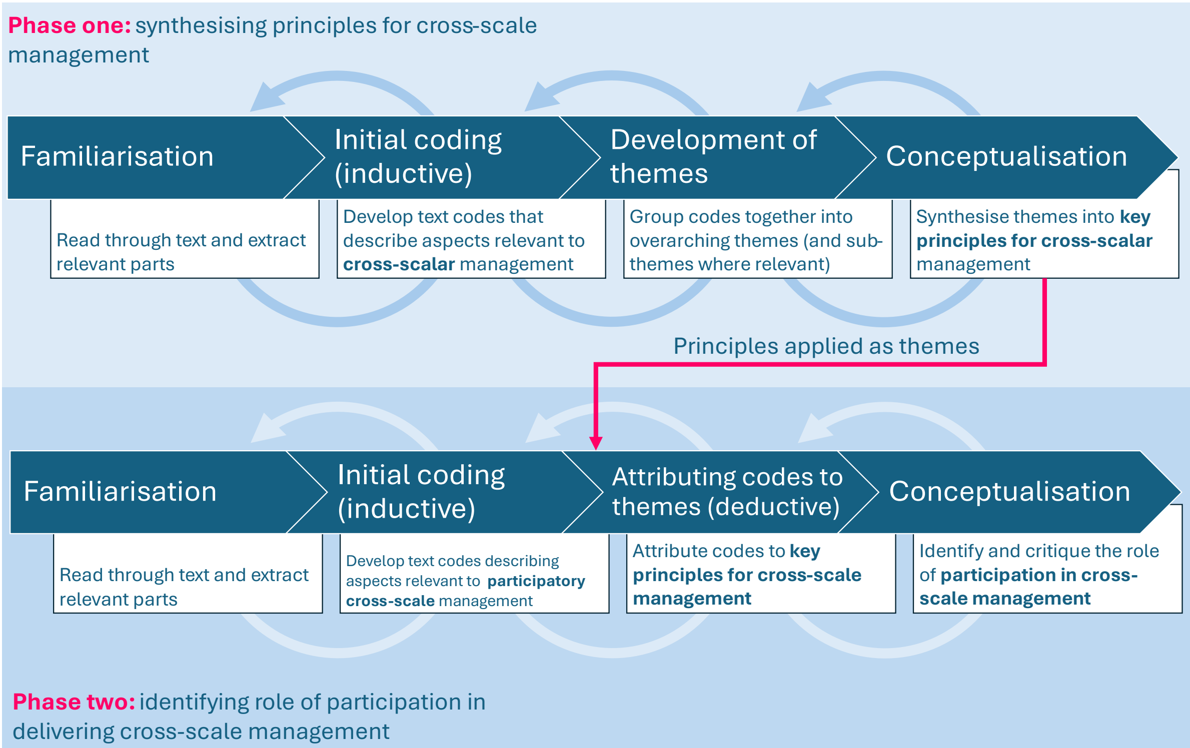


Figure 3.1: *The phases and process of the systematic thematic analysis methodology used to (i) synthesise principles for cross-scale eutrophication management and (ii) identify the role of participation in successfully applying them.*

In the first phase, initial codes were developed inductively that described the significance of scale for eutrophication management in the data, these were then grouped into sub-themes and themes to identify patterns of meaning and relationships between codes. These themes were then synthesised into principles for the cross-scale management of eutrophication, according to whether the drivers addressed were direct, indirect or both types in interaction. This process is illustrated in **Figure 3.2**: An illustration of the derivation of the principles for cross scale management. Codes were generated to describe the problematisations of scale in the literature. These initial codes were grouped into sub-themes that encapsulated an overarching scale challenge in eutrophication management. The type of driver and type of scale addressed informed the grouping into sub-themes, and were further used as categories that supported the final synthesis of the sub-themes into the overarching principle for cross scale management. Consequently, while this process is presented as linear, it should be noted that the coding process was iterative and as important themes emerged, the research data was revisited and recoded to investigate themes more strongly.. In the second phase, again, relevant text was coded inductively to identify key contributions of participation to eutrophication management.

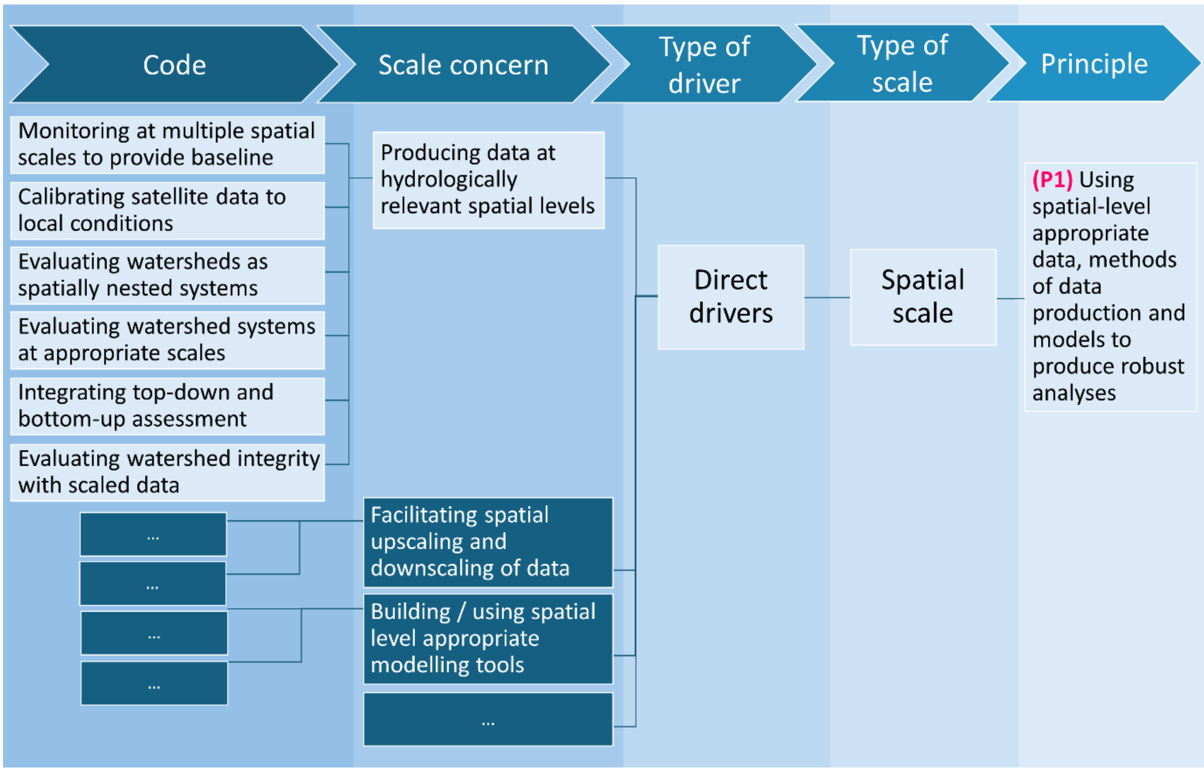


Figure 3.2: An illustration of the derivation of the principles for cross scale management. Codes were generated to describe the problematisations of scale in the literature. These initial codes were grouped into sub-themes that encapsulated an overarching scale challenge in eutrophication management. The type of driver and type of scale addressed informed the grouping into sub-themes, and were further used as categories that supported the final synthesis of the sub-themes into the overarching principle for cross scale management. Consequently, while this process is presented as linear, it should be noted that the coding process was iterative and as important themes emerged, the research data was revisited and recoded to investigate themes more strongly.

However, grouping the codes according to themes was top-down and deductive, using the principles for cross-scale management that were derived in the first phase. Codes were grouped according to whether they represented a potential contribution of participation to the implementation of a given principle for cross-scale management. For example, the code "Increasing spatial resolution of monitoring through citizen's science" was grouped with the principle (principle 1) "Using spatial-level appropriate data, methods of data production and models to produce robust analyses."

3.4 Results and discussion

My results and discussion section is divided into three parts, according to three primary approaches to managing eutrophication 'across scales' that I derived from the literature: the management of direct drivers **(section 3.1)**, indirect drivers **(section 3.2)** and interacting direct and indirect drivers **(section 3.3)**. Direct drivers and processes are those that directly constitute or impact a given eutrophic socioecological system; for example, surface run-off, landcover, fertiliser and wastewater inputs and soil management. These types of drivers were solely analysed using temporal and spatial scales in the reviewed literature. Indirect drivers and processes impact eutrophication more diffusely. Central in the literature reviewed here were indirect drivers that influenced human action, including regulation, market dynamics, technological change, values and attitudes. However, there were some 'ecological' drivers, particularly changes in climate, that could readily be classified as indirect based on the reviewed literature. Sociopolitical and temporal scales were the primary scales used to analyse these types of drivers; however, both spatial and organisational scales were also relevant. The interactions between direct and indirect drivers define how more diffuse contextual influences could manifest in direct impacts on eutrophication, perhaps most notable by influencing direct human drivers. For example, the impact of policies on farmer soil management practices or the impact of algal blooms on attitudes to management interventions. A representation of the different relevant scales and levels, and the interactions between direct and indirect drivers is provided in **Figure 3.3**. The distinction I make between the direct and indirect mirrors that established by the Millennium Ecosystem Assessment (Nelson *et al.*, 2006). However, it diverges in the respect that the framework developed here does not take direct and indirect to be synonymous with 'ecological' and 'social' respectively. This reflects discourses in the integrated water management and socioecological systems literature that critique the arbitrary and persistent treatment of the social and ecological as siloed, and emphasise the significance of non-local and more indirect drivers. (Liu *et al.*, 2013; Schlüter *et al.*, 2019; Hertz, Mancilla Garcia and Schlüter, 2020; Bennett and Reyers, 2024).

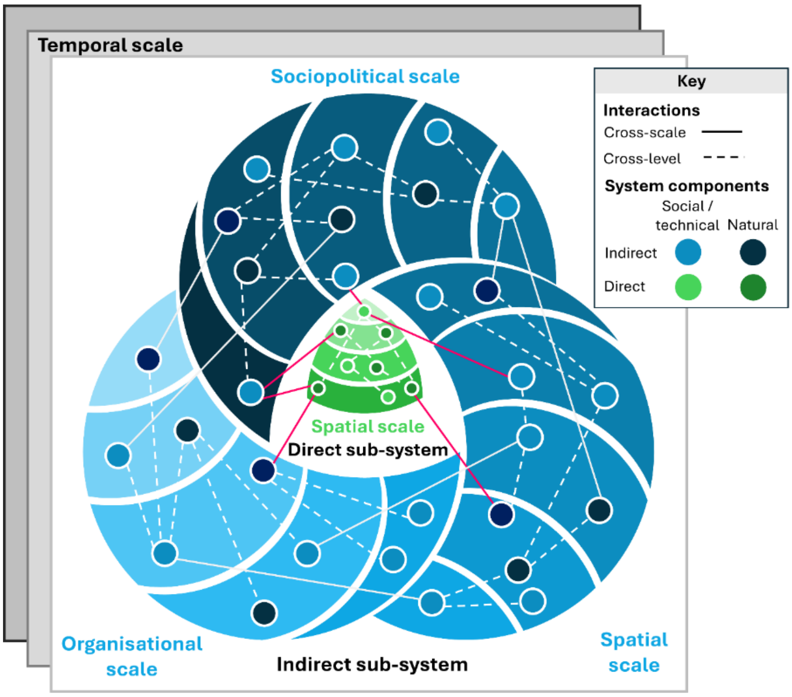


Figure 3.3*: A representation of the scales, cross-level and cross-scale interactions that have important implications for the successful management of eutrophication. We distinguish between two sub-systems: the 'direct sub-system' (in green) and the indirect sub-system (in blue).*

Distinguishing between the direct and indirect has significance for cross-scalar management because direct and indirect drivers are approached in different ways, for different purposes. Direct drivers and processes are generally the focus when developing on-the-ground management strategies, whereas indirect drivers and processes are primarily important for understanding contextual constraints and developing a social context that favours their development and implementation. Different scales are typically used to analyse the direct and indirect systems in the literature. Direct drivers are typically analysed using spatial and temporal scales, while sociopolitical scales are dominant it in analyses of indirect system drivers. Cross-level and cross-scale interactions are typically analysed within the direct or indirect sub-systems, analyses of cross-scale interactions between the direct and indirect systems are limited. Nevertheless, understanding both their internal cross-level and cross-scale interactions, and the cross-scale interactions between the two sub-systems is essential. Otherwise, it is not possible to develop governance and management that has the necessary responsive to both the

Table 3.3: Summary of characteristics of reviewed literature

Theme	Sub-Theme	Number of papers
Type of paper	Empirical	34
	Conceptual / theoretical or methodological development	7
	Review	9
Geographic focus	Africa	5
	Asia	2
	Europe	10
	North America	15
	Oceania	1
	South and Central America	1
Waterbody type	River (whole watershed)	20 (18)
	Lake (whole watershed)	13 (3)
	Sub-catchment	6
	Groundwater	4
	Estuary	1
	Coastal / oceanic	5
	International waterbodies	9
Issues addressed in addition to eutrophication	None (eutrophication only)	9
	Nitrates	7
	Harmful algal blooms	4
	Biodiversity	3
	Sediment	3
	Soil health	2
	Climate change	2
	Drinking water	3
	Drought / water scarcity	2
	Flooding	1
	Fisheries	1
	Nutrient recycling	1
	Pesticides	3
	Other water quality parameters	8
	Ecosystem services	4
	Holistic assessment of pressures	4
Type of driver addressed	Direct	39
	Indirect	33
	Interacting direct and indirect	22

direct and indirect drivers of eutrophication and for developing management strategies that are both technically effective and socially feasible (Rounsevell *et al.*, 2021).

In each section, I first synthesise principles for the effective management of eutrophication across scales, according to whether they consider direct or indirect drivers, or the interactions between both types. I then discuss the potential of participatory governance processes to contribute to the application of the identified principles, highlighting where this issue remains unexplored or further research is needed.

3.4.1 Principles for the participatory cross-scale management of direct drivers

I identified 5 principles for approaching the management of the direct drivers of eutrophication across spatial scales (**Table 3.4**). Firstly, the specificity of hydrological processes to particular spatial levels and the significance of 'emergent' system properties means that managing eutrophication across spatial levels requires data, methods of analysis and models that are appropriate to a given spatial level **(principle 1)**. For example, indicators of ecosystem integrity like macroinvertebrates at the river reach level may not be appropriate for assessment at the river-basin level. Instead, emergent properties like hydrologic regulation that were imperceptible at the river reach level may be more appropriate indicators. The same spatial specificity of process and emergent system properties mean that it is important to develop management strategies based on an understanding of multiple spatial levels and their interactions **(principle 2)**. The significance of different drivers of eutrophication may vary across spatial scales, which deeply impacts what pressures are identified and to how management strategies are spatially targeted **(principle 2i)**. To illustrate, while an assessment of pressures at catchment level may identify agricultural land as a key source of nutrient load, analysis at the smaller spatial levels may allow the pinpointing of farms that make a disproportionate contribution (Yoder, Chowdhury and Hauck, 2020). Evaluating at multiple spatial levels can also can allow the better targeting of management strategies **(principle 2ii)**, including wetlands whose efficacy is affected by topography at the watershed level and soil properties at the site level. Multi-spatial-level analysis can also identify the interactions between drivers and processes across spatial levels, which is particularly critical for evaluating the impact of management interventions **(principle 2iii)**. Approaches to the management of eutrophication increasingly emphasise the need to link site and farm level implementation of measures to catchment-level change, as governance and management of water systems focuses increasingly on achieving watershed-level outcomes. Integrating knowledge of different spatial levels is essential for ensuring that management implemented across spatial levels is aligned **(principle 3)** to achieve water quality goals across spatial levels **(principle 4)**. The implementation of the WFD demonstrates the importance of this process. Management scenarios that formulated at the basin-level must be downscaled to smaller spatial levels for the development of tangible and implementable measures. These plans in turn must not solely address more local-level concerns, but also result in positive outcomes for the river basin level. Therefore, efforts need to be made to understand how measures can be aligned across spatial levels to address both sets of concerns. The management of eutrophication places specific demands on both water and land is managed across spatial levels, which can deeply impact other ecosystem services and vice-versa. Consequently, it is necessary to develop management strategies that are conscious of the links between eutrophication and other ecosystem services across spatial levels. By doing so it can be possible to increase synergies and minimise trade-offs between the management of eutrophication and other ecosystem services. For example, by understanding how methods to improve soil health can have synergies with reducing nutrient losses to water, or understanding where the spatial demands of particular land or water uses mean they cannot co-exist **(principle 5)**.

Temporal scales received less attention than spatial scales in the reviewed literature and the implications of temporal level specificity for managing eutrophication were less well explored. Nevertheless, I identified 6 principles for managing direct drivers across temporal scales **(Table 3.4)**. In the reviewed papers, managing eutrophication across temporal scales requires the use of data, methods of data production and models that have the appropriate temporal resolution and extent to identify direct drivers of eutrophication that operate over different timeframes **(principle 6).** For example, monitoring data at yearly interval can obscure important seasonal variation in direct drivers of eutrophication and the impacts of event-driven nutrient losses. Analysing systems over various timeframes is therefore extremely valuable for identifying both the 'fast' and 'slow' direct drivers **(principle 8),** and the interactions between that are key contributors to eutrophication **(principle 9).** This understanding can then be used inform management efforts; for example, by identifying how long term changes like land-use and climate change could confound management efforts that focused solely on 'faster' drivers like fertiliser applications. Monitoring over at adequate resolution over longer timescales could illuminate how changes in conditions could affect the efficacy of planned interventions over time **(principle 10)**, in response to seasonal changes, climate change and maintenance efforts. Understanding this temporal variation in efficacy can improve capacity to manage eutrophication adaptively, and change management strategies as key direct drivers change. For example, by identifying where management approaches like lake aeration based on destratification may have changed the mechanism of internal phosphorus loading and require a new management approach. One author also highlighted the importance of analysing the temporal variation in relationships between drivers and processes relevant to eutrophication and those of other ecosystem functions **(principle 11)**.

Understanding these relationships can be important for establishing how benefits, synergies and trade-offs of managing for any one ecosystem service may vary over timeframes.

Table 3.4: Principles for the management of direct drivers of eutrophication across spatial levels and timeframes synthesised through thematic analysis of the reviewed papers.

Principle		Theme (count)	Reference
Principle 1: Using spatial-level appropriate data, methods of data production and models to produce robust analyses.		Producing data at hydrologically relevant spatial levels (13)	(Birhanu et al., 2019; Flotemersch et al., 2016; Gebrehiwot et al., 2021; E. F. Jones et al., 2021; König et al., 2021; McCluney et al., 2014; Mosquera et al., 2023; Shan et al., 2023; Shupe, 2017; E. D. Smith et al., 2021; van der Laan et al., 2017; Yevenes et al., 2022)
		Facilitating spatial upscaling and downscaling of data (5)	(A. S. Downing et al., 2014; Flotemersch et al., 2016; Jessel & Jacobs, 2005; Qiu et al., 2018; Royer et al., 2020)
		Developing and using spatial level appropriate modelling tools (3)	(Shan et al., 2023; E. D. Smith et al., 2021)
		Monitoring measures at appropriate spatial levels to support evaluation (2)	(Daroub *et al.*, 2011; van der Laan *et al.*, 2017; Yoder, Chowdhury and Hauck, 2020)
Principle 2: Informing strategy development with multi-spatial level analysis	**Principle 2i:** Understanding variation in primary drivers of eutrophication and their relationships across spatial levels to facilitate strategy development.	Understanding multiple relevant spatial levels (7)	(Le Maitre *et al.*, 2007; Enloe, Schulte and Tyndall, 2017; Berkowitz *et al.*, 2020; Royer *et al.*, 2020; Zimnicki *et al.*, 2020; Singh *et al.*, 2021; Tschikof *et al.*, 2024)
		Identifying key drivers and processes at different spatial levels (7)	(Jessel & Jacobs, 2005; Le Maitre et al., 2007; Shortle et al., 2020; Siegmund-Schultze et al., 2018; Singh et al., 2021; E. D. Smith et al., 2021; Yoder et al., 2020)
		Identifying spatial-level dependent relationships (3)	(Qiu et al., 2018; Singh et al., 2021; E. D. Smith et al., 2021)
	Principle 2ii: Evaluating conditions at multiple scales for the effective siting of measures.	Informing strategy development with multi-spatial level analysis (3)	(Brils *et al.*, 2014; Berkowitz *et al.*, 2020; Zammali *et al.*, 2021)
	Principle 2iii: Understanding how changes in drivers, processes and interventions at one spatial level can result in changes at other spatial levels	Targeting measures spatially (2)	(Shortle *et al.*, 2020; Smith, Balika and Kirkwood, 2021)
		Understanding interactions between direct drivers across spatial levels (5)	(Amblard & Mann, 2021; Booth et al., 2016; A. S. Downing et al., 2014; McCluney et al., 2014; Zimnicki et al., 2020)
		Recognising emergent behaviour in watershed systems (1)	(Flotemersch *et al.*, 2016)
Principle 3: Integrating knowledge of different spatial levels to align management across levels.		Integrating knowledge of multiple spatial levels (5)	(Brils *et al.*, 2014; Birhanu *et al.*, 2019; Berkowitz *et al.*, 2020; Zimnicki *et al.*, 2020; Tschikof *et al.*, 2024)
		Managing synergistically across spatial levels (4)	(Jessel and Jacobs, 2005; Qiu *et al.*, 2018; Siegmund-Schultze, Köppel and Sobral, 2018; Royer *et al.*, 2020)
Principle 4: Ensuring that any measures deliver water quality goals at all relevant spatial levels.		Evaluating measures at multiple spatial levels (3)	(Oenema *et al.*, 2010; Daroub *et al.*, 2011)
		Evaluating combinations of measures at relevant spatial levels (4)	(Oenema *et al.*, 2010; McCluney *et al.*, 2014; Shortle *et al.*, 2020; Zammali *et al.*, 2021)
Principle 5: Informing management approaches with knowledge of interactions between drivers and processes relevant to eutrophication and those of other ecosystem functions across spatial levels.		Understanding relationships between ecosystem services across spatial levels (3)	(Qiu et al., 2018; E. D. Smith et al., 2021; Zimnicki et al., 2020)
Principle 6: Using data, methods of data production and models that have the appropriate temporal resolution and extent for the driver or process of interest to be observed.		Monitoring at adequate temporal resolutions to understand impacts of event transfers (3)	(Dietrich and Funke, 2009; McGonigle *et al.*, 2014; König *et al.*, 2021)
		Monitoring at adequate temporal resolutions and extents to identify temporal variation in drivers (1)	(Shupe, 2017)
		Monitoring at adequate temporal resolutions and extents to identify temporal variations in BMP efficacy (1)	(Zammali *et al.*, 2021)
		Monitoring measures at adequate temporal resolutions and extents to link management efforts and water quality impacts (2)	(McGonigle *et al.*, 2014; Yoder, Chowdhury and Hauck, 2020)
		Modelling at appropriate temporal resolutions and extents (1)	(Shan *et al.*, 2023)
Principle 7: Understanding how the primary drivers and processes of eutrophication, and the relationships between them, differ across timeframes.		Identifying major drivers and processes across different timeframes (2)	(A. S. Downing et al., 2014; McGonigle et al., 2014)
		Understanding co-evolution of drivers over time (3)	(Schönach *et al.*, 2018; Siegmund-Schultze, Köppel and Sobral, 2018; Siman and Niewiarowski, 2023)
		Understanding impact of short-term variation in key drivers (1)	(Siegmund-Schultze, Köppel and Sobral, 2018)
		Understanding the impacts of long-term variation in key drivers (2)	(Schönach *et al.*, 2018; Siegmund-Schultze, Köppel and Sobral, 2018)
Principle 8: Identifying cross-level interactions or how changes in drivers and processes observable at one temporal level can impact those observable at other levels		Identifying cross-temporal level interactions including between 'fast' and 'slow' drivers and legacy effects (4)	(McCluney *et al.*, 2014; Yoder, Chowdhury and Hauck, 2020; Siman and Niewiarowski, 2023)
Principle 9: Evaluating how changes in conditions over time can affect the efficacy of interventions.		Understanding impacts of temporal variation in biophysical drivers on BMP efficacy (2)	(Daroub *et al.*, 2011; Zammali *et al.*, 2021)
		Understanding impacts of maintenance on BMP efficacy over time (1)	(Yoder, Chowdhury and Hauck, 2020)
Principle 10: Managing adaptively in response to changes in key drivers over time		Adapting management to changes in drivers (1)	(Schönach *et al.*, 2018)
Principle 11: Determining the temporal variation in relationships between drivers and processes relevant to eutrophication and those of other ecosystem functions.		Understanding changes in synergies and trade-offs between ecosystem services across timeframes (2)	(Qiu *et al.*, 2018; Siegmund-Schultze, Köppel and Sobral, 2018)

Participatory approaches were largely used to overcome difficulties accessing or generating the data and knowledge needed to develop multi-scalar systems understandings (Flotemersch *et al.*, 2016; Yoder, Chowdhury and Hauck, 2020; Zimnicki *et al.*, 2020; Gebrehiwot *et al.*, 2021; Singh *et al.*, 2021; Shan *et al.*, 2023). A synthesis of the contribution that participation can make to systemic cross-scale management is given in **Figure 3.4**. Consequently, participatory approaches could support the application of all of the identified principles of the cross-scalar management of direct drivers by overcoming difficulties **(principle 1, 6)** obtaining data at relevant spatial levels and timeframes, and at adequate resolutions. However, the role of participation was only discussed further in relation to management across spatial scales, and its contribution to cross-temporal scale management was neglected.

At the most basic level, collaborations between organisations across sociopolitical levels with landowners, and farmers at the local-level are important for obtaining the access to land needed to obtain relevant data (Berkowitz et al., 2020; Jetoo, 2018; McGonigle et al., 2014; Sigler et al., 2018; A. Smith & Stirling, 2010). Collaboration between public and private actors across sociopolitical levels can also leverage the resources needed to implement monitoring at higher spatial and temporal resolutions (Enloe et al., 2017). However, the key contribution of participatory water management groups like demonstration farms and catchments, watershed management groups and citizen's science initiatives is the active production of knowledge (Enloe et al., 2017; Gebrehiwot et al., 2021; E. F. Jones et al., 2021; König et al., 2021; Shupe, 2017; A. Smith & Stirling, 2010; E. D. Smith et al., 2021; Wuijts et al., 2021; Yevenes et al., 2022).

Citizen or community science can allow **(principle 1**, **6)** higher spatial and temporal resolution of water sampling (Jones et al., 2021; König et al., 2021; Shupe, 2017; Smith et al., 2021; Wuijts et al., 2021), as well as increasing the spatial and temporal extent of coverage beyond typical government monitoring at low spatial and temporal resolutions (Gebrehiwot et al., 2021; König et al., 2021; Shupe, 2017). Community science was typically seen as a tool for building high resolution knowledge of a small area with high relevance to landowners, rather than as an alternative to official sampling regimes (König et al., 2021). However, citizens science can be particularly important where official government sampling did not exist or was inadequate (Gebrehiwot et al., 2021; König et al., 2021; Yevenes et al., 2022).

Through participatory forums, participants could also directly contribute their existing knowledge of direct drivers of eutrophication, particularly at the catchment and smaller spatial levels (Brils et al., 2014; Jetoo, 2018; Kastens & Newig, 2008; McGonigle et al., 2014; Royer et al., 2020; Tschikof et al., 2024). Coupling higher-spatial-level analysis with stakeholder engagement at smaller spatial levels can **(principle 2i)** improve understandings of how key drivers may differ across those levels. For example, the participation of farmers can be important for contributing evaluations of nutrient loss-risk and drivers at farm, field and sub-field spatial levels, identifying hotspots and drivers that may not be perceptible from higher level analyses (Jessel and Jacobs, 2005; McGonigle *et al.*, 2014; Sigler *et al.*, 2018; Royer *et al.*, 2020). Collaboration between farmers and other organisations across sociopolitical levels can **(principle 2ii)** support the identification of opportunities for mitigation through supplying access to sites and providing experiential knowledge. They can **(principle 2iii)** also allow the evaluation of farm-level mitigation efforts on catchment-level water quality by supporting the implementation of monitoring that can link farm-level interventions with catchment-level water quality changes (Berkowitz et al., 2020; Enloe et al., 2017; Jetoo, 2018; Kastens & Newig, 2008a; McGonigle et al., 2014; E. D. Smith et al., 2021). Engagement of farmers at the catchment level can also generate knowledge on current management practices (Royer *et al.*, 2020), which has been highlighted as an important knowledge gap for understanding how interventions at farm level can result in water quality outcomes at higher spatial levels (Daroub *et al.*, 2011). The multi-level knowledge that can be produced through participation is an important resource for aligning management across spatial levels. By ensuring that **(principle 3)** differences between system dynamics at higher spatial levels and lower ones are highlighted, **(principle 4)** participation can contribute to the implementation of management that delivers water quality goals across spatial levels (Enloe et al., 2017; König et al., 2021; E. D. Smith et al., 2021; Zammali et al., 2021)

Participatory approaches can also be an important resource for understanding eutrophication management in relation to other ecosystems services (Siegmund-Schultze, Köppel and Sobral, 2018; Zimnicki *et al.*, 2020; Tschikof *et al.*, 2024). Evaluations of ecosystem services at large spatial levels can be important for harmonisation across administrative boundaries, while local-level, participatory evaluations of ecosystem services can capture the heterogeneity of how these services are perceived and experienced at smaller spatial levels. By supporting analysis of the dynamics between ecosystem services related to eutrophication and others at the local level, participatory **(principle 5)** evaluations can support the development of management processes that are both aligned across spatial levels and cognisant of any trade-offs between ecosystem services (Tschikof *et al.*, 2024). The contribution of participatory approaches to the alignment of management across scales and between ecosystem services can be strengthened by moving beyond instrumental participation whereby governmental or academic actors use the produced data to produce management scenarios independently of participants. Representative participatory processes where stakeholders contribute directly to the development and evaluation of multi-spatial-level management scenarios offer the opportunity to develop more context-specific and feasible measures, informed by local stakeholder knowledge. (Jessel and Jacobs, 2005; Royer *et al.*, 2020; Tschikof *et al.*, 2024).

3.4.2 Principles for the participatory cross-scale management of indirect drivers

I synthesised 11 principles for managing indirect drivers across sociopolitical scales **(Table 3.5)**. This group of papers focused on largely social drivers of eutrophication that, unlike changes in management practices, did not directly impact nutrient dynamics. Indirect drivers instead impacted rates of adoption and implementation of measures, which represent fundamental challenges to the mitigation of eutrophication now that pathways of nutrient loss are better understood, and management options have been developed (Yoder, Chowdhury and Hauck, 2020).

There were two primary focuses when it came to the management of indirect drivers of eutrophication across scales or levels: (i) the drivers across levels in a multi-level governance system that impact its effective internal functioning for the mitigation of eutrophication as a policy goal (Folke *et al.*, 2007; Ostrom, 2009; Partelow, 2018), and (ii) those affecting farmer engagement in environmental or management schemes. Comparatively few papers explored drivers outside of changes in governance or agricultural practices like variations in cultural values, demographics, diets, markets or technological and infrastructural change. For example, few papers highlighted the links between energy system change and eutrophication even where policy and market changes incentivise land-use change to produce biofuels (Enloe, Schulte and Tyndall, 2017; Siman and Niewiarowski, 2023). The limited exploration of the relationships between broader indirect drivers and decision-making across scales can be considered a research key gap (J. A. Downing et al., 2021; McCluney et al., 2014).

Governance systems were generally conceptualised as containing multiple levels that are hierarchically spatially nested (e.g international, national, regional). In some cases, this included governance levels that are formulated around the spatial extent of hydrologically relevant levels, most notably the river-basin level in the implementation of the EU's Water Framework Directive (WFD). In these cases, cross-scale or cross-level management involves ensuring that sociopolitical drivers distributed across these levels are aligned to facilitate the successful implementation of policies for addressing eutrophication. Firstly, by **(principle 12)** ensuring that policy targeting eutrophication is coherent across policy levels by identifying key policy drivers and addressing mismatches, this includes **(principle 13)** identifying interactions between different areas of policy and addressing mismatches to establish policy coherence[iii] across sectors, across all governance levels. In addition to coordinating horizontally across policy sectors, implementing effective governance means **(principle 14)** aligning across adjacent or overlapping jurisdictions within governance levels. Aligning across jurisdictions can be important for aligning across both sectors and space. For example, by aligning across the governing organisations of EU member states to mitigate eutrophication in a shared river basin.

A critical question for developing coherent and effective multi-level governance systems for addressing eutrophication is where the decision-making power to develop policy instruments and management strategies should reside. For many of the papers reviewed here, successful governance across levels requires the effective **(principle 15)** blending of top-down and collaborative, bottom-up governance to achieve the implementation of policy as real-world measures. This process can involve; **(principle 15i)** the use of a wider variety of policy instruments, including market-based instruments, or **(principle 15ii)** integrating devolved decision making across multiple sociopolitical levels with top-down regulation and enforcement. Integrating the two approaches was seen to gain benefits of bottom-up approaches like improved buy-in and adaptation to local conditions, while responding to the so-far limited success of voluntary approaches to reducing diffuse nutrient losses. Achieving this integration meant **(principle 15iii)** Developing approaches for both integrating knowledge, priorities and actions across governance levels. Of critical importance is ensuring that local knowledge and needs are fed to higher governance levels to ensure that any higher-level policies, including regulations, incentives and strategies are sensitive to local conditions and/or provide the flexibility to adapt policy implementation to realities at the local level. **(principle 16)** Ensuring that the processes for integrating the priorities of actors across governance levels into higher level policy are transparent and accountable can both build credibility and improve buy-in and implementation. Facilitating this process and ensuring the effective operation of multi-level governance systems overall, means **(principle 17)** developing adequate capacity across relevant sociopolitical levels to not just participate in governance, but also to develop, implement and maintain measures. A key aspect of capacity building is **(principle 18)** developing processes for knowledge production, sharing and social learning to enable effective governance across levels. Implementing knowledge sharing infrastructure and processes is essential to ensure that data

---

[iii] Vertical policy coherence refers to the degree that policy instruments or tools and implementation processes are aligned with the policy goals that they are supposed to achieve. Horizontal policy coherence refers to the degree that this is supported by the instruments and implementation processes of other policy goals. For example, the degree to which agricultural policy supports water management policy (Cairney, 2002).

and experiential knowledge is generated, shared and used effectively across governance levels to manage eutrophication effectively and adaptively.

Actors across governance levels generally operate at a specific governance and spatial level. This scale specificity can pose several challenges to effective cross-scale management because it means some groups of actors, like environmental NGOs, may not have the capacity to participate in governance at certain key levels. One means of **(principle 19)** addressing the challenges posed by the scale specificity of actors is changing the design of forums for collaborative governance to facilitate the participation of actors who operate at different spatial levels. However, individual actors may also need to make efforts to understand or even operate across multiple levels. **(principle 20)** Identifying and working with trusted intermediaries can also be an important way of bridging sociopolitical levels by improving farmer participation in environmental schemes, particularly where there is a lack of trust between farmers at the local level and higher levels of government.

While each of these aspects is important, the development of effective multi-level governance systems and the implementation of strategies is likely to be highly context-dependent. Therefore, a key principle for successful cross-scale management is **(principle 21)** identifying how broader indirect drivers interact across sociopolitical levels to influence policy implementation and farmer engagement, and adapting governance accordingly. In their review of empirical studies on water quality management in Great Barrier Reef Catchments, Taylor & Eberhard (2020) identified a wide variety of interacting drivers from the individual to the community, to the national level that impact farmer participation in environmental programmes. For example, participation can be encouraged by indirect drivers at the community level including information sharing, extension by trusted intermediaries and social recognition. The better understanding of the significance of these drivers for policy success or failure is inhibited by limited evaluation of governance arrangements. Several authors highlighted a need for processes for **(principle 22)** assessing the efficacy of governance arrangements and identified this as a key gap in research on governing eutrophication effectively across scales. This gap is reflected in the small body of only 4 papers, discussed in **section 3.3**, that analyse the links between changes in indirect governance drivers and direct drivers of eutrophication, and subsequent impacts on water quality.

Table 3.5: Principles for the management of indirect drivers of eutrophication across sociopolitical levels synthesised through thematic analysis of the reviewed papers.

Principle (P)	Theme (count)	Reference
Principle 12: Ensuring that governance targeting eutrophication is coherent across governance levels by identifying key policy drivers and addressing mismatches.	Using multi-level governance frameworks to integrate across levels (4)	(Jetoo, 2018; Amblard and Mann, 2021; Wuijts *et al.*, 2021; Shkaruba *et al.*, 2024)
	Adapting to legacy governance arrangements (2)	(Amblard and Mann, 2021; Rowbottom *et al.*, 2022)
	Maintaining consistent higher-level policy-signals, funding and enforcement (3)	(Taylor and Eberhard, 2020; Amblard and Mann, 2021; Shkaruba *et al.*, 2024)
	Introducing mechanisms for implementing higher-level policy across levels (2)	(Wuijts *et al.*, 2021; Shkaruba *et al.*, 2024)
	Understanding impact of lower level governance on policy implementation (5)	(Wuijts *et al.*, 2021; Rowbottom *et al.*, 2022)
Principle 13: Ensuring that policy is coherent across sectors, across governance levels by identifying interactions between different areas of policy and addressing mismatches.	Achieving cross-sectoral coherence across levels (4)	(Brils et al., 2014; A. S. Downing et al., 2014; Siman & Niewiarowski, 2023; Wuijts et al., 2021)
	Building cross-sectoral networks across governance and hydrological levels (1)	(Wuijts *et al.*, 2021)
	Integrating with land-use policy (2)	(Brils *et al.*, 2014; Siman and Niewiarowski, 2023)
	Integrating with energy policy (3)	(Enloe, Schulte and Tyndall, 2017; Siegmund-Schultze, Köppel and Sobral, 2018; Siman and Niewiarowski, 2023)
	Integrating with fisheries policy (1)	(A. S. Downing et al., 2014)
Principle 14: Aligning across jurisdictions to achieve horizontal coordination across governance levels.	Coordinating horizontally and vertically across jurisdictions (2)	(Meyer and Thiel, 2012; Enloe, Schulte and Tyndall, 2017; Siegmund-Schultze, Köppel and Sobral, 2018; Berardo, Turner and Rice, 2019)
	Coordinating with new hydrological governance levels (1)	(Kastens and Newig, 2008)
Principle 15: Developing effective mixes of top-down, bottom-up and participatory governance to implement policy as real-world measures **Principle 15i:** Using a variety of policy instruments across governance levels.	Expanding policy tools across sociopolitical levels (2)	(Taylor and Eberhard, 2020; Amblard and Mann, 2021)
Principle 15ii: Integrating devolved decision making across multiple sociopolitical levels with top-down regulation and enforcement	Introducing flexibility to local conditions through bottom-up decision-making (2)	(Jetoo, 2018; Amblard and Mann, 2021)
	Combining top-down approaches with local participation (7)	(Kastens and Newig, 2008; Meyer and Thiel, 2012; Brils et al., 2014; Jetoo, 2018; Taylor and Eberhard, 2020; Amblard and Mann, 2021; Rowbottom et al., 2022)
	Identifying limitations to bottom-up (4)	(Meyer and Thiel, 2012; Brils *et al.*, 2014; Rowbottom *et al.*, 2022; Siman and Niewiarowski, 2023)
Principle 15iii: Developing approaches for integrating priorities, knowledge and action across governance levels	Developing processes for feeding local needs and knowledge to higher levels (2)	(Siegmund-Schultze, Köppel and Sobral, 2018; Berardo, Turner and Rice, 2019)
	Developing processes for connecting top-down and bottom-up action (3)	(Brils *et al.*, 2014; McGonigle *et al.*, 2014; Wuijts *et al.*, 2021)
Principle 16: Developing governance systems that integrate priorities in a transparent and accountable manner to build credibility and improve implementation.	Developing transparent processes for integrating priorities across levels (2)	(Jessel and Jacobs, 2005; Taylor and Eberhard, 2020)
	Investigating stakeholder motivations across levels (1)	(McGonigle *et al.*, 2014)
Principle 17: Ensuring that there is capacity across relevant sociopolitical levels to develop, implement and maintain measures.	Addressing administrative barriers to local access to higher-level funding (1)	(Amblard and Mann, 2021)
	Building capacity for monitoring across levels (5)	(van der Laan *et al.*, 2017; Jetoo, 2018; Gebrehiwot *et al.*, 2021; König *et al.*, 2021; Shkaruba *et al.*, 2024)
	Building capacity for enforcement of regulation across levels (1)	(Shkaruba *et al.*, 2024)
	Building capacity across governance levels to engage farmers at the local level (2)	(Enloe, Schulte and Tyndall, 2017; Taylor and Eberhard, 2020)
	Developing funding streams to support cross-level participation (3)	(Enloe, Schulte and Tyndall, 2017; Jetoo, 2018; Taylor and Eberhard, 2020)
	Building cross-level implementation capacity (2)	(Wuijts *et al.*, 2021)
Principle 18: Developing processes and systems for knowledge production, sharing and social learning across levels to improve capacity and credibility.	Engaging stakeholders across sociopolitical levels to implement monitoring (5)	(Enloe, Schulte and Tyndall, 2017; van der Laan *et al.*, 2017; Jetoo, 2018; Gebrehiwot *et al.*, 2021; König *et al.*, 2021)
	Supporting strategy development through effective cross-scale monitoring (4)	(van der Laan *et al.*, 2017; Jetoo, 2018; Gebrehiwot *et al.*, 2021; König *et al.*, 2021)
	Developing data collection and storage that facilitates trust-building across sociopolitical levels (3)	(Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020)
	Introducing data infrastructure for exchanging knowledge across levels (3)	(Brils *et al.*, 2014; McGonigle *et al.*, 2014; Taylor and Eberhard, 2020)
	Developing social learning across levels (4)	(Brils *et al.*, 2014; van der Laan *et al.*, 2017; Jetoo, 2018; Taylor and Eberhard, 2020)
Principle 19: Addressing the challenges posed by the scale specificity of actors to facilitate cross-level governance.	Building stakeholder capacity to across multiple spatial and sociopolitical levels (4)	(Kastens and Newig, 2008; Meyer and Thiel, 2012; Brils et al., 2014; Jetoo, 2018)
	Developing tools to support stakeholder engagement across spatial levels (3)	(Jessel and Jacobs, 2005; Brils *et al.*, 2014; Zammali *et al.*, 2021)
	Building awareness of cross-spatial level impacts of actions (2)	(Meyer and Thiel, 2012; Taylor and Eberhard, 2020)
Principle 20: Identifying and working with trusted intermediaries to address mistrust of higher-level governance and improve farmer adoption.	Using trusted intermediaries to bridge levels (3)	(Enloe, Schulte and Tyndall, 2017; Siegmund-Schultze, Köppel and Sobral, 2018; Taylor and Eberhard, 2020)
Principle 21: Adapting governance approaches according to key indirect drivers across sociopolitical levels to improve policy implementation and farmer adoption in a specific context.	Adapting governance arrangements to sociopolitical drivers across levels (5)	(Enloe, Schulte and Tyndall, 2017; Taylor and Eberhard, 2020; Rowbottom *et al.*, 2022)
Principle 22: Implementing processes for assessing multi-level governance arrangements.	Evaluating multi-level governance arrangements (3)	(Kastens and Newig, 2008; Meyer and Thiel, 2012; Taylor and Eberhard, 2020)

Participatory approaches were seen as highly valuable for the cross-scale management of indirect drivers (**Figure 3.4**). First, through developing better multi-scalar systems understandings by gaining insights into key indirect drivers (Jessel and Jacobs, 2005; Meyer and Thiel, 2012; Enloe, Schulte and Tyndall, 2017; Siegmund-Schultze, Köppel and Sobral, 2018; Royer *et al.*, 2020; Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020; Amblard and Mann, 2021; Tschikof *et al.*, 2024). Engaging actors at the level of implementation, most notably famers and landowners, can generate insights into indirect drivers across sociopolitical levels **(principle 21)** that drive unsustainable practices, inhibit change or make certain management approaches unfeasible. For example, in their participatory case study, Taylor & Eberhard (2020) identified the importance of gaining social capital at the community level for encouraging changes in practices. Other authors identified the importance of trusted intermediaries for engaging farmers in collaborative platforms and driving practice change (Enloe, Schulte and Tyndall, 2017; Yoder, Chowdhury and Hauck, 2020; Amblard and Mann, 2021). Another important insight was the need to build flexibility into regulation and subsidy schemes so farmers can adapt their practices to their needs, particularly when faced with external changes like shifts in climate or markets (Enloe, Schulte and Tyndall, 2017; Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020). Both Jessel & Jacobs (2005) and Royer et al., (2020) found that engaging actors across multiple sociopolitical levels can enrich the insights provided by engaging actors at one level. Higher-level policy makers establish policy goals and contextual factors that can facilitate action, while local-level stakeholders that take action at the ground level. Therefore, engaging both groups of actors can provide a stronger assessment of the feasibility of management scenarios (Jessel and Jacobs, 2005; Royer *et al.*, 2020).

In addition to being centres for the production of knowledge, collaborative platforms can act as bridging organisations that facilitate knowledge exchange and social learning across sociopolitical and spatial levels **(principle 18)**. They can also connect actors horizontally across levels (Kastens and Newig, 2008a; McGonigle *et al.*, 2014; Enloe, Schulte and Tyndall, 2017; Jetoo, 2018; Royer *et al.*, 2020; Taylor and Eberhard, 2020). McGonigle et al., (2014) advocate for collaborative demonstration catchments as important bridging organisations that can embed policy questions into catchment-level research, while also feeding embedding knowledge of indirect drivers across levels into policy. Enloe et al., (2017) instead highlight the role that catchment-level collaborative partnerships can play in catalysing peer-to-peer knowledge exchange on strategies for mitigating nutrient losses. In both instances, collaborative partnerships became trusted intermediaries **(principle 20)** and increased engagement in management activities where trust in higher level government was low (Enloe, Schulte and Tyndall, 2017; Royer *et al.*, 2020).

