Systems water management for catchment scale processes:

Development and demonstration of a systems analysis framework

Chief Scientist’s Group report

Date: May 2021

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Professor Doug Wilson
Chief Scientist

Executive summary

Environmental management is a global problem, revealing a challenge to minimise pressures on the natural environment. The goal must be to achieve sustainable development, with economic growth supported by ecosystem services. In this context, water can be seen as an environmental integrator – a system that supports ecological functions and provides resources essential for the existence of human society and growth. However, in the case of water management approaches that address water resources, flooding and water quality in an integrated way, we need to explore the complex interdependences of the water system to understand ways of minimising the impact of development.

Systems thinking provides a structured approach to understand complex problems. It provides a shared view of the system that allows us to see the ‘big picture’, understand dependencies, consider different perspectives and ensure that components of a system work together to achieve the objectives of the whole. This enables us to understand multiple complex interactions and develop tools for improved system understanding and cause-effect analysis. Systems thinking allows us to collaboratively develop more coherent management options and policies. This could be done by developing systems-level conceptual and simulation models, which can be used to identify and address ‘key systemic leverage points’. These are defined as the points of intervention, including technological, management and policy that create the biggest positive change in the system as a whole. Ultimately, a systems approach provides multiple outcomes while seeking to account for and prevent unintended consequences.

The Systems Water Management for Catchment Scale Processes (CASYWat) project was a result of a collaboration between the Environment Agency, the Royal Academy of Engineering and Dr Ana Mijic (Imperial College London) through a National Environment Research Council (NERC) Innovation Placement. The project’s aim was to co-develop an innovative approach for systems-based understanding, structuring and analysis of relevant environmental, technical and social processes in the context of catchment water management in the UK. The work directly addressed the UK government’s 25 Year Environment Plan (25 YEP) ambition to apply systems thinking to environmental management. The 25 YEP Cumbria Catchment Pioneer (CCP) was selected to test the implementation of developed systems approaches.

The main objectives of the CASYWat projects were: (1) to develop a novel concept of Systems Water Management (SYWM) as a framework to provide the Environment Agency and its stakeholders with an overview of water management system complexity in the context of water planning; (2) to propose a generic approach to SYWM mapping and showcase the value of a systems-level analysis to the Environment Agency and its stakeholders; and (3) to inform the Environment Agency and its stakeholders about lessons learnt, the potential of the work and future improvements. The proposed SYWM framework was developed primarily as a theoretical understanding supported by scientific literature and technical reports. We acknowledge the limitations of the study in terms of participatory engagement and we discuss potential approaches for co-delivery throughout the report.

The SYWM framework explicitly accounts for water management, natural capital, ecosystem services and footprint concepts, and has shown that most (if not all) water management critical interactions could be analysed by mapping three **key feedback loops** and seven **high-level components** (subsystems). We refer to this structure as a **SYWM meta-model**. In the meta-model, the concept of **quality of life** (QoL) is perceived as a direct driver of development that influences **local demand-supply;** in this study, we include water use and food consumption. The resources provision supports a **local**

economy component, and, in turn, economic sectors (such as agricultural, service and industry) contribute to an increase in QoL. In the SYWM meta-model, this creates conditions for further development, defining the **reinforcing development loop**.

It is assumed that local demand-supply balance is achieved by providing ecosystem services (ES), either directly or supported by built infrastructure. We categorise ES into 2 subsystems. We define the provision of ES through infrastructure and land management as **human made services** (for example, water abstractions). The functioning of the local water environment and direct provision of ES that cannot be imported is represented by the level of **environmental services** (for example, water quality and flood regulation). The environmental services (ENS) provision depends on the functioning of the natural environment defined through **catchment state** (for example, surface water flow) as altered by **human impacts** (for example, water pollution). We assume that the QoL is a direct function of ENS provision*,* which defines the SYWM **balancing environmental loop**. Finally, we recognise the need for development in which the level of ENS provision is directly linked with the infrastructure operation and planning. This is defined by human made services that should be designed to manage the environment and compensate for environmental impacts of human activities. This defines the SYWM **reinforcing infrastructure loop**.

The developed theoretical framework and the SYWM meta-model were applied in 2 case studies: firstly, to understand the overall state of the water environment in England from a systems perspective, and secondly, to practically address selected environmental problems in respect of CCP's Windermere lake water quality. The case studies were analysed through a 3-step process, which included system understanding, systems map structuring and water management analysis.