The knowledge of indirect drivers of practice change produced stakeholder engagement can be used to increase coherence both vertically across sociopolitical levels and between sectors **(principle 12 - 14)** (Jessel and Jacobs, 2005; Meyer and Thiel, 2012; Enloe, Schulte and Tyndall, 2017; Royer *et al.*, 2020; Taylor and Eberhard, 2020; Amblard and Mann, 2021; Wuijts *et al.*, 2021). Participatory forums can be valuable for building indirect drivers across levels into governance approaches; for example, by integrating local needs and requirements into higher level regulation, grant schemes and other policy instruments **(principle 15ii - 16, 21)**. These higher-level indirect drivers can then better support farmers and other actors in implementing management strategies to mitigate eutrophication (Meyer and Thiel, 2012; Enloe, Schulte and Tyndall, 2017; Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020). The reviewed literature contained few case studies of the integration of the outcomes of local-level participation into policy, and this has been highlighted as an important evidence gap (Amblard and Mann, 2021; Rowbottom *et al.*, 2022). However, Yoder et al., (2020) and Enloe et al., (2017) both found that involving agricultural actors in developing regulations or subsidy schemes can both increase the alignment of set rules with the realities of farming and farmer practices with policy goals (Enloe, 2017; Yoder et al., 2020). The improved congruence of higher-level policies with local level contexts and needs can be conceptualised as an increase in 'experienced' policy coherence (Huttunen, 2015) and was associated with higher compliance with regulation (Enloe, Schulte and Tyndall, 2017; Yoder, Chowdhury and Hauck, 2020). This suggests that integrating participation into the development of regulation can contribute to the successful integration of top-down regulation and devolved bottom-up efforts to mitigate eutrophication. However, the contribution of multi-level participation to policy coherence across sociopolitical levels and sectors, and its subsequent impacts on eutrophication requires further exploration.

Instead, the most frequently identified contribution of participation to the effective bridging of top-down and bottom-up governance, was the integration of varied priorities across sociopolitical levels into management strategies **(principle 15iii, 16)** (Jessel and Jacobs, 2005; Siegmund-Schultze, Köppel and Sobral, 2018; Royer *et al.*, 2020; Amblard and Mann, 2021; Tschikof *et al.*, 2024). In part, this can be achieved through the participation of stakeholders across multiple sociopolitical and spatial levels in systems modelling and the development of multi-level management scenarios (Jessel and Jacobs, 2005; Royer *et al.*, 2020; Tschikof *et al.*, 2024). Engaging stakeholders in this way can facilitate priority integration across levels by identifying concerns that may not be apparent to actors and analyses at single levels (Jessel and Jacobs, 2005; Siegmund-Schultze, Köppel and Sobral, 2018; Royer *et al.*, 2020). For example, the interactions and trade-offs between eutrophication management and other ecosystem services and social goals, including food and energy production and water availability

(Jessel and Jacobs, 2005; Siegmund-Schultze, Köppel and Sobral, 2018; Tschikof *et al.*, 2024). Importantly, engaging actors across sociopolitical levels in these processes can also reveal where priorities may differ across levels, allowing them to be better integrated into management strategies, increasing their coherence (Royer *et al.*, 2020; Wuijts *et al.*, 2021; Tschikof *et al.*, 2024). Identifying any clashes in priorities can be supported by implementing collaborative platforms across different sociopolitical and spatial levels, beyond the national and river basin levels (Meyer and Thiel, 2012; Taylor and Eberhard, 2020; Wuijts *et al.*, 2021; Bitterman and Koliba, 2023). For example, Wuijts et al., (2021) suggest developing collaborations at the local level where measures are physically implemented can be essential as this level is often where conflicts appear.

Integrating priorities effectively across levels and sectors through collaboration was also considered central to the development of transparent, credible and legitimate governance systems that favour the implementation of management strategies (**principle 15, 16**) (Jessel and Jacobs, 2005; Kastens and Newig, 2008b; McGonigle *et al.*, 2014; Enloe, Schulte and Tyndall, 2017; Royer *et al.*, 2020; Taylor and Eberhard, 2020; Amblard and Mann, 2021). However, as highlighted by several authors, the effective integration of eutrophication management with other priorities is not an automatic consequence of participatory processes. There was also some suggestion that the use of community science can increase both accountability and the implementation of measures across sociopolitical levels to improve water quality. Primarily, this was through increasing public awareness of water quality and consequently the level of scrutiny faced by government actors (König *et al.*, 2021). Nevertheless, both governance structures and processes for collaborative management must be well designed to achieve these goals (Jessel and Jacobs, 2005; Kastens and Newig, 2008a; Meyer and Thiel, 2012; Siegmund-Schultze, Köppel and Sobral, 2018; Amblard and Mann, 2021; Wuijts *et al.*, 2021; Bitterman and Koliba, 2023). The success of these processes for supporting accountable and credible governance relies strongly on the 'seriousness' of the process. While participatory governance is presented as a means to integrate priorities and feed lower-level needs and priorities to higher levels of governance, this needs to be consciously built into governance processes to be successful and meaningful (Kastens and Newig, 2008a; Royer *et al.*, 2020; Taylor and Eberhard, 2020; Amblard and Mann, 2021; Tschikof *et al.*, 2024). This includes transparent processes for deciding on what should be priorities in the case of clashes, for example over land-use (Jessel and Jacobs, 2005; Amblard and Mann, 2021).

3.4.3 Principles for the cross-scale management of interacting direct and indirect drivers and the role of participation

While direct and indirect drivers of eutrophication were often treated separately in the reviewed papers, several authors advocated for the consideration of the interactions between direct and indirect drivers across scales. In discussions of interactions between indirect and direct drivers, 'cross-scale' management meant two different things. In some cases, it meant identifying and managing interactions between direct and indirect drivers and processes that are seen to operate over different temporal, spatial or organisational levels. For example, national-level policy can impact wetland coverage at the catchment level, despite not being considered as 'located' on the same spatial level. Alternatively, effectively managing cross-scale interactions referred to ensuring the compatibility of the spatial and temporal dimensions of key social and ecological drivers, termed socioecological 'fit.' 'Spatial misfit' can occur, for example, when the spatial coverage of regulation mandating a phosphorus load limit did not cover the full spatial extent of a eutrophic watershed. Alternatively, a 'temporal misfit' can result from the misalignments between the timings of fertiliser applications and heavy rainfall, encouraging nutrient loss in run-off (Cash *et al.*, 2006; Folke *et al.*, 2007).

I synthesised 6 principles for managing interacting direct and indirect drivers across scales **(Table 3.6)**. Cross-scale management that considered the interactions between both indirect drivers and direct drivers across scales relies on **(principle 23)** producing and using models and research outputs at spatial and temporal resolutions and extents with high relevance to stakeholder groups and **(principle 24)** demonstrating the links between changes in management at the field or farm level and water quality. Both principles are important for engaging stakeholders across sociopolitical levels in strategy development and implementation. across sociopolitical levels. Producing systems analyses based on stakeholder needs has a key role in **(principle 25)** developing governance that incorporates understandings of direct drivers across spatial levels and timeframes into governance across sociopolitical levels, which are embedded in **(principle 25i)** management strategies that are coherent across spatial levels. Effectively managing direct drivers across spatial levels can mean aligning the spatial dimensions of governance and management with those of key ecological drivers. For example, by ensuring that the spatial extent of governance and management efforts is appropriate for socioecological system. Further, **(principle 25ii)** integrating both the spatial and the temporal characteristics of ecological direct drivers into governance and management efforts was seen as important for effective management. For example, by **(principle 25iii)** developing adaptive multilevel governance and management systems that can respond to changes in direct drivers across spatial levels and over time, or in response to improved understandings of system drivers.

Developing effective multi-level governance systems and management also relies on **(principle 26)** incorporating understandings of interactions between direct and indirect drivers across scales into governance. This means first **(principle 26i)** understanding the role of interactions between indirect and direct across scales in driving eutrophication. Of particular importance is **(principle 26ii)** identifying cross-scale interactions between policy drivers across sociopolitical levels and sectors and direct drivers of eutrophication. Identifying these interactions is essential to ensure that environmental policies, and other policy sectors are aligned with eutrophication management goals. Authors frequently highlighted policy sectors that can impact key direct drivers like land-use, agricultural management practices and wastewater treatment as essential for effective management of eutrophication. Identifying these interactions is essential for understanding why policies aimed at mitigating eutrophication succeed or fail. However, **(principle 26iii)** identifying the impacts of the interactions of contextual direct drivers and broader indirect drivers across scales can strengthen policy design and management strategies. Understanding these interactions can also support the **(principle 26iv)** development of adaptive governance and management systems that are responsive to changes in interacting direct and indirect drivers across scales. Again, a number of authors critiqued the limited understanding of how particular policy and governance arrangements can contribute to the mitigation of eutrophication. These authors went beyond evaluating the internal features of governance systems, and instead took an outcome-focused approach that relied on **(principle 27)** developing processes for evaluating governance approaches by their impacts on direct social and ecological drivers of eutrophication across spatial levels and, ultimately, water quality. In many cases, achieving these goals was seen to require further research and, in some cases, **(principle 28)** developing a broader suite of indicators, data sources and modelling tools to facilitate the analysis of eutrophication as a product of a multi-scalar socioecological system of interacting direct and indirect drivers

Table 3.6: Principles for the management of interacting indirect drivers of eutrophication across sociopolitical and spatiotemporal scales.

Principle 23: Producing tools, analyses and research outputs at stakeholder-relevant spatial levels and timeframes to support multi-level strategy development.		Evaluating pressures at stakeholder-relevant spatial levels (2)	(Daroub *et al.*, 2011; Tschikof *et al.*, 2024)
		Generating and using appropriate models for policy-relevant spatial levels (2)	(Dietrich and Funke, 2009; Shan *et al.*, 2023)
		Developing scenarios at stakeholder relevant spatial levels (2)	(Jessel and Jacobs, 2005; Royer *et al.*, 2020)
		Evaluating measures at stakeholder relevant spatial levels (1)	(Zammali *et al.*, 2021)
		Developing indicators that change over stakeholder-relevant timeframes (1)	(McGonigle *et al.*, 2014)
		Modelling at stakeholder-relevant temporal resolutions and extents (1)	(Shan *et al.*, 2023)
Principle 24: Demonstrating links between management at small spatial levels and catchment-level water quality outcomes to engage stakeholders.		Linking field-level changes to catchment-level impacts (4)	(Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020; Amblard and Mann, 2021; Zammali *et al.*, 2021)
Principle 25: Incorporating understandings of direct drivers across spatial levels and timeframes into governance across sociopolitical levels	**Principle 25i**: Developing multi-level governance systems that incorporate understandings of direct drivers of eutrophication across spatial levels into coherent management across those levels.	Developing multilevel governance approaches based on multi-spatial level system understandings (3)	(Jessel and Jacobs, 2005; Qiu *et al.*, 2018; Gebrehiwot *et al.*, 2021)
		Involving 'scale relevant' actors in decision-making (3)	(Brils *et al.*, 2014; Yoder, Chowdhury and Hauck, 2020; Amblard and Mann, 2021)
	Principle 25ii: Integrating the spatial and temporal characteristics of ecological direct drivers into management efforts. Can be conceptualised as spatial socioecological 'fit'.	Ensuring spatial 'fit' in SES governance (6)	(Hufnagl-Eichiner, Wolf and Drinkwater, 2011; Meyer and Thiel, 2012; Schönach *et al.*, 2018; Berardo, Turner and Rice, 2019; Wuijts *et al.*, 2021; Shkaruba *et al.*, 2024)
		Identifying and addressing spatial 'misfit' (5)	(Jessel and Jacobs, 2005; Meyer and Thiel, 2012; Enloe, Schulte and Tyndall, 2017; Schönach *et al.*, 2018; Shkaruba *et al.*, 2024)
	Principle 25iii: Developing adaptive governance and management systems that are responsive to changes in direct drivers across scales.	Collaborating to improve spatial 'fit' (2)	(Meyer and Thiel, 2012; Enloe, Schulte and Tyndall, 2017)
		Responding to both fast and slow ecological processes (2)	(Siman and Niewiarowski, 2023; Shkaruba *et al.*, 2024)
		Adapting management to direct driver change (2)	(Jetoo, 2018; Schönach *et al.*, 2018)
Principle 26: Incorporating understandings of interactions between direct and indirect drivers across scales into governance	**Principle 26i**: Understanding the role of interactions between indirect and direct across scales in driving eutrophication	Understanding co-evolution of direct and indirect drivers (3)	(A. S. Downing et al., 2014; McCluney et al., 2014; Schönach et al., 2018)
	Principle 26ii: Identifying cross-scalar interactions between key indirect policy drivers and direct drivers across sociopolitical levels and sectors.	Understanding cross-scalar impacts of policies across sectors on direct drivers (7)	(Jessel and Jacobs, 2005; Brils *et al.*, 2014; Schönach *et al.*, 2018; Siegmund-Schultze, Köppel and Sobral, 2018; Taylor and Eberhard, 2020; Siman and Niewiarowski, 2023; Shkaruba *et al.*, 2024)
	Principle 26iii: Understanding where interactions between policy drivers and other indirect and direct drivers across scales may contribute to the success or failure of policy and implementation of management.	Identifying indirect and direct drivers that impact policy implementation (6)	(Jessel and Jacobs, 2005; Enloe, Schulte and Tyndall, 2017; Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020; Amblard and Mann, 2021; Zammali *et al.*, 2021)
		Adapting governance to context (1)	(Amblard and Mann, 2021)
		Identifying barriers to farm system / farmer change (4)	(Jessel and Jacobs, 2005; Enloe, Schulte and Tyndall, 2017; Amblard and Mann, 2021; Zammali *et al.*, 2021)
	Principle 26iv: Developing adaptive governance and management systems that are responsive to changes in interacting direct and indirect drivers across scales	Developing policy based on integrated understandings of impacts of interacting indirect and direct drivers across scales (3)	(Siegmund-Schultze, Köppel and Sobral, 2018; Taylor and Eberhard, 2020; Siman and Niewiarowski, 2023)
		Adapting policies in response to changing direct and indirect drivers	(Siegmund-Schultze, Köppel and Sobral, 2018; Taylor and Eberhard, 2020; Siman and Niewiarowski, 2023)
Principle 27: Developing processes for evaluating governance approaches based on changes in direct drivers across spatial levels and water quality.		Evaluating policy impacts on direct drivers and water quality (4)	(Daroub *et al.*, 2011; Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020; Amblard and Mann, 2021)
Principle 28: Developing a broader suite of indicators, data sources and modelling tools to facilitate the analysis of eutrophication as a product of interacting direct and indirect drivers.		Developing novel indicators of socioecological change (3)	(Hufnagl-Eichiner, Wolf and Drinkwater, 2011; Enloe, Schulte and Tyndall, 2017; Amblard and Mann, 2021)
		Evaluating adoption of farm-scale measures to assess policy WQ impacts (1)	(Enloe, Schulte and Tyndall, 2017)
		Modelling interacting indirect and direct drivers effectively (1)	(Siman and Niewiarowski, 2023)

In large part, the role of participation in supporting the more effective management of cross-scale interactions between indirect and direct drivers, was ensuring that knowledge of direct drivers across scales were incorporated into policy and management efforts across relevant sociopolitical levels (**Figure 3.4**).

As with the cross-level governance of direct and indirect drivers, an important contribution of participatory platforms was supporting knowledge production. One of the advantages of collaborative platforms was that they can be used to support the production of data at scales that were relevant to participating actors **(principle 23).** This is both through community science data collection that is developed according to the needs of particular actors (König *et al.*, 2021; Yevenes, Pereira and Bermudez, 2022), and institutional scientific data collection that has been shaped by the feedback of participants in collaborative platforms (McGonigle *et al.*, 2014; Enloe, Schulte and Tyndall, 2017). By supporting the embedding the needs of key stakeholders into data collection, it was thought that participation can better facilitate strategy development and implementation by participating stakeholders (McGonigle *et al.*, 2014; Enloe, Schulte and Tyndall, 2017; König *et al.*, 2021; Yevenes, Pereira and Bermudez, 2022).

Collaborative partnerships, particularly at catchment level, can also facilitate knowledge dissemination across sociopolitical and spatial levels to address several scale challenges. Firstly, some authors found that successful collaborations can improve the acceptance of the links between farm-level practices and nutrient pollution in wider watershed **(principle 24, 26i).** This was seen as important for achieving adoption of measures (Enloe, Schulte and Tyndall, 2017; Sigler *et al.*, 2018) Others saw collaborations at the catchment level as important bridging organisations that can support the integration of knowledge of local level drivers and conditions into policy and decision-making across levels **(principle 25i, 26i)**. This was associated with higher credibility and legitimacy of strategy-making that was better tailored to conditions at the local level (Enloe et al., 2017; Jessel & Jacobs, 2005; McGonigle et al., 2014; Royer et al., 2020; Taylor & Eberhard, 2020) Similarly, developing collaborative platforms for disseminating research focused on specific water bodies was seen to improve the pooling of knowledge that can be used as a resource for good governance (Jetoo et al., 2018). Jetoo et al., (2018) also found that, in the context of the Great Lakes, involving multi-level stakeholders in advisory boards increased the capacity of governance to respond to changes in local conditions and emerging water quality issues **(principle 26iv).** This was attributed to increased knowledge exchange with stakeholders with local expertise. As well as performing a vertical 'bridging' function, collaborations at the river basin level were also associated with horizontal, cross-jurisdictional coordination that can the spatial 'fit; between watershed and jurisdictional boundaries **(principle 25ii)** by increasing the capacity of actors across levels to reimagine management according to hydrologically relevant boundaries (Meyer and Thiel, 2012; Enloe, Schulte and Tyndall, 2017)

Despite being acknowledged as useful platforms for knowledge production on both direct and indirect drivers, few of the papers reviewed here used or evaluated the role of participation in understanding the links between indirect and direct drivers **(principle 26i).** Indirect drivers of eutrophication like attitudes, knowledge and regulation were rarely evaluated in terms of their impacts on direct drivers like soil management, fertiliser application or wastewater treatment. One exception were participatory studies of collaborative management that evaluated the indirect factors influencing farmer engagement in environmental schemes and their implementation of measures for reducing nutrient losses (Enloe, Schulte and Tyndall, 2017; Amblard and Mann, 2021). Both case studies draw links between indirect drivers and changes in management practices and, in the case of Amblard & Mann (2021), qualitative changes in water quality. They stop short of a systematic evaluation of the management and water quality impacts of collaborative management efforts and the indirect drivers that impact these outcomes. Therefore, there remains a need for further evidence of the efficacy of participatory approaches to management, and what features improve their effectiveness (Rowbottom *et al.*, 2022). Nevertheless, they demonstrate the potential of participatory research to elucidate these links, particularly when embedded in collaborative partnerships that are simultaneously collecting management and water quality data. This can strengthen the valuable insights into the factors influencing the success of management efforts that can be generated through the qualitative cross-comparison of multiple case studies suggested by Amblard & Mann (2021). These kinds of insights can be valuable for developing effective policy approaches to eutrophication, by supporting the identification of links between policy and changes in direct drivers and elucidating where policies or strategies are incompatible with conditions at the point of implementation, leading to policy failure **(principle 26iii)** (Jessel and Jacobs, 2005; McGonigle *et al.*, 2014; Enloe, Schulte and Tyndall, 2017; Sigler *et al.*, 2018; Royer *et al.*, 2020; Taylor and Eberhard, 2020; Amblard and Mann, 2021) However, the potential of collaborative platforms to contribute to policy evaluation **(principle 27)** is largely unexplored in the literature and there are few examples in the reviewed literature where the outputs of participatory or collaborative forums for policy evaluation were incorporated into higher-level policy (Kastens and Newig, 2008a; Royer *et al.*, 2020; Taylor and Eberhard, 2020; Amblard and Mann, 2021; Tschikof *et al.*, 2024).

Figure 3.4: *A framework for identifying the contributions participatory processes can make to the cross-scale management of eutrophication, where effective cross-scale management means managing (i) indirect drivers across a sociopolitical levels to improve the internal functioning of sociopolitical system, (ii) direct drivers through implementing measures that deliver across spatial and temporal scales (iii) the interactions between direct and indirect drivers to increase favourable interactions between sociopolitical and ecological systems.*

3.5 Conclusions

Through interdisciplinary qualitative synthesis, I identified three types of cross-scale management that are critical for the management of eutrophication as a systemic socioecological problem and synthesised a framework for how this could be implemented through a participatory approach (**Figure 3.4**). First, it is essential to manage direct eutrophication drivers across spatiotemporal levels to develop effective on-the-ground measures. Participatory research and forums can support this process by improving the production and synthesis of knowledge of direct drivers at key spatial and temporal levels. This is fundamental to the development and alignment management strategies across those scales. Second, it is necessary to align indirect drivers across sociopolitical levels to strengthen systems for implementing management. Participatory processes can improve understandings of how indirect drivers like subsidies influence practice change. However, of greater importance is the role of collaboration in bridging sociopolitical levels and sectors, to build trust and integrate priorities in more transparent multi-level governance systems. Finally, management should address the cross-scale interactions between indirect sociopolitical and direct drivers to ensure that they result in positive outcomes for eutrophication. The role of participation in supporting the management of interactions between direct and indirect drivers across scales was less well explored. However, participatory platforms can be important sites for synthesising knowledge of direct drivers across scales according to stakeholder needs and facilitating its embedding in decision-making across sociopolitical levels. I also suggest that collaborative management platforms can play a greater role in policy evaluation as sites for both ecological and social evaluation and see this a valuable area for further research.

This framework developed herein supports participatory cross-scale management of both direct and indirect drivers and their interactions in a systematic fashion. Therefore, it may be useful for groups engaged in the real-world management of eutrophication who think strategically about (1) how to develop tangible management strategies that deliver water quality goals alongside other priorities across scales, (2) how to bridge actors across sociopolitical levels and advocate for change to achieve implementation and (3) how, through their bridging role, they also act as an important interface between the broader sociopolitical context and the geographically bounded eutrophic system.

This paper contributes to research on the socioecological 'cross-scale' management of eutrophication by interrogating what 'management across scales' actually means across the highly interdisciplinary body of literature that addresses this topic. This interdisciplinary synthesis clarifies and makes explicit the different conceptualisations of scale, level and cross-scale interactions that underpin call for cross-scale management of eutrophication. This contributes some essential terminological and conceptual clarity to an area of research that is sometimes challenged by its own diversity and lack of integration of fundamental concepts. It further illuminates how these conceptualisations are tied to both to the type(s) of driver and the management goals of the practitioner or researcher. In doing so, this work goes beyond references to the 'siloing' of disciplinary approaches that are common in the literature. Instead, by elucidating the underlying purposes of disciplinary approaches it aims to promote the cross-disciplinary understanding that is essential for bridging those siloes. This research further contributes to the bridging of disciplinary siloes, by drawing on these insights to propose a theoretical framework for the systemic cross-scale and cross-level management of eutrophication as a socioecological challenge. Overall, this framework offers a meaningful step towards the interdisciplinary working that is often advocated for in this area.

4 Understanding cross-level and cross-scale interplay for mitigating eutrophication as a socioecological challenge: a place-based participatory process

4.1 Abstract

The eutrophication of surface waters persists across Europe and Water Framework Directive (WFD) implementation is slow. Calls for better management approaches advocate for involving multiple stakeholders, considering social, ecological, and technological drivers, and applying 'multi-level' or 'multi-scalar' approaches. However, multi-level approaches rarely apply 'scales' and 'levels' drawn from the experiences of stakeholders engaged in management efforts, or systematically explore these multi-dimensional drivers. This may limit understandings of how the interplay of scales and levels affects mitigation efforts. To address this limitation, I conducted a place-based participatory case study, centred around Stockholm (Sweden), to elaborate how sociopolitical and hydrological scales became important during efforts to address eutrophication. Misalignments between sociopolitical drivers across levels, including policy goals, legislation, funding, and norms, were found to inhibit the prioritisation and implementation of WFD goals at city, sub-catchment, and micro levels. Furthermore, cross-scale misalignments inhibited actions across relevant sociopolitical levels that were sensitive to drivers across the hydrological scale. Legislation around water and land-use restricted planning according to sub-catchment level dynamics, while knowledge of hydrological drivers at the sub-catchment and micro-level were seen as inadequate to support strategy development or their funding and implementation. Greater efforts are needed to understand and address these misalignments to enable successful eutrophication management, where multiple goals co-exist and must be implemented simultaneously. Enhanced cross-level collaboration may act as an essential enabler by facilitating 'buy-in,' enhancing knowledge of hydrological drivers at the sub-catchment and micro levels and improving their integration into decision-making across sociopolitical levels.

4.2 Introduction

Better societal management of nutrients is an important goal due to both their essential role in agriculture and their detrimental impacts on water quality through eutrophication (Correll, 1999). Eutrophication, like many other sustainability problems, is characterised as one that must be addressed across levels and scales (key scale terminology used in this paper given in **Table 4.1**) (Cordell, Neset and Prior, 2012; Metson *et al.*, 2015b; Withers *et al.*, 2015). However, despite decades of research, policy interventions and strategies developed and targeted across scales, eutrophication remains a central reason for the failure of 60% of EU surface waters to reach good ecological status (Directive 2000/60/EC

Establishing a framework for Community action in the field of water policy, 2000; European Environmental Agency, 2018). Further efforts are required to align mitigation efforts across scales. However, an emerging question is what this means in practice, as sustainability challenges like eutrophication are increasingly treated as 'wicked' systemic problems that emerge from interacting ecological, technological, and social elements (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Vervoort *et al.*, 2012; Head, 2022)

The social, technical, and ecological elements of socioecological systems have historically been dealt with separately, meaning that scales are conceptualised and used in diverse ways to understand systems and develop management strategies (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Vervoort *et al.*, 2012). Governance is a key focus, and sociopolitical scales are commonly used, containing levels like the global, the national and the local (Chowdhury *et al.*, 2014; Rosemarin and Ekane, 2016b). Equally important are hydrological scales, often featuring river-basin, sub-catchment, and plot-levels (Hewett *et al.*, 2009; Reaney *et al.*, 2019). In all cases, the choice of scale and level of focus means deciding which dimensions and dynamics to analyse and which to exclude (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Buizer, Arts and Kok, 2011; Vervoort *et al.*, 2012). This can mean missing important cross-level, or even cross scalar dynamics between the heterogenous elements that drive nutrient processes. For example, focusing at the river-basin hydrological level ignores the disproportionate role that field-level critical source areas play in eutrophication (Pionke, Gburek and Sharpley, 2000; Doody *et al.*, 2012). Similarly, neglecting cross-scale interactions can limit the effectiveness of management strategies by neglecting the impacts of global food prices on mineral fertiliser applications and, consequently, nutrients losses at the field hydrological level (Zou, Zhang and Davidson, 2022). Moving towards more systemic and integrative approaches to managing nutrients means integrating these elements across multiple relevant scales to successfully manage nutrient processes (Cash *et al.*, 2006; Hewett *et al.*, 2009; Moss and Newig, 2010; Buizer, Arts and Kok, 2011; Vervoort *et al.*, 2012; Hüesker and Moss, 2015; Chowdhury and Chakraborty, 2016; Rosemarin and Ekane, 2016c).

To support this process, this research explores the cross-level and cross-scale interactions that emerged in a place-based participatory case study on eutrophication around a sub-catchment in Stockholm, Sweden. Using the perspective of change- agents, (Cash *et al.*, 2006; Buizer, Arts and Kok, 2011; Vervoort *et al.*, 2012) I identify frictions and synergies that emerged from the interplay between different scales and levels for nutrients management (Cash *et al.*, 2006). By doing so, I elucidate some of the implications that inter-level and inter-scalar interactions have for addressing the 'wicked problem' of eutrophication and the achievement of WFD goals.

Table 4.1: Definitions of terminology related to scale, as used in this paper. Many of these terms will be used in different ways across or even within different disciplines. However, in this work, the following definitions are used to avoid issues with conceptual conflation that continue to challenge discussions of scale in socioecological systems management

Term	Definition
Dimension	An aspect of an object of study like space, time or power etc. that can be structured using a particular scale e.g., space can be ordered using many different scales including hydrological (plot, catchment, river-basin) or jurisdictional scales (local, regional, national).[b]
Scale	A graduated reference system that is used to structure a particular dimension of an object of study for analysis e.g., a temporal scale. [ab]
Level	Differentiated units of analysis within a scale e.g., a jurisdictional scale may contain local, regional and national levels.[ab]
Scalar level	A unique level within a specific scale.
Extent	The proportion of a scale that an object or phenomenon occurs over e.g., the spatial extent of a river basin that experiences eutrophication.[b]
Resolution / grain	The smallest unit of change that is measured.[c]
Generalisation	The extrapolation of data, system analyses or solutions developed at one level to other levels.[d] Often referred to as upscaling or downscaling data.
'Right' scaling	Identifying the optimal scale level(s) for analysis, intervention or the magnitude of system throughputs.[d]
Upscaling / downscaling	The propagation of system change from one level to others e.g., P recovery as struvite is upscaled from a lab-based niche innovation to full-scale deployment in wastewater treatment plants (WWTPs).[e]
Outscaling	The extrapolation of data, system analyses or solutions developed for one system to another system[g]
Temporal scale and timeframe	Temporal scales are applied to break time into discrete increments, timeframes are the individual increments or levels within a temporal scale. E.g seconds, minute, hours. [b]
Spatial scale and spatial level	A spatial scale is applied to break the geographic extent of a phenomenon into spatial units or levels. E.g plot, farm, landscape. [b]
Organisation scale and organisational level	An organisational scale is applied to aggregates of individuals within networks and contains levels that are largely defined by the number of individuals. E.g individual, community and nation, or organism, population, biome.[f]
Sociopolitical scales and levels	A jurisdictional scale describes the organisation of governance structures into discrete units or levels that generally operate over a defined spatial extent and are often organised hierarchically. They can also be referred to as jurisdictional, governance or policy scales / levels.[a]

Sources: [a]Cash et al., 2006, [b]Vervoort et al., 2012, [c]Friis et al., 2023, [d]Gibson, Ostrom and Ahn, 2000, [e]Bögel et al., 2022, [f]Cumming et al., 2006, [g]Lam et al., 2020

4.3 Methodology

4.3.1 The case

Stockholm extends across 14 islands where Lake Mälaren, an important source of drinking water, joins the Baltic Sea (Mälarens vattenvårdsförbund, no date). Its 22,603 km^2 catchment (Wallin *et al.*, 2000) contains many drivers that impact its water quality, including Stockholm's population of 1 million (Stockholms Stad, 2023). These pressures mean that 61% of Stockholm's waterbodies fail to reach good nutrient status according to the WFD (Directive 2000/60/EC Establishing a framework for Community action in the field of water policy, 2000; Vatteninformationssystem Sverige, 2023) Consequently, Stockholm Municipality developed a city-wide action plan (Stockholms Stad, 2015;

Vattenmyndigheten Norra Östersjön, 2016) and 'local action plans' for bringing them to 'good' status (Stockholms Stad, 2015).

In several local action plans[iv], allotment gardens were modelled as potential sources of nutrients to waterbodies. Empirical studies of allotments' contribution to nutrient loadings are limited; however, they can be nutrient 'hotspots' in cities and may pose a risk under certain conditions (Wielemaker *et al.*, 2019; van de Vlasakker, Tonderski and Metson, 2022; Sieczko *et al.*, 2023). Consequently, representatives from Sweden's and Stockholm's Allotment Garden Association initiated a research project with the University of Linköping to better understand this issue, using Lake Mälaren-Ulvsundasjön as a case-study **(Box 1)**. Their engagement around the issue of eutrophication, alongside ongoing governance efforts across scales was the impetus for exploring scalar aspects of nutrient management through a participatory lens (Djenontin and Meadow, 2018; Lam *et al.*, 2021).

Box 1: Nutrient losses in Mälaren-Ulvsundasjön

The lake's catchment is highly altered by the introduction of impervious surfaces and artificial drainage, and mostly consists of industrial, residential and commercial areas, roadways and carparks. Only one third is comprised of green areas, including forest and allotment gardens (Stockholms Stad *et al.*, 2021). The high proportion of impervious surfaces mean that nutrient transport in stormwater (urban runoff) is a key concern. There are no direct discharges from wastewater treatment plants into the lake; however, combined sewage overflows can affect Lake Mälaren-Ulvsundasjön during heavy rainfall (Stockholms Stad *et al.*, 2021; Stockholm Vatten och Avfall, 2021). Internal loading of legacy phosphorus into the water column from lake sediment is also a concern (Stockholms Stad *et al.*, 2021).

[iv](Water Revival Systems, 2019; Stockholms Stad and Stockholm Vatten och Avfall, 2020; Stockhoms Stad and Stockholm Vatten och Avfall, 2020; Stockholms Stad *et al.*, 2021; Stockholms Stad, Stockholm Vatten och Avfall and Tyresän, 2022)

4.3.2 Participant engagement

Thirty-eight participants were engaged through interviews and/or workshop participation **(Table 4.2).** Participants were selected that could influence nutrient dynamics at by directly, or indirectly impacting the major drivers of urban eutrophication: land-use and wastewater management (Hobbie *et al.*, 2017; Yang and Toor, 2018; Lyon *et al.*, 2020). Actors were engaged across the multiple 'levels' identified during document and interview analysis. The local action plans for WFD implementation were used to identify an initial list of relevant actors, which was expanded through reviewing academic literature, policy and strategy documents, online searches, and snowballing (Heckathorn and Cameron, 2017). Time considerations and the exploratory nature of the case-study meant that 'depth' rather than 'breadth' was pursued; however, an important limitation is that it was not possible to recruit participants from some key institutions including Stockholm's Development and Planning Boards.

Table 4.2: Institutional and individual stakeholders engaged in the research project, across sociopolitical levels.

Level	Sector	Organisation	Scope
National	Government agency	Swedish Environmental Protection Agency[a] (Naturvårdsverket)	Proposal and implementation of environmental policy.
	Trade organisation	Swedish Water a (Svenskt Vatten)	Trade organisation for water and wastewater operators.
	NGO	Swedish Allotment Garden Association[ab] (Koloniträdgårdsförbundet)	National organisation of allotment garden associations
	Private company	RagnSells[a]	Waste, recycling, environmental services.
River-basin	NGO	The Mälaren Water Conservation Association[a] (Mälarens vattenvårdsförbund)	An NGO that carries out monitoring, attempts to drive collaboration around water quality and provide information. Members include governmental and non-governmental organisations.
County	Regional-level state authority	Stockholm County Administrative Board[b] (Länsstyrelsen Stockholm)	Implementation of national goals at county level. Allocates grants, issues permits for activities that may have impacts on aquatic environments.
City	Multi-municipality association	North Water[a] (Norrvatten)	Produces drinking water (primarily from lake Mälaren) for an association of 14 municipalities.
	Municipal government (decision-making)	City Executive Board[ab] (Kommunstyrelsen)	Implements the political decisions of the city council.
	Municipal government (implementation)	Stockholm Traffic Board[ab] (Trafikkontoret)	Roadway and park management, and role in stormwater handling.
	Municipal government (implementation)	Stockholm Environmental Board[a] (Miljöförvaltningen)	Environmental supervision and monitoring. Responsible for developing and coordinating local action plans (WFD).
	Municipal company	Stockholm Water and Waste[ab] (Stockholm Vatten och Avfall)	Municipal company for wastewater treatment, drinking water production and waste handling
	NGO	Stockholms Allotment Association[ab] (Stockholms Koloniträdgårdar)	Association of allotment gardens in Stockholm.
Sub-catchment	District government	Bromma District Council[b] (Bromma stadsdelsförvaltning)	Responsible the management of parks and other aspects of the urban environment.
Micro	NGO	Individual allotment associations[ab] (Koloniträdgårdsförening)	Organisations that rent land for allotments (primarily from Stockholm municipality).
	Individual	Allotment gardeners[ab]	Individual allotment gardeners

Nature of involvement in the research: a) interview, b) workshop

4.3.3 Data collection and analysis

Data collection occurred between May 2022 and February 2023. Document analysis, interviews and workshops were used to identify, from the perspective of stakeholders, 1) the scales and levels that were important for nutrient management, 2) the driving factors of nutrient dynamics and how they were located across those scales, and 3) the implications the cross-scale and cross level interactions for nutrient management in this context. Interviews and document analysis focused on current perceptions of these interactions, while the workshops enabled researchers to observe how these interactions emerged in-situ during action-focused discussions of a specific case for nutrient management (the allotment gardens).

Documentary sources included legislation, policy statements, and strategies focussing on WFD implementation, water quality and environmental issues, wastewater treatment, stormwater management and land-use planning. Key documents were the Northern Baltic Sea River Basin Management Plan (Vattenmyndigheten Norra Östersjön, 2016), Stockholm Municipality's city-wide action plan to achieve good water status (Stockholms Stad, 2015), and the local action plan for achieving good water status for Lake Mälaren-Ulvsundasjön (Stockholms Stad *et al.*, 2021)

The interview guideline followed the framework developed by Metson et al., (2015) to identify *drivers* (factors that directly or indirectly impact nutrient dynamics) across multiple social, technical, and ecological categories **(Figure 4.1)**. Seventeen institutional actors participated in in-depth, semi-structured interviews in English. Topics included major sources and drivers of nutrient pollution in Stockholm's lakes, current strategies for addressing the issue, and management challenges (interview guideline in **Appendix 1**). Interviews lasted approximately one hour and were conducted online or in person. They were also used to identify further participants for the workshops, and to develop workshop activities.

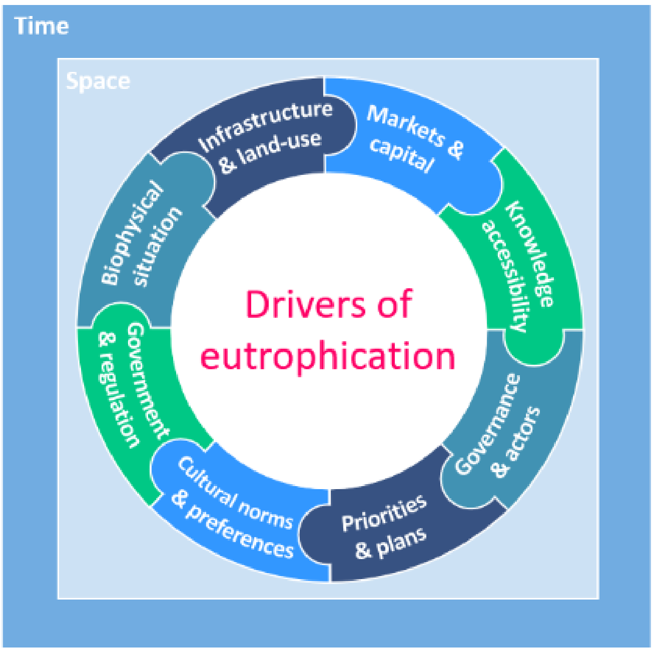


Figure 4.1: *Social, ecological and technological drivers of eutrophication. Adapted from Metson et al., (2015).*

Two half-day workshops were conducted in Swedish, involving twenty-three participants. The workshops had two aims. The first aim was to identify actions and resources that could improve urban allotments as multi-functional green infrastructures that promote good water quality. The second was to explore the multi-scalar and multi-level dynamics that emerged as important during in-situ discussions of WFD implementation at the micro-level. Stakeholder discussions of the role of allotment gardens in addressing eutrophication of lake Mäleren-Ulvsundasjon were therefore an entry point for understanding dynamics that could impact the implementation of water quality management across scales. The first workshop engaged governmental actors and representatives from Stockholm and Sweden's allotment associations. The second workshop involved representatives from Stockholm's allotment association, and those from individual allotment sites. The participants were grouped in this way in an effort to strike a balance between promoting the exchange of ideas between different groups, and the risk that institutional actors could dominate or discourage free discussion.

In the workshops, participants were divided into small groups (3-5 participants) with one mediator / notetaker, and a Dictaphone to record discussions. The first exercise aimed to encourage participants to make explicit their understanding of "what factors affect the relationship between urban agriculture and water quality". 'This was done through the production of 'Mental models' or pictorial representations of individual's tacit understand of how a particular system or phenomenon functions (Jones *et al.*, 2011; Lynam and Brown, 2012). The models consisted of 'factors' that were seen to play a role in mediating the relationship between urban agriculture and water quality, and arrows which represented the relationships between the factors. To support the construction and interpretation of the mental models, participants were provided with a set of 14 'factors' to use when creating their mental models. These 'factors' were derived from stakeholder interviews conducted prior to the workshop (**Table 4.3**). They represented drivers that participants deemed to be important mediators between urban agriculture and water quality. Participants could also add their own factors beyond those provided. Participants were then asked to present their mental models to their small group.

The researchers then presented soil samples and nutrient budgets from the allotment sites, which showed high soil P and excess P applications **(Appendix 2)**. These results were used as boundary

Table 4.3: The 'factors' offered to participants as drivers that are important for mediating the relationship between urban agriculture and water quality.

Factor	Description
Contaminants	Substances that negatively affect the environment.
Pressure on space	High pressure on urban spaces to fulfil multiple goals.
Nature-human connection	How people are connected to non-humans.
Regulatory standards	Rules on how land is used and the practices and products that impact land use.
Water supply and management	Supply and use of water.
Soil and plant management	Decisions and actions involving soil, plants and inputs in the garden.
Access to information	The existence of and access to knowledge, or the means to investigate questions.
Monitoring schemes	Data collection and sharing on relevant topics.

objects to stimulate discussions in exercise two. Exercise two asked participants to identify actions stakeholders could take to improve the capacity of urban allotments to create benefits for water quality. Researchers identified the five most commonly selected factors impacting the relationship

between water quality and urban agriculture. Participants were first asked to consider which of the factors their organisation can directly impact and what actions should they take. They were then asked to identify other key stakeholders that could impact the given factors and what actions they should take. Participants within the small groups were then asked to select the actions that they thought would best improve the capacity of urban allotments to reduce nutrient use and loss. In the final exercise, each small group presented the actions to the wider group. Exercise three then concluded with a group vote, with each participant having 5 stickers to distribute amongst the actions and associated stakeholders they thought would be most impactful (workshop outline in Appendix 3).

Interview, workshop and documentary data were analysed in an iterative process using a qualitive content analysis approach, combining deductive and inductive coding approaches (Cho and Lee, 2014). Initial coding of the data was deductive, using codes derived from the framework developed by Metson et al., (2015). This maximised the identification of a broad range of system drivers. Successive rounds used codes derived inductively from the data that categorised text according to the scale and/or level they were located at by participants (e.g. 'national' & 'micro'), what kind of interaction was occurring (e.g. 'inter-sociopolitical level'), and the nature of the drivers that were participating in the interactions (e.g. 'legislation' or 'goal alignment.') The final stage was identifying which interactions acted as barriers or enablers in the case study context, to draw conclusions about the implications that cross-scale and cross-level interactions have for nutrient management.

4.4 Results and discussion

4.4.1 The scales and levels for nutrient management

Two important scales for nutrient management were synthesised from the interviews, workshops and document review data: a sociopolitical scale and a spatially nested hydrological scale **(Table 4.4)**. For clarity, here I follow Cash et al., 2006 in distinguishing 'scales' from 'levels.' I define a scale as a conceptual framework that is used to structure analysis of objects of study according to certain dimensions (e.g. time, space, power, or interconnectedness), which may be used alone or in some combination to define a scale (Vervoort *et al.*, 2012). Levels within a scale are then used to demarcate where there is expected to be a meaningful change in observed characteristics (Gibson, Ostrom and Ahn, 2000).

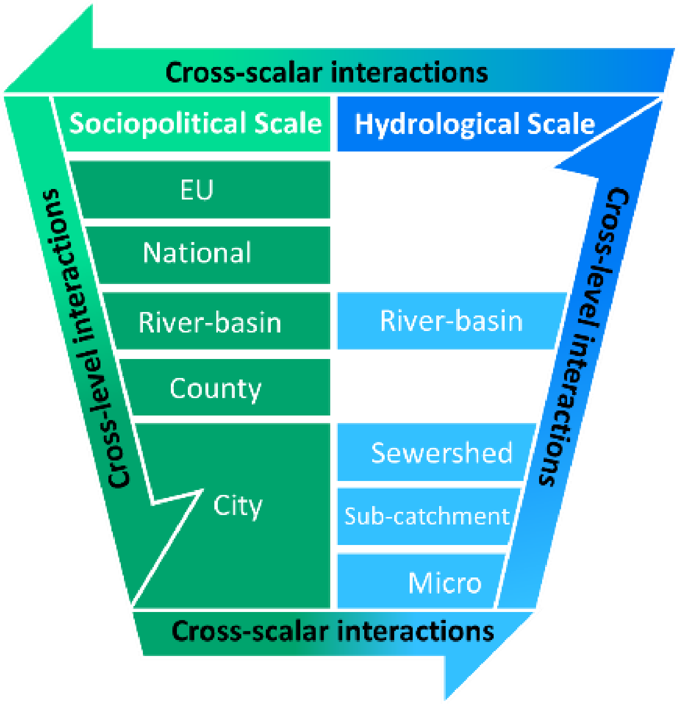


Figure 4.2: *Scales and levels for phosphorus management in Stockholm. Hydrological levels are aligned with the sociopolitical level that has direct responsibility for strategy development for WFD implementation at this level.*

Levels in the sociopolitical scale were the EU, national, river-basin (referred to as the river-basin authority), county, and city levels **(Figure 4.2)**. All of these levels were referenced by participants as significant for mitigating eutrophication in the case-study context, aligning with previous research on Swedish water governance that identified a polycentric governance structure (Moss and Newig, 2010; Jager *et al.*, 2016; Söderberg, 2016; Nykvist, Borgström and Boyd, 2017). The sociopolitical levels were internally heterogenous, containing multiple organisations with overlapping jurisdictions (Jager *et al.*, 2016; Nykvist, Borgström and Boyd, 2017). They also differed in terms of their hydrological level(s) of concern, and their power over political goal setting, decision-making and resources at other levels. Consequently, it is conceivable that the city level could be sub-divided into individual sectors or organisations of concern; for example, governance actors at the city-level frequently referred to challenges that arose from the divided jurisdictions of the municipal boards. This reflects the role of the perceptions of both the interviewee and interviewer in shaping empirical knowledge of how socioecological systems are structured (Bhaskar *et al.*, 2010). Similarly, levels could be defined for social groups and individuals. However, the levels defined here reflect those that emerged most often in the research data and, interestingly, references were rarely made to specific social groups outside of the governance sphere and individual characteristics like environmental attitudes. Instead, interviewees across levels were more likely to highlight sociopolitical drivers that could be characterised as structural.

The hydrological scale consisted of the river-basin, city (referred to as the sewershed[v]), sub-catchment and micro-levels, where the hydrology at a given level was a product of biogeophysical, social and infrastructural elements. These levels largely reflected the levels for strategic planning defined in policy documents and referred to by government participants. Participants from the allotment gardens did not refer to multiple hydrological levels or other levels with a spatial dimension. This likely reflects their focus on the micro-level of the allotments as their 'area of jurisdiction.' The addition of sewershed and micro-levels expands on the hydrological levels that have been highlighted as important for cross-scale interactions in previous research on the implementation of the WFD (Hüesker and Moss, 2015). Participants identified many drivers across both scales that engaged not only in important interactions across levels within a scale, but also across scales. These interactions and their implications for nutrient management will be presented in the subsequent section.

[v] The term 'sewershed' refers to the water catchment created by sewer and stormwater networks that direct water to Stockholm's WWTPs to be emitted as point sources into coastal waters (Ventura and Kim, 1993). The municipality currently has 2 WWTPs (Broma and Henriksdal); however, Broma is being decommissioned and its influent will be redirected to Henriksdal (Stockholm Vatten och Avfall [Stockholm Water and Waste], no date).

Table 4.4: A summary of the levels within the interacting sociopolitical and hydrological scales and the drivers that indirectly or directly shape nutrient dynamics.

Sociopolitical level	Drivers of nutrient dynamics	Hydrological level	Drivers of nutrient dynamics
EU	EU policy goals EU legislation		
National	Legislation and legislative power including implementation of EU law. Policy and policy-making power. National funding.	-	-
River basin authority	Development of legally binding river-basin management plans. Distribution of responsibility for implementing the WFD to both lower and higher sociopolitical levels.	River basin Drainage basin for entire river system.	Agriculture land use.[a] Urban land use.[a] Small drains.[a] WWTPs.[a] Horse farms.[a] Internal loading.[a] Natural background load.[a] Rainfall
County	Issuance of permits for activities that may impact water quality. Interpretation and implementation of the WFD. Mediation of access to state funding.	-	-
City Municipal political decision-making bodies Municipal boards and companies) Local action plan working groups District administrations	Strategy development for WFD Implementation at city and sub-catchment level. Land-use planning power within municipal boundaries. Wastewater infrastructure planning, implementation and management. Policy-making. Policy implementation. Funding from municipal taxation.	Sewershed The extent covered by Stockholm's centralised wastewater treatment system.	Population Capacity and degree of wastewater treatment Percentage of combined pipelines Percentage of impervious surfaces Misconnections and combined sewage overflows (CSOs) Pipe leakage Rainfall
		Sub-catchment Drainage area produced by natural catchment and technical catchment.	Land-use type and area[b] Topography Stormwater treatment facilities[b] Misconnections and CSOs (links to city-wide WWT system) Internal loading[c] Contribution from upstream waterbodies[d] Rainfall
		Micro Smallest spatial scale differentiated in hydrological modelling and management strategies	Land-use (loss co-efficient is applied according to land-use types)[e] Site history Stormwater infrastructure Soil moisture Rainfall

a) Derived from North Baltic Sea River Basin Management Plan
b) Requirements of the StormTac model that was used to calculate stormwater (diffuse) loading from land-based sources.
c) Derived from ALcontrol assessment (ALcontrol Laboratories and SLU, 2019; Stockholms Stad *et al.*, 2021).
d) Bällstaån stream is considered a major contributor and has its own action plan (Stockholms Stad *et al.*, 2021).
e) Derived from StormTac database.

4.4.2 Cross sociopolitical level interactions, and implications

Eight key drivers were seen to interact across sociopolitical levels to inhibit or enable nutrient management: 1) goals, 2) institutional norms, 3) legislation, $) interpretation and enforcement of legislation, 5) availability of funding, 6) collaboration and knowledge exchange, and 7) infrastructure implementation **(Table 4.5)**

4.4.2.1 Nutrient management requires greater goal alignment across sociopolitical levels

Participants both from across Stockholm's municipal government and from non-governmental water organisations saw WFD goals as insufficiently embedded into institutional norms across sociopolitical levels, particularly to implement nutrient management in a context with multiple priorities and jurisdictions. As explained by interviewees from Stockholm's municipal government, at city-level, several municipal boards have a role in implementing local action plans because they have jurisdiction over key drivers including land-use and wastewater infrastructure. However, as in other research (Moss, 2004; Cettner *et al.*, 2013; Söderberg, 2016; Bohman, Glaas and Karlson, 2020; Rowbottom *et al.*, 2022), the majority of interviewees in Stockholm's municipal government perceived a persistent 'siloing' of thinking and priorities. Together, these interviews can be taken to indicate that water quality goals have not been adequately integrated into norms at city level. As explained by an interviewee from Stockholm's environmental board:

"If they are remodelling a street that can be a perfect time to … have some kind of measure that will clean the water ... Because it's cheaper if you already are there and changing things." (Interviewee 7)

Aligning with other construction projects was seen as an enabler of the implementation of water quality measures, as has been argued elsewhere (Tscheikner-Gratl *et al.*, 2016). Interviewees from Stockholm's Environmental Board and municipal water company stated that alignment of different municipal boards around construction projects was key, particularly where one board had jurisdiction over relevant infrastructures but had limited expertise in water quality issues. These interviewees indicated that proactively communicating opportunities and aligning plans were not part of boards' planning norms. Therefore, opportunities to implement water quality measures alongside other developments were frequently missed. As found previously, this paper argues that this poses an important barrier to the implementation of nutrient management and the WFD (Cettner *et al.*, 2013; Bohman, Glaas and Karlson, 2020; Rowbottom *et al.*, 2022).

Further analysis of the interview data suggested that further challenges arise due to the variety of other existing and emerging goals that must be implemented in a high-density city by city-level actors. As highlighted by an interviewee from Stockholm's traffic board, many of these goals originate from multiple sociopolitical levels in the form of "*legislation and the EU directives that I have to look at and … the goals from the political part, and in the city."* (Interviewee 16) From the research data, it is clear that water quality goals must be prioritised and often integrated with these goals at city-level to enable management implementation (Söderberg, 2016; Stafford-Smith *et al.*, 2017; Nieuwenhuis *et al.*, 2021). All participants identified goals that have implications for nutrient management. Actors identified a variety of goals that have implications for nutrient management, including urban development and increasing housing in the city, maintaining the direct re-use of sewage sludge on agricultural land, improving urban biodiversity, and adapting to and mitigating climate change.

Urban development and increasing housing in the city, and adapting to and mitigating climate change were a concern across all types of research data and groups engaged in this research. My synthesis of the research data suggests that conflicts and synergies between these goals and nutrient management stems from their mutually strong links to land use and management, which was a critical concern for the majority of participants. Key concerns included the reallocation of land set aside for stormwater infrastructure for housing development, which were expressed by interviewees from city-level water and environmental organisations. Conversely, site, city and national level allotment garden representatives were concerned that any perceived impacts of allotments on water quality could encourage the redevelopment of those sites. Maintaining or increasing the use of land for greenspace was also almost ubiquitously seen as important for climate change adaptation across participants and bodies of research data. Improving urban biodiversity, also emerged as a key goal that impacted land use in the city. This was primarily mentioned by participants from allotment gardens, as they saw allotment gardens as key green spaces for promoting urban biodiversity. However, several governmental interviewees and workshop participants also drew links between the presence and management of allotment spaces to urban biodiversity. Six participants from governmental and non-governmental environmental, water and waste organisations across sociopolitical levels highlighted another key policy goal that this research finds significant for nutrient management in Stockholm. Namely, the management of sewage sludge and its direct re-use on agricultural land. This issue was similarly linked to land use in the city due to an increased shift towards decentralised stormwater treatment in the city.

Development was most commonly stated as competing with water quality goals. Interviewees from Stockholm's environmental board and wastewater company found that clashes frequently arose between the municipal boards over plans for particular micro-level sites, slowing the implementation of WFD goals, as found in other studies (Söderberg, 2016; Sandström, Söderberg and Nilsson, 2020).

There was a sense that water quality was increasingly prioritised over development, with one interviewee from the environmental board stating that in the event of a clash they *"probably would get a pond instead of the building."* (Interviewee 7) They attributed this to a strong embedding of water quality goals at county level, and their refusal of permits for projects that could negatively impact water quality according to WFD rules. Nevertheless, achieving the prioritisation of water quality goals was seen as an ongoing challenge. As stated by an engineer from Stockholm Water and Waste, it was considered inappropriate to block other plans for spaces, particularly when plans for stormwater infrastructures were at early stages:

"Every time there is a new plan for housing or something they contact us and say, 'I're planning a new kindergarten and houses here, and I see that you have a space for a dam, oh what should I do?' And that's very good, but then I haven't come that far maybe on that particular place and maybe there are some obstacles … so I can't say 'Oh stop it,' or 'You have to clear that space.'" (Interviewee 6)

Taken together, these issues suggest that the WFD is not being translated into appropriate strategic decisions on land-use at city-level (Söderberg, 2016; Bohman, Glaas and Karlson, 2020). Instead, this analysis indicates that ongoing clashes between policy goals and jurisdictions in urban water management inhibit WFD implementation (Barbosa, Fernandes and David, 2012; Bohman, Glaas and Karlson, 2020; Sandström *et al.*, 2020).

Interview participants from Stockholm's traffic and environmental boards, and its municipal water company felt there was a risk that WFD goals would not be achieved in Stockholm. As stated by an interviewee from Stockholm's municipal water and waste company, it is projected that all the nutrient management measures outlined in the local action plans need be implemented to achieve WFD targets:

"If the total load that has to be removed is 80 kilos maybe, I have tried to get measures that take away 120, a little bit more, but in many action plans it has not been possible. So, when the action plans come to us, I should have to do everything in order to reach good chemical and ecological status." (Interviewee 6)

As well as the interview participants, the municipal planning documents reviewed indicated that there are a limited number of appropriate sites at the micro-level, which means there may not be alternatives if they are used for other purposes.

Drawing together this evidence, my analysis indicates that it may not be possible to achieve WFD goals if the challenges posed by high and increasing infrastructure density in urban catchments are not recognised and addressed (Kaur, Hewage and Sadiq, 2022). Participants suggested that a stronger political mandate at both city and national-level was needed, as well as better guidance and processes for prioritising water quality goals to effectively embed into the institutional norms of the municipal boards at city-level. This is likely to be essential for addressing the challenges of implementing water quality infrastructures in an urban environment (Ferguson *et al.*, 2013; Söderberg, 2016; Glaas, Hjerpe and Jonsson, 2018; Bohman, Glaas and Karlson, 2020).

4.4.2.2 Legislation disfavours the prioritisation of nutrient management at city-level

As seen in other case studies, legislative drivers including the WFD, the Swedish Environmental Code, and the legally binding River Basin Management Plans were perceived as essential enablers of nutrient management (Dawson *et al.*, 2018). However, the power at city-level for enforcing the WFD was seen as inadequate (Söderberg, 2016; Glaas, Hjerpe and Jonsson, 2018). Sub-catchment level local action plans for WFD implementation are not legally binding, a barrier that must be overcome through other drivers. In the event of clashes between water quality and other city-level priorities, the strict interpretation of the WFD by the County Administrative Board was seen as an essential driver for the prioritisation of water quality goals. As stated by one interviewee:

"My gold card is that I have the EU legislation and I also have my Länsstyrelsen [the County Administrative Board]. … And the good thing for us is that my county board has been quite hard on my Stadsbyggnadskontoret [City Planning Board] and Exploateringskontoret [City Development Board] to really look into the water issues." (Interviewee 7)

Where city-level legal powers do not exist, the interpretation and enforcement of national and EU level legislative drivers at county-level, can enable the prioritisation of water quality and nutrient management. However, this is not currently translating into the strong prioritisation and implementation of WFD goals at city level.

Conflicting national-level legislation on urban run-off management posed further challenges because, as indicated by an interviewee from Stockholm's traffic board, there are *"many different legislations that do not really talk to each other and that say different things."* (Interviewee 16) Consequently, municipal interview participants intimated that responsibilities for managing urban run-off are poorly defined and had to be interpreted and negotiated politically at city-level. Stockholm Water and Waste were given responsibility for the city's stormwater infrastructure; however, transfer of the ownership is still ongoing and hinders implementation at this level. This problem has persisted since first identified by Cettner et al., in 2013 (see also Glaas, Hjerpe and Jonsson, 2018; Bohman, Glaas and Karlson, 2020). Several municipal interviewees advocated for a change in relevant legislation to support city-level management efforts; however, they also indicated that this is a challenging and slow process (Söderberg, 2016).

4.4.2.3 *Misalignments between responsibilities and funding reduce capacity for implementation*

Together with political decision-making at city-level, this research found that legislative drivers also played a central role in generating misalignments between available funding and the level of responsibility for implementing the WFD at city-level. (Cettner *et al.*, 2014; Söderberg, 2016; Qiao *et al.*, 2019; Wihlborg, Sörensen and Alkan Olsson, 2019; Suleiman, 2021)

Stockholm Water and Waste is responsible for a considerable number of infrastructural wastewater measures in the local action plans (Stockholms Stad *et al.*, 2021). However, its available funding streams were deemed inadequate by several participants across municipal organisations represented here. This was seen to be a result of low fee levels determined by the interpretation of The Act on Public Water Services by city-level political actors (Lag om allmänna vattentjänster [Act on Public Water Services], 2006), and the lack of access municipal wastewater companies have to other forms of national-level funding for water quality projects. According to interviewees, the result is that Stockholm Water and Waste primarily relies on municipal boards like the Traffic Board (Trafikkontoret) financing stormwater facilities and then transferring them ownership. Overall, this was seen as driving a low rate of investment in new infrastructure by the company and inhibiting the implementation of nutrient management at city-level. One interviewee from Stockholm's environmental board stated:

"The water company tries to do it as much as possible, but … they only build new things when something breaks. So, if a pipe in the street breaks, they go in there and they try to replace it, maybe a little bit more, and this is like the investment level that they are working at, at the moment." (Interviewee 7)

According to these interviewees, improving funding streams was seen as essential to allow Stockholm Water and Waste to implement measures to achieve WFD goals, alongside the company's other priorities.

4.4.2.4 *Goal integration is driving a cultural shift towards 'multi-functional' spaces and infrastructures*

Municipal participants repeatedly referred to the need to implement the WFD alongside other priorities in a high-density urban environment as a key challenge. This was seen by many participants, particularly in Stockholm's environmental board, as driving a cultural shift towards 'multi-functional' measures and spaces that could integrate multiple goals, avoiding conflict over micro-level spaces.

Achieving synergies between goals was seen as essential, with one participant from the environmental board asking, *"how do I get the message that climate adaptation and water quality are very often connected if I do it in a good way?"* (Interviewee 3) Green spaces and infrastructures like rain beds were seen by several participants in Stockholm's water company, its environmental boards and from Stockholm's county administrative board as offering the potential to integrate nutrient capture with other urban goals. This reflects ongoing practitioner and academic discourses (Kiparsky *et al.*, 2013; Kuitert, Willems and Volker, 2023). However, as highlighted by both governmental and allotment garden workshop participants, managing infrastructures and green spaces like allotment sites for multiple sustainability benefits is not the norm (Cettner, Söderholm and Viklander, 2012). Consequently, several participants in both Stockholm's traffic and environmental boards saw a need for greater 'multi-functional' thinking in norms across the city-level. In the words of one participant from the environmental board:

"Taking care of the blue green spaces along the roads… did not use to be the part of the job. But guess what? Now it is, that's the point. So, I need to make sure that people ... take responsibility as a whole, as a team, right? Otherwise, you have the silo kind of mentality." (Interviewee 12)

According to these participants, building 'multi-functional' thinking into institutional norms will require organisations to develop new knowledge and to work more collaboratively with actors across sociopolitical levels. Further, they variously suggested that this process will require personnel, time, funding and support from city and national-level political actors to enable these organisations to work in new ways. These are frequently suggested as enabling factors in sustainable urban water management (Cettner *et al.*, 2013; Wihlborg, Sörensen and Alkan Olsson, 2019; Bohman, Glaas and Karlson, 2020; Suleiman, 2021).

Table 4.5: Cross sociopolitical level interactions that emerge as the result of the distribution and state of drivers across sociopolitical levels, and their implications for nutrient management in this context.

Sociopolitical level	Driver	State of Driver	Overall implication for nutrient management
EU	Legislation: WFD[a]	WFD mandates improvements in water quality and P management at river basin and sub-catchment level.	Nutrient management and water quality goals are not sufficiently embedded across the relevant sociopolitical levels. Changing this is essential for implementing nutrient management in a high-density city, where there is limited space and competing values around how the space should be used. This includes a high number of policy goals that must be implemented at city-level.
	Goals: multiple priorities	Multiple goals originate from this level, including wastewater system decarbonisation.	
National	**Legislation:** Swedish Environmental Code[b]	The WFD as it is transposed in the Swedish Environmental code and Environmental Quality Standards (EQS) prohibits the deterioration of water quality.	
	Institutional norms: Prioritisation of water quality	Improving water quality is a policy goal and legal requirement; however, the political mandate from this level is considered weak.	
	Goals: multiple priorities	Multiple goals originate from this level, including increasing housing.	
River-basin authority	Legal powers: RBMPs	Improving water quality is embedded in legally binding RBMPs	
County	**Legal powers:** jurisdiction over land-use planning	Have jurisdiction over land-use decisions that have a high likelihood of negatively impacting water quality.	
	Interpretation of legislation: Interpretation of WFD / EQS	WFD / EQS are interpreted strictly by county administrative boards.	
City	**Policy:** city and local action plans for improving water quality	Improving water quality is a policy goal and embedded in city and local action plans for achieving better water quality.	
	Institutional norms: prioritisation of water quality, planning	Water quality has not been fully embedded into the institutional norms of all the municipal boards. This means missed opportunities to implement water quality infrastructures alongside other projects, and frequent planning clashes with other goals.	
National	**Legislation:** division of responsibility at city-level	Legislation contains unclear divisions of responsibility for water quality management at city level.	Strict interpretation of the WFD / EQS at county-level favours the implementation of nutrient management. However, this is inhibited by a lack of legislation that defines responsibility for managing urban run-off at city-level, and insufficient legal powers at city level. The need to negotiate responsibilities at city-level is slowing implementation.
County	Interpretation of legislation: interpretation of WFD / EQS	WFD / EQS are interpreted strictly by county administrative boards, which can achieve prioritisation of water quality goals.	
City	**Legal powers:** local action plans	Local action plans are not legally binding, so other drivers are important for implementation.	
	Division of responsibility: responsibility for stormwater infrastructure	Division of responsibility for managing urban run-off is not defined at national level. Therefore, it needs to be negotiated at city-level, which is an ongoing process.	
National	**Legislation:** Public Water Services Act[c]	The fees charged by municipal water and waste companies may not exceed the amount needed to cover the necessary costs of building and running wastewater treatment and drinking water production facilities.	The funding and capacity for implementing nutrient management at city-level are misaligned with responsibility for implementing the WFD at this level. Stockholm Water and Waste are the body legally responsible for managing stormwater infrastructures. However, current funding streams are deemed inadequate for the company to implement the mandated infrastructure. Instead, they rely on the construction of infrastructure by other municipal boards. This slows implementation of nutrient management.
	Funding: national funds for water projects	National-level funding is accessible to municipal boards, but not to municipal companies.	
City	**Division of responsibility:** responsibility for stormwater infrastructure	The municipal company, Stockholm Water and Waste has been designated legal ownership and responsibility for stormwater infrastructure.	
	Interpretation of legislation: interpretation of Public Water Services Act	The municipal council interprets the Public Water Services Act to decide the fees that Stockholm Water and Waste can charge.	
	Funding: funding for Stockholm Water and Waste	National funding for water quality projects is not available to Stockholm Water and Waste. Wastewater treatment fees are inadequate for Stockholm Water and Waste to invest significantly in stormwater infrastructure.	
	Stormwater infrastructure: Implementation of stormwater infrastructure	Stormwater infrastructure must be built by other municipal boards and their ownership transferred to Stockholm Water and Waste.	
EU	**Goals:** multiple priorities	Multiple goals originate from this level, including the WFD and climate change mitigation.	High urban density and a high number of priorities that must be implemented at city level are driving a shift towards green spaces and infrastructures for nutrient management. This is because they are seen to offer 'multi-functionality,' whereby multiple priorities can be addressed simultaneously. However, the capacity to design and implement these kinds of measures is seen as low, due to limited funds, time and support. All of which inhibit the embedding of 'multi-functional thinking' into institutional norms at city-level.
National	**Goals:** multiple priorities	Multiple goals originate from this level, including climate change adaptation.	
	Support: support for capacity development	Limited political mandate and provision of support for embedding 'multi-functional thinking' into norms across the city-level.	
City	**Goals:** multiple priorities	Multiple goals must be implemented at this level, including water quality improvements, housing development, climate change adaptation and mitigation, and increasing biodiversity.	
	Institutional norm: multi-functional infrastructure	Interest in green spaces and infrastructures is growing.	
	Institutional norm: multi-functional thinking	There is a perceived need for city-level actors to think in 'multi-functional' ways to integrate multiple priorities.	

Directive 2000/60/EC Establishing a framework for Community action in the field of water policy, 2000
SFS 1998:808 Miljöbalk [Swedish Environmental Code], 1998
SFS 2006:412 Lag Om Allmänna Vattentjänster [Act on Public Water Services], 2006

4.4.3 Cross-scale interactions and implications

Cross-scale interactions between sociopolitical and hydrological drivers had further implications for the implementation of nutrient management and eutrophication mitigation. The following key hydrological drivers participated in cross-scale interactions with sociopolitical drivers: 1) infrastructure density, 2) centralisation of stormwater treatment, 3) level and capacity of treatment in wastewater treatment plants (WWTPs), and 4) knowledge gaps and uncertainties regarding catchment and 5) micro-level hydrological drivers and dynamics. Key interacting sociopolitical drivers were a) goals, b) institutional knowledge norms, c) legislation, d) legal power, and e) funding **(Table 4.6)**.

4.4.3.1 Hydrological drivers and other priorities constrain opportunities for nutrient management

Overall, this research found that cross-scale interactions between water quality goals, other priorities and hydrological drivers shaped and often severely constrained opportunities for implementing nutrient management. High density of impervious surfaces was identified in documentary sources, workshops and interviews as an important driver of nutrient dynamics. This driver was deemed relevant at all hydrological levels and was expected to increase due to development pressure. Taken together, these sources suggested that interactions between high infrastructure density, higher level goals like climate change mitigation, and economic drivers placed strict limitations on the degree to which the built environment of the city could be transformed. This was a particular concern amongst city-level municipal representatives who had responsibility for transforming urban spaces and wastewater infrastructure. The issue was also referenced by a representative from Svensk Vatten as an example of some of the challenges realising EU level legislation as a nation state: *"It's an extreme climate footprint to rebuild the cities, existing ones, so … I say no to rebuilding existing cities."* (Interviewee 1) These interviewees intimated that this challenge limited the types of infrastructures that were considered for reducing diffuse urban nutrient losses and constrained where they could be placed. Climate mitigation goals posed further challenges for managing nutrient pollution as there was growing pressure to decarbonise the water sector. As expressed by one interviewee from Stockholm Water and Waste:

"In some years I should be resource neutral. Sometimes they call it climate neutral. And … I who work a bit above that or below that I say that it's going to be really difficult because in order to improve water quality I should do a lot of measures on the whole plant, like in the pipes and everything so that's going to be difficult." (Interviewee 6)

The concerns expressed by interview participants indicate that their remains a lack of clarity around how EU and national-level goals to decarbonise the wastewater treatment sector can be resolved with the significant infrastructural change needed to mitigate nutrient losses.

The analysis found that the move towards separating combined areas of Stockholm's sewer system also had important implications for nutrient management, particularly if wider systemic interactions and potential trade-offs were not considered (Metson *et al.*, 2015b; McPhearson *et al.*, 2022; Metson, Brownlie and Spears, 2022). According to an interviewee from Stockholm Water and Waste, separation would redirect stormwater away from WWTPs that "*could contain metals and other pollutants, but not nutrients and organic matter, which the treatment plants are built for and which improve the sludge*" (Interviewee 15). As discussed previously, six participants from governmental and non-governmental environmental, water and waste organisations discussed the links between managing diffuse urban water pollution and wastewater nutrient circularity. While two interviewees highlighted the controversies around this practice, overall, separation was seen as a way to deliver the city-level goal of improving sludge quality and maintaining its re-use in agriculture. Further analysis of interview and documentary data identified the reduction health risks from contaminated water, and targets for combined sewage overflow reduction in the proposed update to the EU's UWWTD as other key drivers of sewer separation.

The cross-level interactions synthesised from these data sources suggest that an insensitivity to catchment-level drivers could mean that implementing these higher-level goals at sewershed level could negatively impact nutrient dynamics at catchment level. As highlighted by interviewees from both water and environmental organisations, combined systems where stormwater is treated in WWTPs can be "*good because you clean phosphorus and nitrogen in the treatment plants anyway, so it's like this to double the functionality*," (Interviewee 3 from Stockholm's Environmental Board). This means directing stormwater away from WWTPs to achieve CSO reduction and sewage sludge re-use targets through sewer separation can conflict with nutrient management goals. As a participant from Svensk Vatten pointed out: "*If you have to avoid having more than 1% CSO you have to separate. But if, on the other hand, you're not allowed to have urban runoff untreated [in-line with the new UWWTD] then it will be very expensive*," (Interviewee 1) this is because more decentralised treatment will be needed to treat stormwater that was previously treated centrally (Alves *et al.*, 2016).

Overall, this research finds that implementing further decentralised facilities to deal with the additional nutrient load may be unrealistic when considering the ever-increasing pressure on space; particularly, as there remains a high degree of uncertainty that micro-level hydrological drivers like soil moisture, history of the site and land-use values will allow even the current planned sites to be used.

Therefore, separation of the combined wastewater system according to nutrient dynamics at the sewershed level may be unfavourable to nutrient management at sub-catchment level. Consideration of sub-catchment level drivers may instead favour alternative measures or combinations of measures. For example, one interviewee from Stockholm Water and Waste suggested better upstream source control, while an interviewee from the environmental board highlighted that reductions in CSOs in Stockholm had already been achieved by increasing the capacity of the centralised wastewater treatment system. This resonates with arguments that both centralised and decentralised solutions, as well as nature-based solutions, should be integrated for better management (Alves et al., 2016; Cettner et al., 2012; Marsalek & Schreier, 2009)

4.4.3.2 Legislation inhibits planning decisions according to sub-catchment level nutrient dynamics

Constraints generated by cross-scale interactions between hydrological drivers and other priorities were seen as exacerbated by legislative drivers that prevented city-level actors implementing management strategies in-line with dynamics at sub-catchment level. This mirrors findings that inappropriate legislation can limit responsiveness to ecological drivers and inhibit the implementation of nutrient management at city-level (Nykvist, Borgström and Boyd, 2017).

Municipal participants cited legislation around stormwater as a key example. At present, the Planning and Building Act obliges new building developments to perform stormwater treatment on-site, with no obligations for existing buildings (SFS 2010:900 Plan- och bygglag [The Planning and Building Act], 2010). However, the municipality has no power to define what form of stormwater handling should be performed, as explained by an interviewee from Stockholm's Traffic Board:

"You cannot say exactly what kind of stormwater handling you want in this place, you can only say this surface can be used for stormwater handling. ... You cannot say that you want tree planting here or something, that's not allowed." (Interviewee 16)

This means that interpretation is left to the developer, which this research suggests may pose challenges for the implementation of measures according to the nutrient dynamics in a particular sub-catchment. Weaknesses in the Planning and Building Act (SFS 2010:900 Plan- och bygglag [The Planning and Building Act], 2010) have previously been identified as a barrier to sustainable urban water management in Sweden (Glaas, Hjerpe and Jonsson, 2018).

Similarly, while national and city-level guidance for the management of stormwater recommends that stormwater be managed close to its source; however, my synthesis of insights from policy documents and interview data suggests it is not supported by existing legislation. The Public Water Services Act (SFS 2006:412 Lag om allmänna vattentjänster [Act on Public Water Services], 2006) obliges municipal water companies to take responsibility for stormwater management, which can act as a driver that favours end-of-pipe rather than upstream management. The issue was summarised by an interviewee from Stockholm‘s Environmental Board:

“Stockholm Water… have to take care of the stormwater, but maybe it would be better if the stormwater gets infiltrated outside the house, instead of put in a pipe, but the legislation says that they have to have a pipe. So, if someone says I want the pipe then they have to give them a pipe. So it's not always easy.” (Interviewee 7)

Representatives from allotment sites and organisations also provided insights into how city-level regulation could influence micro-level land-use practices that were important for nutrient dynamics at this level. For example, allotment garden representatives in the second workshop also suggested that changes in city-level rules and regulations could set expectations for how the allotment sites, leased from the city, should be managed. A key action developed in this workshop for improving the sustainability of urban agriculture in these sites was introducing explicit guidelines for nutrient and water management at city-level. A second was the provision of appropriate support could encourage actors at the micro-level of the allotment gardens to take greater responsibility for nutrient management. In both the interviews and workshops, participants from allotment garden sites and organisations proposed that nutrient management education could be added to existing environmental certification schemes that are provided by the Swedish Allotment Association. The municipality could then support the process by providing incentives for certification like lower rates for land rental.

Overall, this research demonstrates a need to address current unfavourable cross-scale interactions, largely attributed to unfavourable rules and legislation around land-use, to facilitate changes in land-use and water management according to nutrient dynamics at the sub-catchment and micro-level.

4.4.3.3 Uncertainties and knowledge gaps require changes in knowledge production norms

Further analysis suggested that more unfavourable cross-scale interactions occurred as a result of misalignments between two key drivers. The first was knowledge of nutrient dynamics across hydrological levels. The second was norms around acceptable levels of uncertainty embedded in legislation and political decision-making at city and national-level. Of central importance, were uncertainties around nutrient dynamics and drivers at sub-catchment level, as well as uncertainties around the efficacy of micro-level green infrastructures for nutrient management. This research found that these challenges played a key role in whether certain strategies were considered viable, were funded or were given legal weight.

Uncertainties around catchment-level dynamics were primarily highlighted as a concern by interviewees from Stockholm's Traffic Board and Stockholm Water and Waste. Uncertainties in drivers and nutrient dynamics at the sub-catchment level were seen by these participants as incompatible with the knowledge standards embedded in legislation at national level. For, example one interviewee from the Traffic Board saw this as a key reason that local action plans were not given legal weight:

"There are criteria in the legislation that you have for those action programmes, and you have to have good enough quality on the data … And those things are not very good at the moment." (Interviewee 16)

The interviewee from the Traffic Board further explained that uncertainty and knowledge gaps around hydrological drivers at various levels had inhibited the development of appropriate legislation for handling urban run-off:

"Normally the national authorities, when they are responsible for a law, they also take out little guidelines for how it's supposed to be done in detail. But for stormwater, for example, it really does almost not exist." (Interviewee 16)

According to this interviewee, the development of clear legislation and guidance was inhibited by knowledge gaps concerning stormwater dynamics and the effectiveness of stormwater treatment facilities at both the micro- and catchment-level. As found here, other research has found that the lack of clear guidelines can act as a barrier to implementing management solutions (Qiao *et al.*, 2019), and there have already been calls for greater coordination of stormwater legislation at national level (Nykvist, Borgström and Boyd, 2017).

Similar uncertainties existed around micro-level drivers for both specific land-use types and management facilities. Different participant groups revealed different key knowledge gaps, demonstrating the value of engaging participants across sector and sociopolitical levels. Gaps in understanding of the role of allotment gardens in eutrophication was a key concern for research participants from both individual allotment sites, and Stockholm and Sweden's allotment garden associations. In the workshops, these participants identified uncertainties and knowledge gaps around the state of allotment garden micro-level drivers like fertilisation rates, cropping and soil management practices and their impacts on sub-catchment level nutrient dynamics. One representative of the allotment garden associations highlighted that these knowledge gaps meant that it was currently necessary to scale down knowledge from conventional agriculture:

"There is a lot of knowledge gaps … and what I are working with is much from like the conventional farming or growing and I try to take those advice that are actually being developed for big scale and scale it down, which is not always so suitable." (Interviewee 17)

Analogous barriers emerged around the use of green infrastructures like rain gardens for mitigating nutrient losses. Participants from the traffic board, the environmental board, and Stockholm Water and Waste saw rain gardens as having the potential to address multiple priorities in a small space, which one representative from Stockholm's Environmental Board found made them likely to attract funding. However, participants from the traffic board and Stockholm Water and Waste also stated that knowledge of how green infrastructures, including rain gardens, function as facilities for nutrient retention at the micro-level is insufficient. For example, an interviewee from the traffic board stated:

"About the planting pits, I have to find out how they work over time because I think that if you have a leakage of nutrients you can't… there might be a leakage like the first year and the second year, but what happens after five years or 10 years? I don't know that yet." (Interviewee 2)

The use of green infrastructures for mitigating nutrient losses is an area of ongoing research (Lundy *et al.*, 2022) and several municipal participants stated that there were current collaborations between the municipality and academic actors in Stockholm. Nevertheless, overall, this analysis finds that the shift towards micro-level multifunctional spaces and infrastructures for improving water quality was seen as a move towards strategies and technologies whose effectiveness is more uncertain. Consequently, while the participants who referenced these types of spaces and infrastructures saw this shift as necessary, misalignments with institutional knowledge standards within and across sociopolitical levels posed a barrier to their implementation. One outcome experienced by interviewees in the traffic and environmental boards was difficulties financing green infrastructures that were intended for nutrient management through stormwater funding schemes. Other authors have highlighted similar difficulties around funding for blue-green solutions and a reluctance to implement them due to uncertainties regarding their efficacy (Wihlborg, Sörensen and Alkan Olsson, 2019; Suleiman, 2021).

Participants across all groups suggested changes in norms around knowledge production to address these barriers, largely to fill knowledge gaps and create greater alignment with knowledge standards by reducing uncertainty. As argued in the adaptive governance literature (Huitema *et al.*, 2009), monitoring and evaluation were seen as key sociopolitical drivers for filling knowledge gaps. However, participants across the traffic and environmental boards noted difficulties getting funding for monitoring and evaluation. They found it was particularly challenging to implement monitoring over the timeframes necessary to understand micro-level nutrient dynamics and their role in sub-catchment level ecological change. Overall, this research found that knowledge generation and learning were insufficient to prompt changes in sociopolitical decision-making around nutrient management, a key barrier to adaptive governance (Nykvist, Borgström and Boyd, 2017).

Addressing this funding problem was obviously seen as key; however, many participants across the engaged groups saw a need for greater changes. As a wicked problem, eutrophication is characterised by high uncertainty and requires strategies for developing and implementing strategies under these circumstances (Thornton *et al.*, 2013). In-line with this concern, several participants advocated for changes in norms around knowledge production at city-level. Several advocated for more experimental, 'learning by doing' approaches, whereby new and "innovative" measures would be implemented despite uncertainties around their efficacy. The need for this kind of approach was primarily linked to difficulties in evaluating measures when not in-situ and the necessity to develop novel, multi-functional measures. Finally, many participants argued for more collaborative approaches to not only support a shift in norms towards 'learning-by-doing,' but to address sociopolitical misalignments by building connections between actors and increasing buy-in. The desire to change knowledge production norms was by no means universal across participants, and several interviewees from the environmental board also intimated that this reflected a similar divide between city-level government actors more broadly. Nevertheless, the calls for shifts towards more experimental and collaborative knowledge production resonates strongly with literature on the sustainable management and governance of socioecological systems. This body of literature frequently advocates for collaborative and experimental approaches as powerful tools for mitigating highly uncertain 'wicked problems' (Bettini et al., 2015; Huitema et al., 2009; Sandström, Söderberg, & Nilsson, 2020).

4.4.3.4 High rate and longevity of change is needed for successful nutrient management

Temporality played an essential role in cross-scale alignments and misalignments, as has been argued in other literature (Cumming, Cumming and Redman, 2006). Interviewees identified two key challenges rooted in the temporal dimensions of hydrological and sociopolitical drivers. The first was how quickly hydrological drivers emerge or change in negative ways, versus the apparent slowness of changes in regulation, behaviour change and infrastructure. This is a commonly identified cause of mismatches between governance arrangements and the socio-ecological systems (Epstein *et al.*, 2015). As stated by one interviewee from Stockholm Water and Waste:

"So if I are going to have clean water in 2027 -good luck!- I need faster measures because changing people's behaviour, it takes time. And I don't have the time. ... Regulation is the best thing, if you can get it to work." (Interviewee 6)

Despite the expressed need for changes in regulation and legislation, some interviewees from the environmental and traffic boards were doubtful that national-level legislation would change in the timeframes needed to achieve WFD goals. For example, an interviewee from the traffic board stated that *"the need for revising the legislation in Sweden have been on the agenda for a long time, but it doesn't happen very much,"* (Interviewee 16) which made it challenging to effectively distribute responsibility for water quality measures at the city-level.

The second challenge that emerged from the interviews was how to "keep the flame" burning over the timeframes necessary to achieve ecological change. In other words, sustaining goals, knowledge, expertise and water quality measures themselves over various sociopolitical cycles, in order to achieve the desired changes in nutrient dynamics (Folke *et al.*, 2007). Interviewees from Stockholm's city council and environmental board expressed concern that changes in Sweden's and Stockholm's political leadership could lead to the de-prioritisation of water quality goals and reduced funding. However, there was also a perception that the WFD and corresponding national-level legislation would be an important driver for maintaining water quality goals over national and city-level political cycles. This issue was also seen as important at the micro-level, as responsibility for managing water quality facilities changes hands. The challenge was described by one interviewee from Stockholm's environmental board:

"For instance, if you have… rain gardens along the streets, right? You need to explain to the entrepreneurs taking care of it that that you shouldn't put nutrients on it. … because it's a green factory in disguise, right? It's supposed to retain stuff … So it's very much like you need to keep the flame and you need to keep the knowledge going." (Interviewee 12)

This quote also reflected a concern expressed by several interviewees in Stockholm's environmental board that knowledge and expertise needed to maintain measures had to be preserved in the long term (Hansen and Pauleit, 2014; Wihlborg, Sörensen and Alkan Olsson, 2019; Bohman, Glaas and Karlson, 2020; Suleiman, 2021). Again, funding was a key issue and several participants stated that there was a lack of funding and resources for maintaining water quality measures over the timescales needed to see recovery from the ecological impacts of nutrient over-enrichment. These misalignments with ecological timeframes can act as important barriers to effective nutrient management (Folke *et al.*, 2007; Huitema *et al.*, 2009). In addition to providing funding for maintenance, participants from Stockholm's traffic and environmental boards suggested that the municipality implement educational programmes and make them a requirement of its procurement processes, supporting the acquisition and the long-term maintenance of knowledge and expertise.

4.4.3.5 Collaboration facilitates implementation through goal integration and multi-functional thinking

Collaboration and mutual learning across and between sociopolitical levels were seen as essential for addressing the cross-scale misalignments generated by both knowledge gaps and unfavourable legislative drivers. Firstly, collaboration was seen as essential by interviewees from the environmental board for achieving goal alignment and 'buy-in' across the municipal boards. This was seen as important to reduce the lack of stronger legal obligations to the WFD at sewershed and sub-catchment level. One interviewee from the environmental board described the logic behind an increase in collaboration around the local action plans:

"But only for the action plans, there has been a collaborative group between the executors and the knowledge producers almost. … To make sure that everyone is on track with what I are working towards, and that everyone has the knowledge and has the ownership of it." (Interviewee 3)

Overall, there was a perception amongst these participants that increasing buy-in through collaboration could increase responsiveness and action that was in-line with nutrient dynamics, particularly where national and city-level legal drivers were unfavourable. In this respect, collaboration can enable the development and implementation of recommendations for watershed management (Koontz and Newig, 2014) that are also more aligned with the features of socioecological systems (Pahl-Wostl *et al.*, 2007; Moss, 2012; Glaas, Hjerpe and Jonsson, 2018; Bohman, Glaas and Karlson, 2020).

Secondly, in both the interviews and workshops, working collaboratively was presented as essential for disseminating knowledge of important drivers across hydrological levels to actors across the sociopolitical scale. While different participants focused on different types of knowledge, the importance of cross-level collaboration for knowledge exchange was common across all groups. Collaborative knowledge production and exchange was seen as a way to improve strategy development and responsiveness to key drivers across relevant sociopolitical levels. Cross-level collaboration was also seen by representatives from the environmental and traffic boards, and allotment garden representatives as fundamental for developing novel 'multi-functional' spaces and infrastructures. This agrees with findings across relevant literature on urban water issues, and goal integration (Serrao-Neumann *et al.*, 2017; Bohman, Glaas and Karlson, 2020; Kuitert, Willems and Volker, 2023) Both governmental and allotment garden representatives in the workshops proposed that city-level municipal actors and could collaborate with allotment associations and individual gardeners at the micro-level on pilot projects. Interviewees from both the environmental boards and allotment garden associations suggested that there was a need for 'bridging organisations' to facilitate collaboration across the city-level, which can act as important enablers of social learning (Pahl-Wostl *et al.*, 2007; Moss, 2012). Through these mechanisms, this research suggests that collaboration could reduce some of the uncertainties that are currently inhibiting strategy development and the implementation of nutrient management.

Table 4.6: Cross-scale interactions that emerge as the result of the distribution and state of drivers across both sociopolitical and hydrological scales, and their implications for nutrient management in this context.

Scalar Level	Driver	State of Driver	Implication for nutrient management
EU	**Legislation:** UWWTD[a] emerging legislation	Emerging legal requirement to reduce CSOs to < 1% dry weather flow.	Policy goals, legislation and high infrastructure density at sewershed and sub-catchment level interact to shape and severely constrain options for nutrient management. Separating combined networks to address CSOs is an emerging goal. However, high infrastructure density at sub-catchment level means it may not be possible to introduce the decentralised stormwater treatment needed to deal with stormwater that is currently treated centrally. Therefore, drivers and dynamics at multiple hydrological levels need to be considered when planning the implementation of measures to achieve CSO reductions.
National	**Goal:** Decarbonisation	Decarbonisation goals limit the extent to which the built environment and can be changed.	
City	**Goal:** Reduction of CSOs	The reduction CSOs is an emerging goal to improve water quality and to support the application of sewage sludge to land.	
Sewershed	**Infrastructure:** Wastewater network	A high proportion of Stockholm's wastewater network is combined, and a significant amount of stormwater is currently treated centrally in WWTP.	
	Water contaminants: Wastewater influent quality	Stormwater in influent reduces nutrient concentrations and introduces contaminants.	
		This challenges certification through the REVAQ[b] sewage sludge quality scheme and therefore, its application to agricultural land.	
Sub-catchment	**Nutrient sources:** combined sewage overflows (CSOs)	Sub-catchments are impacted by P inputs from CSOs.	
	Nutrient sources: urban run-off (stormwater)	Urban run-off or stormwater is a major source of P in sub-catchments.	
	Infrastructure: infrastructure density	High infrastructure density means there is limited space for implementing decentralised stormwater management.	
Micro	Biophysical conditions: site characteristics	Not all available sites are appropriate for stormwater infrastructure. For example, if the land was reclaimed from lake-bed.	
National	**Legislation:** the Planning and Building Act[c]	The planning and building act obliges new building developments to treat their own stormwater onsite. However, the municipality has no legal powers to define what form of stormwater management should be implemented.	Existing legislation and rules (including the Planning and Building Act[d] and the Water Services Act[e]) give inadequate power to shape land-use and water planning according to sub-catchment level hydrological dynamics. This poses significant challenges to nutrient management in-line with the intentions of the local action plans. Similar issues are apparent at micro-level and are seen to inhibit the development of strategies for allotment garden sites.
		There are no obligations for existing building developments to treat stormwater.	
	Legislation: Public Water Services Act[d]	The Public Water Services Act obliges the municipal water company to provide sewage and stormwater treatment to existing developments. This is seen to favour end-of-pipe solutions.	
City	**Legal powers:** stormwater planning	The municipality has limited legal powers define what forms of stormwater infrastructure are placed and where.	
	Regulation: land-use guidelines	The municipality does not set requirements for nutrient management in allotment sites.	
Sub-catchment	**Technical and natural hydrology:** placement of stormwater treatment facilities	Topography and existing infrastructure, including pipe networks, define hydrological connectivity and where stormwater treatment facilities may be usefully placed.	
Micro	Biophysical conditions: site characteristics	Not all available sites are appropriate for stormwater infrastructure	
	Land-use: nutrient management	No existing guidelines on how nutrients should be managed in allotment sites	
National	**Knowledge norms:** legally binding action plans	Knowledge norms require low uncertainty in nutrient sources, flows and drivers to make local action plans legally-binding.	Uncertainties and knowledge gaps around nutrient dynamics at multiple levels are incompatible with knowledge standards at multiple sociopolitical levels. Uncertainties in knowledge of sub-catchment level dynamics prevents local action plans being made legally binding. Knowledge gaps also inhibit the use of green spaces and infrastructures for nutrient management. Participants identified several knowledge production norms as inhibiting knowledge production to address some of these uncertainties. Namely, limited collaboration across and between levels and scales, insufficient monitoring and evaluation, and lack of 'learning-by-doing' approaches.
City	**Legal powers:** Local action plans	Local action plans for P management are not legally binding due to national knowledge norms and high uncertainty of sub-catchment level dynamics.	
	Knowledge production norms: cross-level collaboration	Current levels of collaboration for knowledge across the city level, and across levels are insufficient.	
		'Learning-by-doing' approaches are uncommon.	
		Insufficient monitoring and evaluation of measures.	
Sub-catchment	**Knowledge certainty:** sub-catchment P sources, flows and drivers	Knowledge of sub-catchment level P sources, flows and drivers has high uncertainty.	
Micro	**Knowledge gap:** nutrient removal efficacy of green infrastructures	The efficacy of green infrastructures for nutrient removal is uncertain.	
	Knowledge gap: Allotment P sources, flows, and drivers	Uncertainties in P sources, flows and drivers in allotment sites pose challenges to the development of management strategies.	
	Knowledge production norms: cross-scale collaboration	Current levels of collaboration across the city level, and across levels are minimal.	
EU	Legislation: WFD	The WFD was seen as an important driver for maintaining water quality goals at lower sociopolitical levels during sociopolitical changes like national or city level elections.	Participants highlighted the need to maintain water quality goals, expertise and measures over the ecological timeframes needed to observe system change. Funding and processes for knowledge exchange are essential to ensure the maintenance of water quality measures over the necessary timeframes and were seen as insufficient.
National	**Government:** government change	Changes in government may lead to the deprioritisation of water quality goals and reductions in funding.	
	Funding: funding for maintenance	Funding is unavailable for the long-term maintenance and monitoring of infrastructure..	
City	**Government:** government change	Changes in government may lead to the deprioritisation of water quality goals and reductions in funding.	
	Funding: funding for maintenance	Funding is unavailable for the long-term maintenance and monitoring of infrastructure.	
	Knowledge: Knowledge of water quality management	Knowledge of how to manage water quality and to maintain water quality measures like raingardens must be maintained across ecological timeframes.	
Micro	**Knowledge:** Knowledge of water quality management	Knowledge of good practices or how to maintain water quality measures must be maintained across ecological timeframes.	