A number of recommendations arose from developing systems maps using the SYWM framework and meta-model. Regional (multiple catchments) water management (RWM) analyses emphasised the need for water planning coordination between sectors such as water and housing. This could be approached from a water neutrality perspective. The role of environmental services, and in particular, surface water quality, is proposed as an indicator that could be used to inform land and infrastructure planning, including coordinating water supply and wastewater infrastructure design and operation. The role of urban water demand management could significantly contribute to optimising overall system performance. Finally, the study recommended using the developed RWM systems map (in current or revised versions) as a starting point for open discussion about the water management system and to communicate key feedbacks that may lead to unintended consequences. This is demonstrated, for example, by interactions between flood management, urbanisation and consumption behaviour, potentially leading to an increase in flood risk if water demand reductions result in decreases in abstractions and increases in environmental flows. A range of relevant stakeholders should be included in these discussions, with beneficiaries (for example, industry sectors) and users (for example, citizens) being an essential part of the water management governance system.

Analysis of the water quality system of the Windermere Lake in Cumbria conceptualised the role of activities resulting from service and industry sectors, and tourism in particular, in defining the water management issues and informing possible measures for water pollution management. Leverage point analysis revealed that most infrastructure and technological solutions, unless implemented across the system as a whole, will be limited in solving the systemic causes of Windermere lake water pollution. However, infrastructure schemes such as wastewater recycling and reuse, as well as providing timely and relevant information about consumption and the state of the local environment to local stakeholders, residents and visitors, could provide significant systems-level water quality benefits. The role of coordination and environmental regulation, in particular linked to a visitor economy, was emphasised as a high leverage point. Beyond the UK, global trends such as the climate emergency and the Green New Deal could potentially fundamentally change how we think about and evaluate complex human-natural water systems.

This work, while covering multiple water management aspects, could potentially be developed and implemented further. In this work, we have limited the analyses by focusing on water and inland ecosystems and selected sectors relevant to water management. However, this scope could easily be expanded in future studies by introducing additional elements within SYWM subsystems. Concepts such as ecology and biodiversity, additional ecosystems such as marine, industry (for example, mining) and service sectors (for example, energy and transport) could be added to the SYWM framework. Finally, we need to refine and expand the high-level maps by working together with stakeholders. We hope that this work will help to promote systems thinking in the context of catchment water management and that the SYWM framework and meta-model will be used as a guide for analysing, modelling and assessing water management systems, thereby creating a range of case studies to validate SYWM thinking.

Acknowledgements

This report is a result of discussions and input from many people I have worked with during my placement and in writing this report. My biggest thanks go to Dave Forrow from the Environment Agency. Dave is a genuine systems thinker. His passion to understand environmental management from a systems perspective and develop approaches that could influence UK policy and regulation reform made this study possible in the first place.

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1 Background

1.1 Global context of environmental management

We live in times of multiple challenges, yet environmental management should be our key priority to address. In the 1970s, the seminal 'Club of Rome' 'Limits to growth' systems work by Donella Meadows and colleagues showed how the world may be moving towards collapse due to overuse of the non-renewable resources and environmental pollution driven by our model of economic growth [1]. At the time, however, the proposed 'equilibrium' concept to manage pressures on the environment by constraining population and industrial growth seemed too politically and socially radical. The hope was that an 'alternative' model would emerge based on the role of technology and innovation to increase efficiency and minimise pollution to counter collapse [1].

Almost fifty years later, we are exactly where that very simple systems 'limits' model predicted we might be. The 'Business as Usual' scenario aligns with historical data on environmental (non-renewable resources, pollution), economy (sectors outputs per capita) and population growth indicators from 1970 to 2010 [2]. While the socio-economic indicators such as gross domestic product (GDP) and population show general upward trends, the state of the environment is revealing the price of that growth. Although improving basic human needs such as nutrition and sanitation, most countries globally are currently performing outside defined per capita biophysical boundaries with respect to CO_2 emissions (66% of countries), phosphorous and nitrogen (55%) and ecological footprint (57%), with most of the overuse linked to satisfying qualitative social goals such as high life satisfaction in high-income countries [3].

Finally, while some countries have managed to stabilise their use of resources and can be classified as 'biophysically stable economies', that use is at levels way above the capacity of the local environmental system, with implications for global sustainability balance [4]. This creates a tension between the need to reduce resource consumption, while also improving social performance measured by the quality of life indicators. Solutions such as improving physical and social provisioning systems by promoting equity and sufficiency still remain difficult to achieve. High-level documents such as the European Environment Agency's (EEA) state of the environment report 2020 show that historically, policy interventions have been fragmented and isolated from one another [5]. Systems analysis in the '70s accurately predicted our current situation and its development to this point. It also set out alternative paths, which, unfortunately were not pursued. It would seem sensible to return to taking systems-based approaches, which had previously predicted so accurately how things would develop over time and which pointed at ways to best manage for a more sustainable future.

1.2 Focus on water management

In order to manage the environment more systemically and to understand the environment as a system, we need to have a starting point to decide on the boundary of the analysis. Many argue that water can be used as an environmental integrator within and across subsystems. It is, at the same time, both a component of nature necessary to support biodiversity and a resource essential for the production of commodities and maintenance of the entire economy for the benefit of society [6], [7].

However, the economy poses huge pressures on the water environment through impacts on water quality, flooding and water resources. Water use and water management is a key driver of water flow alterations, with direct implications for water quality. Globally, 85 to 90% of total water consumption is used for irrigated agriculture. Other uses include industrial and domestic water supply [8]. The role of water consumption creates a direct link with human behaviour and the need to understand a range of consumption patterns and the effects those are having on water resources [9]. In addition, although water management may seem a place-based local issue, things like the import and export of products and crops result in water resources traversing global boundaries. Global water footprint data from 1996 to 2005 indicate that 20% of the global water footprint was for export, primarily related to trade in agricultural products [10]. Water scarcity and the resulting transboundary social and political issues mean that global and national governance has an increasing influence over local water management. Consequently, system interests operate across multiple scales.

Impact on water quality is through multiple sources of pollution discharges and diffuse sources. Globally, dominant sectors that are responsible for nutrients, sediment and organic pollutant loads include agriculture, mining, urban infrastructure and tourism [11]. However, pressures, impacts and management might be regionally different. For instance, analysis of global wastewater data suggests that the level of wastewater treatment ranges from 70% on average in high-income countries to as low as 8% in low income countries [12]. This has a significant impact on the level of phosphorous released into watercourses [13].

Finally, society and the economy are exposed to the impacts of flooding. Global analysis showed that economic growth and investments in flood infrastructure resulted in a decrease in flood vulnerability [14]. However, a well-known effect of adaptation is increased urbanisation in those areas with increased flood protection, which can lead to unintended consequences and increased vulnerability [15]. Research in the US has shown that up to a 12.5% increase in the extent of the 100-year flood plain may occur as a result of future development in flood protection zones [16].

It is clear that if water governance and management are to deal with water quality, flooding and resources in an integrated way, various bodies involved in the water system, including governments, local authorities, water managers, land planners and infrastructure operators, as well as landowners, farmers and tourist operators, and ultimately citizens, need to cooperate at different levels. These players are ‘stakeholders’ with different issues, interests and potentially different agendas. However, they often have little common ground on which to collaborate and/or information to collaborate around [7], which can occasionally result in conflict. There are partnerships and collaborative planning theories that apply to water management, such as Ostrom’s theory of common-pool resources [17],[18], as well as frameworks for analysing sustainability of social-ecological systems [19]. However, systems-level understanding and using information in the form of data and evidence remain key issues, and they can sometimes be a barrier in implementing theoretical concepts [20].

1.3 The role of systems thinking

Systems thinking provides a structured approach to understand complex problems. It provides a shared view of the system that allows us to see the ‘big picture’, understand dependencies, consider different perspectives and ensure that components of a system work together to achieve the objectives of the whole [21]. This helps us develop a better understanding of current systems and multiple complex cause-impact relationships that have led to an issue we are trying to address [22]. The value of systems thinking as a predictive tool is primarily to better understand the underlying causes, and for different bodies to work together to develop more coherent management options and policies. This could be done by developing systems-level conceptual and simulation models, which can be used to identify and address ‘key systemic leverage points’. These are defined as the points of interventions, including technological, management and policy that create the biggest positive change in the system as a whole [22]. Ultimately, a systems approach provides multiple outcomes while seeking to account for and prevent unintended consequences.

In the context of development, systems thinking is crucial for assessing interdependence between UN Global Goals for Sustainable Development (SDGs) [23]. This includes addressing SDG synergies (one SDG promotes another) and trade-offs (SDGs are mutually restricting) within specific locations [24] and across spatial boundaries [25]. This is crucial to ensure that focusing on a single SDG (for example, SDG 6 on clean water and sanitation [26]) does not undermine the progress on and maximise the co-benefits from achieving other goals. Finally, systems thinking has a role in SDG implementation to facilitate better collaboration and a multi-stakeholder approach [27]. In this work, we will explore complex system interdependences in the context of water as a renewable resource, and implications on water management decisions for sustainable development.