The EU Urban Wastewater Treatment Directive is currently under revision (Directorate-General for Environment, 2022).
The REVAQ certification scheme is operated by the Swedish Water & Wastewater Association, the Federation of Swedish Farmers (LRF), the Swedish Food Federation and the Swedish Food Retailers Federation (Swedish Water [Svensk Vatten], 2020).
SFS 2010:900 Plan- och bygglag [The Planning and Building Act], 2010
SFS 2006:412 Lag Om Allmänna Vattentjänster [Act on Public Water Services], 2006

4.5 Conclusions

Nutrient management and the mitigation of eutrophication are frequently characterised as requiring solutions that are aligned across 'scales' and 'levels'. However, empirical analyses of what this means in practice are scarce. This paper has begun to address this gap by using a participatory approach to explore the importance of cross-level and cross-scale dynamics for the downscaling of the WFD, from the perspective of some of the actors involved. I have demonstrated that there is no one level or even scale that can be used in isolation to understand the drivers of nutrient losses and to develop strategies for their mitigation. Instead, efforts need to be made to understand how parts of the system that are often treated separately interact to enable or inhibit the mitigation of eutrophication.

I show that cross-level analysis can be valuable in contexts where multiple sociopolitical levels are identified as strategically important for nutrient management. In this case, cross-level analysis identified several misalignments that needed to be addressed to counteract the fragmentation of EU-level WFD goals during the process of downscaling. Clear divisions of responsibility are important for ensuring goal alignment across the relevant sociopolitical levels and can potentially be supported by clear expectations set at national level. Where responsibility for implementation is clearly established, it must be matched by the capacity to achieve coordinated action by relevant actors, particularly when multiple policy goals have the potential to clash. Finding synergies between nutrient management and other priorities can be of vital importance in these cases. However, this is not always possible and novel measures like green infrastructures come with levels of uncertainty that can generate disagreements over their place in nutrient management. In this case study, an important barrier at city-level was the lack of legal weight given to sub-catchment level local action plans, which could only partially be compensated for by enforcement at county-level and the generation of 'buy-in' through collaboration. Therefore, it is necessary to have appropriate guidance, processes, legal powers and planning norms that ensure the prioritisation of water quality goals where synergies cannot be found between conflicting priorities. Another essential enabler is ensuring that available resources match the expectations placed on actors across sociopolitical levels for implementing nutrient management. In Stockholm, this could mean addressing misalignments between the expectations placed on the municipal water company for implementing the WFD at sewershed and sub-catchment levels, and the legislation and city-level political decisions that dictate the company's funding streams.

Cross-scale analysis builds on cross-level analysis by identifying outcomes for nutrient management that arise as a result of the interactions between hydrological and sociopolitical drivers across both scales. Hydrological drivers across multiple levels play a fundamental role in dictating what kinds of measures can be implemented effectively and where. However, policy goals and legislation originating from multiple sociopolitical levels interact with these drivers to shape or inhibit the implementation of water quality measures. This issue can become particularly critical when these drivers create inflexibility in what types of measures can be implemented and where. As demonstrated by this case study, high coverage of soils with impervious surfaces at sewershed and sub-catchment levels are key hydrological drivers in the urban environment. Together with decarbonisation goals, the high density of infrastructure strongly constrained mitigation options. Cross-scale interactions between other policy goals and hydrological drivers can also negatively impact nutrient dynamics, particularly when policy goal implementation is insensitive to nutrient dynamics across hydrological levels. Consequently, it is necessary for decision-making across multiple sociopolitical levels to be responsive to drivers across the hydrological scale.

Achieving the necessary responsiveness to hydrological drivers can be inhibited by several cross-scale misalignments. In my case study, incompatibilities between institutional knowledge standards and uncertainties concerning nutrient drivers and processes across hydrological levels inhibited plans being given legal weight, funded, and implemented. Similar issues arose around the use of novel measures for managing nutrient losses, most notably green spaces and infrastructures that are increasingly seen as 'multi-functional' measures for resolving multiple policy goals. Unfavourable legislation, particularly around land-use and water planning, can compound these issues by undermining coordinated planning and action according to hydrological dynamics. There is a critical need to address these cross-scale misalignments to implement nutrient management goals in this context, a process that also requires aligning policy change, funding and the longevity of goals and expertise to the temporality of hydrological processes. Enhanced cross-level and cross-scale collaboration can play a central role by facilitating goal alignment or 'buy-in' across levels and scales and filling some important knowledge gaps. Most notably, collaboration can be a way to generate highly contextual knowledge across levels, and to develop and assess novel measures.

My analysis has identified many misalignments that are inhibiting the successful implementation of nutrient management, many of which would not have been identified without conducting cross-level and cross-scale analysis using a participatory approach. These findings demonstrate the importance of working with actors to identify and address cross-level and cross-scale misalignments to address the 'wicked problem' of eutrophication.

This paper adds evidence to the body of literature that advocates for a systemic and 'cross-scale' approach to the management of eutrophication, by highlighting critical implications for achieving WFD goals that only become apparent when considering not just multiple levels, but multiple scales. This offers an expansion on purely hydrological or governance perspectives, and even many socioecological perspectives that frequently focus only on one aspect. This is despite the theory's commitment to approaching these aspects symmetrically, from an interdisciplinary perspective. Furthermore, by distinguishing key scales, levels and interactions across them through practitioner insights, I emphasise the value of using practitioner perspectives to inform cross-scale analyses. This contrasts to the majority of multi-scale socioecological systems work, which usually assumes key scales and levels a priori.

5 Navigating scales in collaborative catchment management: the dual role of catchment partnerships in managing catchments as coupled human and natural systems

5.1 Abstract

The 'wickedness' of human impacts on water systems has driven an evolution towards more systemic, integrative and participatory management. However, their continued intractability has led to criticism that inadequate attention has been paid to scale, cross-level and cross-scale dynamics in addressing critical water challenges as systemic socioecological problems. Participatory governance organisations at the catchment or watershed level are often put forward as a potential solution to 'bridging' levels and scales; however, it remains unclear whether and how these types of organisations can contribute to the cross-scale management of catchments. This paper clarifies some of the contributions participatory catchment organisations can make to cross-scale management through a case study of four Scottish collaborative catchment partnerships. I introduce a conceptualisation of cross-scale catchment management as the management of interacting multi-level and multi-scale sub-systems of direct and indirect drivers to outline a dual role for catchment partnerships in cross-scale management. Catchment partnership act both as (i) actors for developing management strategies that align across spatial scales to achieve sustainability goals up to catchment level and (ii) for improving the alignment of indirect social, economic and political drivers across scales, increasing the likelihood that management strategies will be implemented that are compatible with catchment conditions. Based on this dual role, I outline some strengths of catchment partnerships, outline some limitations and barriers they face in fulfilling this dual role and finally discuss how the role of participatory catchment organisations in cross-scale water system management can be enhanced going into the future.

5.2 Introduction

As 'wicked problems,' water sustainability challenges are defined by their emergence from the complex interactions between social, ecological and technological factors, uncertainty or disagreement regarding their causes and potential solutions, and their need for multi-stakeholder solutions (Head, 2022). The intractability and 'wickedness' of negative human impacts on water systems has driven an evolution in research, policy and management approaches to critical water challenges (Benson, Jordan and Smith, 2013; Giakoumis and Voulvoulis, 2018). This evolution has seen a significant shift towards more systemic and integrative management perspectives based on hydrological boundaries and participatory governance (Benson, Jordan and Smith, 2013; Giakoumis and Voulvoulis, 2018). Noteworthy examples include the embedding of integrated water resource management approaches into the UN's sustainable development goal 6 (SDG6), "Ensure availability and sustainable management of water and sanitation for all" (Carlsen and Bruggemann, 2022); the development of the EU's Water Framework Directive (WFD) based on Integrated Water Resource Management (IWRM) (Moss et al., 2020; Water Framework Directive 2000/60/EC); and the emergence of "bottom-up" integrated catchment management initiatives that have been implemented worldwide (B. R. Cook *et al.*, 2013; Rouillard and Spray, 2017).

Many of the approaches in the current 'integrated' management paradigm take the river basin or catchment spatial level as the key level for management and governance, while recognising water system management as a 'multi-level' and/or 'multi-scale' effort (Rouillard and Spray, 2017; Carlsen and Bruggemann, 2022; Moore *et al.*, 2024). However, several authors have argued that progress to date to align management across 'scales' have been inadequate and that this is a key factor in the continued failure to improve the health of aquatic ecosystems. To overcome this, scholars advocate for a greater consideration of scale, cross-level and cross-scale interactions from a socioecological systems perspective in catchment management (Gain *et al.*, 2021; Whaley, 2022; Bennett and Reyers, 2024; Moore *et al.*, 2024). Considering scale, cross-level and cross-scale interactions is essential both for the development of on-the-ground management strategies (key scale terminology used in this paper given in Table 5.1). It is also fundamental to the successful functioning of multi-level governance systems to enable their implementation (Bennett & Reyers, 2024; Gain et al., 2021; M.-L. Moore et al., 2024; Whaley, 2022; Young, 2002). Consequently, there is a need to consider how the participatory governance organisations that are increasingly prominent in water management can navigate these scale challenges. This is an important consideration if they are to play their envisioned role in achieving sustainable water systems.

This paper aims to clarify whether and how participatory water governance institutions at the catchment level can play a role in enhancing the systemic 'cross-scale' management of water. I investigate this issue through an explorative case study of four Scottish collaborative catchment partnerships, based on document analysis and semi-structured stakeholder interviews. I aim to answer the following research questions:

(i) What is the added value of collaborative partnerships for addressing scale challenges in the socioecological management of catchments?
(ii) What barriers and limitations are experienced by these catchment partnerships in addressing scale challenges?
(iii) How can these barriers and limitations be addressed so catchment partnerships can better contribute to cross-scale catchment management?

By addressing these questions my aim is to strengthen the role that collaborative partnerships can play in addressing critical water issues.

Table 5.1: Definitions of terminology related to scale, as used in this paper. Many of these terms will be used in different ways across or even within different disciplines. However, in this work, the following definitions are used to avoid issues with conceptual conflation that continue to challenge discussions of scale in socioecological systems management

Term	Definition
Dimension	An aspect of an object of study like space, time or power etc. that can be structured using a particular scale e.g., space can be ordered using many different scales including hydrological (plot, catchment, river-basin) or jurisdictional scales (local, regional, national).[b]
Scale	A graduated reference system that is used to structure a particular dimension of an object of study for analysis e.g., a temporal scale. [ab]
Level	Differentiated units of analysis within a scale e.g., a jurisdictional scale may contain local, regional and national levels.[ab]
Scalar level	A unique level within a specific scale.
Extent	The proportion of a scale that an object or phenomenon occurs over e.g., the spatial extent of a river basin that experiences eutrophication.[b]
Resolution / grain	The smallest unit of change that is measured.[c]
Generalisation	The extrapolation of data, system analyses or solutions developed at one level to other levels.[d] Often referred to as upscaling or downscaling data.
'Right' scaling	Identifying the optimal scale level(s) for analysis, intervention or the magnitude of system throughputs.[d]
Upscaling / downscaling	The propagation of system change from one level to others e.g., P recovery as struvite is upscaled from a lab-based niche innovation to full-scale deployment in wastewater treatment plants (WWTPs).[e]
Outscaling	The extrapolation of data, system analyses or solutions developed for one system to another system[g]
Temporal scale and timeframe	Temporal scales are applied to break time into discrete increments, timeframes are the individual increments or levels within a temporal scale. E.g seconds, minute, hours. [b]
Spatial scale and spatial level	A spatial scale is applied to break the geographic extent of a phenomenon into spatial units or levels. E.g plot, farm, landscape. [b]
Organisation scale and organisational level	An organisational scale is applied to aggregates of individuals within networks and contains levels that are largely defined by the number of individuals. E.g individual, community and nation, or organism, population, biome.[f]
Sociopolitical scales and levels	A jurisdictional scale describes the organisation of governance structures into discrete units or levels that generally operate over a defined spatial extent and are often organised hierarchically. They can also be referred to as jurisdictional, governance or policy scales / levels.[a]

Sources: [a]Cash et al., 2006, [b]Vervoort et al., 2012, [c]Friis et al., 2023, [d]Gibson, Ostrom and Ahn, 2000, [e]Bögel et al., 2022, [f]Cumming et al., 2006, [g]Lam et al., 2020

5.3 Conceptual basis

In this research, I draw on socioecological systems theory to define the 'cross-scale' management of water systems, distinguishing between 'direct' and 'indirect' system drivers to outline a dual role for collaborative catchment partnerships in implementing systemic cross-scale water management.

In socioecological systems theory, critical water challenges are considered emergent properties of socioecological systems consisting of interacting social, technical and ecological drivers (Liu *et al.*, 2007; Ostrom, 2009). These drivers are conceptualised as operating across multiple 'scales'. Spatial, temporal, organisational and sociopolitical scales are commonly used to structure and analyse socioecological systems. These scales are sub-divided into internal 'levels'; for example, a spatial scale can contain the plot, field, farm and catchment spatial levels. Different scales and constituent levels may be applied according to their relevance to the system of analysis and the choice of the analyst. Sociopolitical scales are commonly applied to the analysis of the indirect governance drivers of water systems but are largely considered irrelevant to the direct ecological aspects. Similarly, the subdivision of a scale into particular internal levels may be appropriate for the analysis of some components but not others. For example, a Global 'level' in a spatial scale is considered relevant for the analysis of both hydrological and economic drivers. However, subsequent spatial levels like the EU bloc, national, and regional levels have little significance for hydrological drivers. When observing across different levels in an applied scale, drivers and processes may become 'visible', 'invisible' or change according to the level of observation. For example, on a yearly timeframe (temporal level), fertiliser inputs to a catchment may be the primary anthropogenic driver of eutrophication in a lake. In contrast, on a multi-decadal timeframe, land-use change through the drainage of swampland may be the most significant driver (Siman & Niewiarowski, 2023). Furthermore, while system drivers and processes may be treated as operating on different levels and even within different scales for analytical purposes, they may nevertheless be in interaction with each other. Consequently, in socioecological systems theory, effective cross-scale management means taking into account diverse drivers across various scales and levels, as well as the 'cross-level' and 'cross-scale' interactions between them (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Gain *et al.*, 2021; Whaley, 2022; Bennett and Reyers, 2024).

Drawing further on socioecological systems theory, I make a distinction between the 'direct' and 'indirect' drivers of water system challenges (Nelson *et al.*, 2006; Rounsevell *et al.*, 2021), and suggest that the socioecological system can be usefully divided into a 'direct' and 'indirect' sub-system for socioecological cross-scale management, as they are often treated separately and analysed using different scales. The 'direct' sub-system consists of social, ecological and technical drivers across 'scales' and 'levels' that are considered to directly impact the chemical and ecological status of a given water system. These are drivers like riparian cover, nutrient inputs, and land-use that are usually the focus of physical on-the-ground measures. Typically, spatial and temporal scales are used to analyse these drivers. Conversely, 'indirect' sub-system drivers are those that are thought to impact water systems in a more indirect or diffuse way. These are drivers like environmental attitudes, technological development, and regulation that interact across 'scales' and 'levels' primarily to determine whether on-the-ground measures are successfully implemented through their influence on human behaviour. A variety of scales are used to analyse these drivers; however, sociopolitical scales are most commonly applied due to the socioecological systems literature focus on governance. Overall, cross-level and cross-scale interactions both within and between the direct and indirect sub-systems determine outcomes for the chemical and ecological status of water systems (these interactions are represented in **Figure 5.1**).

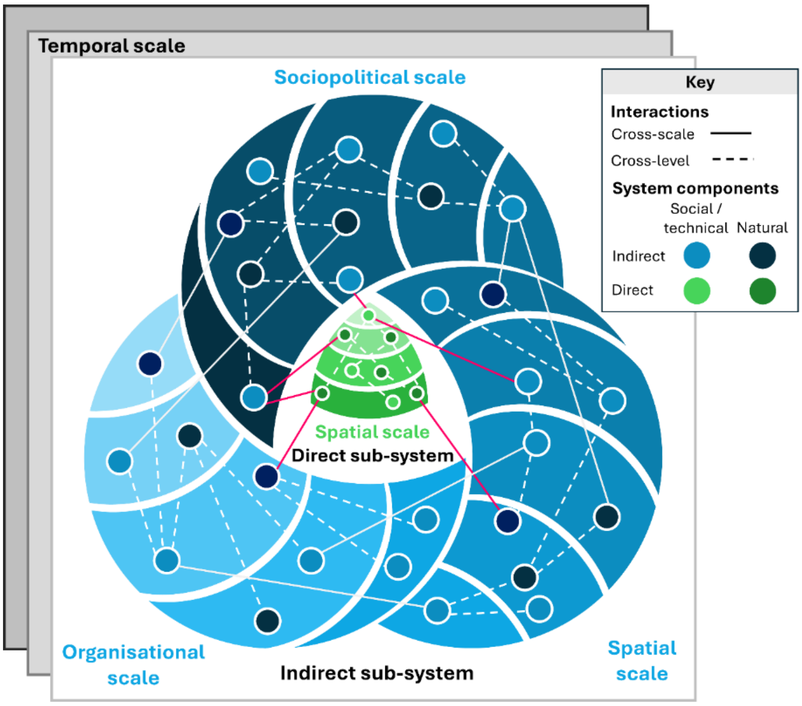


Figure 5.1: A representation of the scales, cross-level and cross-scale interactions that have important implications for the successful management of eutrophication. We distinguish between the 'direct sub-system' and the 'indirect sub-system'. The 'direct sub-system' (in green) consists of the direct sub-system drivers which are considered when developing on-the-ground management strategies. The indirect sub-system (in blue) consists of the broader factors that can more indirectly influence system dynamics and whether management is successfully implemented. Both the 'direct' and 'indirect' sub-systems consist of social, technical and ecological components and analysed in scale terms. Different scales are typically used to analyse the 'direct' and 'indirect' sub-systems in the literature. Direct drivers are typically analysed using spatial and temporal scales, while sociopolitical scales are dominant it in analyses of 'indirect' sub-system drivers. Cross-level and cross-scale interactions are typically analysed within the direct or indirect sub-systems, analyses of cross-scale interactions between the 'direct' and 'indirect' sub-systems are limited.

I use concept of the 'direct' and 'indirect' subsystems to define a dual role for catchment management organisations in cross-scale management. The first is as an actor in the direct sub-system that physically implements on-the-ground measures. The second is as actor in the indirect sub-systems that navigates, impacts and mediates between indirect drivers to influence the likelihood of favourable changes in direct sub-system drivers i.e. the implementation of management strategies. This conceptualisation of the dual role of catchment partnerships identifies two essential aspects that need to be assessed to answer my research questions. The first is whether the catchment partnerships offer opportunities to improve the development of management strategies that align across spatial and temporal scales to achieve sustainability goals up to the catchment level. The second is whether catchment partnerships improve the alignment of indirect drivers across scales, increasing the likelihood that management strategies will be implemented. The dual aspect of cross-scale management forms the foundation of my evaluation of the role of catchment partnerships in cross-scale water system management, exploration of limitations and barriers, and how the role of catchment partnerships can potentially be enhanced going into the future.

5.4 Methods

5.4.1 The catchments and their partnerships

This research investigates four river catchments in Scotland, UK: the Spey, Dee, South Esk and Dreel (**Figure 5.2**). These catchments were selected as they offer diverse cases in terms of their physical and social characteristics (**Table 5.2**), as well as the organisational structure and age of their partnerships (**Table 5.3**). The catchments vary significantly in terms of size, topography and land-cover. A large portion of the catchments of the River Spey, River Dee and River South Esk lie in the mountainous Cairngorms National Park. These catchments therefore have strong transitions between hilly uplands to flat lowlands along their river courses, accompanied by higher rainfall and lower temperatures in the mountainous areas. The upland portions of the catchments are dominated by heather moorland and montane landcover. Commercial forestry occurs on the slopes of the upper river valleys. Arable areas and improved grasslands are largely limited to the bottom of the river valleys and the lowland areas of the catchments. The River South Esk

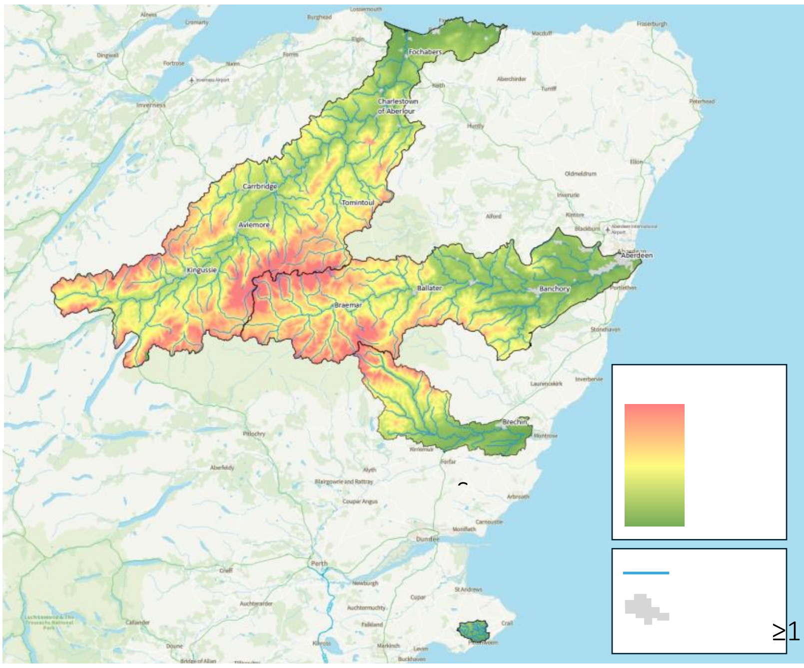


Figure 5.2: *The placement of the four case study catchments, their river courses, areas of population density ≥100 people per km² and topography.*

has the highest proportion of lowland areas, and highest relative area of arable land. In contrast, farming in the Dee and Spey catchments is primarily livestock rearing, which is reflected in the higher relative proportion of improved grasslands in these catchments. In contrast, the Dreel catchment is an intensively farmed lowland catchment.

The catchment partnerships vary in terms of their age, organisational structure and the circumstances of their founding. The Dreel Burn Initiative is the most recently established partnership and can be considered the most 'bottom-up' in the respect that it was initially formed by a community group. This contrasts to the other three catchment partnerships that were established or co-founded by statutory bodies, primarily in response to the WFD (Diaz-Kope and Miller-Stevens, 2015). Only the Spey Catchment Initiative exists as a separate legal entity, and became a Scottish Charitable Incorporated Organisation (SCIO) in 2022. The partnerships share many of the same partners, particularly statutory bodies and NGOs. However, the National Farmers Union of Scotland is represented on three of the partnerships. Several of the partnerships also include landowning estates and industrial partners, which mostly have commercial interests within the relevant catchments. Specific priorities vary; however, each partnership addresses (i) water quality (ii) resilience to water scarcity, drought and flood, which is closely tied to (iii) improving resilience to climate change. The partnerships also aim to (iv) increase biodiversity and protect key species, which relies on (v) restoring and creating habitats. However, (v) restoring and creating habitats like wetlands and riparian woodlands are also frequently linked to increasing (ii) resilience to water scarcity, drought and flood and (iii) climate change. The four catchment partnerships also all address (vi) economic and cultural development and (vii) access and recreation to a greater or lesser degree. A full breakdown of the catchment partnerships' pressures and priorities is given in (**Table 5.4**).

Table 5.2: Case study catchments and their characteristics.

Catchment Characteristics	Spey	Dee	South Esk	Dreel
Catchment area (km2)	3172	2100	564	35
Population	42,233 (13 persons per km^2)	123,004 [a] (60 persons per km^2)	10,167 (18 persons per km^2)	438 [b] (13 persons per km^2)
Topography	Mostly upland areas. Approx 1300m change in elevation	Mix of upland and lowland areas. Approx 1300m change in elevation	Mix of upland and lowland areas. Approx 1000m change in elevation	Lowland catchment Approx 250m change in elevation
Average yearly rainfall (mm)	680.5 - 2214.6	772.3 - 2,007.90	739.5 - 2,007.90	678.9 - 911.2
Average yearly temperature (^{o}C.)	3.8 - 8.6	3.8 - 8.6	4.6 - 8.6	9.2
Land cover (%)	Spey (%)	Dee (%)	South Esk (%)	Dreel (%)
Heather	46	46	20	0
Woodland	21	20	12	4
Improved Grassland	10	15	13	38
Other Grassland	9	5	28	0
Arable and Horticulture	4	6	25	56
Suburban	1	2	1	2
Other	9	7	2	0

a) The City of Aberdeen is considered only partially within the Dee catchment
b) The village of Anstruther is considered outside of the Dreel catchment

Table 5.3: Characteristics of the case study catchment partnerships.

Partnership Characteristics	Spey Catchment Initiative[a]	Dee Catchment Partnership[b]	River South Esk Catchment Partnership[c]	The Dreel Burn Initiative[d]
Year established	2010	2003	2008	2019
Establishment	Established by the Spey Fishery Board in response to the WFD and the designation of the Spey as a Special Area of Conservation.	Established in 2003 in response to the WFD and the designation of the Dee as a Special Area of Conservation.	Co-founded by Angus City Council and South Esk Rivers and Fisheries Trust.	Established by the Anstruther Improvements Association, a local community development group and a local landowner.
Organisational structure and staffing	Two-tier Scottish Charitable Incorporated Organisation (SCIO) that has a steering group, a board of trustees and five members of full and part-time staff.	The partnership is divided into a management board and the wider partnership.	An informal collaboration where the partnership has two project officers, funded by the local authority.	An informal collaboration with two strands: 1) The Dreel Burn Catchment Initiative, established in 2019. 2) The Dreel Burn Investment Readiness Partnership, established in 2023.
Partners	Partners include several statutory bodies and environmental NGOs, Scotland's national farmers' union, a key landowner, land management organisations and a beverage company that operates a large number of whisky distilleries within the Spey catchment.	Partners include several statutory bodies and environmental NGOs, Scotland's national farmers' union, a key landowner and two research institutions.	Partners include several statutory bodies and environmental NGOs, Scotland's national farmers' union, a land management organisation and a research institution.	Partners include the founding community group, several statutory bodies and environmental NGOs, a major landowner, a consultancy, several organisations focused on green tech and/or finance, and two research institutions.
Funding	Named funders include three statutory bodies: Nature Scot, the Cairngorms National Park Authority and the Spey Fishery Board and two major distillery operators within the catchment. Matched funding has also been provided by landowners in the catchment.	Funding for staffing is provided by organisations in the Dee Catchment Partnership management team. Project-based funding has been obtained from the Scottish Government and National Lottery. However, private and corporate funding is of increasing importance.	The local authority is the long-term funder of the partnership. Statutory funds have been obtained for individual projects.	Initial funding for the Dreel Burn Catchment Initiative was provided by the National Lottery Community Fund. Other funders include the local authority, private and third sector organisations. The Dreel Investment Readiness Partnership was funded by the Facility for Investment Ready Nature in Scotland (FIRNS.

a) Spey Catchment Initiative, 2023, 2024, b) Dee Catchment Partnership, 2007, 2022 c) River South Esk Catchment Partnership, 2009, 2017, 2021 d) Malecki, 2022

Table 5.4: Pressures and priorities of the case study catchment partnerships.

Partnership priorities and pressures	Spey Catchment Initiative[a]	Dee Catchment Partnership[b]	River South Esk Catchment Partnership[c]	The Dreel Burn Initiative[d]
Achieve good water quality	Maintain good water quality status by ensuring good wastewater treatment and addressing septic tank sources.	Reduce nutrient inputs from diffuse agricultural, forestry, septic tank and urban sources.	Reduce nutrient inputs from diffuse agricultural and forestry sources, and point wastewater sources.	Reduce nutrient inputs from diffuse agricultural and point wastewater sources.
	Address agricultural diffuse pollutant inputs in smaller water bodies.	Address other diffuse pollutants from agriculture like pesticides and sheep dip.	Address other diffuse pollutants from agriculture	Address other diffuse pollutants from agriculture
	Mitigate temperature rises.	Reduce leachate from landfills and formal industrial sites.	Reduce sediment loading e.g. by reducing livestock river bank erosion.	Reduce leachate from historic landfill.
		Reduce sewage overflows.		Reduce sewage overflows.
Increase resilience to water scarcity, drought and flood	Achieve balance between abstraction and flow. Introduce compensation flows where abstractions are resulting in low flows	Improve water resource management to mitigate pressures from growing population.	Improve water resource management through reporting abstraction and increasing landscape storage.	Improve water resource management by optimising agricultural abstraction.
	Implement natural flood and drought management based on habitat restoration for improving landscape water storage	Improve flood management by improving land management, and coordinating schemes across the catchment.	Improve flood management by raising awareness and introducing area-based approaches to flood management.	implement natural flood management.
Improve resilience to climate change	Peatland restoration and forestry as a carbon store for climate change mitigation and stabilise river water levels in response to climate change related extremes in rainfall	Implement strategies for stable flow levels to improve resilience to climate change related droughts and floods.	Implement strategies for long-term management of water levels to improve resilience to climate change related pressures like decreased rainfall.	Explore Sustainable Drainage Systems (SuDS) to improve resilience to increases in rainfall induced by climate change.
	River restoration to mitigate climate change related temperature rises and floods	Explore Sustainable Drainage Systems (SuDS) to improve resilience to increases in rainfall induced by climate change.		
	Implementing natural flood management to improve resilience to climate change related extremes in rainfall	Restore habitats to boost carbon storage and mitigate increasing water temperatures.		
Restore and create habitats	Restore watercourses, riparian habitats, peatlands, wetlands and forests, or create new habitats.	Restore wetlands, flood plains, wet and riparian woodlands, bankside grasslands and urban watercourses.	Restore watercourses, grasslands and wetlands, or create new habitats.	Increase riparian planting.
	Remove in-stream blockages to improve river flow, and fish passage.	Remove in-stream blockages to improve river flow, and fish passage.	Remove in-stream blockages to improve river flow and fish passage, and promote river engineering that supports a natural flow regime.	Remove in-stream blockages to improve river flow, and fish passage.
Increase biodiversity and protect key species	Increase numbers of Atlantic salmon, freshwater pearl mussel, sea lamprey, and voles.	Increase numbers of Atlantic salmon, freshwater pearl mussel and otters.	Increase numbers of Atlantic salmon, freshwater pearl mussel and otters by improving in-stream and riparian habitats, and regulating fishing.	Increase fish and bird populations by improving in-stream and riparian habitats.
	Explore the reintroduction of beavers	Explore the reintroduction of beavers		
Reduce invasive species	Reduce invasive American mink, giant hogweed, Japanese knotweed, white butterbur and water crowfoot.	Reduce invasive American mink, giant hogweed, Japanese knotweed, water crowfoot, and escapees from commercial and private ponds.	Reduce invasive Japanese knotweed, giant hogweed, Himalayan balsam, signal crayfish, mink, and rainbow trout.	Reduce invasive giant hogweed.
Increase economic and cultural development	Sustainable fisheries management, built environment expansion, forestry, tourism and investment in natural capital and carbon markets.	Employing local people in restoration activities and supporting sustainable agriculture	Support the sustainable development of the local economy, particularly those based on the area's natural resources .	Support local agriculture and businesses.
Improve access and recreation	Improve access to rivers and lochs, balancing this with environmental requirements.	Mitigate some of the negative environmental impacts of tourism and recreation to balance environmental, land management and recreational interests	Improve river based recreation, including riverside walks.	Improve access to the river.

a) Spey Catchment Initiative, 2023, 2024, b) Dee Catchment Partnership, 2007, 2022 c) River South Esk Catchment Partnership, 2009, 2017, 2021 d) Malecki, 2022

5.4.2 Participant engagement, data collection and analysis

Twenty-two participants across four catchment partnerships participated in semi-structured interviews **(Table 5.5).** The participants were selected according to their current or previous engagement in the catchment partnerships under study, and to represent the spectrum of individual and organisational actors that were involved in the partnerships across sociopolitical levels. Key sectors included government, NGOs, landowning estates, farmers, and industrial actors operating within the catchment (Hobbie *et al.*, 2017; Yang and Toor, 2018; Lyon *et al.*, 2020). Efforts were also made to engage actors across the multiple sociopolitical 'levels' that were represented in the catchment partnerships, from national and regional levels down to the level of individual farmers. Catchment partnership websites and publications were used to identify an initial list of interviewees, this was further expanded through reviewing strategy documents, new stories, online searches, and snowballing in consultation with participants (Heckathorn and Cameron, 2017). An important limitation to this sampling strategy is that it largely excluded the perspective of non-participants in catchment partnerships, as this was outside the scope of the research. Interviewing actors who had previously been involved in catchment partnerships but had since become non-participants gave us some insights into the reasons for non-participation. Nevertheless, expanding my understanding of why key actors do not engage in collaborative catchment management can enrich perspectives on how they can function more effectively.

Table 5.5: Participant organisations and the catchment partnerships they have engaged with.

Organisation	Sector	Catchment
Aberdeen City Council	Government, city	Dee
Angus City Council	Government, council area	South Esk
Anstruther Improvements Society	NGO, charity, community improvement	Dreel
Balcaskie Estate	Landowner, regenerative farmer	Dreel
Cairngorms National Park Authority	Government, statutory body, national park authority	Dee, South Esk, Spey
Dee District Salmon Fishery Board and River Dee Trust	Government, statutory body, fishery	Dee
Diageo	Business, distillery operator	Spey
Esk Rivers Trust	NGO, charity, nature conservation	South Esk
Farmer	Farmer	Dee
Fife Coast and Countryside Trust	NGO, charity, nature conservation	Dreel
Forth Rivers Trust	NGO, charity, nature conservation	Dreel
Jahama Estates	Landowner, business	Spey
JHI	Research institution	Dreel
National Farmers Union Scotland	NGO, members association, lobbyist	NFUS
National Farmers Union Scotland	NGO, members association, lobbyist	Dee
Nature Scot	Government, statutory body, nature conservation	Spey
Rhizorcore	Business, start-up, fungal technologies	Dreel
Scottish Forestry	Government, forestry regulator	Dee, Spey
SEPA	Government, environmental regulator	Dreel
Spey Catchment Initiative	NGO, charity, catchment partnership	Spey
Spey Fishery Board	Government, statutory body, fishery	Spey

Participants were asked about their organisation's role in catchment partnerships; key environmental concerns, drivers and goals in the catchment; the importance of scale in catchment management; key challenges to catchment management; the role, strengths and limitations of catchment partnerships for achieving catchment management and the future of catchment partnerships. Data collection occurred between May 2024 and April 2025. Interviews lasted approximately one hour and were conducted online using Microsoft Teams. The interviews were transcribed and then analysed through thematic analysis (Braun and Clarke, 2022).

Coding was performed in in NVIVO 15 (Lumivero) and followed the process in **Figure 5.3.** Initial coding was conducted inductively but was structured by the research questions and informed by a socioecological systems perspective on scale, cross-level and cross-scale dynamics outlined in **Section 5.3.** The research questions provided 3 overarching categories for the development of initial codes: (i) The added value of collaborative partnerships for addressing scale challenges in the socioecological management of catchments, (ii) the barriers faced by catchment partnerships in addressing scale challenges and their limitations, and (iii) how their role in addressing scale challenges may be improved going into the future. Codes were then reviewed and analysed to identify deeper underlying patterns of meaning, grouping them into themes that provided insights into the overarching research questions. Coding and grouping into themes were performed iteratively in several rounds, involving the review and reformulation of both codes and themes before their synthesis into a coherent narrative.

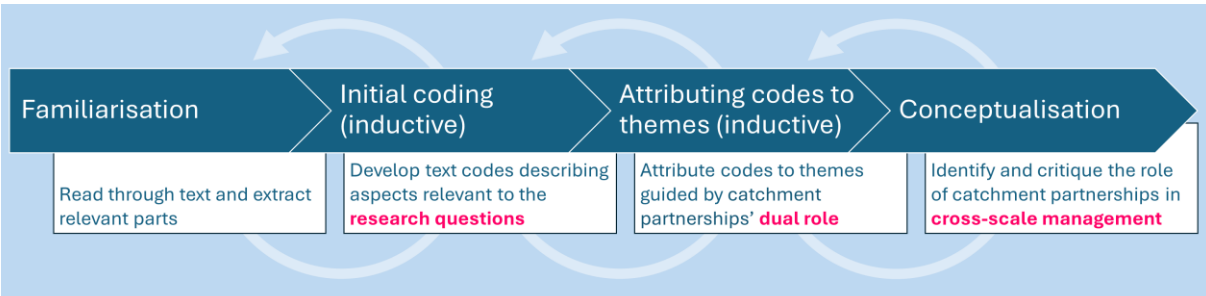


Figure 5.3: *The thematic analysis process that was used to systematically analyse interview data. Each phase was informed by the research questions and the dual role of catchment partnerships as actors for aligning indirect drivers across sociopolitical levels to achieve positive outcomes for catchment management across spatial levels.*

5.5 Results

In this section I first discuss the added value of catchment partnerships for cross-scale management and the barriers and limitations to this role. I break both the discussion of the added value of catchment partnerships to cross-scale management and their barriers and limitations into two parts, following the dual role that I have defined for catchment partnerships in cross-scale management. The first part presents some of the successes and limitations of catchment partnerships in navigating and mediating indirect drivers across sociopolitical level to create a better enabling context for implementing catchment management. The second part instead presents the contribution of the catchment partnerships to the management of direct drivers across spatial and temporal scales. It also discusses the challenges and limitations faced by catchment partnerships in attempting achieve positive outcomes for collaborative catchment management across all relevant levels. Each section will be organised according to the themes derived from the thematic analysis of my interviews. In general, there was strong agreement across the interviewees around many of the key themes. However, I highlight several areas where there was a divergence amongst participants. Most notably, over the role of different types of knowledge in catchment partnerships, the feasibility of obtaining extensive private investment in catchment uplift and regarding imbalances in the power to make decisions over land and water use.

5.5.1 Aligning indirect drivers across sociopolitical levels: Bridging actors, integrating priorities, facilitating exchange and 'de-risking' action

Interviewees identified many ways in which catchment partnerships played a mediating role between the broader indirect socioecological context and on-the-ground change, resulting in positive outcomes for catchment management. Overall, the most fundamental were their capacity to bridge actors across sociopolitical levels, integrate their priorities, facilitate knowledge exchange and social learning, and reduce perceptions of risk associated with implementing management strategies.

5.5.1.1 Bridging actors across sociopolitical levels to concentrate expertise, resources and upscale delivery

This analysis found that, the capacity of catchment partnerships to catalyse the implementation of measures for catchment uplift lay in their ability to engage and bridge actors across sociopolitical levels. The majority of interviewees saw the engagement of diverse stakeholders as a key strength of their partnership, which allowed catchment partnerships to concentrate both expertise and delivery power at the catchment level that was not available at the level of individual partner organisations.

Through synthesis of the interview data, it became clear that all of the catchment partnerships concentrated catchment management expertise by engaging government bodies, environmental

NGOs, research institutions, land managers and, in the case of the Dreel, community groups that had cross-scale insights into catchment dynamics and challenges. Interviewees from across the partnerships and groups represented here also highlighted the importance of engaging partners with expertise in the logistical and managerial aspects of delivering projects, including navigating the funding and regulatory landscape across sociopolitical levels. This research also found that catchment partnerships concentrated delivery power by engaging several groups of actors with the authority to facilitate or prevent projects. The first key group highlighted by interviewees were government bodies across sociopolitical levels with relevant statutory powers, including local authorities, catchment fisheries boards and national-level government bodies like Nature Scot. The second group were public and private owners of land and key infrastructures like dams. The final group of actors were public bodies, NGOs, private landowners and industry actors with access to resources and delivery capacity.

By concentrating diverse expertise and delivery capacity, catchment partnerships were seen by the majority of interviewees to catalyse catchment-level management beyond the capabilities of individual partner organisations. This effect was summarised by a participant from a river conservation trust engaged in the Dreel partnership:

"All of the talk was kind of moving towards landscape-scale delivery, catchment-scale delivery … And I realised that I had kind of been delivering on a piecemeal project by small project basis; that's where the funding was. And so, for us, it was a real chance to try and figure out how do you do that? What does that look like? And I realised that you absolutely can't do that without partnerships. It's almost impossible, especially for a size of an organisation like I are. So I kind of felt like it's only in building those catchment partnerships and making those more effective connections and sharing out the delivery that that's ever going to be accomplished." (IE18)

In part, interviewees attributed this to catchment partnerships' networks of catchment management expertise. However, interviewees gave equal significance to the access to expertise that allowed catchment partnerships and their member organisations to navigate broader indirect sociopolitical and socioeconomic drivers. Of critical importance across the interviews was expertise in facilitating project delivery by mobilising finance and dealing with issues like regulation and licensing. Interviewees also found that the inclusion of partners like public funding bodies gave them access to expertise that could improve their ability to access public funds and reduce the risk of projects being blocked.

5.5.1.2 *Delivering against both catchment and organisational goals to increase engagement and implementation*

This work suggests that an important mechanism by which the catchment partnerships achieved the engagement of key stakeholders is by demonstrating their ability integrate stakeholder priorities. Most notably, by delivering against the statutory, commercial and environmental priorities of partners.

Interviewees from SEPA, a local authority and Nature Scot partially attributed their participation to the partnership's potential to deliver against their statutory duties. For example, an interviewee from the Scottish Environmental Protection Agency suggested that the *"compliance regulatory side … will only go so far in terms of addressing pressure. So, I need to work in partnership to deliver wider objectives for river basin planning"* (IE2). Several of the catchment partnerships in this case study were initiated partially in response to EU-level legislation like the Water Framework Directive and the Habitats Directive. Consequently, catchment partnerships were recognised by these governmental participants as delivery mechanisms for both these higher level policies and more local-level policy like fisheries plans.

Delivering against the statutory duties of government partner institutions, catchment partnerships could leverage greater access to funding and support. In several cases, this meant accessing stable longer-term funding for staff that could greatly increase the capacity of catchment partnerships to build relationships, conduct scoping and implement projects. As described by one interviewee from the River South Esk Catchment Partnership:

"I still have continued to work on the catchment partnership work because it kind of aligns with all the local authorities, biodiversity and climate strategy as well. And because I're such a rural authority, it's quite nice that it all sits together. So, the Council provide a sort of facilitation role, supporting staff time, that kind of half-time officer role for the partnership to continue really because I've not had really any funding since 2011 from anyone else. So that's how it kind of persists." (IE13)

My analysis further suggests that the capacity of catchment partnerships to act as a delivery partner for achieving organisational priorities was also a key catalyst for industry engagement. This was suggested by participants in both the Spey and the Dreel catchment, which most explicitly aimed to engage private partners. The industry partners interviewed here also stated that an important reason for engaging with catchment partnerships was its contribution to their organisational sustainability goals. For example, external sustainability reporting in-line with national or international standards, as remarked by an interviewee from a commercial organisation working with the Spey Catchment Initiative, *"the catchment initiative is something that when I are getting audited, I hold up and go 'Look* *at this, I're part of this. This ticks so many boxes.'"* (IE15) Furthermore, based on the interviews, catchment partnerships could also catalyse industry engagement by identifying where the goals of the catchment partnership are aligned with the commercial priorities of industries within the catchment. This is best exemplified by the Spey Catchment Initiative, which has partnered with several industrial partners based on a shared need for *"cold, clean fresh water"* (IE22).

5.5.1.3 Peer-to-peer exchange and demonstration projects to build trust, upscale and outscale adoption

Interviewees from each of the catchment partnerships expressed that, by identifying and integrating organisational priorities across sectors and sociopolitical levels, catchment partnerships were able to build a reputation as a *"slightly neutral voice in this, or an impartial voice … they're seen as a kind of somewhere in the middle and therefore trusted"* (IE17, Scottish Forestry, multiple partnerships). The view of catchment partnerships as neutral bridging organisations was primarily expressed by four participants from statutory bodies and NGOs. However, it should be noted that participants from the farming community and from the Spey, Dreel and South Esk partnerships highlighted gaps in engagement and power imbalances between catchment partnerships and the farming community. These issues are discussed further in **Section 5.5.2.1**.