2 Context

In the past, across the UK, approaches to tackling environmental issues have been 'relatively' straightforward. Regulatory agencies have controlled major isolated symptoms of a number of acute impacts through top-down regulation directed at major accountable and responsible parties and/or by hard engineering targeted at key locations. Treating these particular types of problems as 'simple' has led to clear, demonstrable, cost-effective and undisputed positive outcomes. Aspirations at the time were to tackle direct impacts. For example, tackling gross organic pollution by regulation for improved sewage treatment or building flood defence structures within our towns and cities [28].

Today's problems, however, are more complex, less evident, more dispersed and more interdependent. They also require multiple statutory, business and the public to take action. Consequently, the rapid improvement we have experienced so far (for example, water quality and climate change), is plateauing in many locations. It can be argued that this is because the relative significance of problems causing the issues has been shifting to more complex stresses (for example, diffuse pollution sources) which are difficult to resolve. In addition, this could be due to the solutions we already have not being implemented effectively. Further, evidence, such as the UK National Ecosystem Assessment (UKNEA) [29] and EEA report [5] are suggesting that the current broader environmental management framework is unlikely to lead to a sustainable environment. In effect, it might be failing in the context of current and future problems. Wildlife and human wellbeing in the UK is being significantly impacted as a consequence of the lack of coherence and gaps in environmental management and policy implementation [30].

2.1 The government's 25 Year Environment Plan

In 2018, the UK government published its 25 Year Environment Plan (25 YEP) in recognition of these challenges, and as a direct response to the UKNEA and other evidence [31]. The aspiration for the 25 YEP is that '*within a generation (25 years), our country will be the healthiest and most beautiful place to live, work and bring up a family. With the vision for this country to be cleaner, greener, healthier and a more prosperous place to live and work*.' The 25 YEP highlights the need to put the environment at the heart of planning and development to create better places for people to live and work and sets out '*government action to help the natural world regain and retain good health*'. The plan includes the UK government's commitments to 6 primary goals for environmental improvement over the next 25 years.

In the context of water management, the role of freshwater links strongly with 3 25 YEP goals: (i) achieving clean and plentiful water, (ii) reducing the risks of harm from environmental hazards and (iii) thriving plants and wildlife. The 25 YEP recognised the role of fresh and clean water in supporting all human activity, including the economy, through a wide range of ecosystem services. At the same time, the interactions between natural capital assets have been emphasised, including complex links between freshwater, land and soils and the biosphere (Figure 1). While it is clear that accounting for these physical interactions will be crucial in developing systems approaches to water management, it is also noticeable that the role of people (for example, by taking socio-ecological framings such as [19]), has not been explicitly considered.

The 25 YEP plan supplementary evidence report clearly identifies that many of the problems we are dealing with in environmental management are complex and uncertain [32]. These problems need to be understood and managed through systems- and futures-based approaches. The 25 YEP itself partially reflects this need, referring to a variety of sub-systems (food system, energy system, ecosystems, agricultural systems, and identifying some specific systemic-related actions (for example, *"Ultimately, we want* *to move towards an approach in which the 14 local areas are mapped and managed more as a system").* Similarly, the need to consider factors influencing change is recognised, but this has yet to be developed.

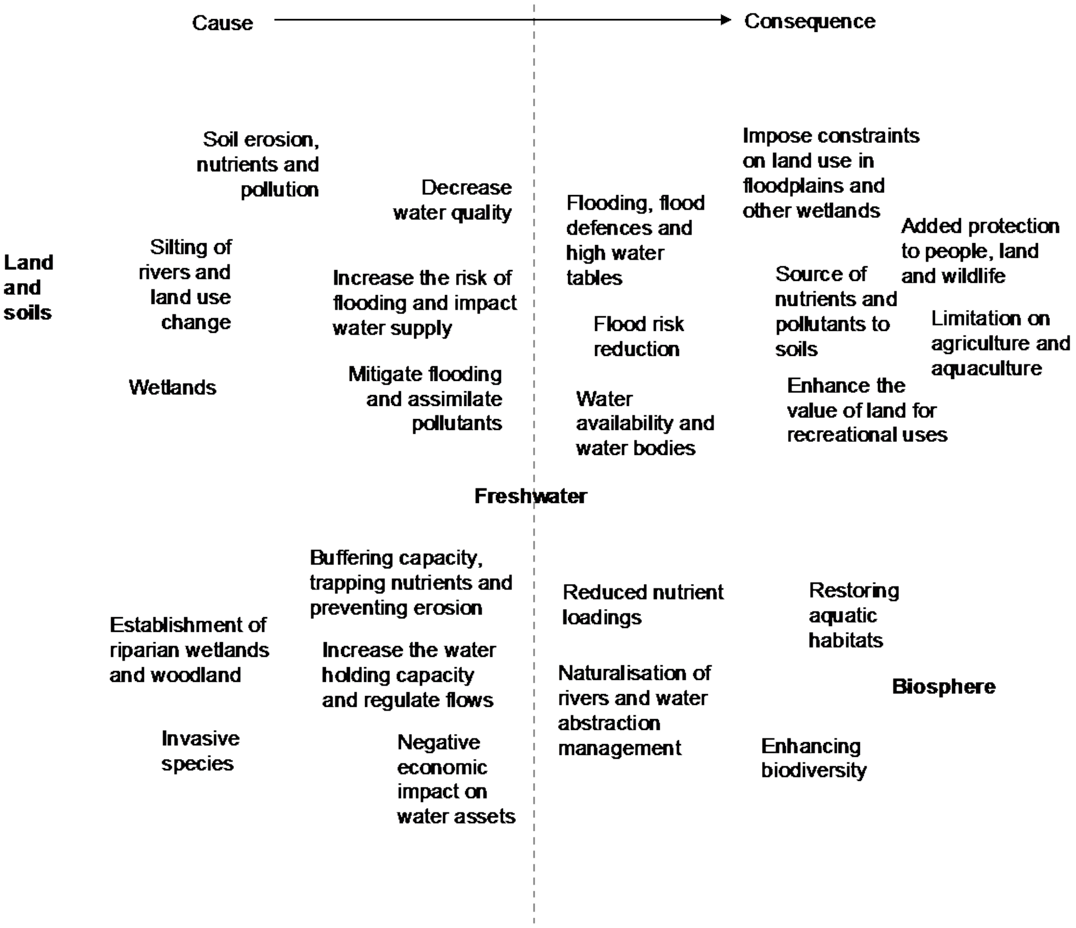


Figure 1 Summary of cause-consequence interactions between freshwater, land and soils and biosphere in the context of 25 YEP

Systems thinking is a concept that fundamentally underpins one of the main approaches in the 25 YEP plan (natural capital) and other important concepts (for example, ecosystem resilience). However, although critical to deliver the potential benefits of the natural capital approach, there is a serious risk that application in the context of a systems understanding framework is not realised in practical delivery of these other management concepts diminishing these benefits. Indeed, the UK Natural Capital Committee has identified, in its response to the government's progress report on 25 YEP implementation [33], "*that the integrated,* ***system based approach*** *the 25 YEP demands is at real risk of being lost"* [34]. Consequently, this makes the work presented in this report particularly significant.

2.2 The Cumbria Catchment Pioneer

To test the 25 YEP implementation mechanisms, 4 pioneers were selected with specific challenges that needed to be urgently addressed. One of 4 key objectives for the pioneers to test was "*Demonstrating a joined-up, integrated approach to planning and delivery of integrated solutions".* From a water management perspective, the Cumbria catchments, in common with many other catchments, are impacted by a wide range of environmental pressures. They have also suffered devastating floods in recent years, with the cost to Cumbria of Storm Desmond in 2015 estimated to be £500 million [35].

Consequently, Cumbria was selected as one of 4 pioneer projects to inform the development and implementation of the 25 YEP. The Cumbria Catchment Pioneer (CCP) is being led by a range of organisations operating through the Catchment Pioneer Steering Group.

The CCP encourages strong engagement of local communities to address how water and land can be managed more effectively to increase the resilience of the system to flooding and environmental degradation. However, it also highlights the major water management challenge Cumbria faces due to the complex environmental, institutional, technical and social interactions in the catchment water management system. The main objective identified above was further refined in the Cumbria pioneer to "*take a more integrated* ***systems-based approach*** *to deliver integrated solutions*". This work took the opportunity under the remit of the pioneer to test if we can maximise natural, social and economic capital by focusing on water management within catchment decision making tools.