Interviewees across the catchment partnerships who were responsible for both on-the-ground engagement and higher level management mentioned peer-to-peer engagement as a core mechanism for building trust. This was seen as particularly important for engaging members of the farming community. Taking everything together, building relationships on an individual level was essential to bridge between the individual and community level and the higher sociopolitical levels represented by the organisations commonly engaged in catchment partnerships. The non-statutory nature of catchment partnerships was also though to support this process and improve farmer engagement. As exemplified by one interviewee from the Spey Catchment Initiative:

"Staff who are brilliant at liaising with, with farmers and with landowners, estate owners and so on and the government bodies and being able to do so in a way that is non-confrontational. Because at the end of the day, first of all, I can't make people do anything, and I think I've got to persuade them to come along with us, but I're not a regulator, I're not Nature Scot, I're not the Environmental Protection Agency, I're not Scottish forestry, I're not the government, I're not a local authority. And you know, these people can arouse certain suspicions, raise hackles or whatever, whereas I don't need to do that. And I're going in very much as the intermediary, the interface between all of these organisations." (IE9)

From the interview data, it became clear that a major bridging role was played by individuals in the catchment partnership that were already strongly embedded in a community or had a similar background. For example, interviewees from the Dreel partnership all mentioned the important role played by their founding community group. And interviewees across all the catchment partnerships mentioned key individuals with strong connections to the farming community. For example, NGO representative engaged in the Dreel Catchment Partnership stated:

"The other thing that they've done incredibly well is the engagement work that's done from [partnership member] who is … exceptionally good at understanding the farming community because he grew up in that community. He is part of that community. And the discourse that has to happen between landowners, there are very few practitioners in this space in terms of social engagement that know how to converse with the farming sectors and I'm not sure [he] would be able to tell you himself how he does. He's just he's part of that community, so he has that ear in terms of that. He's just interested in how to connect all the pieces together. And that's crucial that there's somebody very good at doing that." (IE12)

Drawing together this evidence, I suggest that the capacity of catchment partnerships to perform a bridging role as trusted intermediaries is essential for achieving widespread engagement and adoption of catchment management measures. I further suggest that demonstration projects and associated outreach are an important means by which catchment partnerships can facilitate the implementation and upscaling of catchment management strategies through. Governmental, landowner, research and NGO representatives from the Dreel, Spey and South Esk partnerships all found that demonstration projects could both raise awareness of the types of measures that could be implemented and reduce perceptions of risk. This was seen as particularly powerful for supporting peer-to-peer exchange between trusted individuals, whereby one farmer would adopt a measure that had been implementation by a trusted peer. However, interviewees highlighted the significance of formal demonstration projects and outreach processes for encouraging adoption within the catchment, building political support and even out-scaling to other catchments. As stated by an interviewee from a national park authority, involved in the Dee, South Esk and Spey partnerships:

"You need to have delivery on the ground to show people what you mean to really get the biggest benefit. You know, small-scale demonstration, but ramp it up. By having successful small-scale, you can get the large-scale ones going to really make a difference." (IE1)

Smaller scale projects were therefore an important mechanism whereby catchment partnerships could catalyse larger scale change.

5.5.1.4 'De-risking' action by providing test cases for catchment uplift

The concept of demonstration was also embedded in the notion, put forward by interviewees from the Dreel and Spey partnerships, that catchments and their partnerships could be 'test cases' for exploring novel ways of implementing catchment management. Interviewees from the Dreel catchment had ambitions to use the relatively small Dreel catchment to develop lessons-learned that could be applied to bigger catchments. Others discussed the use of the Spey catchment as a testing ground to evaluate how high-level policy like the emerging Woodland Carbon Code functioned upon on-the ground implementation. Both catchments were also seen as important test cases for understanding how catchment uplift could be turned into a business case for catalysing private investment. This reflects emerging discourses in the socioecological systems literature that advocates for synthesising learning and knowledge generated through 'experimentation' at the local level. The aim being to develop more general insights that can be applied at larger spatial levels, building on the benefits of context-specific research (Balvanera *et al.*, 2017; Bennett and Reyers, 2024). By acting as testing grounds, catchment partnership could play an important role in reducing perceptions of risk and even improve unfavourable political and economic conditions for achieving good chemical and ecological status at the catchment level. Ultimately, several interviewees felt that catchment partnerships could catalyse the upscaling and out-scaling of different management concepts by acting as robust organisations for facilitating social learning.

5.5.2 Aligning indirect drivers across sociopolitical levels: Engagement gaps, integration issues, policy challenges and resource limitations

Despite playing an important role in bridging actors across sociopolitical levels and mediating indirect drivers across levels to support the upscaling of catchment management efforts, my analysis found that catchment partnerships faced noteworthy barriers and limitations. Of central concern was limited bridging between the catchment level and the level of individual farms, which this work suggests contributed to challenges (1) integrating different priorities at the catchment level, (2) compensating for limited political and economic incentives for engagement and (3) accessing adequate resources for collaborative management.

5.5.2.1 Continuing gaps in engagement across sociopolitical levels

In most cases, I found that the catchment partnerships were most successful at the vertical and horizontal bridging of government bodies and NGOs operating at national and regional level. Many interviewees across the partnerships, identified a need to improve catchment partnerships' bridging of these types of organisations and private actors, landowners and communities. This was seen as essential to increase cross-sectoral bridging, improve catchment partnerships' access to resources and ultimately upscale interventions to achieve change at the catchment-level.

Interviewees identified several key industrial actors that should be more engaged with catchment partnerships to achieve these ambitions, and were unique to the individual catchments. Interviewees from the Spey and Dreel catchment partnerships saw a need for better engagement of actors across the agricultural and food supply chain. In the South Esk and the Dee catchments, interviewees saw a need to improve links to actors in the catchments' important commercial ports. In the Spey partnership, an important priority was increasing the catchment coverage of the distilleries engaged in the partnership. However, landowner participation was more commonly stated as a fundamental need by interviewees across all catchment partnerships. As put by one interviewee in the Dee catchment partnership, representing a statutory fishery body *"the critical one is landowner and land manager engagement. If you don't have an incentive for them to get behind this, all the money in the world and all the ability to deliver in the world means nothing."* (IE5) Equally fundamental was improving engagement of the farming community and land managers more broadly. Many interviewees echoed the sentiment of a interviewee from a statutory fisheries body involved in the Spey Catchment Initiative, who remarked:

"I think that the only concern I have is a lot of decisions are made without involving the people that live and work on the land. And I always start with the people that live and work on the land and work up a project from there. Never try to work a project from the top down, never works … I mean, if you don't have the buy in from the farmers, the gamekeepers and whoever else is working on the land, the project's doomed to failure." (IE8)

Interviewees from all catchment partnerships expressed concern that the limited vertical bridging of farming communities and land managers limit access to diverse expertise and perspectives across sociopolitical and spatial levels. In this respect, it could undermine one of the key strengths of catchment partnerships that had been highlight by interviewees across the partnership. Many interviewees emphasised that the low participation of these groups could undermine buy-in and the implementation of measures at the spatial extent needed. However, a less mentioned but equally critical issue was that the low participation of these groups represented a failure to ensure procedural justice, which is a core motivation for in participatory governance. This issue was illustrated by an interviewee from the farming community who had participated in catchment partnerships previously:

"There are bodies of people who are employed and spend their whole lives being able to go to these meetings and there are people who are affected, who have other lives and find it very difficult to find the time even if they are given the opportunity to be there and represent, in equal measure, their side of the argument." (IE21)

This evidences how important it remains to consider power dynamics in collaborative governance organisations like catchment partnerships, and adds nuance to the view of these organisations as neutral bridging organisations outlined in **Section 5.5.1.3**.

5.5.2.2 Integrating diverse perspectives at the catchment-level

Interviewees raised several important issues at the catchment partnership, organisational and individual levels that contributed to the non-participation or even exclusion of key actors. There was limited mention of catchment or actor level barriers to landowner or industry actor participation, but barriers to farmer and community engagement were a stronger focus.

Participants from the farming community and the River South Esk partnership highlighted the need to adjust to the needs to different types of stakeholders to facilitate their full participation. Their suggestions included adjusting the timings of catchment partnership meetings to enable farmer attendance or adjusting communication styles to ensure that discussions could be understood by all participants. Interviewees also found that a fundamental differences in what type of knowledge was perceived as useful and reliable could be a significant barrier to farmer engagement. In this research, I found that these differences could include divergent perspectives on the value of experiential knowledge versus modelling in flood management, the problems and dynamics of catchment systems and what types of mitigation strategies would be practical and effective. Equally important were perceived differences in priorities between farming representatives and the broader partnership. Where these differences arose, interviewees expressed concern that they could lead to the exclusion of farming representatives from catchment partnerships. An interviewee from the National Farmers Union, Scotland expressed several of these concerns, stating:

"As I said, it's a privilege to be invited and to be allowed to participate. So that is the key thing. However, the challenges are that … the majority seem to be on a similar page to each other, whereas the farming voice is sometimes quite remote from that. And it's very challenging, and I've often felt like I'm just moaning. I'm the controversial one, I'm the one that's saying something that doesn't quite fit with the majority. This is democracy and I get that, and I accept that fully. But sometimes you feel like you're a very small, minor voice that perhaps isn't understood properly and, more often than not, it's not that you're not heard, it's just that the majority want to do something differently." (IE19)

5.5.2.3 Unclear policy and market signalling and incentives for catchment management

Addressing these barriers to engagement at the catchment partnership and individual levels could facilitate implementation, particularly where the individuals or organisations had the capacity to implement measures. The evidence compiled here suggests that priorities could also be negotiated at the catchment level to a certain extent; however, interviewees suggested that there were limited incentives at higher sociopolitical levels that could facilitate this process, and this contributed to the non-participation of key actors.

Nine participants, representing all the catchment highlighted the lack of adequate incentives for encouraging farmer participation. These participants included representatives from the farming community, landowners, environmental NGOs, the national park authority and local government. This indicates that it is a widely recognised and cross-cutting issue. Two interviewees from NGOs engaged in the Dreel and South Esk partnerships pointed to the ongoing legacy of policy incentives for agricultural intensification and a perceived instability in policy signalling. Specifically, that previous EU and national government policy had pushed for higher productivity and intensification and this legacy was still in effect. However, all nine participants critiqued incentives for engaging in environmental uplift and working collaboratively, describing them as poorly developed and uncertain. These participants commonly criticised the development of a new agricultural support scheme to replace the EU's Common Agricultural Policy payment schemes. They saw the emerging scheme variously as (i) offering no incentives for collaborative landscape management, (ii) offering payments for environmental measures that were insufficient for covering costs to the farmer, and (iii) having little flexibility to encourage the implementation of environmental measures that were adapted to the size, conditions and environmental potential of individual farms. Moreover, the ongoing development and uncertainty around the scheme was seen by interviewees from the National Farmers Union and the South Esk Partnership to pose a further barrier to farmer participation. Many of these issues were summarised by an interviewee working with the River South Esk Catchment Partnership, who commented:

"I think the Scottish Government could be sorting themselves out with this. I're still waiting to hear what the new agriculture policy is, having left Europe. They still haven't done that ... They've started this requirement for a whole farm plan, but they're not given the whole story. And I don't believe it's because they are being underhand, it's because they haven't figured it out for themselves yet. But what that's doing is, all of these things, and then also having [the Agri-Environment Climate Scheme] that just isn't a genuine carrot it's making farmers, if they ever had it, lose trust in them." (IE20)

The general consensus among interviewees across the catchment partnerships was that emerging nature markets also offered limited and uncertain incentives for farmers, industry actors and landowners to engage in catchment partnerships and environmental action. Carbon markets were regarded as the only natural capital markets that were operating; however, interviewees from the Spey and the Dreel catchment partnerships highlighted some ongoing issues including the distribution of carbon credits between tenant farmers and landowners. When mentioned, other frameworks and markets for green finance like biodiversity or water were seen as undeveloped and offering limited incentives for engagement of private investors. A participant from the Dee Catchment Partnership, based in city government described how this posed a barrier to private investment in catchment uplift:

"I think the frustration is that there's been a lot of effort being put into carbon markets and climate change seems to be more of a focus in people's minds. I're not seeing the same on the biodiversity side of things, and I'm aware Nature Scot are looking into this and there is work but it seems that I're still years away from the private finance coming on board really. And like a lot of these things involving private buyers, it's trying to get the balance of actually meaningful work as opposed to green washing as well." (IE4)

5.5.2.4 *Insufficient resourcing for catchment partnerships as a mechanism for statutory delivery*

As higher level sociopolitical and socioeconomic drivers failed to adequately incentivise participation in catchment management, further analysis finds that so did they challenge catchment partnership goals of achieving long-term change at catchment-level. Three interviewees from the Dee, Dreel and Spey catchment partnerships, representing two statutory bodies and a research organisation found that catchment partnerships were not sufficiently embedded in governance despite being recognised as delivery mechanisms for legislation and policy across sociopolitical levels. This issue was introduced by an interviewee from Nature Scot, who stated:

"I think I would like to see it get more political support. So, for example, the Scottish biodiversity thing, that was just published fairly recently, didn't really recognise catchment partnerships as a huge mechanism for delivering change. And I think they are, potentially. And actually I felt that there could have been more support in the Scottish biodiversity thing. So, I'd like to see more political support coming from the top, AKA Scottish Government, for the idea of catchment partnerships." (IE16)

This reflected concerns expressed by four governmental participants from across the catchment partnerships that the public funding for catchment partnerships was inadequate and not well-suited for the realities of operating the partnerships successfully. Interviewees stated that there was limited public funding available for stakeholder engagement activities, limiting the capacity of catchment partnerships to play a bringing role across sociopolitical levels. Over the long-term, there was also seen to be a lack of funding for employing and maintaining staff, scoping projects and maintaining them. Interviewees also found that while capital funding had previously been comparatively accessible, recent national-level government funding problems had resulted in the shrinkage and even withdrawal of public money from environmental funds. Many interviewees saw this as a core challenge to the operation of catchment partnerships.

5.5.3 Aligning direct drivers across spatial and temporal scales: cross-scale characterisation and delivery at scale(s)

Ultimately, the key reason for the development of catchment partnerships was to go beyond disconnected small-scale projects to realise catchment-level sustainability. This research contends that achieving this goal required the alignment of management across spatial levels from site and farm level to river reach to catchment-level. Interviewees saw catchment partnerships as facilitating this process primarily through facilitating the characterisation of catchments across spatial levels and moving from a site-based focus to catchment level management visions.

5.5.3.1 Building capacity for cross-scale catchment characterisation

This analysis found that catchment partnerships facilitated the management of direct drivers across spatial levels partially by engaging actors with expertise that spanned spatial levels. In general, interviewees felt that they had sufficient information to implement measures. Interviewees linked this to the mobilisation of different types and scales of knowledge through the engagement of diverse stakeholders in catchment partnerships. As stated by one interviewee from the Spey Catchment Initiative, *"I've got a very strong baseline of knowledge because there is a wealth of knowledge within the organisations that that make up my membership."* (IE9) Key actors included governmental and non-governmental organisations with formal scientific data to community groups and individual land managers with important experiential knowledge. Their varied expertise and perspectives could support catchment characterisation across spatial levels and partnership working was seen to facilitate the identification of pressures and intervention opportunities across the extent of the catchment. However, as will be discussed further in **Section 5.5.4.1,** representatives from research and commercial organisations perceived more knowledge gaps and data limitations than other groups.

Just over half of the interviewed participants highlighted that catchment partnership could facilitate monitoring and evaluation of the catchment at spatial and temporal resolutions that were more specific to the needs to the catchment than statutory monitoring. These participants represented research institutions, community groups, statutory bodies and NGOs. Public bodies and research institutions that were partner institutions often fulfilled this role. However, community science had an important role in several catchment partnerships. In most partnerships, community science largely involved the engagement of volunteers in invertebrate monitoring as an indicator of catchment ecological health. However, in the community-founded Dreel Catchment Initiative, the majority of interviewees highlighted the value of the water quality monitoring performed by the community for identifying problems and potential causes that were invisible to lower spatial and temporal resolution monitoring.

5.5.3.2 *Moving from site-based to catchment-level visions and delivery*

Many of those interviewed saw the development of a shared catchment-level 'vision' as a central strength of catchment partnerships. All the catchment partnerships had developed a shared catchment-level vision that outlined key pressures and suggested potential measures. The Dee, Spey and South Esk partnerships had all co-developed full catchment management plans and had delivered or planned to deliver further management plans. While there was some scepticism about how actively catchment management plans were used in the planning processes of individual partner organisations, when they were mentioned, participants generally saw them as an important output of catchment partnerships. In the words of one interviewee involved in the Dee, South Esk and Spey catchment partnerships, catchment management plans are value because partnerships *"need some kind of guiding principles to what I're all going for, you know, and it's a way of bringing my collective priorities, my collective organisational priorities together"* (IE1, Cairngorm National Park Authority, multiple catchment partnerships). Catchment management plans were largely seen as useful boundary objects (Star, 1989) that encouraged action according to a common vision at the catchment scale.

5.5.4 Aligning direct drivers across spatial and temporal scales: diverging systems understandings and limited scaling

While this research suggests that catchment partnerships could support the characterisation of catchments across spatial levels and the development of catchment-level management perspectives, interviewees highlighted some key barriers to this process. Most significant were challenges resolving differing stakeholder perspectives on legitimate and useful knowledge at what scales and ultimately leveraging catchment-level visions into catchment-level delivery.

5.5.4.1 *Resolving perspectives on what knowledge and at what scales*

As discussed previously, the majority of interviewees did not see knowledge gaps to be a significant barrier to action. However, there were several noteworthy exceptions that highlighted the significance of the challenge of coming to a shared understanding of direct catchment drivers across scales. The data here suggests that this challenge was rooted in the diverse perspectives of the stakeholders engaged in the catchment partnership, who had different ideas on the type and scale of data should be produced for particular purposes. These tensions were most apparent in the Dreel catchment where catchment characterisation was still ongoing; however, many of the issues raised were referenced by interviewees from other catchments. This suggests that they may have broader relevance to participatory water management.

A central tension emerged around the role of experiential knowledge versus scientific types of data. Interviewees from the research and commercial institutions engaged in this research were more likely to emphasise the need for scientific forms of data at spatial and temporal levels that satisfied values of scientific integrity. A participant representing a major landowner and commercial partner in the Spey catchment stated that integrated scientific data at the catchment-level was important for private sector engagement:

"One good thing about private industry, in my experience is it will react on good data. … one of the biggest weaknesses is that if you are a … bad landowner and you were like, 'yeah, whatever, I'm just going to not get engaged' you can obfuscate your responsibilities because there's very little data." (IE22)

For this interviewee, a lack of catchment-level baselining was problematic as it prevented the evaluation of the impacts of site-based mitigation efforts across the catchment. This in turn could inhibit private-sector engagement, as this data would allow reporting against corporate sustainability goals and requirements, and monetising uplift in emerging nature markets. Developing the kind of data needed to demonstrate 'landscape level' nature uplift for the purposes of private investment was a core focus of the Dreel partnership. However, in this case an important concern was how to balance the unknown needs of potential investors in environmental uplift with values around scientific integrity. Some interviewees emphasised the need for simple landscape or catchment level indicators to suit potential investors, others emphasised the need for indicators with high scientific integrity. In the words of one interviewee from a water research organisation, who worked with the Dreel catchment partnership:

"My thing is very much about building the proper evidence base and being able to monitor change … to make sure the whole thing's not built on shaky foundations and then you can then build transparency and sort of trust and data into it. It reduces some of the risks of the investment, not realizing its potential, I suppose, but also things like reputational risk from greenwashing or perceived greenwashing." (IE3)

Conversely, other interviewees felt that the added value of scientifically 'robust' characterisations of catchment-level pressures and opportunities was not necessarily worth the cost and time-investment. Instead, they placed higher value in the capacity of experiential knowledge to support decision making and implement measures more quickly. For example, a participant from the Dreel Catchment Partnership stated:

"If I take a more pragmatic land-based approach to restoring my landscapes, working with first principles and land managers and people who can look at the lay of the land and say, you know, I

understand the basic principle that slowing the flow within a catchment is good for water quality and good for water quantity … actually you can you can walk across a landscape and you can say well that hedgerow could be enriched, I could create a wetland there, I could re-meander the burn there and all that stuff is going to be good without necessarily having to prove it to the nth degree with scientific research." (IE14)

5.5.4.2 Achieving ambitions of change at scale(s)

A review of the interview data and key partnership documents evidences that all of the catchment partnerships had noteworthy successes in developing and delivering projects within their respective catchments. Nevertheless, six interviewees across the partnerships saw a need to improve the implementation of projects to achieve goals across different spatial levels. For some interviewees in the Spey and South Esk catchments this meant upscaling from individual projects to expand the spatial extent of catchment planning. In the case of the Spey, this meant upscaling from individual projects to catchment-level uplift. As stated by a participant representing a major landowner in the Spey, current efforts remained *"piecemeal down the whole catchment"* (IE22) and fell short of the full-scale catchment approach that was needed to ensure good water quality. As a result, the Spey partnership had shifted their ambitions to target measures at the level of individual tributaries or sub-catchments, upscaling from a focus on individual sites to achieve larger scale change. For other interviewees it meant implementing planning at a spatial extent that recognised the connection of the catchment to coast and the urban to rural. Others emphasised the need to out-scale from working with a narrow selection of landowners and managers to achieve more widespread implementation across the catchment. Conversely, for the South Esk partnership, the goal was instead to downscale from a catchment-level plan to plan for individual sub-catchments. Interviewees from the partnership saw this as important to address the unique conditions and priorities at smaller spatial levels. For example, addressing the specific concerns of urban areas.

5.6 Discussion

This work has proposed and applied a multi-scale novel socioecological systems framework to support the evaluation of catchment partnerships and the challenges that they face. The framework encourages researchers to approach catchment partnerships and related organisations as playing a dual role as agents for change in socioecological sub-systems of direct and indirect drivers. By evaluating catchment partnerships as participants and mediators both within and between these sub-systems, I suggest that researchers can more meaningfully evaluate the impacts of collaborative water management organisations, identify barriers and propose solutions that can improve the role that they play in water management. This work therefore offers an extension of the conceptual foundations of the systemic evaluation of catchment partnerships and the diagnoses of barriers and enablers. This approach may further be applicable to other collaborative water governance organisations (Andriollo *et al.*, 2021).

Using this framework, I have demonstrated that catchment partnerships have important added value to the systemic cross-scale management of catchments. However, noteworthy barriers remain that disincentivise stakeholder participation in catchment partnerships and reduce their capacity to implement measures to improve catchment sustainability across spatial levels. Drawing on my interviews and the wider academic literature, I now discuss some potential next steps for strengthening the role that collaborative catchment partnerships play in the systemic cross-scale management of critical water challenges as systemic socioecological problems.

Firstly, the challenges I identified suggest that catchment partnerships should strengthen shared 'cross-scale' understandings of direct sub-system drivers. To do so, partnerships should explicitly discuss and come to an early initial consensus on what types of knowledge are to be produced, at what scales, for what purposes and how they should be integrated (Balvanera *et al.*, 2017). My analysis demonstrated that building shared understandings of the direct drivers of catchment challenges across scales is not solely about whether data is available, but whether key actors see the same type of knowledge as valuable. This is a recurring theme in much of the literature addressing collaborative catchment management and is a critical integration challenge of the interdisciplinary and transdisciplinary approaches that underpin integrative management (Ayre & Nettle, 2015; Balvanera et al., 2017; Marshall et al., 2010; Rollason et al., 2018). Achieving this integration is critical for successful collaborative catchment management and is likely to become more pressing as efforts are made to increase the engagement of farmers and private sector investors. This is because, as demonstrated by the case studies here, the increasing the diversity of actors will likely increase the variation in expectations regarding the type of data that is needed and at what spatial and temporal resolutions.

Secondly, catchment partnerships should improve the implementation and alignment of catchment management across spatial levels through increasing the engagement of key stakeholders across sociopolitical levels. In my analysis, farmers, landowners and, in some cases, private investors were identified as key groups that required increased engagement. Catchment partnerships are generally expected to bridge actors within and between sociopolitical and spatial level (Waylen *et al.*, 2023). However, there is currently inadequate bridging between the level of the catchment partnerships and the level of individual farmers and land managers. This reflects the comparative low engagement of these groups in and by catchment partnerships (Rollason *et al.*, 2018). To improve their bridging of sociopolitical levels, catchment partnerships should develop strong understandings of both the regulatory and market landscape, and the priorities of key actors that they wish to engage. As demonstrated by my results, gaining these insights is important for catchment partnerships to identify where they can leverage their capacity as a commercial and statutory delivery partner. This was identified as a key mechanisms for increase the willingness of actors to engage in collaborative management. Of central importance is catchment partnerships taking advantage of emerging policy changes and markets, for example, interviewees highlighted the emerging Scottish government requirements around land reform.

Improving the engagement of key stakeholders also means ensuring that partnerships gain and/or retain personnel that have the skills to build relationships, communicate effectively and resolve conflicts in a transparent and non-confrontational way. Interviewees frequently highlighted these characteristics as essential for catchment partnerships' bridging role, which reflects the findings of previous research (Marshall et al., 2010; Rouillard & Spray, 2017). My results also demonstrated that to achieve this goal, catchment partnerships may need to adjust their variety of engagement activities to ensure that diverse groups are able to fully participate in the partnerships (Allen et al., 2011; Marshall et al., 2010; Rouillard & Spray, 2017). Expanding the types of engagement activities undertaken by the catchment partnerships may mean engaging more strongly with and even catalysing stakeholder groups like farming clusters at smaller spatial levels, as suggested by interviewees in the South Esk catchment partnership. This further evidences that making effective use of existing forums and even catalysing them can increase implementation and build trust between catchment partnerships and key groups (Marshall, Blackstock and Dunglinson, 2010). Furthermore, some interviewees suggested that granting greater autonomy to these groups in implementing management strategies may be powerful for transforming engagement into aligned management across spatial levels. It would also constitute a step closer to the greater transfer of power and autonomy envisioned in full cooperative integrated catchment management (Rollason *et al.*, 2018). By increasing engagement through these mechanisms, catchment partnerships can play a critical role in mediating or translating higher level indirect policy, regulatory and market drivers for stakeholders involved in project implementation at the site level (Rollason *et al.*, 2018). In this respect, catchment partnerships can fulfil ambitions to build an intermediary sociopolitical level that can strengthen the bridging between high-level policy frameworks and site-level activities (Amblard & Mann, 2021; Surridge et al., 2009).

Finally, there should be an increase in both incentives for engaging in collaborative management and resources available for implementing collaborative projects. In part, this relies on resolving the disconnect between top-down governance arrangements and the bottom-up efforts that was identified in my research, and other catchment partnership case studies (Rollason et al., 2018;

Rouillard & Spray, 2017; Surridge et al., 2009). Overcoming the barriers posed by limited high-level political and economic indirect drivers identified by interviewees may be beyond the scope of catchment partnerships. However, based on my results, I highlight several actions that partnerships can take to better incentivise stakeholder participation. The first is to advocate for greater policy incentives for farmers to engage in collaborative working as the Scottish government develops a new agricultural support scheme. The second is to build catchment partnerships' profiles and organisational capacities as delivery partners for both statutory and commercial goals that are in-line with the environmental goals of the partnership. This could include adopting different organisational structures to gain better access to more resources, as demonstrated by the Spey Catchment Initiative. The third is to act as test cases for the development of more effective policy and market frameworks for encouraging engagement and investment in environmental uplift. By performing these roles, catchment partnerships could again act to strengthen the bridging between high-level policy frameworks and site-level activities (Surridge, Holt and Harris, 2009). This time by translating indirect drivers like needs, priorities and capacities at the local level into improvements in higher level policy and market frameworks to support local implementation (Rollason et al., 2018; Rouillard & Spray, 2017).

5.7 Conclusions

This paper aimed to gain insights into whether and how participatory catchment management organisations can support the systemic 'cross-scale' management of water, distinguishing a dual role for catchment partnerships in cross-scale management. The first, was implementing management that aligned across spatial and temporal levels to achieve sustainable outcomes across spatial levels and timeframes. The second was navigating and mediating between indirect drivers across sociopolitical levels to achieve positive outcomes for catchment management across spatial levels. I investigated this issue through a qualitative case study of four Scottish catchment partnerships, identifying some of the key areas where catchment partnerships added value and where they faced noteworthy barriers.

Partnerships had important added value for navigating and mediating between indirect drivers to achieve on-the-ground implementation of catchment management. Firstly, they bridged actors vertically and horizontally across sociopolitical levels to concentrate expertise, increase delivery power and upscale implementation. The bridging role played by catchment partnerships relied, in part, on partnerships' capacity to navigate and integrate the statutory, commercial and environmental goals of the catchment partnership and its partners at the catchment level. The bridging of sociopolitical levels was also facilitated by partnerships' use of peer-to-peer exchange and demonstration projects to build trust, facilitate knowledge exchange and social learning. Finally, catchment partnerships could improve bridging by acting as 'test cases' for novel approaches to catchment uplift, reducing the perceived risk of implementing measures and improving engagement at the farm and site level. Catchment partnerships also had added value for ensuring that management strategies were aligned according to key direct drivers across spatial levels by concentrating cross-level expertise and catalysing data collection across key spatial levels and timeframes. In addition, they promoted a move beyond site-level planning to deliver catchment-level outcomes.

However, catchment partnerships faced some serious limitations and barriers. While partnerships played an effective bridging role in some respects, there still remained challenges achieving the bridging between the catchment level and individual land managers. Barriers to this bridging role existed at the catchment level, where there were difficulties integrating diverse priorities and accommodating different engagement needs. Further barriers were presented by limited higher-level policy and market incentives for engagement in catchment management. Finally, the role of catchment partnerships in developing and implementing management strategies that aligned direct drivers across spatial levels was challenged by issues accommodating diverse perspectives on the relevance of knowledge types, dynamics within the catchment and key priorities. Ultimately, these barriers stood in the way of catchment partnerships achieving their ambitions of catchment level change.

Finally, I suggest that catchment partnerships could more effectively fulfil their dual role in cross-scale management by strengthening shared 'cross-scale' understandings of direct sub-system drivers, improving the engagement of key stakeholders across sociopolitical levels to better align management efforts, and increasing incentives across sociopolitical levels for engaging in collaborative catchment management.

This research therefore contributes to the body of research that evaluates the role of catchment partnerships and collaborative organisations in water governance. It does so not just by drawing together insights from multiple catchment partnerships to identify common successes and challenges and propose steps forward that may have wider relevance to catchment partnerships, particularly in the Scottish context. It also proposes a novel multi-scale and multi-level socioecological systems framework for conceptualising and evaluating collaborative water management partnerships. Further research should focus on how this framework could be developed into a methodology for more fully characterising the contribution of catchment partnerships to improving cross-scale management. A key aspect will be developing indicators for evaluating outcomes for catchment ecological health overall based on direct drivers, as well as evaluating indirect aspects like awareness raising and policy change.

6 Synthesis and conclusions

In this chapter, **section 6.1** first reintroduces the thesis research topic, aims, objectives and approach. **Section 6.2** turns to the contribution that each paper makes to answering the research objectives and aims. **Section 6.3** outlines the broader implications of this research for theory and practice. **Section 6.3.1** first summarises the practioner-relevant empirical insights into eutrophication and collaborative catchment management developed in the two case studies (**Chapter 3** and **4**). **Section 6.3.2** then discusses how the conceptual insights developed in pursuit of the research objectives can support better theory-informed cross-scale management in policy and practice. **Section 6.4** discusses the limitations of this research and, finally, **Section 6.5** comments on some implications of this work for the conceptualisation of scale in socioecological systems theory and outlines areas for future research to further develop systemic, participatory approaches to cross-scale management.

6.1 Summary of research topic, aims, objectives and approach

This thesis has contributed both conceptual and practical insights on how to approach 'cross-scale management' as a systemic socioecological problem. It also suggests important contributions that participatory governance can make to cross-scale management, recognising the normative and practical importance of participation for addressing critical water challenges. These insights have relevance to both academic research and practice. This thesis achieves these research aims by combining literature-based conceptual development with empirical case studies to fulfil the following research objectives:

Objective 1 - Contribute to an interdisciplinary, systemic perspective on the significance of scale for the development of 'cross-scale' management of eutrophication as a critical water challenge:

- **1.1 –** Identify what 'scales' emerge as most relevant in the management of eutrophication as a socioecological problem. (**Chapter 2** and **3**)
- **1.2 –** Explore what can be gained from integrating multiple scale perspectives to understand eutrophic systems and their management. (**Chapter 3**)
- **1.3 -** Develop some key principles for cross-scale management of eutrophication from a socioecological perspective. (**Chapter 2**)

Objective 2 – Identify key contributions that participatory approaches can make to systemic cross-level and cross-scale management, by:

- **2.1** – Understand whether and how current collaborative efforts at the catchment level contribute to bridging scales in efforts to implement catchment management. (**Chapter 4**)

- **2.2 –** Assess whether and how participatory approaches can support the application of the key principles established in sub-objective **1.3** (**Chapter 2, 3** and **4**)

This is important because critical pressures on water systems remain widespread despite the proliferation of research, policy and management efforts over the last few decades (Recuero Virto, 2018; Andriamahefazafy *et al.*, 2022; Bilalova, Newig and Villamayor-Tomas, 2025). The persistence, complexity and multi-stakeholder nature of critical water problems like eutrophication have led to their labelling as 'wicked problems.' In response, there has been an evolution towards more systemic, 'integrative' approaches to water management, based on participatory management according to hydrological boundaries (Benson et al., 2013; Giakoumis & Voulvoulis, 2018; Pahl-Wostl et al., 2012). The most widespread approach is Integrated Water Resource Management (IWRM), which has become embedded in policy approaches from the global to the local level. Noteworthy examples include the Global-level UN Sustainable Development Goals, the international-level EU Water Framework Directive and the local-level catchment-based approach (CaBA) popularised in England (Allouche, 2017; Carlsen & Bruggemann, 2022; Collins et al., 2020; Moss et al., 2020). Despite this evolution, progress against these goals has been mixed and critical pressures still remain or have even intensified. This has largely been attributed to poor governance, including the failure to address some of the conceptual critiques of 'integrative' approaches like IWRM that have persisted since its (re-)emergence in the 1990s (Pahl-Wostl *et al.*, 2012; Bilalova, Newig and Villamayor-Tomas, 2025) A key critique is that, despite drawing on socioecological systems theory, integrated water management approaches neglect some of its core concepts. An important gap in integrated management approaches is how to address scale and cross-scale dynamics, which are of central importance in socioecological systems theory (Bennett & Reyers, 2024; Gain et al., 2021; M.-L. Moore et al., 2024; Whaley, 2022) These critiques echo the claim, expressed across both academic and policy spheres, that the management of water systems requires more integrated management across 'scales.'

6.2 Contribution to research objectives

This section outlines the contribution of the three chapters to addressing the research and policy gaps articulated in the aims and objectives. This will take the format of a discussion of the conceptual insights developed in **Chapter 1** and how the empirical findings in the two case studies relate to these insights. I will then outline their implications for cross-scale management of water management from a socioecological systems perspective, in relation to current perspectives in the academic literature.

6.2.1 Research objective 1: Contribute to an interdisciplinary, systemic perspective on the significance of scale for the development of 'cross-scale' management of eutrophication

In **Chapter 1** I conducted an integrative review to identify the significance of scale for the management of eutrophication (**objective 1.1**) and develop principles for managing eutrophication across 'scales' from a socioecological systems perspective (**objective 1.2**). This synthesis identified a large number of different scales and internal levels that can be used to structure the analysis of a eutrophic water system. The variety of approaches to scale reflects arguments that scale has a socially constructed component. They are not selected independently of the specific context in which they are used and are contingent on the perspective and needs of the researcher or practitioner (Manson, 2008; Vervoort *et al.*, 2012; Whaley, 2022; Friis *et al.*, 2023). However, I do distinguish some key types of scales and important distinctions in how they are applied that may be useful for informing the systemic cross-scale management of water systems more broadly.

A core difference in the application of scales emerged between the 'direct' and 'indirect' sub-systems that I derived from the qualitative evidence synthesis conducted in **Chapter 1**. Both sub-systems fundamentally contribute to the emergence of eutrophication in overall socioecological systems. However, these subsystems can be distinguished based on a strong divide in the types of drivers and processes that are their focus. Direct drivers were the primary focus of literature looking at on-the-ground management efforts and indirect drivers were the concern of research that looked largely at the enabling sociopolitical context. Direct drivers are those that directly impact or constitute a given eutrophic socioecological system and include fertiliser inputs, soil texture, topography and land-use practices. These drivers are considered to act within the spatial and temporal boundaries of the water body / system of concern, boundaries which often follow surface water hydrology but are ultimately defined according to the perspective and needs of the analyst(s) (de Loë and Patterson, 2018). Indirect drivers and processes instead impact eutrophication more diffusely, frequently by influencing the behaviour of humans and organisations. Indirect drivers include subsidies, market dynamics, and attitudes towards the environment.

Different scales were typically applied to analyse the direct and indirect. Direct drivers were solely analysed using spatial and temporal scales and 'cross-scale' management required the development of management strategies that were aligned across spatial and temporal levels to deliver positive sustainability outcomes across these scales. An example could be ensuring that an increase of riparian planting at the spatial level of the river reach was not negated by catchment-level shift from woodland to intensive farmland. Indirect drivers were instead primarily analysed using sociopolitical scales that had both spatial and political power dimensions (Vervoort *et al.*, 2012).

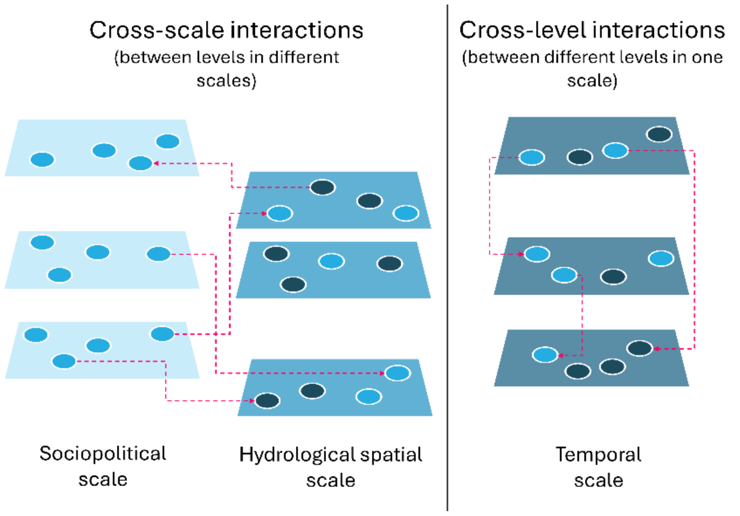


Figure 6.1*: A pictorial representation of cross-scale and cross-level interactions. In socioecological systems research, the term 'cross-scale' is often applied to refer to interactions across different levels e.g. different spatial levels. This contributes to the neglect of interactions between system components that are conceptualised as operating across different scales.*

The clear divide between research that focused on direct drivers and those that focused on indirect drivers contributed to a strong focus on 'cross-level' interactions, and the comparative neglect of cross-scale interactions. This is because authors typically applied a single scale for the analysis of an individual sub-system and therefore only analysed internal cross-level interactions across that single spatial, temporal or sociopolitical scale. These interactions were frequently referred to as 'cross-scale' interactions, despite the conceptual distinction between 'cross-level' and 'cross-scale' interactions made in the socioecological systems literature (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Glaser and Glaeser, 2014). In the socioecological systems theory, 'cross-level' refers to interactions across levels within the same scale, while 'cross-scale' means interactions between levels in different scales (**Figure 6.1**). The frequent conflation of these terms has previously been criticised as an important barrier to the analysis, discussion and interdisciplinary synthesis needed for systemic cross-scale management (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Glaser and Glaeser, 2014). I echo this critique and emphasise the need to explicitly conceptually separate and address both cross-level and cross-scale interactions. Currently, the failure to make this analytical distinction masks and potentially contributes to the limited attention paid to important interactions between the indirect and direct drivers of the system. This critical gap was identified in **Chapter 1**, and resonates with broader critiques that integrated water management approaches and socioecological systems research more broadly, inadequately consider cross-scale interactions (Gain *et al.*, 2021; Whaley, 2022; Bennett and Reyers, 2024; Moore *et al.*, 2024).

In response to these analytical insights, I then developed a theoretical framework for approaching the analysis and management of eutrophic socioecological systems (**Figure 6.2**). The framework makes an explicit conceptual distinction between 'direct' and 'indirect' drivers and 'cross-level' and 'cross-scale' interactions. These developments address two conceptual weaknesses in the socioecological systems literature. First, the arbitrary delineation between the social and the ecological, often resulting in the neglect of one or the other (Schlüter *et al.*, 2019; Hertz, Mancilla Garcia and Schlüter, 2020; Bennett and Reyers, 2024). Second, the limited attention paid to cross-scale interactions, as opposed to cross-level interactions (Gain *et al.*, 2021; Whaley, 2022; Bennett and Reyers, 2024; Moore *et al.*, 2024).

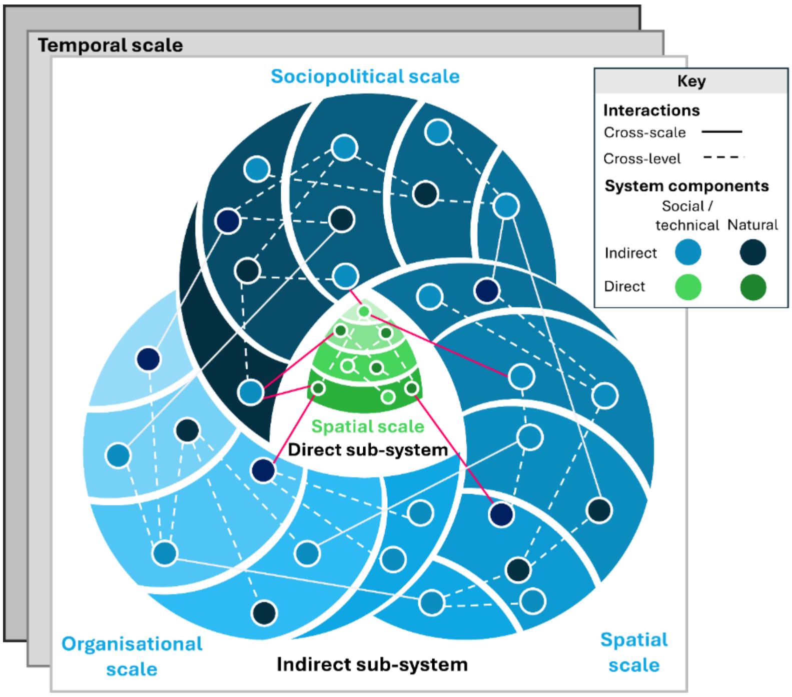


Figure 6.2: A Reproduction of the heuristic developed in Chapter 3, which treats socioecological water systems as multi-level and multi-scale 'direct' and 'indirect' sub-systems. Drivers and processes are in constant cross-scale and cross-level interactions, both within and between each sub-system. The 'direct sub-system' is presented in green and the indirect sub-system in blue.

The conceptualisation of water socioecological systems as consisting of interacting multi-level and potentially multi-scalar indirect and direct sub-systems primarily derived through the synthesis in **Chapter 3.** However, the definitions of 'direct' and 'indirect' drivers was strongly informed by those developed in the Millenium Ecosystem Assessment (Nelson *et al.*, 2006), with one key difference. Though it is often the case, my interpretation does not assume that 'indirect' drivers are necessarily social, or 'direct' drivers are solely ecological. Instead, my framework distinguishes between the 'direct' and 'indirect' purely based on the perceived tangibility of the mode and nature of the impact of a given driver on eutrophication in a spatially bounded system. This is based primarily on the results of the analysis in **Chapter 3**, which found that some ecological drivers, like change in climate, could be more readily classified as indirect. However, it also reflects discourses in both integrated water management and the wider socioecological systems literature (Schlüter *et al.*, 2019; Hertz, Mancilla Garcia and Schlüter, 2020; Bennett and Reyers, 2024). First, authors critique the persistent treatment of the social and the ecological as siloed, despite the ostensibly systemic and holistic commitments of these approaches. Secondly, it acknowledges the importance of spatiality in its delineation of the direct sub-system, while leaving space for concepts like 'telecoupling' that emphasise the significance impacts of supposedly distant drivers(Liu *et al.*, 2013).

This differentiation offers an explanation for the differences in the types of scales typically applied to these types of drivers (**Figure 6.2**). In this research, I foreground the role of driver characteristics, and the purpose and scope of research and management efforts in defining which sub-system, or both, is the primary focus. For example, researchers and practitioners focusing on policy recommendations will more deeply consider indirect drivers. Conversely, those looking to plan a system for decentralised treatment of urban run-off will be more concerned with direct drivers across relevant spatial levels and timeframes. However, this framework emphasises that the interactions across these two subsystems are nevertheless essential to consider supporting effective management.

Distinguishing between 'indirect' and 'direct' drivers and focusing on their interactions across levels and scales in some ways falls short of emerging trends in socioecological systems research that advocate for a move beyond 'interactionalism'[vi] (Preiser *et al.*, 2018; Hertz, Mancilla Garcia and Schlüter, 2020; Bennett and Reyers, 2024). However, I suggest that this research takes a step towards this goal by explicitly establishing that the 'direct' and 'indirect' are not synonymous with the 'ecological' and the 'social'. By distinguishing drivers based on how they act in a given eutrophic socioecological system, I can gain a more nuanced understanding drivers of eutrophication and how to use scales to best understand their interactions. It also supports a more critical approach and transparent to decision making about where system boundaries are drawn, what scales and applied, which drivers and their interactions are considered and what cross-scale management strategies are proposed. Furthermore, in the framework, the direct and indirect sub-systems are treated as

[vi] Socioecological systems research has been criticised as falling short of its theoretical commitment to treating social and ecological aspects of systems as inseparably intertwined. Instead, critics find that the majority of socioecological systems research remains 'interactionist', giving precedence to either the 'social' or 'natural' components of the system and perceiving interactions between the two as only existing in a single temporal snapshot. More recent work recommends embedding 'relationalism' more strongly into socioecological systems research. Relationalism emphasises that components of the system are not static, and do not exist separately from or 'pre-exist' their relationships with other system components. Authors argue that this ontological shift can help breakdown the persistent siloing of the 'social' and 'natural' in socioecological systems analyses, as well as encouraging a view of systems and their components as in a dynamic relationship that is both historical and ongoing. This can support both stronger analyses of causality and adaptive management (Preiser *et al.*, 2018; Hertz, Mancilla Garcia and Schlüter, 2020; Bennett and Reyers, 2024).

intertwined and drivers as participating in cross-level and cross-scale interactions both within and between the sub-systems. Consequently, the conceptualisation of water socioecological systems developed here addresses two key gaps in the integrated water management and socioecological systems literature: (1) the neglect of interactions between direct and indirect social, ecological and technical drivers (Rounsevell *et al.*, 2021), and (2) the limited attention paid to truly cross-scale interactions, which are frequently conflated with cross-level interactions (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Glaser and Glaeser, 2014). This again offers a move towards systems analyses that more effectively treat social and ecological components as deeply intertwined and relational (Bennett & Reyers, 2024; Hertz et al., 2020; Preiser et al., 2018).

In addition to addressing important conceptual gaps in integrated water management and socioecological systems approaches to water challenges, I suggest that this conceptualisation also has strong resonance with practioner approaches. The purpose-driven analytical divide between the direct and indirect offers a kind of modularity that may map more usefully onto the realities of an organisation engaged in eutrophication or catchment management. This is illustrated by the dual role of catchment partnerships' in cross-scale management that was identified in **Chapter 4.** Catchment partnerships first act as an agent in the direct sub-system that aims to physically implement on-the-ground measures, which is the focus of the principles from cross-scale management of direct drivers (**principle 1 - 10**). However, they also are also embedded in the indirect sub-system. Therefore, they must both navigate and mediate internal cross-level and cross-scale interactions between indirect drivers (**principle 11 - 20**), as well as cross-scale interactions between the two sub-systems to achieve favourable outcomes for catchment management (**principle 21 - 28**). Overall, while these concepts require both testing and further development, their resonance with existing practitioner perspectives implies that they may offer an opportunity to increase the stakeholder-relevance of socioecological systems scale concepts that have struggled to find purchase in policy and practitioner spheres (Vervoort *et al.*, 2012; Gain *et al.*, 2021; Bennett and Reyers, 2024).

In addition to synthesising a theoretical framework for approaching water systems as multi-level and multi-scale socioecological systems, **Chapter 3** further proposes some concrete steps for its operationalisation. Again, this addresses a well-recognised challenge in the development of sociological approaches to systemic water management, which is the sometimes limited translation of strong concepts into practical guidance. This is an issue that has been highlighted as particularly critical when it comes to scale (Carpenter and Bennett, 2011; Partelow, 2018; Gain *et al.*, 2021; Khodaparast *et al.*, 2025). Principles for the 'cross-scale' management of direct drivers focused on (i) conducting analyses across multiple relevant spatial levels and timeframes, using appropriate data (**principle 1, 2, 6** and **7**), (ii) identifying cross-level interactions and aligning management accordingly to deliver water quality improvements across spatial levels and timeframes (**principle 3, 4, 8,** and **9**), and (iii) ensuring that management approaches are compatible with other ecosystem services (**principle 5, 10**, and**11**). 'Cross-scale' management of the indirect sub-system meant ensuring the internal coherence of indirect drivers across sociopolitical levels to generate an enabling context for successful management. For example, aligning drivers across sociopolitical levels to encourage farmer participation in environmental schemes, including policies, trusted intermediaries and the attitudes and capacities of individual farmers.

Principles for achieving 'cross-scale' management of indirect drivers focused primarily on governance issues. Specifically, (i) vertical and horizontal alignment across governance levels, including

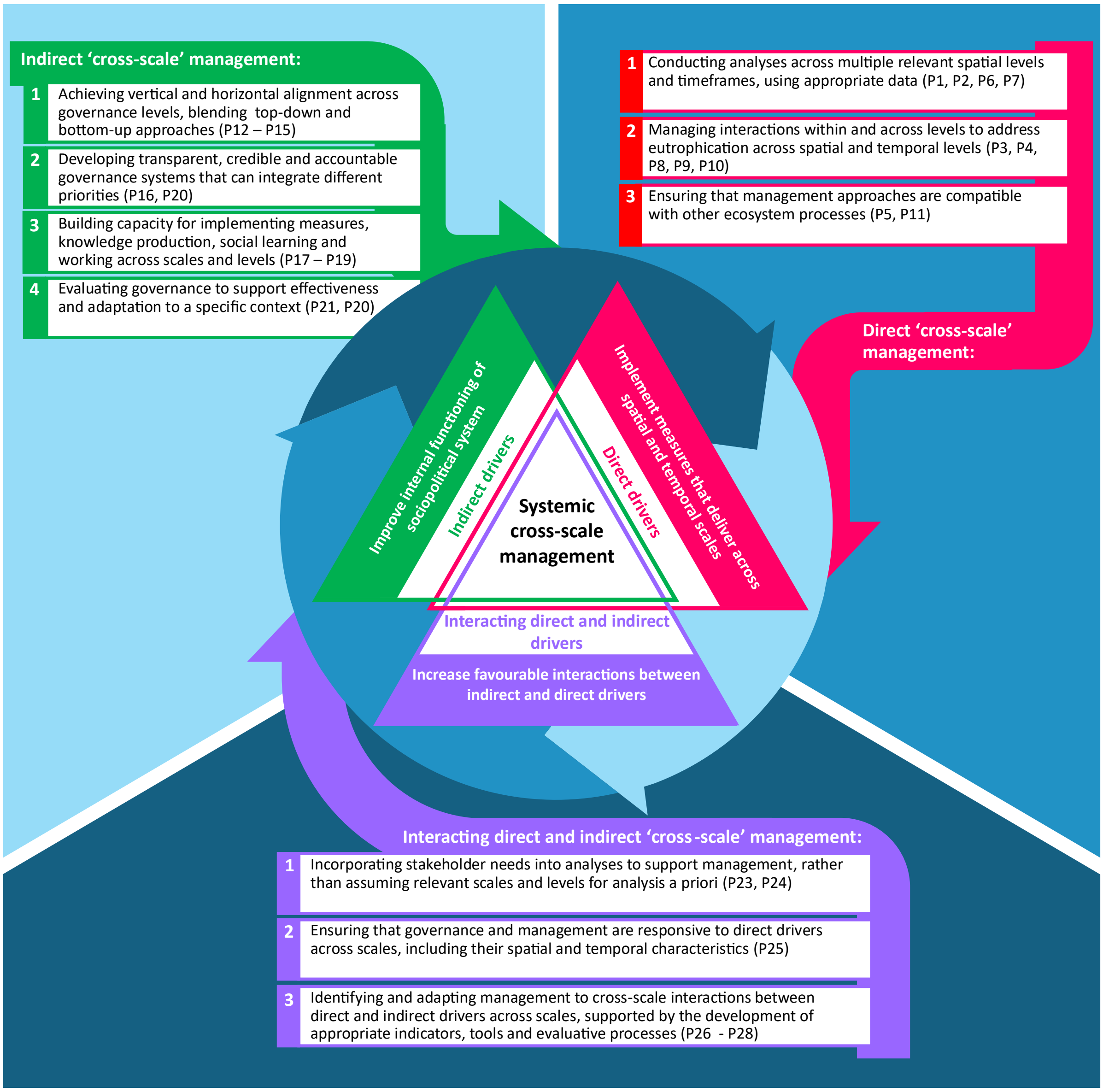


Figure 6.3: *The systemic cross-scale management of eutrophication as a product of interacting indirect and direct sub-systems. Drivers engage in cross-level and cross-scale interactions within their respective sub-systems, which are organised across different levels and scales. They also engage in cross-scale interactions between the two subsystems.*

the effective blending of top-down and bottom-up approaches (**principle 12 – 15**), (ii) developing transparent, credible and accountable governance systems that are capable of integrating different priorities (**principle 16, 20**), (iii) building capacity across sociopolitical levels to implement and maintain measures, engage in knowledge production and social learning and operate across different scales and levels (**principle 18, 19**), and (iv) evaluating and adapting governance to a given context (**principle 21, 22**).

However, the cross-scale management of eutrophication as an emergent property of the overall socioecological system relied on understanding and intervening in the cross-scale interactions between these two sub-systems. Managing these interactions was essential for ensuring that the 'indirect' enabling context was responsive to 'direct' drivers across scales, and had favourable outcomes for the 'direct' sub-system and eutrophication overall. Effective 'cross-scale' management of the interacting direct and direct meant (i) incorporating stakeholder needs into analyses to support management, rather than assuming relevant scales and levels for analysis a priori (**principle 23, 24**), (ii) ensuring that governance and management were responsive to direct drivers across scales, including their spatial and temporal characteristics (**principle 25**) and (iii) identifying and adapting management to cross-scale interactions between direct and indirect drivers across scales, supported by the development of appropriate indicators, tools and evaluative processes (principle 26 - Principle 28). This synthesis is presented in **Figure 6.3**.

Both the framework and proposed principles were empirically examined through the two case studies. This lends credibility to the idea that they can contribute to stronger systemic, cross-scale analyses and management approaches both within academia and in practice. The key scales drawn from interviews and workshops with practitioners in the case study in **Chapter 3** strongly reflected those developed in **Chapter 1** and were also highly purpose-driven (de Loë & Patterson, 2017; Manson, 2008). As argued in **Chapter 1**, practitioners in Sweden defined different scales for the strategic planning of on-the-ground interventions (direct drivers) and to describe the broader enabling context (indirect drivers). In **Chapter 3**, the use of multiple hydrological spatial levels for strategic planning reflected the central role of spatial scales in the cross-scale management of the 'direct' sub-system in **Chapter 1**. Likewise, the sociopolitical scale that emerged as important in **Chapter 3** was similar to that commonly used for cross-scale management of the 'indirect sub-system' or enabling context in **Chapter 1**.

The scales and internal levels derived in **Chapter 3** were an important framework used by participants to identify and 'locate' drivers and explain barriers to eutrophication mitigation. Key drivers were 'located' across multiple levels within the two scales, and their cross-level and cross-scale interactions were intrinsic to participants' explanations of the emergence of eutrophication and barriers to management. Many of the interactions and the resulting barriers and enablers of cross-scale management reflect the principles developed in **Chapter 1**: they highlight the importance of implementing direct management across multiple spatial levels, the need for horizontal and vertical bridging of the indirect sociopolitical sub-system, and the significance of cross-scale interactions between the direct and indirect sub-systems for successful management (full breakdown given in **Table 6.1**). Overall, there are strong resonances between the stakeholder-derived scales and real-world management challenges in **Chapter 3** and the concepts and principles for cross-scale management developed in **Chapter 1.** This suggests that the concepts and principles developed herein may have utility for improving the consideration of scale and cross-scale and cross-level interactions in real-world integrated eutrophication management (Gain *et al.*, 2021; Whaley, 2022; Bennett and Reyers, 2024; Moore *et al.*, 2024).

To summarise, this research makes two important contributions to water governance and socioecological systems research. The first is by extending socioecological systems concepts to strengthen the analysis of interactions across the diverse drivers in socioecological systems, by introducing the concept of 'direct' and 'indirect' sub-systems that can be evaluated using various scales, making explicit the differences in how these subsystems are addressed in research and management, and emphasising the significance of both cross-level and cross-scale interactions within and between the two sub-systems. The second is by addressing critiques that socioecological systems concepts, particularly around scale, are theoretically developed but lack practical guidance. I address this gap by developing tangible steps for approaching systems analysis and management, informed by both the academic literature and empirical work. Overall, I propose that the heuristic and principles for cross-scale management developed in this research can support more robust systems analyses by both researchers and practitioners.

Table 6.1: An assessment of how the principles for cross-scale management developed in Chapter 3 appear in the case study of eutrophication management in Chapter 3 to illustrate their potential relevance to real-life practice.

Chapter heading	Direct	Indirect	Interacting direct and indirect
4.4.2.1 Nutrient management requires greater goal alignment across sociopolitical levels	(**Principle 2i, 2iii**) Implement eutrophication management through multi-spatial level analysis at river basin, sub-catchment levels and site-levels (**Principle 3**) Understand the limitations placed on achieving river basin level goals by sub-catchment and micro-level drivers like high infrastructure density (**Principle 4**) Ensure that water quality goals are delivered across spatial levels by evaluating the impacts of separating combined parts of the sewer system at city-level versus sub-catchment level	(**Principle 12 - 14**) Integrate eutrophication mitigation goals horizontally and vertically across levels, sectors and jurisdictions to improve its prioritisation (**Principle 15ii**) Match top-down EU, national and river basin authority level regulation and enforcement with the flexibility to define management at city level (**Principle 15iii**) Improve prioritisation of eutrophication management over other goals across levels, sectors and jurisdictions to increase opportunities to implement eutrophication mitigation alongside other construction	
4.4.2.2 Nutrient management requires Legislation disfavours the prioritisation of nutrient management at city-level		(**Principle 12**) Improve vertical policy coherence so EU, national and county-level legislative powers are no longer undermined by lack of legal power at the city-level to implementing catchment-level management plans (**Principle 13**) Improve horizontal policy coherence to improve management, particularly of urban run-off (**Principle 14**) Decrease fragmentation of jurisdiction over key infrastructures to increase coordination and delivery of infrastructures	
4.4.2.3 Misalignments between responsibilities and funding reduce capacity for implementation		(**Principle 17**) Match legislative responsibilities for addressing eutrophication at city-level with statutory funding provision to improve implementation capacity	
4.4.2.4 Goal integration is driving a cultural shift towards 'multi-functional' spaces and infrastructures		(**Principle 15iii**) Integrate policy goals by implementing 'green' multifunctional infrastructures for eutrophication management to improve implementation	
4.4.3.1 Hydrological drivers and other priorities constrain opportunities for nutrient management			(**Principle 26iii**) Understand the constraints that climate mitigation goals and high infrastructure density place on eutrophication mitigation options (**Principle 26iii**) Evaluate where actions in line with EU and national policy goals for combined sewer separation and agricultural sewage sludge reuse may challenge eutrophication mitigation at sub-catchment level
4.4.3.2 Legislation inhibits planning decisions according to sub-catchment level nutrient dynamics			(**Principle 25i**) Ensure land use planning legislation supports the implementation of urban run-off management according to sub-catchment level dynamics (**Principle 25i**) Ensure water services legislation supports the implementation of decentralised urban run-off management according to site and sub-catchment level dynamics
4.4.3.3 Uncertainties and knowledge gaps require changes in knowledge production norms	(**Principle 1 - 2ii**) Improve knowledge of micro-level drivers for relatively unstudied land use types to develop more effective strategies	(**Principle 18**) Develop resources and processes for monitoring and evaluation of measures to improve credibility (**Principle 18**) Implement learning-by-doing approaches to incorporate green 'multi-functional' approaches to eutrophication mitigation (**Principle 18**) Implement participatory and collaborative governance to increase cross-sociopolitical-level alignment and increase buy-in	(**Principle 24**) Limited demonstration of the effectiveness of green micro-level infrastructures at improving catchment-level eutrophication inhibits their adoption (**Principle 25i**) Knowledge of drivers and dynamics of eutrophication at smaller spatial levels is seen as insufficient for developing legislation, guidance and legally binding management plans (**Principle 25iii**) Improve monitoring and evaluation of management efforts to support adaptive governance (**Principle 26iv**) Implement learning-by-doing approach to green 'multi-functional' infrastructures to support adaptive management
4.4.3.4 High rate and longevity of change is needed for successful nutrient management		(**Principle 18**) Implement educational resources and requirements to maintain expertise for eutrophication management across time	(**Principle 25ii**) Respond more quickly to changes in direct drivers of eutrophication (**Principle 25ii**) Maintain prioritisation, expertise and measures over necessary ecological timescales to see reductions in eutrophication (**Principle 25ii**) Develop funding streams for maintaining measures over necessary ecological timescales to see reductions in eutrophication
4.4.3.5 Collaboration facilitates implementation through goal integration and multi-functional thinking		(**Principle 15iii**) Implement collaborative / participatory governance to facilitate priority integration and buy-in across levels (**Principle 20**) Build bridging organisations to facilitate social learning across sociopolitical levels	(**Principle 25i**) Implement collaborative / participatory governance processes to promote cross-level and cross-scale knowledge exchange and facilitate governance responsiveness to direct drivers across spatial levels

6.2.2 Research objective 2: Identify key contributions that participatory approaches can make to systemic cross-level and cross-scale management

The ultimate aim of this thesis was not just to establish some principles for the systemic cross-scale management of eutrophication, but to contribute to participatory approaches to cross-scale management in both research and practice. Participation has increasingly been held as fundamental to good water governance, and is an important underlying principle of both integrated water management approaches and socioecological systems approaches (Stringer *et al.*, 2006; von Korff *et al.*, 2012; Han *et al.*, 2024). Participation is seen as essential for developing strong systems understandings and performing the integration necessary to achieved balanced outcomes according to multiple perspectives and priorities. Participation is also considered a core component of just and fair governance, and achieving procedural justice (Lawrence, Daniels and Stankey, 1997; Aleu, Larsen and Methner, 2022). However, efforts at participatory water governance have been criticised as inadequately integrated into governance and poorly executed, with some authors even describing it as 'misused' (Benson, Jordan and Smith, 2013; Benson, Gain and Giupponi, 2020; Aleu, Larsen and Methner, 2022; Seigerman *et al.*, 2023). Consequently, any efforts to improve environmental governance should deeply consider how these changes can be best integrated with participatory approaches. A key aspect of this is elucidating where participatory processes can add value to systemic cross-scale management, paying attention to both the more instrumental and normative aspects of participation (Arnstein, 1969).

Chapter 1 used an integrative literature review to produce a framework for the systemic and participatory cross-scale management of eutrophication. The framework was synthesised by first (i) identifying important concerns around scale in eutrophication management, (ii) developing some principles for addressing those challenges (detailed in **Table 3.4** - **Table 3.6**, and summarised in **Figure 6.3**), and (iii) outlining some of the key contributions that participation can make to applying those principles (**Figure 3.4**). Participation could contribute to all three 'types' of cross-scale management. In the case of the cross-scale management of direct drivers, participatory approaches could be an important means to strengthen system understandings at important spatial and temporal levels, aligning management across spatial levels and improving synergies with other ecosystem services (**principle 1 - 6**). The experiential knowledge of participants was a core aspect of this; however, participants could also contribute to formal scientific knowledge through mechanisms like community science. Participation could also play an important role in facilitating the cross-scale management of indirect drivers. Again, the knowledge and experiences of participants were key, as they could support a better understanding of the success or failure of policy that aimed to engage participants in environmental management. Perspectives on 'experienced' policy coherence could also contribute to improvements in policy coherence overall (**principle 12 - 15, 21**). Participation could also facilitate trust-building, knowledge exchange and social learning across sociopolitical levels (**principle 18, 20**). Furthermore, an important contribution of participation was supporting the integration of multiple stakeholder priorities (**principle 15, 16**), allowing a greater embedding of procedural justice into governance. Finally, participation could increase favourable interactions between direct and indirect drivers across scales. Firstly, by supporting the development of systems analyses at more stakeholder-relevant spatial and temporal levels (**principle 23**). Secondly, by improving stakeholder awareness of links between activities at one spatial level and others. Mostly notably, farm-level practices and outcomes for catchment-level water quality (**principle 24, 25**). Finally, participation can contribute to more effective and adaptive governance of eutrophication by supplying information on local needs, conditions and their changes over time to relevant sociopolitical levels (**principle 25, 26**).

Chapter 3 demonstrates the capacity of participatory approaches to illuminate key scales for eutrophication management, and identify critical cross-level and cross-scale interactions between direct and indirect eutrophication drivers. This offers an important expansion on existing research in collaborative governance by specifically interrogating how participation can contribute to scale-sensitive management both in theory and practical terms (Benson, Jordan and Smith, 2013; Benson, Gain and Giupponi, 2020; Aleu, Larsen and Methner, 2022; Seigerman *et al.*, 2023). **Chapter 4** builds further on the conceptual insights developed in **Chapter 1** by evaluating the theoretical framework and principles for cross-sale management developed herein. It does so by assessing whether and how organisations for participatory catchment management in Scotland had added value for the cross-scale management of catchments in Scotland. This case study offers an opportunity to identify where the principles developed for cross-scale management of eutrophication may have relevance for catchment management more broadly. It also adds nuance to them by clarifying some of the limitations and barriers that can inhibit the role of participation in cross-scale management, as well as some suggestions for overcoming these barriers so catchment partnerships can more play a meaningful role in cross-scale management. Many of the areas where catchment partnerships were perceived to improve cross-scale catchment management in **Chapter 4** reflected those identified in **Chapter 1**. However, the case study of Scottish catchment partnerships also suggested some other areas where participation could add value to cross-scale management. A full comparison between the role of participation in cross-scale management developed in **Chapter 1** and the added value, barriers and limitations of catchment partnerships identified in **Chapter 4** is given in **Table 6.2.**

Many of the benefits of catchment partnerships for cross-scale management identified in **Chapter 4** related to their concentration, production and exchange of cross-level and cross-scale knowledge of direct and indirect drivers and their interactions. The catchment partnerships were able to concentrate cross-level and cross-scale expertise at the catchment level through the engagement of diverse actors who operated across different sociopolitical and spatial levels. This reflects discourse in the literature on participatory watershed management that emphasises both the need to consider dynamics across spatial, temporal and sociopolitical scales for successful management, and the benefits of collaborative catchment partnerships for mobilising the necessary expertise (Marshall, Blackstock and Dunglinson, 2010; Rouillard and Spray, 2017; Waylen *et al.*, 2023). It also suggests that paying better attention to stakeholder 'scales', which are not typically used as a tool to inform stakeholder engagement (White *et al.*, 2018), may be useful to improve the bridging of top-down and bottom-up catchment management (Rouillard and Spray, 2017).

In line with the conclusions of **Chapter 1,** the participatory nature of catchment partnerships was seen to offer opportunities to improve the management of indirect drivers across relevant scales. The case study builds on the limited previous research into the role of catchment partnerships in improving policy coherence by further evidencing the benefits of engaging partners with expertise in navigating funding and regulatory landscapes (Blackstock *et al.*, 2023). It then suggests a further role for catchment partnerships in policy coherence by highlighting their status as sites for policy testing and evaluation that can access diverse experiences of both indirect political and socioeconomic drivers (**principle 12**) (Enloe, Schulte and Tyndall, 2017; Taylor and Eberhard, 2020; Yoder, Chowdhury and Hauck, 2020). Internal knowledge production, exchange and social learning have long been recognised as a key strength of catchment partnerships (Mostert *et al.*, 2007; Allen *et al.*, 2011; Waylen *et al.*, 2023). However, **Chapter 4** expands on this literature and the findings of **Chapter 1** by emphasising the significance of demonstration projects and experimentation for encouraging actor participation within the catchment and even outside of it (this offers an expansion on **principle 18**, given in **Table 6.2**).

Demonstration projects and experimentation with novel management strategies, policies and funding schemes were essential mechanisms used by the catchment partnerships to upscale and even outscale catchment management to other catchments. The importance of demonstration projects has been explored in the case of the adoption of agricultural practices, which is of high relevance to catchment management (Sutherland and Marchand, 2021; Lox *et al.*, 2025). However, this mechanism of social learning appears to have received limited specific attention in watershed management despite its apparent value to participatory management in **Chapter 4** (Allen *et al.*, 2011; Sutherland and Marchand, 2021; Lox *et al.*, 2025), value that is reflected in the policy-driven development of so-called 'demonstration' watersheds and catchments (Allen *et al.*, 2011; McGonigle *et al.*, 2014; Enloe, Schulte and Tyndall, 2017). Understanding how to design demonstration projects that can support the upscaling and outscaling of catchment management in a given context could be extremely valuable for strengthening catchment partnerships' role in cross-scale management. I therefore suggest that this could be an important area for future research.

The catchment partnerships in **Chapter 4** also facilitated improved cross-scale catchment management by playing an effective bridging role as trusted intermediaries (**principle 18, 20**). As trusted intermediaries catchment partnerships not only increased engagement of key actors in catchment management (Cook, Atkinson, et al., 2013; Rouillard & Spray, 2017), they also encouraged actors to bridge spatial levels by moving from a focus on the site or farm-level to catchment-level visions. Playing an effective bridging role relied on catchment partnerships successfully integrating the priorities of diverse actors, something that is has been identified as a critical challenge in catchment management (**principle 20**) (Blackstock, Kelly and Horsey, 2007; Brian R. Cook *et al.*, 2013; Rouillard and Spray, 2017; Waylen *et al.*, 2023). In **Chapter 4,** this largely meant catchment partnerships demonstrating their capacity to deliver against the statutory, commercial, and environmental priorities of key governmental and industry partners. In several cases, this reflected greater focus on private sector investment as catchment partnerships navigated unfavourable indirect public funding drivers (K. L. Blackstock et al., 2007; Waylen et al., 2023). Overall, catchment partnerships were seen to play an effective role as a bridging organisation and catalyse implementation by concentrating resources, expertise and improving delivery capacity beyond the capability of individual partner organisations (**principle 17**).

In addition to contributing to the alignment of indirect drivers across level needed to favour the implementation of catchment management, **Chapter 4** demonstrates that collaborative catchment partnerships can support the effective management of direct drivers across spatial and temporal scales. This reflects the findings in **Chapter 1**. The studied catchment partnerships facilitated data production through both formal research and citizen's science. This enabled the production of knowledge of direct drivers across spatial and temporal scales that were more specific to participants' needs (**principle 1, 6, 23**), as suggested by research on the contribution of citizen's science to effective water management (Enloe, Schulte and Tyndall, 2017; König *et al.*, 2021; Wuijts *et al.*, 2021). In the case study, as reported in the wider literature, the experiential and data-driven knowledge of direct drivers supplied by participants was seen to support the development of on-the-ground management strategies (**principle 3**) (Kastens and Newig, 2008a; Brils *et al.*, 2014; Tschikof *et al.*, 2024). Together, **Chapter 1** and **Chapter 4** contribute to an improved understanding the benefits of implementing participatory approaches for water governance (von Korff *et al.*, 2012).

While **Chapter 4** provided further evidence for the useful contributions that participatory governance approaches can make to cross-scale catchment management identified in **Chapter 1**, it also illuminated some key challenges. These challenges centred around (i) the effectiveness of the bridging role played by catchment partnerships, (ii) the impact of external indirect drivers across sociopolitical levels on stakeholder participation in collaborative catchment management and (iii) the capacity of catchment partnerships to move beyond site-level implementation and achieve catchment-level outcomes. Aligning across and between sociopolitical levels is an important principle for achieving cross-scale management. However, the catchment partnerships studied in **Chapter 4** performed only limited vertical bridging of farming communities and other land managers (**principle 20**), undermining legitimacy and trust building, reducing access to the diverse expertise, resources and delivery capacity and ultimately challenging the coordination and implementation of site-level measures with catchment-level goals (**principle 17**). The insufficient embedding of catchment partnerships in the broader governance system, was also highlighted as limiting their ability to bridge multiple sociopolitical levels (**principle 12, 15ii, 15iii, 21**) (Rollason et al., 2018; Rouillard & Spray, 2017; Surridge et al., 2009). In part, this was due to inadequate statutory resourcing for engagement activities. This reflects earlier criticisms that collaborative catchment management appears to involve the devolution of responsibility and costs, without being matched by agency and resourcing (Cook et al., 2013; Rollason et al., 2018). Further indirect drivers across sociopolitical levels challenged the participation of key actors in collaborative catchment management. At the catchment-level, critical challenges existed around accommodating the engagement needs of different stakeholders, addressing their varied priorities and integrating different perspectives on what constitutes legitimate knowledge (**principle 15iii, 16, 23, 24**) (Ayre & Nettle, 2015; Balvanera et al., 2017; Marshall et al., 2010; Rollason et al., 2018). Indirect drivers at higher sociopolitical levels like poor policy and market incentives also undermined engagement in collaborative catchment management (**principle 12, 21**) (Rollason et al., 2018; Rouillard & Spray, 2017; Surridge et al., 2009). Ultimately, these issues challenged the aspirations of catchment partnerships to move from site-level to catchment-level management. Delivery at scale therefore remains a core challenge for catchment partnerships in contributing to cross-scale catchment management (Waylen *et al.*, 2023).

These conclusions add to the body of literature that highlights the invaluableness of participation to watershed management, but that also emphasises the need for well-designed and serious participatory processes that are capable of realising this potential (Aleu et al., 2022; Benson et al., 2013, 2020; Moss et al., 2020; Seigerman et al., 2023). This thesis makes steps towards this goal by proposing a framework for participatory and systemic cross-scale eutrophication management (**Chapter 1**), evidencing its relevance to broader catchment management (**Chapter 4**) and identifying some of the dynamics that can impact its successful implementation (**Chapter 4**). It also expands on the literature on participatory water governance by introducing a novel conceptualisation of catchment partnerships as having a dual role as agent of change in interacting direct and indirect subsystems. Or, in more practical terms, as influencing and being impacted by both the drivers in the spatially bounded water system where they attempt to implement tangible management, and the broader enabling context. As agents of change in both these systems, catchment partnerships must also play an important role in mediating between these subsystems to successfully implement effective management. This contributes to the academic literature by offering a way to more comprehensively approach evaluation of these organisations and the challenges they face from a systemic perspective. They value of this approach is demonstrated by the novel contributions of Chapter 5 to the body of evidence on the value of catchment partnerships to systemic cross-scale management. For example, the importance of demonstration projects for bridging stakeholders across sociopolitical levels and facilitating spatial upscaling.

By doing so, this research aims to provide a pathway to unlocking the value of participation in the face of a desired shift towards eutrophication and catchment management that is both systemic and embedded across 'scales' (Bennett & Reyers, 2024; Gain et al., 2021; M.-L. Moore et al., 2024; Whaley, 2022).

Table 6.2: Mapping of the added value, limitations and barriers to catchment partnership's role in cross-scale management (Chapter 4), against the principles for participatory cross-scale management developed in Chapter 3. Text in italics represents an expansion on the contribution of participation to cross-scale management based on the case study in Chapter 4.

Type of driver	Contribution of participation to cross-scale management	Value added by catchment partnerships	Limitations and barriers
Direct	Enable data production at key spatial and temporal levels e.g. through citizen's science (principle 1, 6).[a]	5.5.1.4[b] Facilitating monitoring and evaluation of the catchment at a spatial and temporal resolutions beyond those performed by statutory monitoring (principle 1, 6).	
	Improve knowledge of drivers and mitigation options through experiential knowledge at different spatial levels (principle 2).	5.5.1.4 Concentrating varied expertise and perspectives to support catchment characterisation across spatial levels, identifying pressures and intervention opportunities across the extent of the catchment (principle 2).	5.5.2 Limited vertical bridging of farming communities and land managers reduces access to diverse expertise and perspectives across sociopolitical and spatial levels (principle 2).
	Facilitate the alignment of management across spatial and temporal levels through producing and integrating cross-level knowledge e.g. through demonstration catchments (principle 3, 4).		5.5.4.2 Challenges implementing projects to achieve goals across different spatial levels, beyond the site-level (principle 3, 4, 17).
	Increase synergies with other ecosystem services across spatial levels by providing local-level perspectives (principle 5).	**Not specifically discussed**	**Not specifically discussed**
Indirect	Improve understandings of *and support adaptation to* important indirect drivers that impact policy *and management* implementation (principle 12, 14, 21).	5.5.1 Accessing partners with expertise in the logistical and managerial aspects of delivering projects, including navigating the funding and regulatory landscape across sociopolitical levels (principle 21).	5.5.2.4 Low embedding of catchment partnerships in governance despite being recognised as delivery mechanisms for legislation and policy across sociopolitical levels (principle 12, 15ii, 15iii, 21).
	Strengthen policy coherence by providing on-the-ground insights into 'experienced' policy coherence (principle 12, 15ii, 15iii, 21).	5.5.1.3 Supporting the improvement of policy implementation and experienced policy coherence, by evaluating how high-level policy might function upon on-the-ground implementation (principle 15ii, 21).	5.5.2.3 Barriers to environmental action and collaboration posed by ongoing policy incentives for agricultural intensification, instability in policy signalling and limited policy incentives (principle 12). 5.5.2.3 Limited and uncertain market incentives for farmers, industry actors and landowners to engage in catchment partnerships and environmental action (principle 12, 21). 5.5.2.4 Low embedding of catchment partnerships in governance despite being recognised as delivery mechanisms for legislation and policy across sociopolitical levels (principle 12, 15ii, 15iii, 21).
	Support the integration of eutrophication management and other priorities across sociopolitical levels (principle 15iii, 16).	5.5.1.2 Delivering against the statutory, commercial and environmental priorities of partners to integrate priorities and engage key stakeholders (principle 15iii).	5.5.2.2 Challenges integrating different priorities can lead to the exclusion of farming representatives from catchment partnerships (principle 15iii, 16).
	Facilitate knowledge exchange and social learning across sociopolitical levels through creating bridging organisations, building trust *and supporting experimentation and demonstration* (principle 18).	5.5.1 Performing vertical and horizontal bridging, facilitating the exchange of cross-scale expertise (principle 18). 5.5.1.2 Facilitating the implementation and upscaling of catchment management strategies through demonstration projects and associated outreach (principle 18). 5.5.1.3 Acting as 'test cases' for exploring novel ways of implementing catchment management, including on-the-ground management strategies, effective policies and new funding strategies (principle 18).	
	Increase engagement at the local level by increasing trust across sociopolitical levels *to increase adoption of measures* (principle 20).	5.5.1.2 Performing a bridging role as trusted intermediaries to encourage widespread engagement and adoption of catchment management measures (principle 18, 20). 5.5.1.2 Building trust by identifying and integrating priorities across sectors and sociopolitical levels, particularly with members of the farming community (principle 20).	5.5.2 Limited vertical bridging of farming communities and land managers prevents procedural justice, and trust building (principle 20). 5.5.2 Gaps in engagement undermine trust building, reducing buy-in and implementation (principle 20). 5.5.2.2 Low flexibility according to the engagement needs of different participants can prevent participation of key groups like farmers (principle 20).
	Acting as bridging organisations to leverage greater resources and improve delivery capacity at key levels (principle 17).	5.5.1 Concentrating delivery power by engaging actors with the authority, resources and / or delivery capacity to facilitate or prevent projects (principle 17). 5.5.3 Catalysing catchment-level management beyond the capabilities of individual partner organisations by concentrating diverse expertise and delivery capacity (principle 17).	5.5.2 Limited vertical and cross-sectoral bridging of industry actors, landowners and communities reduces access to resources and delivery capacity (principle 17). 5.5.2.4 Inadequate and poorly designed public funding that fails to match the realities of operating catchment partnerships, including funding for stakeholder engagement (principle 17).
Interacting direct and indirect	Ensure that data and systems analyses are produced at stakeholder-relevant spatial levels and timeframes e.g. through participatory modelling (principle 23).	5.5.1.4 Facilitating monitoring and evaluation of the catchment at spatial and temporal resolutions that were more specific to the needs to the catchment than statutory monitoring (principle 23).	5.5.2.2 & 5.5.4 Difficulties addressing different perspectives on legitimate and useful knowledge, including farmer perspectives, reduces engagement and implementation (principle 23). 5.5.4 A lack of catchment-level baselining could prevent the evaluation of the impacts of site-based mitigation efforts across the catchment, undermining corporate sustainability reporting that could motivate private-sector engagement (principle 23).
	Build understanding and acceptance of links between field-level practices and water quality at higher spatial levels through acting as trusted intermediaries (principle 24, 26i). *and developing visions that link multiple spatial levels* (principle 3, 24, 25).	5.5.3 Developing a shared catchment-level 'vision', to move from project or site-level delivery to coordinated management at the catchment level (principle 24, 25).	5.5.2.2 Difficulties addressing different perspectives on hydrological dynamics and legitimate management strategies can reduce farmer engagement (principle 23, 24).
	Integrate local drivers and conditions into policy and decision-making across levels by feeding local knowledge and needs to higher policy levels (principle 25i, 26i).	5.5.1 Concentrating cross-scale insights into catchment dynamics and challenges at the catchment-level to facilitate management (principle 25i).	
	Improve the adaptability of governance and management to changes in conditions and emerging issues by providing timely experiential knowledge (principle 26iv).	**Not specifically discussed**	**Not specifically discussed**

a) Principle for cross-scale management as given in Chapter 1.

b) Heading where further discussion of the given 'value added' or limitation / barrier can be found in Chapter 4

6.3 Implications for research and practice

This thesis has relevance to policy in two ways. As stated in **Chapter 1.3**, the first is through providing place-based, stakeholder relevant empirical insights as embedded participatory research. **Chapter 6.4.1.1** therefore presents practitioner-relevant insights into the cross-scale challenges to the management of eutrophication as a systemic socioecological problem in Stockholm, Sweden. **Chapter 6.4.1.2** then provides an evaluation of the benefits and limitations of catchment partnerships in supporting participatory cross-scale management of catchments in Scotland and some potential solutions.

The second contribution of this thesis is supporting theoretically informed cross-scale management through the development of a heuristic that takes an almost modular approach to the systemic cross-scale management of eutrophication and catchment management more broadly (**Figure 6.2**).

6.3.1 Empirical insights into place-based cross-scale water management

6.3.1.1 Cross-scale barriers to eutrophication management in Stockholm, Sweden

Chapter 3 provides a cross-level and cross-scale socioecological analysis of eutrophication management in Stockholm, Sweden. This case study therefore provides valuable insights into the challenges facing eutrophication management as part of the downscaling of WFD river basin management plans in Stockholm.

Analysis of cross-level sociopolitical interactions revealed that the strong goal setting of the WFD at the EU, national and river-basin levels has become fragmented at the city-level where implementation largely occurs. Eutrophication management required greater goal alignment across sociopolitical levels, including greater horizontal alignment between Stockholm's municipal boards to take advantage opportunities for implementing eutrophication mitigation infrastructures alongside other construction projects and reduce clashes over how spaces should be used. This could be supported by changes in legislative and political drivers at national and city-level that disfavoured the prioritisation of eutrophication mitigation at city-level; for example, giving legal weight given to sub-catchment level plans, better defining responsibilities for managing urban run-off at city-level, and increasing funding sources for the municipal water company to implement catchment plans.

Cross-scale analysis revealed that the successful cross-scale management of eutrophication required decision making across the sociopolitical scale that supported sustainable nutrient dynamics at multiple hydrological levels. Efforts must be made to address misalignments between the available knowledge of nutrient dynamics and the standards required to implement measures and make plans legally binding. Formal scientific knowledge production may be appropriate in some cases; however, experimentation and learning-by-doing approaches may also have an important role. Where hydrological drivers and dynamics were characterised, there must be regulations, incentives and resources that encourage changes in infrastructure, practices, water management and land use change according to those dynamics. One important example is addressing gaps in planning regulation that give the municipality limited power to coordinate stormwater management by new developments. Another is ensuring that separating combined parts of the sewer network did not generate trade-offs if the decentralisation of urban run-off treatment was not feasible in all sub-catchments. Finally, it is essential to increase the pace of policy and legislative responses to changes in ecological drivers, and ensuring that funding is available for maintaining management efforts over the extended timeframes required to see ecological change.

6.3.1.2 Benefits and limitations of catchment partnerships for participatory cross--scale catchment management in Scotland, UK

Chapter 4, identifies some of the important contributions that catchment partnerships are making to cross-scale catchment management. I also establish some limitations and barriers that they face and suggest some actions that could be taken to address some of those barriers. These insights may be valuable for strengthening the role of catchment partnerships in cross-scale catchment management in Scotland.

The catchment partnerships in the case study had all implemented and further catalysed the implementation of catchment management interventions on the ground. By doing so, they demonstrated their capacity to align 'indirect' drivers across sociopolitical scales to improve conditions for implementation. The catchment partnerships did this in several ways. Firstly, they concentrated expertise at the catchment level. This provided partnerships with the capacity to mobilise resources and implement projects above and beyond the capabilities of individual member organisations. Secondly, they had, at least to some extent, navigated and integrated the priorities of different stakeholders across sociopolitical levels to increase engagement and upscale implementation. Thirdly, they acted to increase awareness of environmental measures and reduce perceptions of risk at the individual level by both acting as trusted intermediaries and demonstrating catchment management measures. By doing so, they catalysed the upscaling and out-scaling of the adoption of catchment management measures. Finally, catchment partnerships could enable the development of catchment-scale test cases that could be used to catalyse social learning and changes in catchment management that could be out-scaled to other catchments.

However, there remained important gaps in engagement across sociopolitical levels that stalled the implementation of management across spatial levels. A critical gap was farmer engagement, which inhibited farm-level management and upscaling to catchment-level change. At the catchment partnership level, the fundamental challenge was integrating the diverse needs and perspectives at the level of the catchment. There was concern that farmers and their representatives may be excluded due to the divergence of their perspectives and priorities from those of the majority of partnership participants. At the national level, the primary barriers were insufficient policy and market incentives for collaborative catchment management. Barriers included the uncertain and poorly formulated incentives provided by Scotland's previous and emerging Agri-Environment Climate Scheme (AECS), and the limited emergence of formal market mechanisms for environmental uplift beyond the carbon markets. Limited market incentives also acted as a barrier to increased engagement of landowners and private industry. Higher level indirect drivers also posed a barrier to the delivery of environmental projects by catchment partnerships.

Overall, catchment partnerships were seen as insufficiently embedded in Scottish governance systems despite acting as a recognised mechanism for statutory delivery. The resourcing supplied at national level did not support stakeholder engagement activities, the long-term retention of staff, project scoping or project maintenance. These issues posed challenges for the efficacy and longevity of the partnerships.

The case study identified two major strengths of the studied catchment partnerships for supporting the development and implementation of on-the-ground measures for 'direct' cross-scale management. The first was mobilising actors across sectors and sociopolitical levels that could contribute cross-spatial-level data and expertise, or support the production of knowledge at catchment-relevant spatial and temporal levels The second strength was the co-development of a shared vision for catchment-level change, which was seen to facilitate upscaling from fragmented site-based projects that may not deliver benefits at the overall catchment level. However, achieving a shared 'cross-scale' understanding of direct drivers was also challenged by the diversity of actors participating in the catchment partnerships. A core challenge was the integration of different forms of knowledge including formal scientific knowledge, experiential knowledge and community science contributions. Stakeholders had different perspectives on what type of knowledge should be produced and at what scales to achieve their individual aims, at an appropriate level of cost, and according to their perception of what was a satisfactory standard of knowledge. A key point of discussion was to what extent catchments needed to be characterised 'scientifically'. For some interviewees it was important to present data that was perceived as high integrity, particularly where the data was intended to underpin frameworks for private investment in nature uplift. It was also seen as useful for industry partners who aimed to report their participation in catchment projects against internal environmental goals and external statutory requirements. Others instead emphasised that the time and resources required to characterise a catchment 'scientifically' could be a barrier to action in the face of collapsing timeframes for addressing ecological pressures.

Integrating management across relevant spatial levels also remained a challenge. Members from each catchment partnership expressed ambitions to increase the spatial extent of stakeholder engagement and project implementation. Several also aimed to improve the targeting of key spatial levels from individual river reaches and sub catchments to the level of the catchment itself.

I suggest several steps forward that could address some of the barriers outlined and improve the role of catchment partnerships in cross-scale catchment management in Scotland. Firstly, catchment partnerships should strengthen their development of shared 'cross-scale' understandings of direct system drivers. To do so, they should explicitly discuss and come to an early consensus on what types of knowledge are to be produced at what scales and make plans for their integration. Secondly, catchment partnerships should increase their engagement of key stakeholders across sociopolitical levels to improve cross-spatial-level catchment management. Important mechanisms include peer-to-peer relationship building and building their reputation as a delivery partner by leveraging an understanding of the commercial and statutory requirements of key actors. Finally, catchment partnerships should push for better incentives and resources for collaborative management. In Scotland, a valuable avenue could be pushing for incentives for farmer engagement in collaborative management in the developing agricultural support scheme.

6.3.1.3 Empirical insights into participation and systemic, cross-scale water management

An extensive cross-comparison of the two case studies has limited usefulness due to their different empirical focuses and methods of investigation. **Chapter 4** focuses on the formal governance of eutrophication in an urban catchment in Stockholm, while **Chapter 5** focuses on non-governmental catchment management organisations focusing on catchments with a major proportion of rural land in Scotland. They also differ in terms of whether they use participatory approaches to investigate cross level and cross scale interactions (**Chapter 4**) or to investigate how participatory organisations influence and navigate cross-level and cross-scale interactions (**Chapter 5**). However, both provide some insights into the potential contributions and limitations of participatory approaches to cross-scale, systemic water management. They also provide empirical evidence that can be drawn on to identity some common types of cross-level and cross-scale interactions that impact water governance.

Both case studies demonstrate the importance of goal alignment across sociopolitical levels and integration with other goals. In the case study in Sweden (**Chapter 4**), interview participants primarily focused on aligning different policy areas and governance actors within and across sociopolitical levels. In contrast, participants in the case study in Scotland emphasised the capacity of partnerships to deliver against the goals of multiple actors. Key actors included not just the catchment partnership itself and statutory bodies, but also commercial partners and landowners. These differences likely reflect the diversity of the types of actors and organisations primarily engaged in the two case studies. However, I tentatively suggest that it may also reflect the status of the City of Stockholm as a major regulator, landowner and controller of key infrastructure in the catchment studied. Meaning that the engagement and negotiation largely appeared to be necessary between municipal boards at sub-catchment level.

Further, both Stockholm's municipal actors and members of Scotland's catchment partnerships found that national level resources and policy were mismatched with expectations for local level organisations to deliver statutory water quality goals. Interviewees from Stockholm's municipal government largely linked this to national-level legislation, and city-level political decision making that resulted in inadequate resourcing for the delivery of infrastructure. In Scotland, statutory bodies frequently engaged with catchment partnerships as means of statutory delivery, including of WFD goals. However, participants commented that the resources made available at national level did not reflect the devolution of responsibility to non-statutory catchment-level organisations. One community group participant even referred to this as 'statutory neglect,' reflecting concerns in the literature that aspirations to make water governance more participatory and locally-relevant appear to fail due to being chronically under-resourced. Participants in the Scottish case study also had a much greater focus on commercial partners and market mechanisms for delivering the resources needed to deliver catchment management. Again, this likely reflects the non-governmental nature of catchment partnerships. However, it may indicate wider differences in how responsibility and capacity for delivering water management across the public and private sphere is perceived in the two countries.