2.3 Collaboration with the Royal Academy of Engineering

In 2017, the Royal Academy of Engineering approached Defra and the Environment Agency to share their learning on systems management in relation to environmental management. This followed the development of similar approaches into other policy areas such as healthcare [36]. Together it was agreed that water catchment management would be an interesting area to apply systems thinking. A joint workshop was organised between the Academy, Defra and the Environment Agency, to explore systems thinking, analysis and management in the context of water catchment systems.

Following the first workshop, it was decided the Cumbria Catchment Pioneer (CCP) would be a good candidate project for further exploration of the application of systems thinking to catchment management. A second CCP Systems Thinking Workshop was held in Cumbria with local stakeholders, facilitated by the Academy and hosted by the Freshwater Biological Association [37]. Interest and enthusiasm for further exploring the potential for systems approaches to water and environmental management was high both nationally and locally. Therefore, opportunities to continue the work and apply this in the context of the CCP were pursued. The Environment Agency, in collaboration with the Academy, developed an outline proposal for a Natural Environment Research Council (NERC) Innovation Placement and sought applications from academics to develop outline project bids. Dr Ana Mijic (Imperial College London) was selected to develop a full bid and this bid was successful in gaining placement funding. In October 2018, Dr Mijic began a 1-year project funded NERC placement, working with the Environment Agency, to progress the proposed project, 'Systems Water Management for Catchment Scale Processes (CASYWat)'.

2.4 Overview of the CASYWat project and report

The CASYWat project was designed with the aim of developing an innovative approach to systems-based understanding, structuring and analysis of relevant environmental, technical and social processes in the context of the 25 YEP and CCP, as a foundation for a novel Systems Water Management (SYWM) framework. Explicit visual representation of multiple sectors and water users, and their connectivity, as well as the system as a whole, will support better understanding and communication for a wider range of stakeholders. This will allow more structured and directed conversations and develop a shared purpose and collective strategy for integrated catchment management and engagement in planning options for improved system operation. This hypothesis is used as a basis for a conceptual representation of a catchment water management system (Figure 2).

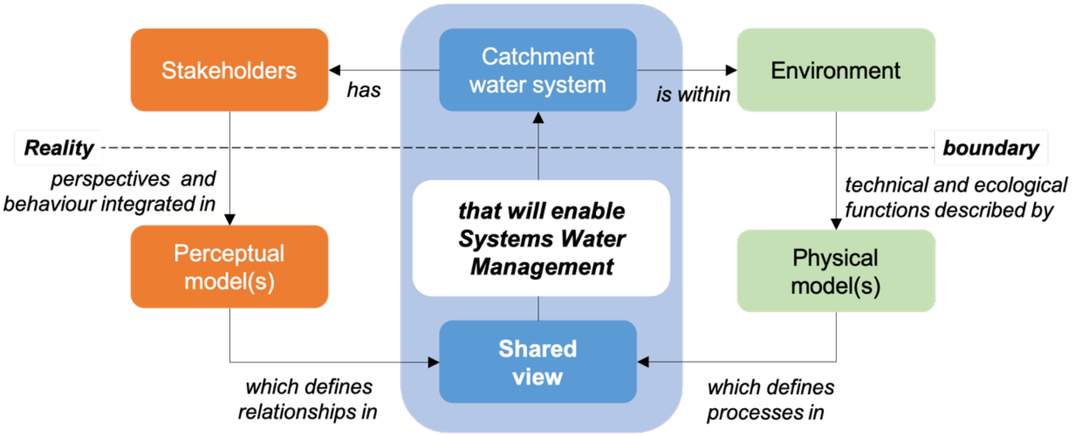


Figure 2 Conceptual representation of a catchment water management system

To achieve the project's aim, the following objectives were defined and linked with the 25 YEP CCP strategic goals (Table 1):

1. To develop a novel concept of SYWM and provide the Environment Agency and its stakeholders with an overview of water management system complexity in the context of water planning and specific environmental challenges (for example, lake water quality) and motivate discussions and brainstorming between relevant stakeholders.
2. To propose a generic approach for SYWM mapping and showcase the value of systems-level analysis to the Environment Agency and its stakeholders by providing insights into unintended consequences of water management decisions, and how these could be addressed by having a holistic view of key factors that contribute to system dynamics.
3. To inform the Environment Agency and its stakeholders about lessons learnt, the potential of the work and how it could be taken forward through either qualitative socio-economic analysis or to inform data collection and systems model simulations.

Table 1 CASYWat objectives (O) mapped on the CCP strategic goals

25 YEP CCP	Link with CASYWat project objectives
Testing new tools and methods as part of a natural capital approach	Ob1: SYWM framework as a way of understanding the limits of environmental system functioning in the context of natural capital and local economy.
Pioneering and 'scaling up' the use of new funding opportunities	Ob2: SYWM mapping to understand how the environment supports the economy and wellbeing (which can be broader than the physical catchment boundary).
Demonstrating a joined-up, integrated approach to planning and delivery	Ob1 and Ob2: Providing a shared view using the SYWM that could support discussions, integration and coordination of the water management decisions.

Grow our understanding of what works, share lessons best practice	Ob2 and Ob3: Using a SYWM approach to mapping to understand cause-consequence pathways, impacts and intervention measures.

The CASYWat work was originally planned to be carried out by involving a wide range of relevant stakeholders through a number of workshops. However, the work became a hybrid theoretical/partial engagement study that relied on more than 200 referenced scientific publications and technical reports. Partial participation was achieved through the CCP systems thinking workshop, involvement in the national water leaders' engagement group and regular meetings with the Environment Agency national and CCP teams. The final report draws on these discussions and input.

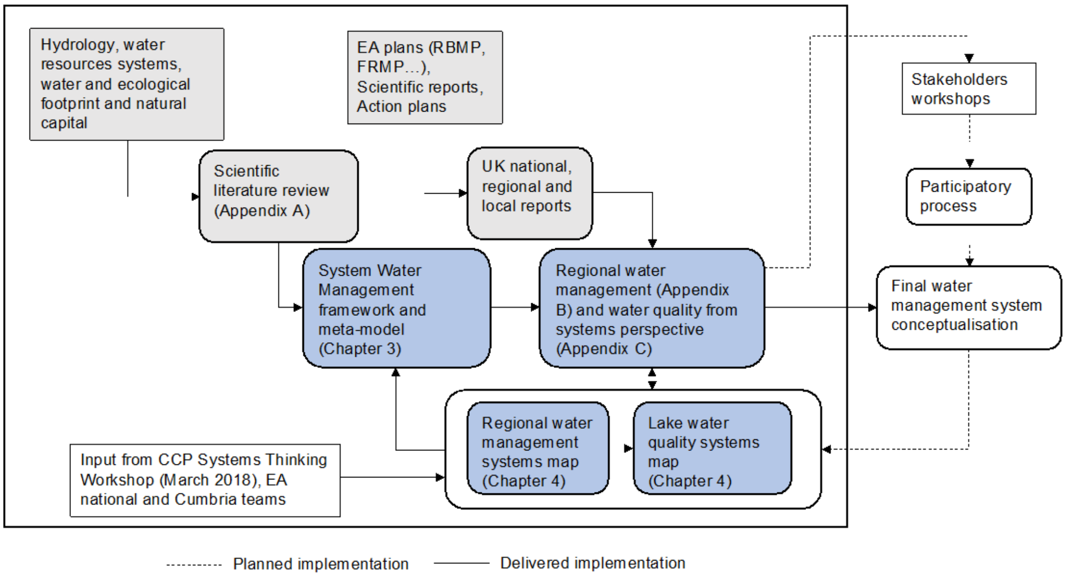


Figure 3 The CASYWat implementation (planned and delivered) and link with report chapters

Both robust theoretical development and practical demonstration were considered important for the work. The work is broadly divided and described in 2 stages representing these two aspects (Figure 3). The first part included developing the SYWM framework, which was informed by scientific literature from multiple academic fields. For brevity of the main report, a review of literature and much of the theoretical development is in Appendix A. We summarise how the SYWM framework was informed and developed through published theory in Chapter 3.

The developed framework then informed the second part of the study, which aimed to understand the state of the water environment in England from a systems perspective and to define the key components of the regional water management system conceptualisation. Finally, the work focused on the Windermere and River Leven catchment within CCP, where the CASYWat meta-model was tested to see if it could practically address selected water environment problems in respect of Windermere lake water quality. Detailed reviews of interactions and processes that informed development of systems maps are provided in Appendix B for regional water management and Appendix C for Windermere lake water quality systems. Main results for both case studies are presented in Chapter 4.

While we recognise the limitations of the approach, in particular with respect to participatory engagement and practical implementation, we still hope the work presented in this report is useful in addressing 25 YEP Pioneer objectives (Table 1). Finally, we hope that the work will provide the basis for future development of a full implementation framework. In the concluding Chapter 5, we summarise our findings and how the work could be developed further as a social process.