Finally, the two cases evidenced the challenges of navigating diverse stakeholder norms around what constitutes useful and robust knowledge, a challenge that only intensifies when working across different levels and scales. In both cases, issues arose over the perceived quality of knowledge at catchment level and regarding the effectiveness of measures at micro (in the case of Sweden) and catchment scale (in both cases). Conflicting perspectives emerged between different groups across the two case studies. In the Swedish case study, they emerged between different municipal actors at city level. In contrast, in the Scottish case study, research and industry partners were more likely to require data that was characterised as 'scientifically robust'. Conversely, statutory, farming and NGO partners were more likely to favour experiential knowledge. Again, these results should be interpreted with caution due to the limitations of both studies, and the contextual nature of what data is considered appropriate under what circumstances. However, overall, they do indicate that the role of different types of knowledge should be explicitly negotiated and collectively decided in collaborative governance. Otherwise, they can lead to conflicts that can arise even at very late stages in projects.

Taken together, I finally propose that the case studies in both **Chapter 4** and **5** give further evidence of the importance of experimental and learning-by doing-approaches to catchment management. The analysis in **Chapter 5** found that participants saw experimentation and demonstration as a core strength of catchment partnerships, which contributed to upscaling and outscaling the uptake of management interventions. This resonates with the perspective of some of the interviewees in **Chapter 4**, as well as the outcomes of the Stockholm workshop, which advocated for more experimental, collaborative knowledge production that focused on learning-by doing.

6.3.2 Implications for theory-informed cross-scale research and management

The second contribution of this thesis is to propose a conceptual approach to participatory and systemic cross-scale management of eutrophication (**Chapter 1**) and catchment management (**Chapter 4**). This framework expands on socioecological systems scale concepts in a way that addresses gaps in existing socioecological frameworks and increases stakeholder-relevance (Bennett & Reyers, 2024; Gain et al., 2021; Vervoort et al., 2012). By proposing a conceptual approach and synthesising some tangible principles for how it can be approached, this thesis aims to support the better embedding of participatory and systemic cross-scale management into integrated approaches to the management of critical water challenges (Bennett & Reyers, 2024; Gain et al., 2021; M.-L. Moore et al., 2024; Whaley, 2022) .

The heuristic developed in **Chapter 1** takes an almost modular approach to the systemic cross-scale management of eutrophication and catchment management more broadly (**Figure 3.3**). This 'modular' approach is derived from the qualitative evidence synthesis presented in **Chapter 1**, and adds nuance to critiques of water system management and the socioecological systems literature that find they neglect either the social or the biogeophysical. Instead, it proposes that there is a divide in both research and practice between approaches that address 'direct' drivers and those that focus on 'indirect' drivers. 'Direct' drivers are simply those that are perceived to have tangible physical impacts on eutrophication or other catchment challenges within a defined spatial boundary, and may be ecological, technological or social. For example, a social 'direct' driver could include farmer soil management practices. 'Indirect' drivers instead have a more diffuse impact and are generally the social, political and economic aspects that make changes in practices, technologies and infrastructures and management efforts more or less likely. However, ecological concerns like climate change can also be categorised as indirect, as an overarching concern that both impacts direct drivers and tends to inform management action in as a key contextual backdrop. As stated in **Chapter 1,** direct drivers are typically targeted when developing tangible on-the-ground interventions, while indirect drivers are generally the focus when making efforts to develop an enabling social and often governance system.

Based on this these results, I suggest that the apparent 'neglect' of either the social or biogeophysical in the reviewed literature can instead be reframed as a purpose-based, bridgeable separation between different 'types' of cross-scale management that is perhaps more practical for practitioners engaged in catchment management. Purpose-based because the attention paid to different types of drivers is not arbitrary, but defined according to different cross-scale management challenges. Bridgeable because while the cross-scale management of direct and indirect drivers is often approached separately for particular purposes, authors have demonstrated the value and importance of addressing the cross-scale interactions between them to achieve positive outcomes (see **Chapter 3.4.3**). More practical, as **Chapter 5** tentatively indicates, because the conceptual division between the direct and indirect can provide a framework for systemic cross-scale management that perhaps maps more closely to the organisational realities of being engaged in catchment management.

In **Chapter 4**, I outline a dual role for catchment partnerships that reflects the fact that catchment partnerships aim to coordinate and implement management strategies that deliver positive outcomes for catchment management across relevant spatial levels from field to farm to river reach, all the way to catchment-level. Catchment partnerships are therefore concerned with 'direct' cross-scale management and, as directed in **Chapter 3**, should consider spatial and temporal scales and the interactions within and between them to deliver effective management across all relevant spatial levels and timeframes. However, they must also deeply consider how indirect drivers across sociopolitical levels impact the feasibility of desired changes and how they can act to improve the situation. 'Indirect' cross-scale management means considering both how they themselves can operate effectively and successfully engage other actors in catchment management under the influence of indirect drivers located across sociopolitical scales. The final piece of 'cross-scale' management is then evaluating the cross-scale interactions between the direct and indirect, and how they may evolve over time. This is something that should be embedded in 'direct' management to improve resilience in the face of changes in indirect drivers like changes in public funding, market demand and policies. It should also be considered in 'indirect' management to ensure that indirect drivers like knowledge, attitudes and regulation are responsive to catchment ecological realities, and minimise negative impacts from changes in these types of indirect drivers.

All actors who have relevance to eutrophication and catchment sustainability should consider both types of drivers and their interactions to a certain extent. However, treating indirect and direct drivers as interacting sub-systems that are the subject of different management purposes introduces a flexibility to focus on a particular type of cross-scale management according to the remit of the actor in question. This complements the concept of 'scales' and 'levels' as not just a tool for understanding the system itself, but also a framework to help define what is within the direct sphere of influence of a given actor, what they can influence indirectly and what is more-or-less completely outside of their influence. Actors may be more or less engaged in implementing on the ground management than catchment partnerships, or more or less influential in the sociopolitical system. Therefore, they will consider the different types of cross-scale management more or less deeply. The systemic scale concepts developed and interrogated in this thesis, particularly their focus on considering interactions both within and between subsystems, can support this without resorting to familiar silos. Furthermore, the principles for participatory and systemic cross-scale management also developed herein can provide a checklist for how this can be approached effectively through participatory governance.

In summary the primary contribution of this thesis is to propose and empirically evaluate a middle-range theory for approaching the management of eutrophication (Chapter 1) and catchment management (Chapter 4) as participatory, multi-scale, socioecological systems challenges. This addresses key gaps in the application of socioecological conceptualisations of scale in water governance research by offering a framework that breaks down persistent and artificial divides between the social and ecological. It instead distinguishes between 'direct' and 'indirect' drivers in interacting subsystems. This preserves meaningful differences in how these types of drivers are approached in both research and practice while introducing a more analytical and less arbitrary approach to systems analyses. This approach further recognises the multiple scales that can be meaningfully applied for system analyses, and aims to strengthen cross-level and cross-scale analyses by emphasising the significance of interactions across and between indirect and direct subsystems.

This work further contributes to the water governance literature by defining tangible principles for actioning this framework, and outlining key ways that participation can contribute to its application. These principles therefore offer an important expansion on existing research on participation in water governance by outlining how participation can practically contribute to systemic cross-scale management of water systems. Finally, this work demonstrates the value of applying this framework to the evaluation of collaborative water governance organisations. By highlighting the dual role that these organisations can play as agents for change in both the direct and indirect sub-systems, I suggest that this framework can guide more nuanced analyses of how these organisations function in multi-level and multi-scale socioecological systems.

6.4 Limitations

This research has several limitations. The integrative review in Chapter 1 reviewed few papers from outside of Europe and North America, meaning these perspectives are largely missing and differences between contexts are unexplored. This is reflective of both the language of the literature reviewed (papers in English) and the broader systemic limitation of the academic knowledge system, which continues to reflect colonial legacies. Secondly, the scope of the review is limited to eutrophication to enable a broad interdisciplinary perspective while allowing a deeper engagement with the specific characteristics of this socioecological problem. However, relevant perspectives from the broader literature on water management may prove valuable to extend the insights developed here.

The qualitative case studies in Chapter 3 and 4 exhibit the typical limitations of this type of research approach. Namely, that they can give in-depth insights into a particular context but a larger number of case studies that are designed for cross-comparison are needed to produce more generalisable knowledge. Furthermore, stakeholder perspectives are an invaluable resource for understanding socioecological systems dynamics; however, these are naturally partial, and research outcomes are shaped by which stakeholders were invited and agreed to participate in the research. Gaps in stakeholder engagement are addressed in the individual chapters. Furthermore, as stated in the outline of my research paradigm in Chapter 2.1, the research outcomes are deeply impacted by my own positionality and the positionality of my participants.

A further important limitation of this research is its almost exclusively qualitative approach. While this research was explorative in nature and is able to somewhat illuminates key socioecological dynamics through stakeholder perspectives, using a more mixed methods approach would be a rich avenue for future research. A central focus of this research is the evaluation of whether management efforts are successfully delivering positive outcomes for catchment sustainability across relevant spatial and temporal levels. This was explored to some extent in Chapter 4 through document analysis and stakeholder interviews. However, a good deal of value could be gained from more in-depth stakeholder engagement develop indicators and tools for collaboratively evaluating catchment partnerships outcomes across relevant scales. Co-evaluating outcomes with stakeholders would add more depth to the analysis, as would supporting this process with a more mixed-methods approach that evaluated a variety of indicators for understanding critical outcomes like changes in attitudes, practices, riparian planting and water quality. This would support a fuller evaluation of the role of collaborative catchment partnerships in successful cross-scale management than was possible within the scope of this project.

6.5 Future research directions

6.5.1 Addressing synthesis problems in socioecological scale

This section is primarily a reflection on the current treatment of scale and cross-scale interactions in the socioecological systems literature. It comments specifically on the challenges that arose during the conceptual synthesis conducted **Chapter 3** that I see as barriers to the development of integrative perspectives on scale that may also challenge their operationalisation in practice. I then make some suggestions that I think could support improved analytical clarity and usability of scale concepts in socioecological systems research going forward.

The first challenge emerged around the ontology and epistemology of scale. As a theoretical perspective that is deeply interdisciplinary, tensions emerge in socioecological systems research around the different ontological and epistemological foundations of the disciplines to be integrated. Positivistic perspectives on scale, more common in the natural sciences, approach systems and their processes of operating over intrinsic scales. While, drawing on research in geography, governance perspectives emphasise the social construction of scale and the political work done by these constructed concepts. On the one hand, treating scale as socially constructed makes it challenging to make any knowledge claims about causality in socioecological systems. On the other, relying on positivistic conceptualisations of scale means ignoring the social work that goes into defining scales of relevance, and its real-world implication. Each sits somewhat in critique of the other, and can undermine interdisciplinary work when participants hold different perspectives. As proposed by other authors (Proctor, 1998; Cockburn, 2022; Longo, Isgren and Carolan, 2025), I suggest critical realism based on ontological realism and epistemological relativism can provide a path forward (details of this paradigm given in **Chapter 1.2**).

In conducting this research, I found that adopting a critical realist perspective allowed a 'symmetrical' approach to socioecological systems that was suitable for interdisciplinary integration because it opened up the possibility that both nature and humans played a role in defining scales. I refer to this as 'symmetrical' because it treats both underlying reality of nature and social construction by humans seriously, and allows us to ask both 'what are the implications of approaching scale in this way for water' and 'what are the implications for people?' Consequently, I echo other authors in suggesting that future socioecological research, and particularly work on scale, investigates whether introducing an explicitly critical realist standpoint can strengthen interdisciplinary integration and add value to research outcomes (Proctor, 1998; Cockburn, 2022; Longo, Isgren and Carolan, 2025).

The second challenge can be described as both a linguistic and conceptual challenge. As previously highlighted by several authors (and by me in **Chapter 6.2.1**), the interchangeable use of the terms 'scale', 'level' and 'extent' pose a challenge barrier to the analysis, discussion and interdisciplinary synthesis needed for systemic cross-scale management (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Glaser and Glaeser, 2014). Furthermore, I suggest that there is conceptual conflation or lack of terminological preciseness around two different conceptualisations of 'cross-scale' and 'cross-level' interactions that should be addressed separately.

Authors have critiqued what they see as an excessive focus on the interactions within and across spatial, temporal, organisational and sociopolitical scales. They identify many other forms of scale that can be used by stakeholders to describe socioecological systems, including scales of knowledge, status and innovation. The authors further suggest that cross-level and cross-scale interactions between these scales should also be subject to scrutiny (Cash *et al.*, 2006; Vervoort *et al.*, 2012). However, I find that this stems from two divergent purposes for interrogating scale and cross-level and cross-scale interactions.

The first is rooted in the epistemological and often ontological standpoint that the analysis of a system or a part of a system can be performed using a particular scale and that the choice of scale or level applied can have the effect of making 'invisible' particular drivers and obscuring the impact that these drivers have on each other. Therefore, it is necessary to conduct multi-level and/or multi-scale analysis and identify cross-level and/or cross-scale interactions between these *drivers* or *processes* to understand overall system behaviour. This is the case with spatial, temporal, organisation and sociopolitical scales, which are used to analyse whole systems (Gibson, Ostrom and Ahn, 2000; Manson, 2008).

In the second case, a scale is used simply as a framework to allow the comparison of a particular characteristic of a two or more system components or type(s) of system component. For example, a piece of 'knowledge' can be described using a scale that locates 'context specific' and 'general and universal' at opposite ends (Vervoort *et al.*, 2012). Here, when talking about 'cross-scale interactions' or 'cross-scale dynamics,' the intention is instead to identify the relationship between where a characteristic lands on a descriptive scale, versus the same or another characteristic of another system component. This can then be problematised to understand the implications of this relationship to socioecological system management (Cash *et al.*, 2006; Vervoort *et al.*, 2012). This is the case in socioecological 'fit' where system drivers and processes are conceptualised as having an intrinsic spatial or temporal extents over which they operate. In socioecological 'fit' the congruence between the characteristic spatial or temporal extents between two system components is problematised as favourable or unfavourable for management. A common example is ensuring the spatial coverage of a regulation matches the spatial extent of the targeted ecological system (Moss, 2012; Ward *et al.*, 2019).

Understanding how two or more drivers or processes influence each other is naturally useful, as is the use of scales to frame and describe these relationships. However, I argue that this 'generic' scale-based comparison should not be conceptually or terminologically conflated with the concept of what I term 'systemic' cross-level and cross-scale interactions, which effectively attempts to overcome the limitations placed on systems understandings by the selection of particular scales and levels for system analysis. A pictorial representation of the two different conceptualisations of 'cross-scale' interactions is given in Figure 6.4 to illustrate the distinction. Instead, going forward, the analysis of 'systemic' cross-level and cross-scale interactions and the use of 'generic' scale-based comparisons should be seen as separate but complimentary components of system analysis. The former can support whole-systems understandings by fostering the bridging of scale and level-based systems analyses, while the latter can interrogate and problematise the relationships between system components using scale-based descriptors.

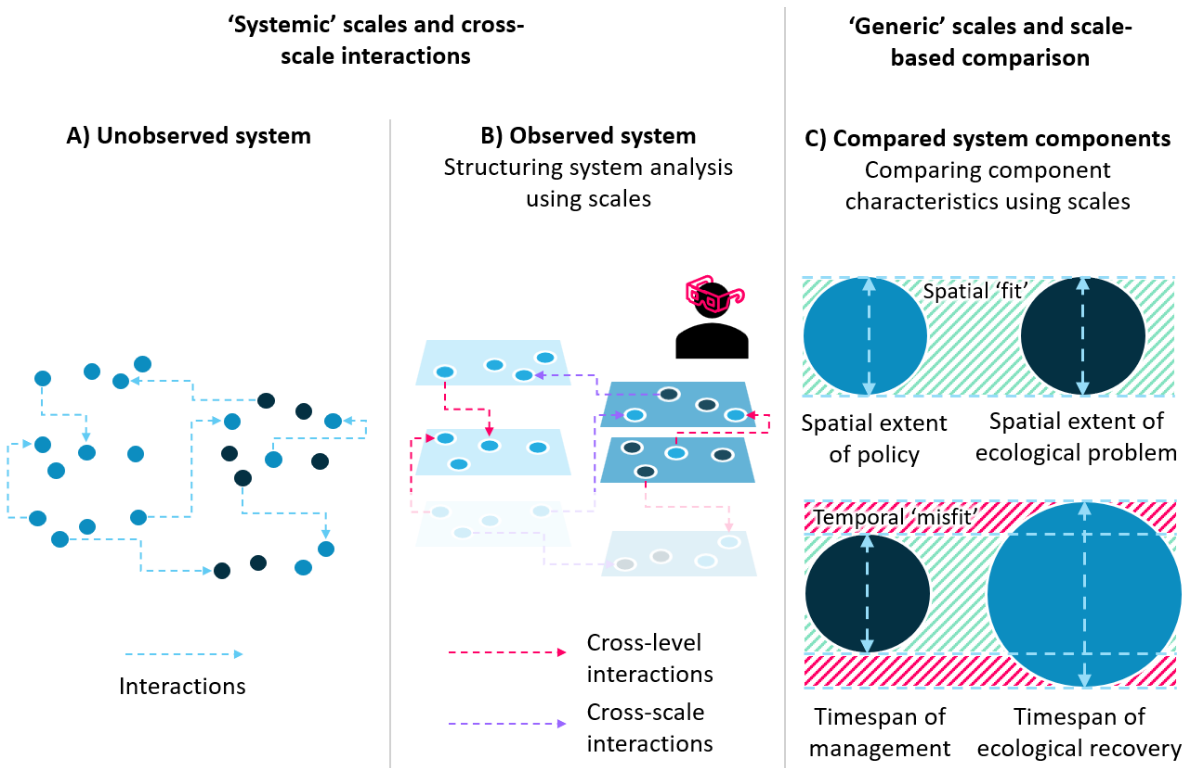


Figure 6.4: The conceptual distinction between 'cross-scale interactions' and scale-informed comparison. Panels a) and b) demonstrate the effect of structuring a system analysis using scales and levels, which can make certain system components 'visible' or 'invisible' to the observer and necessitates the consideration of 'cross-level' and 'cross-scale' interactions. Panel c) illustrates the process of comparison using scales to structure descriptions of system characteristics. This type of comparison is also referred to as investigating cross-scale dynamics. However, I argue this is misleading and should not be conceptually or terminologically conflated with the cross-scale analysis depicted in panel b).

I suggest that distinguishing between 'systemic' scales and cross-scale interactions and 'generic' scales and scale-based comparison is useful and may help to reduce confusion in interdisciplinary work. This is partially based on my own experience. However, I also suggest that this conceptual conflation is the reason for the supposed dearth of literature that addresses scales other than spatial, temporal, organisational and sociopolitical scales in socioecological systems analysis. A lack that was highlighted in by both Cash et al., 2006 and Vervoort et al., 2012. In line with other authors, I further argue that greater care should be taken in socioecological systems research to develop and use terminology precisely with transdisciplinary integration in mind (Gibson, Ostrom and Ahn, 2000; Cash *et al.*, 2006; Vervoort *et al.*, 2012).

6.5.2 Developing an evidence base for participatory and systemic cross-scale management

The ultimate aim of future research should be to produce a robust evidence base that evaluates (i) what contribution the systemic, participatory cross-scale perspectives on management can make to managing eutrophication and wider water challenges, (ii) what key features enable or inhibit its successful implementation in a given context and (iii) generate more general insights that may be applicable across different contexts, as was attempted in **Chapter 1** of this thesis.

Based on this work, next steps would be the further development of the concepts and principles for cross-scale management developed here. This could have several different components. The first being an appraisal of the broader integrated catchment management literature to understand how the principles identified in **Chapter 1** can be further developed beyond their focus on eutrophication. The synthesis of **Chapter 1** and **Chapter 4** conducted to address **Objective 2** in **Chapter 6.2.2** gives early indications that this could be fruitful; however, more evidence is required to refine these principles. However, perhaps more valuable is seeking feedback and re-developing the concepts developed with actors who have a role in catchment management. This is essential for making the research more relevant and usable for practitioners, as concepts like IWRM have been criticised for being difficult to operationalise (Bilalova et al., 2025; Biswas, 2008) and systemic perspectives like socioecological systems are not seen as well embedded into policy practice (Gain et al., 2021; Whaley, 2022).

Finally, further work should build on the qualitative and single case-study based analysis in this thesis to test the framework developed herein empirically. In particular, this means expanding the evaluation of management outcomes to fully understand whether and how the application of the developed principles can achieve results for cross-scale management. This should be systematised across a larger number of studies both assess these outcomes and explore the impact of contextual factors (Bilalova, Newig and Villamayor-Tomas, 2025). Evaluating these outcomes means going beyond the methods used to support the explorative focus of this thesis, to develop a variety of social and ecological indicators that can demonstrate impacts across relevant scales. Consequently, I identify a final area of research that could support this work and research on catchment management more broadly. Currently, there is limited foundational understandings of current management efforts in catchments. Of particular note is a lack of baselining of current farm-level management actions, which can undermine catchment evaluation but may also discourage farmer participation in both research and environmental management schemes due to a lack of recognition. I therefore suggest that conducting this kind of baselining could be valuable both for supporting research and real-world management.

7 Bibliography

ALcontrol Laboratories and SLU (2019) *Undersökning av läckagebenägen fosfor i sediment i vattenförekomster inom Stockholms stad*. Available at: https://miljobarometern.stockholm.se/content/docs/tema/vatten/sediment/Unders%C3%B6kning%20av%20l%C3%A4ckageben%C3%A4gen%20fosfor%20i%20sediment.pdf (Accessed: October 10, 2022).

Aleu, R.B., Larsen, R.K. and Methner, N. (2022) "Participation and marginalization in water governance: probing the agency of powerholders," *Ecology and Society*, 27(4). Available at: https://doi.org/10.5751/es-13680-270433.

Allen, W. *et al.* (2011) "Building collaboration and learning in integrated catchment management: The importance of social process and multiple engagement approaches," *New Zealand Journal of Marine and Freshwater Research*. Available at: https://doi.org/10.1080/00288330.2011.592197.

Allouche, J. (2017) "The birth and spread of IWRM - A case study of global policy diffusion and translation," in *Flows and Practices: The Politics of Integrated Water Resources Management in Eastern and Southern Africa*. Available at: https://doi.org/10.2307/j.ctvh8r2qk.5.

Alves, A. *et al.* (2016) "Evolutionary and holistic assessment of green-grey infrastructure for CSO reduction," *Water (Switzerland)*, 8(9). Available at: https://doi.org/10.3390/w8090402.

Amblard, L. and Mann, C. (2021) "Understanding collective action for the achievement of EU water policy objectives in agricultural landscapes: Insights from the Institutional Design Principles and Integrated Landscape Management approaches," *Environmental Science and Policy*, 125. Available at: https://doi.org/10.1016/j.envsci.2021.08.015.

Andriamahefazafy, M. *et al.* (2022) "Sustainable development goal 14: To what degree have I achieved the 2020 targets for my oceans?," *Ocean and Coastal Management*, 227. Available at: https://doi.org/10.1016/j.ocecoaman.2022.106273.

Andriollo, E. *et al.* (2021) "Collaborations in environmental initiatives for an effective 'adaptive governance' of social–ecological systems: What existing literature suggests," *Sustainability (Switzerland)*. Available at: https://doi.org/10.3390/su13158276.

Armijo, J. *et al.* (2020) "The 2016 red tide crisis in southern Chile: Possible influence of the mass oceanic dumping of dead salmons," *Marine Pollution Bulletin*, 150. Available at: https://doi.org/10.1016/j.marpolbul.2019.110603.

Arnstein, S.R. (1969) "A Ladder Of Citizen Participation," *Journal of the American Planning Association*, 35(4). Available at: https://doi.org/10.1080/01944366908977225.

Ashley, K., Cordell, D. and Mavinic, D. (2011) "A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse," *Chemosphere*, 84(6). Available at: https://doi.org/10.1016/j.chemosphere.2011.03.001.

Ayre, M. and Nettle, R. (2015) "Doing integration in catchment management research: Insights into a dynamic learning process," *Environmental Science and Policy*, 47. Available at: https://doi.org/10.1016/j.envsci.2014.10.011.

Balvanera, P. *et al.* (2017) "Key features for more successful place-based sustainability research on social-ecological systems: A programme on ecosystem change and society (PECS) perspective," *Ecology and Society*, 22(1). Available at: https://doi.org/10.5751/ES-08826-220114.

Bandara, W. and Syed, R. (2023) "The role of a protocol in a systematic literature review," *Journal of Decision Systems* [Preprint]. Available at: https://doi.org/10.1080/12460125.2023.2217567.

Barbosa, A.E., Fernandes, J.N. and David, L.M. (2012) "Key issues for sustainable urban stormwater management," *Water Research*, 46(20). Available at: https://doi.org/10.1016/j.watres.2012.05.029.

Bennett, E.M. and Reyers, B. (2024) "Disentangling the complexity of human–nature interactions," *People and Nature*, 6(2), pp. 402–409. Available at: https://doi.org/10.1002/pan3.10611.

Benson, D., Gain, A.K. and Giupponi, C. (2020) "Moving beyond water centricity? Conceptualizing integrated water resources management for implementing sustainable development goals," *Sustainability Science*, 15(2). Available at: https://doi.org/10.1007/s11625-019-00733-5.

Benson, D., Gain, A.K. and Rouillard, J.J. (2015) "Water governance in a comparative perspective: From IWRM to a 'nexus' approach?," *Water Alternatives*, 8(1).

Benson, D., Jordan, A. and Smith, L. (2013) "Is environmental management really more collaborative? A comparative analysis of putative 'paradigm shifts' in Europe, Australia, and the United States," *Environment and Planning A*, 45(7). Available at: https://doi.org/10.1068/a45378.

Berardo, R., Turner, V.K. and Rice, S. (2019) "Systemic coordination and the problem of seasonal harmful algal blooms in lake erie," *Ecology and Society*, 24(3). Available at: https://doi.org/10.5751/ES-11046-240324.

Berkowitz, J.F. *et al.* (2020) "Coupling watershed modeling, public engagement, and soil analysis improves decision making for targeting P retention wetland locations," *Journal of Great Lakes Research*, 46(5), pp. 1331–1339. Available at: https://doi.org/10.1016/j.jglr.2020.06.016.

Bertule, M. *et al.* (2018) "Monitoring water resources governance progress globally: Experiences from monitoring SDG indicator 6.5.1 on integrated water resources management implementation," *Water (Switzerland)*, 10(12). Available at: https://doi.org/10.3390/w10121744.

Bhaskar, R. *et al.* (2010) *Interdisciplinarity and climate change: Transforming knowledge and practice for my global future*, *Interdisciplinarity and Climate Change: Transforming Knowledge and Practice for My Global Future*. Available at: https://doi.org/10.4324/9780203855317.

Bhaskar, R. (2013) *A realist theory of science*, *A Realist Theory of Science*. Available at: https://doi.org/10.4324/9780203090732.

Bilalova, S. *et al.* (2023) "Pathways to water sustainability? A global study assessing the benefits of integrated water resources management," *Journal of Environmental Management*, 343. Available at: https://doi.org/10.1016/j.jenvman.2023.118179.

Bilalova, S., Newig, J. and Villamayor-Tomas, S. (2025) "Toward Sustainable Water Governance? Taking Stock of Paradigms, Practices, and Sustainability Outcomes," *WIREs Water*, 12(1). Available at: https://doi.org/10.1002/wat2.1762.

Birhanu, B.Z. *et al.* (2019) "A watershed approach to managing rainfed agriculture in the semiarid region of southern Mali: integrated research on water and land use," *Environment, Development and Sustainability*, 21(5). Available at: https://doi.org/10.1007/s10668-018-0144-9.

Biswas, A.K. (2008) "Integrated water resources management: Is it working?," *International Journal of Water Resources Development*. Available at: https://doi.org/10.1080/07900620701871718.

Bitterman, P. and Koliba, C. (2023) "Engagement in water governance action situations in the Lake Champlain Basin," *PLoS ONE*, 18(3 March). Available at: https://doi.org/10.1371/journal.pone.0282797.

Blackstock, K. *et al.* (2023) "Agency and constraint in environmental policy coherence," *Journal of Political Ecology*, 30(1). Available at: https://doi.org/10.2458/jpe.3055.

Blackstock, K.L., Kelly, G.J. and Horsey, B.L. (2007) "Developing and applying a framework to evaluate participatory research for sustainability," *Ecological Economics*, 60(4). Available at: https://doi.org/10.1016/j.ecolecon.2006.05.014.

Bögel, P.M. *et al.* (2022) "An interdisciplinary perspective on scaling in transitions: Connecting actors and space," *Environmental Innovation and Societal Transitions*, 42. Available at: https://doi.org/10.1016/j.eist.2021.12.009.

Bohman, A., Glaas, E. and Karlson, M. (2020) "Integrating sustainable stormwater management in urban planning: Ways forward towards institutional change and collaborative action," *Water (Switzerland)*, 12(1). Available at: https://doi.org/10.3390/w12010203.

Booth, E.G. *et al.* (2016) "From qualitative to quantitative environmental scenarios: Translating storylines into biophysical modeling inputs at the watershed scale," *Environmental Modelling and Software*, 85. Available at: https://doi.org/10.1016/j.envsoft.2016.08.008.

Braun, V. and Clarke, V. (2022) "Thematic Analysis: A Practical Guide," *QMiP Bulletin*, 1(33). Available at: https://doi.org/10.53841/bpsqmip.2022.1.33.46.

Brils, J. *et al.* (2014) "Synthesis and Recommendations Towards Risk-Informed River Basin Management," in *Handbook of Environmental Chemistry*. Available at: https://doi.org/10.1007/978-3-642-38598-8_14.

Buizer, M., Arts, B. and Kok, K. (2011) "Governance, scale and the environment: The importance of recognizing knowledge claims in transdisciplinary arenas," *Ecology and Society*, 16(1). Available at: https://doi.org/10.5751/ES-03908-160121.

Cairney, P. (2002) *Understanding Public Policy: Theories and Issues*, *Understanding Public Policy: Theories and Issues*.

Carias, J. *et al.* (2024) "Economic valuation of Harmful Algal Blooms (HAB): Methodological challenges, policy implications, and an empirical application," *Journal of Environmental Management*, 365, p. 121566. Available at: https://doi.org/10.1016/j.jenvman.2024.121566.

Carlsen, L. and Bruggemann, R. (2022) "The 17 United Nations' sustainable development goals: a status by 2020," *International Journal of Sustainable Development and World Ecology*, 29(3). Available at: https://doi.org/10.1080/13504509.2021.1948456.

Carpenter, S.R. *et al.* (1998) "NONPOINT POLLUTION OF SURFACE WATERS WITH PHOSPHORUS AND NITROGEN," *Ecological Applications*, 8(3), pp. 559–568.

Carpenter, S.R. and Bennett, E. (2011) "Reconsideration of the planetary boundary for phosphorus," *Environmental Research Letters*, 6(1). Available at: https://doi.org/10.1088/1748-9326/6/1/014009.

Cash, D.W. *et al.* (2006) "Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World," *Ecology and Society*, 11(2). Available at: https://doi.org/10.5751/es-01759-110208.

Cettner, A. *et al.* (2013) "Stormwater management and urban planning: Lessons from 40 years of innovation," *Journal of Environmental Planning and Management*, 56(6). Available at: https://doi.org/10.1080/09640568.2012.706216.

Cettner, A. *et al.* (2014) "Sustainable development and urban stormwater practice," *Urban Water Journal*, 11(3). Available at: https://doi.org/10.1080/1573062X.2013.768683.

Cettner, A., Söderholm, K. and Viklander, M. (2012) "An Adaptive Stormwater Culture? Historical Perspectives on the Status of Stormwater within the Swedish Urban Water System," *Journal of Urban Technology*, 19(3), pp. 25–40. Available at: https://doi.org/10.1080/10630732.2012.673058.

Cho, J.Y. and Lee, E.H. (2014) "Reducing confusion about grounded theory and qualitative content analysis: Similarities and differences," *Qualitative Report* [Preprint], (32). Available at: https://doi.org/10.46743/2160-3715/2014.1028.

Chowdhury, R.B. *et al.* (2014) "A review of recent substance flow analyses of phosphorus to identify priority management areas at different geographical scales," *Resources, Conservation and Recycling*. Available at: https://doi.org/10.1016/j.resconrec.2013.10.014.

Chowdhury, R.B. and Chakraborty, P. (2016) "Magnitude of anthropogenic phosphorus storage in the agricultural production and the waste management systems at the regional and country scales," *Environmental Science and Pollution Research*, 23(16). Available at: https://doi.org/10.1007/s11356-016-6930-8.

Cockburn, J. (2022) "Knowledge integration in transdisciplinary sustainability science: Tools from applied critical realism," *Sustainable Development*, 30(2). Available at: https://doi.org/10.1002/sd.2279.

Cook, B. R. *et al.* (2013) "Interrogating participatory catchment organisations: Cases from Canada, New Zealand, Scotland and the Scottish-English Borderlands," *Geographical Journal*, 179(3). Available at: https://doi.org/10.1111/j.1475-4959.2012.00492.x.

Cook, Brian R. *et al.* (2013) "The persistence of 'normal' catchment management despite the participatory turn: Exploring the power effects of competing frames of reference," *Social Studies of Science*, 43(5). Available at: https://doi.org/10.1177/0306312713478670.

Cordell, D., Neset, T.S.S. and Prior, T. (2012) "The phosphorus mass balance: Identifying 'hotspots' in the food system as a roadmap to phosphorus security," *Current Opinion in Biotechnology*, pp. 839–845. Available at: https://doi.org/10.1016/j.copbio.2012.03.010.

Correll, D.L. (1999) "Phosphorus: A rate limiting nutrient in surface waters," *Poultry Science*, 78(5). Available at: https://doi.org/10.1093/ps/78.5.674.

Cumming, G.S., Cumming, D.H.M. and Redman, C.L. (2006) "Scale mismatches in social-ecological systems: Causes, consequences, and solutions," *Ecology and Society*, 11(1). Available at: https://doi.org/10.5751/ES-01569-110114.

Danermark, B. (2019) "Applied interdisciplinary research: a critical realist perspective," *Journal of Critical Realism*, 18(4). Available at: https://doi.org/10.1080/14767430.2019.1644983.

Daroub, S.H. *et al.* (2011) "Best management practices and long-term water quality trends in the everglades agricultural area," *Critical Reviews in Environmental Science and Technology*, 41(SUPPL. 1). Available at: https://doi.org/10.1080/10643389.2010.530905.

Dawson, L. *et al.* (2018) "Impacts of the water framework directive on learning and knowledge practices in a Swedish catchment," *Journal of Environmental Management*, 223. Available at: https://doi.org/10.1016/j.jenvman.2018.06.054.

Dee Catchment Partnership (2007) "Dee Catchment Management Plan ," pp. 1–80.

Dee Catchment Partnership (2022) *Dee Catchment Partnership Delivery Plan 2022 – 2027*.

Diaz, R.J. and Rosenberg, R. (2008) "Spreading dead zones and consequences for marine ecosystems," *Science*. Available at: https://doi.org/10.1126/science.1156401.

Diaz-Kope, L. and Miller-Stevens, K. (2015) "Rethinking a typology of watershed partnerships: A governance perspective," *Public Works Management and Policy*, 20(1). Available at: https://doi.org/10.1177/1087724X14524733.

Dietrich, J. and Funke, M. (2009) "Integrated catchment modelling within a strategic planning and decision making process: Werra case study," *Physics and Chemistry of the Earth*, 34(8–9). Available at: https://doi.org/10.1016/j.pce.2008.11.001.

Directive 2000/60/EC (2000) *Water Framework Directive (2000/60/EC), Official Journal of the European Communities*.

Directorate-General for Environment (2022) *Proposal for a revised Urban Wastewater Treatment Directive*, *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0541*.

Available at: https://environment.ec.europa.eu/document/download/a936c2d5-2e3a-4eb1-a7c6-41ec98f3e72f_en?filename=Proposal%20for%20a%20Directive%20concerning%20urban%20wastewater%20treatment%20%28recast%29.pdf (Accessed: February 7, 2024).

Djenontin, I.N.S. and Meadow, A.M. (2018) "The art of co-production of knowledge in environmental sciences and management: lessons from international practice," *Environmental Management*, 61(6), pp. 885–903. Available at: https://doi.org/10.1007/s00267-018-1028-3.

Dodds, W.K. *et al.* (2009) "Eutrophication of U. S. freshwaters: Analysis of potential economic damages," *Environmental Science and Technology*, 43(1), pp. 12–19. Available at: https://doi.org/10.1021/es801217q.

Donoso, M.C. and Bosch, M.C. (2015) "Integrated water resources management in latin America and the caribbean," in *Sustainability of Integrated Water Resources Management: Water Governance, Climate and Ecohydrology*. Available at: https://doi.org/10.1007/978-3-319-12194-9_2.

Doody, D.G. *et al.* (2012) "Approaches to the implementation of the Water Framework Directive: Targeting mitigation measures at critical source areas of diffuse phosphorus in Irish catchments," *Journal of Environmental Management*. Available at: https://doi.org/10.1016/j.jenvman.2011.09.002.

Downing, A.S. *et al.* (2014) "Coupled human and natural system dynamics as key to the sustainability of Lake Victoria's Ecosystem services," *Ecology and Society*, 19(4). Available at: https://doi.org/10.5751/ES-06965-190431.

Downing, J.A. *et al.* (2021) "Protecting local water quality has global benefits," *Nature Communications*, 12(1). Available at: https://doi.org/10.1038/s41467-021-22836-3.

Dressler, G. *et al.* (2022) "Upscaling in socio-environmental systems modelling: Current challenges, promising strategies and insights from ecology," *Socio-Environmental Systems Modelling*, 4. Available at: https://doi.org/10.18174/sesmo.18112.

Elsawah, S. *et al.* (2020) "Eight grand challenges in socio-environmental systems modeling," *Socio-Environmental Systems Modelling*, 2. Available at: https://doi.org/10.18174/sesmo.2020a16226.

Enloe, S.K., Schulte, L.A. and Tyndall, J.C. (2017) "Public–Private Partnerships Working Beyond Scale Challenges toward Water Quality Improvements from Private Lands," *Environmental Management*, 60(4). Available at: https://doi.org/10.1007/s00267-017-0905-5.

Epstein, G. *et al.* (2015) "Institutional fit and the sustainability of social-ecological systems," *Current Opinion in Environmental Sustainability*. Available at: https://doi.org/10.1016/j.cosust.2015.03.005.

European Community (2000) "Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy," *Official Journal of the European Parliament*, L327(September 1996).

European Environmental Agency (2018a) *EEA Report No 7/2018 European waters Assessment of status and pressures 2018*. Luxembourg. Available at: https://www.eea.europa.eu/publications/state-of-water.

European Environmental Agency (2018b) *EEA Report No 7/2018 European waters Assessment of status and pressures 2018*. Luxembourg. Available at: https://www.eea.europa.eu/publications/state-of-water.

Eurostat (2025) "Sustainable development in the European Union — Monitoring report on progress towards the SDGs in an EU context (2025 edition)." Available at: https://doi.org/10.2785/8386424.

Ferguson, B.C. *et al.* (2013) "The enabling institutional context for integrated water management: Lessons from Melbourne," *Water Research*, 47(20). Available at: https://doi.org/10.1016/j.watres.2013.09.045.

Ferrier, R.C. and Jenkins, A. (2009) "The Catchment Management Concept," in *Handbook of Catchment Management*. Available at: https://doi.org/10.1002/9781444307672.ch1.

Flotemersch, J.E. *et al.* (2016) "A Watershed Integrity Definition and Assessment Approach to Support Strategic Management of Watersheds," *River Research and Applications*, 32(7). Available at: https://doi.org/10.1002/rra.2978.

Folke, C. *et al.* (2007) "The problem of fit between ecosystems and institutions: Ten years later," *Ecology and Society*, 12(1). Available at: https://doi.org/10.5751/ES-02064-120130.

Friis, C. *et al.* (2023) "Enabling spaces for bridging scales: scanning solutions for interdisciplinary human-environment research," *Sustainability Science*, 18(3). Available at: https://doi.org/10.1007/s11625-022-01271-3.

Gain, A.K. *et al.* (2021) "Social-ecological system approaches for water resources management," *International Journal of Sustainable Development and World Ecology*, 28(2). Available at: https://doi.org/10.1080/13504509.2020.1780647.

Gebrehiwot, S.G. *et al.* (2021) "Monitoring and assessment of environmental resources in the changing landscape of Ethiopia: a focus on forests and water," *Environmental Monitoring and Assessment*, 193(10). Available at: https://doi.org/10.1007/s10661-021-09421-3.

Giakoumis, T. and Voulvoulis, N. (2018) "The Transition of EU Water Policy Towards the Water Framework Directive's Integrated River Basin Management Paradigm," *Environmental Management*, 62(5). Available at: https://doi.org/10.1007/s00267-018-1080-z.

Gibson, C.C., Ostrom, E. and Ahn, T.K. (2000) "The concept of scale and the human dimensions of global change: A survey," *Ecological Economics*, 32(2). Available at: https://doi.org/10.1016/S0921-8009(99)00092-0.

Gilmore, B. *et al.* (2019) "Data Analysis and Synthesis Within a Realist Evaluation: Toward More Transparent Methodological Approaches," *International Journal of Qualitative Methods*, 18. Available at: https://doi.org/10.1177/1609406919859754.

Giordano, M. and Shah, T. (2014) "From IWRM back to integrated water resources management," *International Journal of Water Resources Development*, 30(3). Available at: https://doi.org/10.1080/07900627.2013.851521.

Glaas, E., Hjerpe, M. and Jonsson, R. (2018) "Conditions Influencing Municipal Strategy-Making for Sustainable Urban Water Management: Assessment of Three Swedish Municipalities," *Water*, 10(8), p. 1102. Available at: https://doi.org/10.3390/w10081102.

Glaser, M. and Glaeser, B. (2014) "Towards a framework for cross-scale and multi-level analysis of coastal and marine social-ecological systems dynamics," *Regional Environmental Change*, 14(6). Available at: https://doi.org/10.1007/s10113-014-0637-5.

Gusenbauer, M. and Haddaway, N.R. (2020) "Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources," *Research Synthesis Methods*, 11(2). Available at: https://doi.org/10.1002/jrsm.1378.

Han, Z. *et al.* (2024) "Stakeholder engagement in natural resources management: Where go from here?," *Journal of Cleaner Production*, 435. Available at: https://doi.org/10.1016/j.jclepro.2023.140521.

Hansen, R. and Pauleit, S. (2014) "From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for Urban Areas," *Ambio*, 43(4). Available at: https://doi.org/10.1007/s13280-014-0510-2.

Hasan, N. *et al.* (2023) “Global Sustainable Water Management: A Systematic Qualitative Review,” *Water Resources Management*. Available at: https://doi.org/10.1007/s11269-023-03604-y.

Haygarth, P.M. *et al.* (2005) “The phosphorus transfer continuum: Linking source to impact with an interdisciplinary and multi-scaled approach,” *Science of the Total Environment*, 344(1-3 SPEC. ISS.). Available at: https://doi.org/10.1016/j.scitotenv.2005.02.001.

Head, B.W. (2022) *Wicked Problems in Public Policy*, *Wicked Problems in Public Policy*. Available at: https://doi.org/10.1007/978-3-030-94580-0.

Heckathorn, D.D. and Cameron, C.J. (2017) “Network sampling: From snowball and multiplicity to respondent-driven sampling,” *Annual Review of Sociology*, 43. Available at: https://doi.org/10.1146/annurev-soc-060116-053556.

Hertz, T., Mancilla Garcia, M. and Schlüter, M. (2020) “From nouns to verbs: How process ontologies enhance my understanding of social-ecological systems understood as complex adaptive systems,” *People and Nature*, 2(2). Available at: https://doi.org/10.1002/pan3.10079.

Hewett, C.J.M. *et al.* (2009) “A multi-scale framework for strategic management of diffuse pollution,” *Environmental Modelling and Software*, 24(1). Available at: https://doi.org/10.1016/j.envsoft.2008.05.006.

Hillman, M. (2009) “Integrating knowledge: The key challenge for a new paradigm in river management,” *Geography Compass*, 3(6). Available at: https://doi.org/10.1111/j.1749-8198.2009.00278.x.

Hobbie, S.E. *et al.* (2017) “Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution,” *Proceedings of the National Academy of Sciences of the United States of America*, 114(16). Available at: https://doi.org/10.1073/pnas.1618536114.

Howarth, R.W. and Marino, R. (2006) “Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades,” in *Limnology and Oceanography*. Available at: https://doi.org/10.4319/lo.2006.51.1_part_2.0364.

Hüesker, F. and Moss, T. (2015) “The politics of multi-scalar action in river basin management: Implementing the EU Water Framework Directive (WFD),” *Land Use Policy*, 42. Available at: https://doi.org/10.1016/j.landusepol.2014.07.003.

Hufnagl-Eichiner, S., Wolf, S.A. and Drinkwater, L.E. (2011) “Assessing social-ecological coupling: Agriculture and hypoxia in the Gulf of Mexico,” *Global Environmental Change*, 21(2). Available at: https://doi.org/10.1016/j.gloenvcha.2010.11.007.

Huitema, D. *et al.* (2009) "Adaptive water governance: Assessing the institutional prescriptions of adaptive (co-)management from a governance perspective and defining a research agenda," *Ecology and Society*, 14(1). Available at: https://doi.org/10.5751/ES-02827-140126.

Huttunen, S. (2015) "Farming Practices and Experienced Policy Coherence in Agri-environmental Policies: The Case of Land Clearing in Finland," *Journal of Environmental Policy and Planning*, 17(5). Available at: https://doi.org/10.1080/1523908X.2014.1003348.

Jager, N.W. *et al.* (2016) "Transforming European water governance? Participation and river basin management under the EU water framework directive in 13 member states," *Water (Switzerland)*, 8(4). Available at: https://doi.org/10.3390/w8040156.

Järvinen, M. and Mik-Meyer, N. (2020) *Qualitative Analysis: Eight Approaches for the Social Sciences*, *SAGE Open*.

Jessel, B. and Jacobs, J. (2005) "Land use scenario development and stakeholder involvement as tools for watershed management within the Havel River Basin," *Limnologica*, 35(3). Available at: https://doi.org/10.1016/j.limno.2005.06.006.

Jetoo, S. (2018) "Multi-level governance innovations of the Baltic Sea and the North American Great Lakes: New actors and their roles in building adaptive capacity for eutrophication governance," *Marine Policy*, 98. Available at: https://doi.org/10.1016/j.marpol.2018.09.020.

Jones, E.F. *et al.* (2021) "Citizen science reveals unexpected solute patterns in semiarid river networks," *PLoS ONE*, 16(8 August). Available at: https://doi.org/10.1371/journal.pone.0255411.

Jones, N.A. *et al.* (2011) "Mental models: An interdisciplinary synthesis of theory and methods," *Ecology and Society*, 16(1). Available at: https://doi.org/10.5751/ES-03802-160146.

Kastens, B. and Newig, J. (2008a) "Will participation foster the successful implementation of the water framework directive? The case of agricultural groundwater protection in northwest Germany," *Local Environment*, 13(1). Available at: https://doi.org/10.1080/13549830701581713.

Kastens, B. and Newig, J. (2008b) "Will participation foster the successful implementation of the water framework directive? The case of agricultural groundwater protection in northwest Germany," *Local Environment*, 13(1). Available at: https://doi.org/10.1080/13549830701581713.

Kaur, M., Hewage, K. and Sadiq, R. (2022) "Investigating temporal dynamics of urban densification on the buried water infrastructure performance," *Cities*, 129. Available at: https://doi.org/10.1016/j.cities.2022.103836.

Khodaparast, E. *et al.* (2025) “Bridging Social and Ecological Dynamics: A Comprehensive Scientometric Analysis of Social-Ecological Systems Research,” *International Journal of Environmental Research*, 19(4). Available at: https://doi.org/10.1007/s41742-025-00802-x.

Kiparsky, M. *et al.* (2013) “The innovation deficit in urban water: The need for an integrated perspective on institutions, organizations, and technology,” *Environmental Engineering Science*, 30(8). Available at: https://doi.org/10.1089/ees.2012.0427.

König, A. *et al.* (2021) “Can citizen science complement official data sources that serve as evidence-base for policies and practice to improve water quality?,” *Statistical Journal of the IAOS*, 37(1). Available at: https://doi.org/10.3233/SJI-200737.

Koontz, T.M. and Newig, J. (2014) “From Planning to Implementation: Top-Down and Bottom-Up Approaches for Collaborative Watershed Management,” *Policy Studies Journal*, 42(3). Available at: https://doi.org/10.1111/psj.12067.

von Korff, Y. *et al.* (2012) “Implementing participatory water management: Recent advances in theory, practice, and evaluation,” *Ecology and Society*. Available at: https://doi.org/10.5751/ES-04733-170130.

Kuitert, L., Willems, J. and Volker, L. (2023) “Value integration in multi-functional urban projects: a value driven perspective on sustainability transitions,” *Construction Management and Economics*, pp. 1–17. Available at: https://doi.org/10.1080/01446193.2023.2264969.

van der Laan, M. *et al.* (2017) “Towards ecologically sustainable crop production: A South African perspective,” *Agriculture, Ecosystems and Environment*. Available at: https://doi.org/10.1016/j.agee.2016.11.014.

Lam, D.P.M. *et al.* (2020) “Scaling the impact of sustainability initiatives: a typology of amplification processes,” *Urban Transformations*, 2(1), p. 3. Available at: https://doi.org/10.1186/s42854-020-00007-9.

Lam, D.P.M. *et al.* (2021) “Transdisciplinary research: Towards an integrative perspective,” *GAIA - Ecological Perspectives for Science and Society*. Oekom Verlag, pp. 243–249. Available at: https://doi.org/10.14512/gaia.30.4.7.

Lawrence, R.L., Daniels, S.E. and Stankey, G.H. (1997) “Procedural justice and public involvement in natural resource decision making,” *Society and Natural Resources*, 10(6). Available at: https://doi.org/10.1080/08941929709381054.

Liu, J. *et al.* (2007) “Complexity of coupled human and natural systems,” *Science*. Available at: https://doi.org/10.1126/science.1144004.

Liu, J. *et al.* (2013) “Framing sustainability in a telecoupled world,” *Ecology and Society*, 18(2). Available at: https://doi.org/10.5751/ES-05873-180226.

Liu, J. *et al.* (2016) “Framing Sustainability of Coupled Human and Natural Systems,” in *Pandas and People*. Available at: https://doi.org/10.1093/acprof:oso/9780198703549.003.0002.

de Loë, R.C. and Patterson, J.J. (2017) “Rethinking water governance: Moving beyond water-centric perspectives in a connected and changing world,” *Natural Resources Journal*, 57(1).

de Loë, R.C. and Patterson, J.J. (2018) “Boundary Judgments in Water Governance: Diagnosing Internal and External Factors that Matter in a Complex World,” *Water Resources Management*, 32(2). Available at: https://doi.org/10.1007/s11269-017-1827-y.

Longo, S.B., Isgren, E. and Carolan, M. (2025) “Critical sustainability science: advancing sustainability transformations,” *Sustainability Science*, 20(5), pp. 1903–1917. Available at: https://doi.org/10.1007/s11625-025-01667-x.

Lox, S. *et al.* (2025) “Farm demonstration networks as learning environments,” *Agroecology and Sustainable Food Systems*, pp. 1–32. Available at: https://doi.org/10.1080/21683565.2025.2520620.

Luijendijk, E., Gleeson, T. and Moosdorf, N. (2020) “Fresh groundwater discharge insignificant for the world’s oceans but important for coastal ecosystems,” *Nature Communications*, 11(1), p. 1260. Available at: https://doi.org/10.1038/s41467-020-15064-8.

Lun, F. *et al.* (2021) “Influences of international agricultural trade on the global phosphorus cycle and its associated issues,” *Global Environmental Change*, 69. Available at: https://doi.org/10.1016/j.gloenvcha.2021.102282.

Lundy, L. *et al.* (2022) *Systematic review of urban stormwater research in Sweden (2012-2021)*. Available at: https://www.diva-portal.org/smash/get/diva2:1645888/FULLTEXT01.pdf (Accessed: January 4, 2024).

Lynam, T. and Brown, K. (2012) “Mental models in human-environment interactions: Theory, policy implications, and methodological explorations,” *Ecology and Society*. Available at: https://doi.org/10.5751/ES-04257-170324.

Lyon, C. *et al.* (2020) "Five pillars for stakeholder analyses in sustainability transformations: The global case of phosphorus," *Environmental Science and Policy*, 107, pp. 80–89. Available at: https://doi.org/10.1016/j.envsci.2020.02.019.

Le Maitre, D.C. *et al.* (2007) "Linking ecosystem services and water resources: Landscape-scale hydrology of the Little Karoo," *Frontiers in Ecology and the Environment*. Available at: https://doi.org/10.1890/1540-9295(2007)5[261:LESAWR]2.0.CO;2.

Mälarens vattenvårdsförbund (no date) *Dricksvatten*. Available at: https://www.malaren.org/malaren/nyttjande-och-paverkan/dricksvatten/ (Accessed: May 22, 2023).

Malecki, E. (2022) *The Dreel Burn Investigative Report*.

Malone, T.C. and Newton, A. (2020) "The Globalization of Cultural Eutrophication in the Coastal Ocean: Causes and Consequences," *Frontiers in Marine Science*. Available at: https://doi.org/10.3389/fmars.2020.00670.

Manson, S.M. (2008) "Does scale exist? An epistemological scale continuum for complex human-environment systems," *Geoforum*, 39(2). Available at: https://doi.org/10.1016/j.geoforum.2006.09.010.

Marshall, K., Blackstock, K.L. and Dunglinson, J. (2010) "A contextual framework for understanding good practice in integrated catchment management," *Journal of Environmental Planning and Management*, 53(1). Available at: https://doi.org/10.1080/09640560903399780.

Maxwell, J. (2012) *A Realist Approach for Qualitative Research*, *A Realist Approach for Qualitative Research*.

Maxwell, J. and Mittapalli, K. (2010) "Realism as a stance for mixed methods research, in Handbook of mixed methods in social & behavioral research," *Qualitative Social Work*, 13(4).

McCluney, K.E. *et al.* (2014) "Riverine macrosystems ecology: Sensitivity, resistance, and resilience of whole river basins with human alterations," *Frontiers in Ecology and the Environment*, 12(1). Available at: https://doi.org/10.1890/120367.

McDowell, R.W. *et al.* (2020) "Global mapping of freshwater nutrient enrichment and periphyton growth potential," *Scientific Reports*, 10(1). Available at: https://doi.org/10.1038/s41598-020-60279-w.

McGonigle, D.F. *et al.* (2014) "Developing Demonstration Test Catchments as a platform for transdisciplinary land management research in England and Wales," *Environmental Sciences: Processes and Impacts*, 16(7). Available at: https://doi.org/10.1039/c3em00658a.

McPhearson, T. *et al.* (2022) "A social-ecological-technological systems framework for urban ecosystem services," *One Earth*. Available at: https://doi.org/10.1016/j.oneear.2022.04.007.

Metson, G.S. *et al.* (2015a) "Urban phosphorus sustainability: Systemically incorporating social, ecological, and technological factors into phosphorus flow analysis," *Environmental Science and Policy*, 47. Available at: https://doi.org/10.1016/j.envsci.2014.10.005.

Metson, G.S. *et al.* (2015b) "Urban phosphorus sustainability: Systemically incorporating social, ecological, and technological factors into phosphorus flow analysis," *Environmental Science and Policy*, 47. Available at: https://doi.org/10.1016/j.envsci.2014.10.005.

Metson, G.S., Brownlie, W.J. and Spears, B.M. (2022) "Towards net-zero phosphorus cities," *npj Urban Sustainability*, 2(1). Available at: https://doi.org/10.1038/s42949-022-00076-8.

Meyer, C. and Thiel, A. (2012) "Institutional change in water management collaboration: Implementing the European Water Framework Directive in the German Odra river basin," *Water Policy*, 14(4). Available at: https://doi.org/10.2166/wp.2012.011.

Molle, F. (2008) "Nirvana concepts, narratives and policy models: Insights from the water sector," *Water Alternatives*, 1(1).

Moore, A.R. and Kelly, D.M. (2024) "Getting Real About Critical Realist Interviewing: Five Principles to Guide Practice," *International Journal of Qualitative Methods* , 23. Available at: https://doi.org/10.1177/16094069241299311.

Moore, M.-L. *et al.* (2024) "Moving from fit to fitness for governing water in the Anthropocene," *Nature Water*, 2(6), pp. 511–520. Available at: https://doi.org/10.1038/s44221-024-00257-y.

Morée, A.L. *et al.* (2013) "Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century," *Global Biogeochemical Cycles*, 27(3). Available at: https://doi.org/10.1002/gbc.20072.

Mosquera, G.M. *et al.* (2023) "Frontiers in páramo water resources research: A multidisciplinary assessment," *Science of the Total Environment*. Available at: https://doi.org/10.1016/j.scitotenv.2023.164373.

Moss, T. (2004) "The governance of land use in river basins: prospects for overcoming problems of institutional interplay with the EU Water Framework Directive," *Land Use Policy*, 21(1), pp. 85–94. Available at: https://doi.org/10.1016/j.landusepol.2003.10.001.

Moss, T. (2012) "Spatial fit, from panacea to practice: Implementing the EU water framework directive," *Ecology and Society*, 17(3). Available at: https://doi.org/10.5751/ES-04821-170302.

Moss, T. *et al.* (2020) "The EU water framework directive twenty years on: Introducing the special issue," *Water Alternatives*, 13(3).

Moss, T. and Newig, J. (2010) "Multilevel water governance and problems of scale: Setting the stage for a broader debate," *Environmental Management*. Available at: https://doi.org/10.1007/s00267-010-9531-1.

Mostert, E. *et al.* (2007) "Social learning in European river-basin management: Barriers and fostering mechanisms from 10 river basins," *Ecology and Society*, 12(1). Available at: https://doi.org/10.5751/ES-01960-120119.

Mukumbang, F.C., Kabongo, E.M. and Eastwood, J.G. (2021) "Examining the Application of Retroductive Theorizing in Realist-Informed Studies," *International Journal of Qualitative Methods*, 20. Available at: https://doi.org/10.1177/16094069211053516.

Nelson, G.C. *et al.* (2006) "Anthropogenic drivers of ecosystem change: An overview," *Ecology and Society*. Available at: https://doi.org/10.5751/ES-01826-110229.

Newig, J. and Moss, T. (2017) "Scale in environmental governance: moving from concepts and cases to consolidation," *Journal of Environmental Policy and Planning*, 19(5). Available at: https://doi.org/10.1080/1523908X.2017.1390926.

Newig, J., Schulz, D. and Jager, N.W. (2016) "Disentangling Puzzles of Spatial Scales and Participation in Environmental Governance—The Case of Governance Re-scaling Through the European Water Framework Directive," *Environmental Management*, 58(6). Available at: https://doi.org/10.1007/s00267-016-0753-8.

Nieuwenhuis, E. *et al.* (2021) "Towards the integrated management of urban water systems: Conceptualizing integration and its uncertainties," *Journal of Cleaner Production*, 280. Available at: https://doi.org/10.1016/j.jclepro.2020.124977.

Nykvist, B., Borgström, S. and Boyd, E. (2017) "Assessing the adaptive capacity of multi-level water governance: ecosystem services under climate change in Mälardalen region, Sweden," *Regional Environmental Change*, 17(8). Available at: https://doi.org/10.1007/s10113-017-1149-x.

Oenema, J. *et al.* (2010) “Multiscale Effects of Management, Environmental Conditions, and Land Use on Nitrate Leaching in Dairy Farms,” *Journal of Environmental Quality*, 39(6). Available at: https://doi.org/10.2134/jeq2010.0035.

Ostrom, E. (2009) “A general framework for analyzing sustainability of social-ecological systems,” *Science*. Available at: https://doi.org/10.1126/science.1172133.

Pahl-Wostl, C. *et al.* (2007) “Social learning and water resources management,” *Ecology and Society*, 12(2). Available at: https://doi.org/10.5751/ES-02037-120205.

Pahl-Wostl, C. *et al.* (2011) “Maturing the New Water Management Paradigm: Progressing from Aspiration to Practice,” *Water Resources Management*, 25(3). Available at: https://doi.org/10.1007/s11269-010-9729-2.

Pahl-Wostl, C. *et al.* (2012) “From applying panaceas to mastering complexity: Toward adaptive water governance in river basins,” *Environmental Science and Policy*, 23. Available at: https://doi.org/10.1016/j.envsci.2012.07.014.

Partelow, S. (2018) “A review of the social-ecological systems framework: Applications, methods, modifications, and challenges,” *Ecology and Society*. Available at: https://doi.org/10.5751/ES-10594-230436.

Pionke, H.B., Gburek, W.J. and Sharpley, A.N. (2000) “Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin,” *Ecological Engineering*, 14(4), pp. 325–335. Available at: https://doi.org/10.1016/S0925-8574(99)00059-2.

Pranckutė, R. (2021) “Web of Science (WoS) and Scopus: the titans of bibliographic information in today’s academic world,” *Publications*. Available at: https://doi.org/10.3390/publications9010012.

Preiser, R. *et al.* (2018) “Social-ecological systems as complex adaptive systems: Organizing principles for advancing research methods and approaches,” *Ecology and Society*, 23(4). Available at: https://doi.org/10.5751/ES-10558-230446.

Pretty, J.N. *et al.* (2003) “Environmental costs of freshwater eutrophication in England and Wales,” *Environmental Science and Technology*, 37(2), pp. 201–208. Available at: https://doi.org/10.1021/es020793k.

Price, L. (2014) “Critical realist versus mainstream interdisciplinarity,” *Journal of Critical Realism*, 13(1). Available at: https://doi.org/10.1179/1476743013Z.00000000019.

Price, L. and Lotz-Sisitka, H. (2015) *Critical Realism, Environmental Learning and Social-Ecological Change*, *Critical Realism, Environmental Learning and Social-Ecological Change*. Available at: https://doi.org/10.4324/9781315660899.

Price, M.F. (2004) “Navigating social–ecological systems: building resilience for complexity and change,” *Biological Conservation*, 119(4). Available at: https://doi.org/10.1016/j.biocon.2004.01.010.

Proctor, J.D. (1998) “The social construction of nature: relativist accusations, pragmatist and critical realist responses,” *Annals of the Association of American Geographers*, 88(3). Available at: https://doi.org/10.1111/0004-5608.00105.

Proudfoot, K. (2023) “Inductive/Deductive Hybrid Thematic Analysis in Mixed Methods Research,” *Journal of Mixed Methods Research*, 17(3). Available at: https://doi.org/10.1177/15586898221126816.

Qiao, X.-J. *et al.* (2019) “Governance factors of sustainable stormwater management: A study of case cities in China and Sweden,” *Journal of Environmental Management*, 248, p. 109249. Available at: https://doi.org/10.1016/j.jenvman.2019.07.020.

Qiu, J. *et al.* (2018) “Understanding relationships among ecosystem services across spatial scales and over time,” *Environmental Research Letters*, 13(5). Available at: https://doi.org/10.1088/1748-9326/aabb87.

de Raús Maúre, E. *et al.* (2021) “Globally consistent assessment of coastal eutrophication,” *Nature Communications*, 12(1). Available at: https://doi.org/10.1038/s41467-021-26391-9.

Reaney, S.M. *et al.* (2019) “Identifying critical source areas using multiple methods for effective diffuse pollution mitigation,” *Journal of Environmental Management*, 250. Available at: https://doi.org/10.1016/j.jenvman.2019.109366.

Recuero Virto, L. (2018) “A preliminary assessment of the indicators for Sustainable Development Goal (SDG) 14 ‘Conserve and sustainably use the oceans, seas and marine resources for sustainable development,’” *Marine Policy*, 98. Available at: https://doi.org/10.1016/j.marpol.2018.08.036.

Richardson, K. *et al.* (2023) *Earth beyond six of nine planetary boundaries*. Available at: https://www.science.org.

River South Esk Catchment Partnership (2009) *The South Esk Catchment Management Plan*.

River South Esk Catchment Partnership (2021) *River South Esk 2020 Source to Sea Challenge NatureScot Biodiversity Challenge Fund Summary* .

Rollason, E. *et al.* (2018) "Evaluating the success of public participation in integrated catchment management," *Journal of Environmental Management*, 228. Available at: https://doi.org/10.1016/j.jenvman.2018.09.024.

Rosemarin, A. and Ekane, N. (2016a) "The governance gap surrounding phosphorus," *Nutrient Cycling in Agroecosystems*. Available at: https://doi.org/10.1007/s10705-015-9747-9.

Rosemarin, A. and Ekane, N. (2016b) "The governance gap surrounding phosphorus," *Nutrient Cycling in Agroecosystems*. Available at: https://doi.org/10.1007/s10705-015-9747-9.

Rosemarin, A. and Ekane, N. (2016c) "The governance gap surrounding phosphorus," *Nutrient Cycling in Agroecosystems*. Available at: https://doi.org/10.1007/s10705-015-9747-9.

Del Rossi, G. *et al.* (2023) "The Economics of Nutrient Pollution from Agriculture," *Annual Review of Resource Economics*, 15. Available at: https://doi.org/10.1146/annurev-resource-111820-021317.

Rouillard, J.J. and Spray, C.J. (2017) "Working across scales in integrated catchment management: lessons learned for adaptive water governance from regional experiences," *Regional Environmental Change*, 17(7). Available at: https://doi.org/10.1007/s10113-016-0988-1.

Rounsevell, M.D.A. *et al.* (2021) "Identifying uncertainties in scenarios and models of socio-ecological systems in support of decision-making," *One Earth*. Available at: https://doi.org/10.1016/j.oneear.2021.06.003.

Rowbottom, J. *et al.* (2022) "Water governance diversity across Europe: Does legacy generate sticking points in implementing multi-level governance?," *Journal of Environmental Management*, 319. Available at: https://doi.org/10.1016/j.jenvman.2022.115598.

Royer, M.B. *et al.* (2020) "Shared discovery: A process to coproduce knowledge among scientists, policy makers, and stakeholders for solving nutrient pollution problems," *Journal of Environmental Quality*, 49(3). Available at: https://doi.org/10.1002/jeq2.20025.

Sachs, J., Lafortune, G. and Fuller, G. (2024) "SUSTAINABLE DEVELOPMENT REPORT 2024 The SDGs and the UN Summit of the Future." Available at: https://doi.org/10.25546/108572.

Sandström, A. *et al.* (2020) “Assessing and explaining policy coherence: A comparative study of water governance and large carnivore governance in Sweden,” *Environmental Policy and Governance*, 30(1), pp. 3–13. Available at: https://doi.org/10.1002/eet.1871.

Sandström, A., Söderberg, C. and Nilsson, J. (2020) “Adaptive capacity in different multi-level governance models: a comparative analysis of Swedish water and large carnivore management,” *Journal of Environmental Management*, 270. Available at: https://doi.org/10.1016/j.jenvman.2020.110890.

Schlüter, M. *et al.* (2019) “Capturing emergent phenomena in social-ecological systems: An analytical framework,” *Ecology and Society*, 24(3). Available at: https://doi.org/10.5751/ES-11012-240311.

Schönach, P. *et al.* (2018) “The past, present, and future of a lake: Interdisciplinary analysis of long-term lake restoration,” *Environmental Science and Policy*, 81. Available at: https://doi.org/10.1016/j.envsci.2017.12.015.

Seigerman, C.K. *et al.* (2023) “Operationalizing equity for integrated water resources management,” *Journal of the American Water Resources Association*, 59(2). Available at: https://doi.org/10.1111/1752-1688.13086.

Serrao-Neumann, S. *et al.* (2017) “Connecting land-use and water planning: Prospects for an urban water metabolism approach,” *Cities*, 60. Available at: https://doi.org/10.1016/j.cities.2016.07.003.

SFS 1998:808. Miljöbalk [Swedish Environmental Code]. (no date) *SFS 1998:808. Miljöbalk [Swedish Environmental Code].* Available at: https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/miljobalk-1998808_sfs-1998-808 (Accessed: February 20, 2024).

SFS 2006:412 Lag om allmänna vattentjänster [Act on Public Water Services] (2006) *SFS 2006:412 Lag om allmänna vattentjänster [Act on Public Water Services]*. Sweden: https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2006412-om-allmanna-vattentjanster_sfs-2006-412. Available at: https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/lag-2006412-om-allmanna-vattentjanster_sfs-2006-412/ (Accessed: February 20, 2024).

SFS 2010:900 Plan- och bygglag [The Planning and Building Act] (2010) *SFS 2010:900 Plan- och bygglag [The Planning and Building Act]*. Available at: https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/plan-och-bygglag-2010900_sfs-2010-900/ (Accessed: February 20, 2024).

Shan, X. *et al.* (2023) “Modeling nutrient flows from land to rivers and seas – A review and synthesis,” *Marine Environmental Research*. Available at: https://doi.org/10.1016/j.marenvres.2023.105928.

Shkaruba, A. *et al.* (2024) “Why is the eutrophication governance over the Lake of Baikal failing? Land use governance solutions need to account for barriers across sectors, scales, and actor groups,” *Land Use Policy*, 141. Available at: https://doi.org/10.1016/j.landusepol.2024.107136.

Shortle, J.S. *et al.* (2020) “Nutrient control in water bodies: A systems approach,” *Journal of Environmental Quality*, 49(3). Available at: https://doi.org/10.1002/jeq2.20022.

Shupe, S.M. (2017) “High resolution stream water quality assessment in the Vancouver, British Columbia region: a citizen science study,” *Science of the Total Environment*, 603–604. Available at: https://doi.org/10.1016/j.scitotenv.2017.02.195.

Sieczko, A.K. *et al.* (2023) “Seasonal nitrogen and phosphorus leaching in urban agriculture: Dominance of non-growing season losses in a Southern Swedish case study,” *Urban Forestry and Urban Greening*, 79, p. 127823. Available at: https://doi.org/10.1016/j.ufug.2022.127823.

Siegmund-Schultze, M., Köppel, J. and Sobral, M. do C. (2018) “Unraveling the water and land nexus through inter- and transdisciplinary research: sustainable land management in a semi-arid watershed in Brazil’s Northeast,” *Regional Environmental Change*, 18(7). Available at: https://doi.org/10.1007/s10113-018-1302-1.

Sigler, W.A. *et al.* (2018) “Connections among soil, ground, and surface water chemistries characterize nitrogen loss from an agricultural landscape in the upper Missouri River Basin,” *Journal of Hydrology*, 556. Available at: https://doi.org/10.1016/j.jhydrol.2017.10.018.

Siman, K.E. and Niewiarowski, P.H. (2023) “Historical political ecology as qualitative social-ecological system analysis in the Maumee River Watershed,” *Ecology and Society*, 28(1). Available at: https://doi.org/10.5751/ES-13408-280148.

Singh, D.K. *et al.* (2021) “Perspectives on emerging pressures and their integrated impact on large river systems: An insight from the Yellow River basin,” *Journal of Environmental Management*. Available at: https://doi.org/10.1016/j.jenvman.2021.113423.

Smith, A. and Stirling, A. (2010) “The politics of social-ecological resilience and sustainable socio-technical transitions,” *Ecology and Society*, 15(1). Available at: https://doi.org/10.5751/ES-03218-150111.

Smith, E.D., Balika, D. and Kirkwood, A.E. (2021) “Community science-based monitoring reveals the role of land use scale in driving nearshore water quality in a large, shallow, Canadian lake,” *Lake and Reservoir Management*, 37(4). Available at: https://doi.org/10.1080/10402381.2021.1989525.

Smith, V.H. and Schindler, D.W. (2009) “Eutrophication science: where do I go from here?,” *Trends in Ecology and Evolution*. Available at: https://doi.org/10.1016/j.tree.2008.11.009.

Söderberg, C. (2016) “Complex governance structures and incoherent policies: Implementing the EU water framework directive in Sweden,” *Journal of Environmental Management*, 183. Available at: https://doi.org/10.1016/j.jenvman.2016.08.040.

Spey Catchment Initiative (2023) *River Spey Catchment Management Plan*.

Spey Catchment Initiative (2024) *Spey Catchment Initiative Annual Review 2024*.

Stafford-Smith, M. *et al.* (2017) “Integration: the key to implementing the Sustainable Development Goals,” *Sustainability Science*, 12(6). Available at: https://doi.org/10.1007/s11625-016-0383-3.

Star, S.L. (1989) “The Structure of Ill-Structured Solutions: Boundary Objects and Heterogeneous Distributed Problem Solving,” in *Distributed Artificial Intelligence*. Available at: https://doi.org/10.1016/b978-1-55860-092-8.50006-x.

Stockholm Vatten och Avfall [Stockholm Water and Waste] (no date) *Avloppsreningsverk [Sewage Treatment Plant]*. Available at: https://www.stockholmvattenochavfall.se/kunskap/sahar-renas-vatten-och-avlopp/avloppsrening/avloppsreningsverk/ (Accessed: January 17, 2024).

Stockholms Stad (2015) *Stockholms Stads Handlingsplan för god vattenstatus*. Available at: https://start.stockholm/globalassets/start/om-stockholms-stad/politik-och-demokrati/styrdokument/stockholms-stads-handlingsplan-for-god-vattenstatus.pdf (Accessed: September 30, 2022).

Stockholms Stad *et al.* (2021) *Mälaren-Ulvsundasjön Lokalt åtgardsprogräm: Facta och åtgärdsbehov [Mälaren-Ulvsundasjön Local Action Plan: Facts and Required Actions]*. Available at: https://miljobarometern.stockholm.se/content/docs/tema/vatten/sjoar/Ulvsundasjon/Fakta%20och%20%C3%A5tg%C3%A4rdsbehov%20M%C3%A4laren-Ulvsundasj%C3%B6n.pdf (Accessed: September 30, 2022).

Stockholms Stad (2023) *Statistik efter ämnesområde*. Available at: https://start.stockholm/om-stockholms-stad/utredningar-statistik-och-fakta/statistik/befolkning/ (Accessed: October 3, 2023).

Stockholms Stad and Stockholm Vatten och Avfall (2020) *Kyrksjön Lokalt åtgärdsprogram - Fakta och åtgärdsbehov, På väg mot god vattenstatus*. Available at: https://miljobarometern.stockholm.se/vatten/sjoar/kyrksjon/lokalt-atgardsprogram/ (Accessed: April 10, 2023).

Stockholms Stad, Stockholm Vatten och Avfall and Tyresän (2022) *Lokalt åtgärdsprogram för Flaten - Fakta och åtgärdsbehov*. Available at: https://miljobarometern.stockholm.se/vatten/sjoar/flaten/lokalt-atgardsprogram-for-flaten/ (Accessed: April 10, 2023).

Stockhoms Stad and Stockholm Vatten och Avfall (2020) *Råcksta Träsk Lokalt åtgärdsprogram -Fakta och åtgärdsbehov, På väg mot god vattenstatus*. Available at: https://miljobarometern.stockholm.se/vatten/sjoar/racksta-trask/lokalt-atgardsprogram-for-racksta-trask/ (Accessed: April 10, 2023).

Stringer, L.C. *et al.* (2006) "Unpacking 'participation' in the adaptive management of social-ecological systems: A critical review," *Ecology and Society*, 11(2).

Suleiman, L. (2021) "Blue green infrastructure, from niche to mainstream: Challenges and opportunities for planning in Stockholm," *Technological Forecasting and Social Change*, 166. Available at: https://doi.org/10.1016/j.techfore.2020.120528.

Surridge, B., Holt, A. and Harris, B. (2009) "Chapter 1.5. Developing the Evidence Base for Integrated Catchment Management: Challenges and Opportunities," in *Water System Science and Policy Interfacing*. Available at: https://doi.org/10.1039/9781847556622-00063.

Sutherland, L.A. and Marchand, F. (2021) "On-farm demonstration: enabling peer-to-peer learning," *Journal of Agricultural Education and Extension*. Available at: https://doi.org/10.1080/1389224X.2021.1959716.

Swedish Water [Svensk Vatten] (2020) *Decision Order for Revaq [Beslutsordning för Revaq]*. Available at: https://www.svensktvatten.se/globalassets/avlopp-och-miljo/uppstromsarbete-och-kretslopp/revaq-certifiering/am-revaq-01-beslutsordning-revaq-20200109b.pdf (Accessed: November 10, 2023).

Syed, T., Choudhury, E. and Islam, S. (2020) "An assessment of scale-sensitivity in policy design and implementation of the EU water framework directive within the context of the danube basin," *Water Alternatives*, 13(3).

Taylor, B.M. and Eberhard, R. (2020) "Practice change, participation and policy settings: A review of social and institutional conditions influencing water quality outcomes in the Great Barrier Reef," *Ocean and Coastal Management*. Available at: https://doi.org/10.1016/j.ocecoaman.2020.105156.

Thornton, J.A. *et al.* (2013) "Eutrophication as a 'wicked' problem," *Lakes and Reservoirs: Science, Policy and Management for Sustainable Use*, 18(4). Available at: https://doi.org/10.1111/lre.12044.

Tigli, M. *et al.* (2025) "The future of algal blooms in lakes globally is in my hands," *Water Research*, 268, p. 122533. Available at: https://doi.org/10.1016/j.watres.2024.122533.

Torraco, R.J. (2005) "Writing Integrative Literature Reviews: Guidelines and Examples," *Human Resource Development Review*, 4(3). Available at: https://doi.org/10.1177/1534484305278283.

Tscheikner-Gratl, F. *et al.* (2016) "Integrated rehabilitation planning of urban infrastructure systems using a street section priority model," *Urban Water Journal*, 13(1). Available at: https://doi.org/10.1080/1573062X.2015.1057174.

Tschikof, M. *et al.* (2024) "Cross-scale and integrative prioritization of multi-functionality in large river floodplains," *Journal of Environmental Management*, 358, p. 120899. Available at: https://doi.org/10.1016/j.jenvman.2024.120899.

United Nations (2021) *The Second World Ocean Assessment*, *The Second World Ocean Assessment*. Available at: https://doi.org/10.18356/9789216040062.

United Nations Environment Programme (2024) *Progress on Water-related Ecosystems. Mid-term status of SDG Indicator 6.6.1 and acceleration needs, with a special focus on Biodiversity*.

Vattenmyndigheten Norra Östersjön (2016) *Förvaltningsplan 2016-2021 Norra Östersjöns vattendistrikt: Del 4 Förvaltningsplan Åtgärdsprogram för vatten*, *Länsstyrelsen Västmanlands Län*. Available at: https://www.vattenmyndigheterna.se/download/18.7da99fd316a5925e2981028a/1557729300719/Norra%20%C3%96stersj%C3%B6n%20Del%204%20F%C3%B6rvaltningsplan%20-%20%C3%85tg%C3%A4rdsprogram%20f%C3%B6r%20vatten.pdf (Accessed: September 30, 2022).

Ventura, S.J. and Kim, K. (1993) “MODELING URBAN NONPOINT SOURCE POLLUTION WITH A GEOGRAPHIC INFORMATION SYSTEM,” *JAWRA Journal of the American Water Resources Association*, 29(2). Available at: https://doi.org/10.1111/j.1752-1688.1993.tb03200.x.

Vervoort, J. *et al.* (2012) “Exploring dimensions, scales, and cross-scale dynamics from the perspectives of change agents in social-ecological systems,” *Ecology and Society*, 17(4). Available at: https://doi.org/10.5751/ES-05098-170424.

Vieira, E. de O. *et al.* (eds.) (2020) *Integrated Water Resource Management: Cases from Africa, Asia, Australia, Latin America and USA*. Cham: Springer International Publishing. Available at: https://doi.org/10.1007/978-3-030-16565-9.

van de Vlasakker, P.C.H., Tonderski, K. and Metson, G.S. (2022) “A Review of Nutrient Losses to Waters From Soil- and Ground-Based Urban Agriculture—More Nutrient Balances Than Measurements,” *Frontiers in Sustainable Food Systems*. Available at: https://doi.org/10.3389/fsufs.2022.842930.

Wallin, M. *et al.* (2000) *Mälaren miljötillstånd och utveckling 1965–98*. Available at: https://res.slu.se/id/publ/95337 (Accessed: October 3, 2023).

Ward, N.K. *et al.* (2019) “Integrating fast and slow processes is essential for simulating human–freshwater interactions,” *Ambio*, 48(10). Available at: https://doi.org/10.1007/s13280-018-1136-6.

Water Revival Systems (2019) *Lokalt åtgärdsprogram för Järlasjön och Sicklasjön*. Available at: https://miljobarometern.stockholm.se/vatten/sjoar/sicklasjon/lokalt-atgardsprogram/ (Accessed: April 10, 2023).

Waylen, K.A. *et al.* (2023) “Navigating or adding to complexity? Exploring the role of catchment partnerships in collaborative governance,” *Sustainability Science*, 18(6). Available at: https://doi.org/10.1007/s11625-023-01387-0.

Whaley, L. (2022) “Water Governance Research in a Messy World: A Review,” *Water Alternatives*, 15(2).

White, R.M. *et al.* (2018) “Prioritising stakeholder engagement for forest health, across spatial, temporal and governance scales, in an era of austerity,” *Forest Ecology and Management*, 417. Available at: https://doi.org/10.1016/j.foreco.2018.01.050.

Wielemaker, R. *et al.* (2019) “Fertile cities: Nutrient management practices in urban agriculture,” *Science of the Total Environment*, 668. Available at: https://doi.org/10.1016/j.scitotenv.2019.02.424.

Wihlborg, M., Sörensen, J. and Alkan Olsson, J. (2019) "Assessment of barriers and drivers for implementation of blue-green solutions in Swedish municipalities," *Journal of Environmental Management*, 233. Available at: https://doi.org/10.1016/j.jenvman.2018.12.018.

Wilkinson, G.M. (2017) "Eutrophication of Freshwater and Coastal Ecosystems," in *Encyclopedia of Sustainable Technologies*. Elsevier, pp. 145–152. Available at: https://doi.org/10.1016/B978-0-12-409548-9.10160-5.

Withers, P.J.A. *et al.* (2015) "Stewardship to tackle global phosphorus inefficiency: The case of Europe," *Ambio*, 44(2), pp. 193–206. Available at: https://doi.org/10.1007/s13280-014-0614-8.

World Resources Institute (2011) *Eutrophication & Hypoxia Map Data Set*. Available at: http://www.wri.org/resources/data-sets/eutrophication-hypoxia-map-data-set (Accessed: May 12, 2025).

Wuijts, S. *et al.* (2021) "Protection of drinking water resources from agricultural pressures: Effectiveness of EU regulations in the context of local realities," *Journal of Environmental Management*, 287. Available at: https://doi.org/10.1016/j.jenvman.2021.112270.

Wurtsbaugh, W.A., Paerl, H.W. and Dodds, W.K. (2019) "Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum," *Wiley Interdisciplinary Reviews: Water*, 6(5). Available at: https://doi.org/10.1002/WAT2.1373.

Yang, Y.Y. and Toor, G.S. (2018) "Stormwater runoff driven phosphorus transport in an urban residential catchment: Implications for protecting water quality in urban watersheds," *Scientific Reports*, 8(1). Available at: https://doi.org/10.1038/s41598-018-29857-x.

Yevenes, M.A., Pereira, H. and Bermudez, R. (2022) "Citizen Science as a Co-Creative Measure to Water Quality: Chemical Data and Local Participation in a Rural Territory," *Frontiers in Environmental Science*, 10. Available at: https://doi.org/10.3389/fenvs.2022.940778.

Yin, R.K. (2018) *Case study research and applications : design and methods / Robert K. Yin.*, *Paper Knowledge . Toward a Media History of Documents*.

Yoder, L., Chowdhury, R.R. and Hauck, C. (2020) "Watershed restoration in the Florida Everglades: Agricultural water management and long-term trends in nutrient outcomes in the Everglades Agricultural Area," *Agriculture, Ecosystems and Environment*, 302. Available at: https://doi.org/10.1016/j.agee.2020.107070.

Young, O.R. (2002) "The Institutional Dimensions of Environmental Change: Fit, Interplay, and Scale," *Organization* [Preprint].

Zachariadis, M., Scott, S. and Barrett, M. (2013) "Methodological implications of critical realism for mixed-methods research," *MIS Quarterly: Management Information Systems*, 37(3). Available at: https://doi.org/10.25300/misq/2013/37.3.09.

Zammali, M.K. *et al.* (2021) "A generic approach to evaluate costs and effectiveness of agricultural Beneficial Management Practices to improve water quality management," *Journal of Environmental Management*, 287. Available at: https://doi.org/10.1016/j.jenvman.2021.112336.

Zimnicki, T. *et al.* (2020) "On Quantifying Water Quality Benefits of Healthy Soils," *BioScience*. Available at: https://doi.org/10.1093/biosci/biaa011.

Zou, T., Zhang, X. and Davidson, E.A. (2022) "Global trends of cropland phosphorus use and sustainability challenges," *Nature*, 611(7934). Available at: https://doi.org/10.1038/s41586-022-05220-z.

8 Appendices

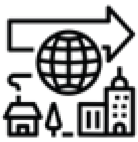
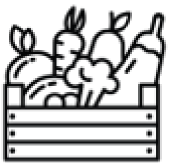
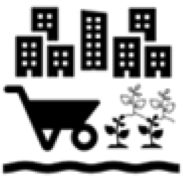
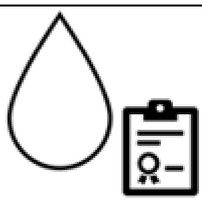
8.1 Appendix 1: Chapter 3 Interview Guideline

1. Can you tell me a bit about your organisation and your role?
2. How would you describe your organisation's top 3 goals and priorities with regards to pollution, waste management and green infrastructure?
    a. Can you give me some examples of how you're pursuing these goals?
3. How does the water quality of Stockholm's lakes appear in your priorities?
    a. What are forms of pollution are of the greatest concern?
    b. How would you describe the major sources of phosphorus pollution in Stockholm's lakes?
    c. Do these differ to sources of nitrogen? How?
    d. What are the impacts of phosphorus pollution in Stockholm's lakes? Ecologically, socially and economically?
    e. How does nitrogen contribute?
    f. How are these impacts assessed?
    g. How has it impacted your organisation and what you do?
4. Can you describe the strategies you have in place for reducing the nutrient pollution of Stockholm's lakes?
    a. Are nitrogen and phosphorus treated differently? Why?
    b. Do the strategies also target other or multiple forms of pollution?

c. In addition to the strategies you've outlined, what strategies do you have that aim to change the behaviour of individuals or organisations?
d. How are these strategies decided upon, implemented and funded?
e. Who plays the most important roles?
f. Why were these strategies chosen / what were the most important considerations when deciding on strategies / What sources of information are used?

5. What role do you see for green infrastructure in improving the water quality of Stockholm's lakes?
    a. Do you see a role for urban allotments as green infrastructure? Why / why not? How?
6. How does the idea of 'circularity' appear in your organisation's visions of a sustainable Stockholm?
    a. Do you have any strategies that aim to improve the circularity of phosphorus? What are they?
    b. What about strategies that may indirectly improve the circularity of phosphorus e.g that aim to improve the circularity of the food system?
7. Can you talk about any barriers you can see to reducing phosphorus pollution in Stockholm's lakes?
    a. Challenges around understanding the sources and impacts / choosing measures / implementation and funding / conflicts with other priorities / information?
    b. What about improving the circularity of phosphorus?
    c. Do you see any potential synergies between managing phosphorus pollution, improving its circularity and urban gardening?
    d. What about potential trade-offs?
    e. How do you think these barriers and trade-offs could be addressed? Are there particular changes you would like to see?

8.2 Appendix 2: Chapter 3 Mental model ‘factors’ (these were supplied in Swedish)

Factor	Definition	Factor	Definition
 Contaminants	Substances that negatively affect the environment.	 Access to information	The existence of and access to knowledge, or the means to investigate questions.
 Lack of space	High pressure on urban spaces to fulfil multiple goals.	 Monitoring schemes	Data collection and sharing on relevant topics.
 Nature-human connection	How people are connected to non-humans.	 Pilot areas / project	The capacity to test new ways of doing things and assess their impacts.
 Regulatory standards	Rules on how land is used and the practices and products that impact land use.	 Waste management	Handling of waste of biological origin both in and outside of gardens.
 Water supply and management	Supply and use of water in the gardens.	 Food production	Availability of edible plants.
 Soil and plant management	Decisions and actions involving soil, plants, and inputs in the gardens.	 Civic participation	The ability to play a role in addressing public concerns through access to people and resources in government.
 Urban Allotments	Land rented from the city by members of the public for cultivation.	 Water quality	The cleanliness of the water and how it impacts its use for leisure, drinking water and as a habitat.

8.3 Appendix 3: Chapter 3 Workshop exercises (these were supplied in Swedish)

Exercise 1 Instructions for Participants
What are mental models? 1. Mental models are my personal understandings of the world around us, how things are and how they work. 2. This exercise asks you to explore and communicate how you perceive urban allotments, water quality, urban sustainability, and the relationships between them. 3. The mental models will be made up of 'factors', which are elements that you think can affect how urban allotments and water quality impact each other and the role they play in urban sustainability. They will also show relationships between the factors, which indicate how you think different factors can impact each other and how strong this impact is. How to do the mental modelling exercise 1. Choose or draw factors: identify factors that you think are related to urban allotments, water quality and the relationship between them. 2. Select factors from those given. 3. You may also write up to 3 of your own. 4. Stick them to the sheet given to you. 5. Show relationships with arrows: Join the factors with arrows to show the relationship between them and the direction of the relationship. 6. Use the arrows given or draw them in black. 7. Think about what the relationship is. 8. Indicate the strength of the relationship by choosing or drawing thicker arrows for stronger relationships. Key questions to consider 1. What factors affect the relationship between urban allotments, water quality and urban sustainability? 2. How can urban allotments impact, or be impacted by water quality? 3. What factors can impact these relationships?

Exercise 2 Instructions for Participants
Key Question What actions should be taken to improve the ability of urban allotments to reduce nutrient use and loss, and play a greater role in urban sustainability? How to do the exercise There will be **3 rounds** to this exercise where you will be asked to identify which **actors** can impact different **factors,** and the **actions** they should take to improve the ability of urban allotments to reduce nutrient use and loss, and to play a greater role in urban sustainability. Round 1: What factors can your organisation directly impact and what actions should they take? 1. **Identify factors** that your organisation can impact. 2. **On blue sticky 'action' cards**, write the name of your organisation and the action they should take. 3. Present your actions to the group and stick them to the sheet. 4. Link the action to the factor it can impact using pen. Round 2: What actions should other actors take? 1. **Identify actors** that can impact the factors on the sheet or are needed to facilitate the actions that have already been identified. 2. **On purple sticky 'action' cards**, write the name of the actor and the action they should take. 3. Present them to the group and stick them to the sheet. 4. Link the action to the factor or existing action it can impact using pen. Round 3: As a group, select 5 actions that you think will be the most beneficial.

8.1 Appendix 4: Chapter 4 interview questions

1) Can you tell me a bit about yourself and your role in the catchment partnership?
2) What organisations have you previously been involved in that focused on collaborative environmental management, if any?
3) What do you think are the most important environmental concerns in the catchment?
4) How would you describe the key causes of environmental problems in the catchment?
5) When it comes to the <x catchment>, what does success look like to you?
6) Why is your organisation involved in the catchment partnership?
7) What is the importance of scale in catchment management?
8) What role do you see for collaborative partnerships in catchment management?
9) What do you think are the key strengths of the catchment partnership currently?
10) What challenges have you encountered as part of the catchment partnership?
11) Are there any changes you would like to see to improve the effectiveness of the catchment partnership? / What do you think makes a good catchment partnership?
12) What do you think are the most important factors for going beyond pilot projects to wider scale implementation? Are there key barriers that you have encountered?
13) What do you think are some key next steps for the partnership?
14) What 3 tips would you make to someone who wanted to start their own catchment partnership?