3 Approach

3.1 Systems thinking concepts

Systems approaches can be defined in many ways: (i) as a way of thinking, that recognises interdependences between different parts of the system; (ii) as a conceptualisation of a system through understanding causal relationships; and (iii) as a collection of tools that can be used for analysis and modelling [21]. In this study, we are using the definition of a system as '*an interconnected set of elements that are coherently organised in a way that achieves something*' [22]. Therefore, to conceptualise something as a system, we need to define its elements, interconnections and the function or a purpose. Understanding a system in a more holistic manner allows us to define its emergent properties, which are those that can be derived from the properties of the system components [21]. The second concept that is crucial to conceptualise a system as defined by [22] is a focus on system dynamics, that is a change of system behaviour over time [38]. Dynamic systems can be conceptualised through a set of feedback loops, which define changes in the interactions (flows) caused by changes in the system elements (stocks). The concept of feedbacks challenges linear thinking and poses a hypothesis that a system can cause (and therefore self-organise) its own behaviour based on its structure (Table 2). Changing elements usually has the least effect; changing links changes system behaviour, while the change in purpose can greatly alter the system as a whole [22].

Table 2 An overview of adapted system thinking concepts [22]

Concept	**Description adapted in CASYWat**
System	Interconnected set of elements that are coherently organised in a way that achieves something and/or produces their own pattern of behaviour over time.
System purpose and/or function	All human systems are designed to achieve something. The system's purpose is best understood from its behaviour, not the stated goals. System purpose defines the human system, while system function applies to natural systems. Perceived purpose of a system also defines where we impose a system boundary.
System behaviour	Systems cause their own behaviour, defined by their structure. System behaviour can be characterised through a series of events (system performance) over time.
Elements (stocks)	Foundations of a system; they are stocks that can be measured and that change over time through the actions of the interconnections (flows).
Links (flows)	Links (flows) between the elements, which could be decisions, rules, physical laws or actions.
Feedback loop	Dynamic representation of the system that describes how the change in an element (stock) impacts the interconnections (flows) into or out of the same element.
Balancing loop	A feedback (goal- or stability seeking) loop that tries to keep the stock within a range of given values.

Reinforcing loop	A feedback loop that enhances whatever direction of change (increase or decrease of value) is imposed on the stock.

Systems thinking embraces complexity as an essential characteristic of a system that can create its highly functioning properties. Complexity allows systems to adapt in changing environments by self-organisation, that is, to be resilient to change. To manage in the context of complexity, functioning systems are understood as a structure or process that is hierarchically organised so that defined subsystems can be conceptualised with sufficient level of detail without creating a highly complicated structure [39]. The hierarchical property of a system reduces the quantity of information that needs to be exchanged between subsystems and increases the system’s resilience. The role of hierarchical arrangement is to essentially support the originating subsystems to achieve their purpose by coordinating the system as a whole so that central control does not override subsystem autonomy, which is necessary for efficiency, resilience and self-organisation [22].

In order to understand the impact of water management decisions, we need to define the water management system and examine its emergent properties in terms of systems thinking. In systems theory, this can be achieved by defining generic causal loop structures (or system archetypes), which can be applied to analyse a specific phenomenon such as limits to growth and ‘tragedy of the commons’ [22]. Here, we adapt the approach to define a ‘problem’ archetype for which a corresponding ‘solution’ model could be found by analysing feedback loops [40]. We argue that by doing so we can revise the purpose of water management and reveal a structure of a functioning water management system, which will redefine the fundamental (core) problem that we need to address. This will enable us to better understand systemic causes and propose a way forward to identify better water management solutions.

3.2 Systems Water Management Framework

Extensive literature review of theoretical concepts relevant to integrated water system conceptualisation (see Appendix A), including water management, natural capital (NC), ecosystem services (ES) and environmental footprint (EF) showed that current approaches cannot fully represent the complexity of a water management system. Water management strength is in understanding physical processes that generate and ultimately constrain the flow of ES. However, broader aspects of environmental and economic sustainability are not yet fully included in the evaluation of system performance. Both footprint and NC concepts address 2 complementary sides of a problem – demand and supply of ES. However, in footprint analysis, land and water aspects have not yet been combined, nor is the impact of land use on water security addressed. In addition, the EF assumes a single use of a land resource, which is for production only. This is addressed by the NC approach, which considers land and freshwater potential to produce multiple ES. However, the approach cannot consider how ES flows generation is affected by changed dynamics of natural systems, and what the explicit role of human activities and economic sectors is in that process.

We argue that by merging and aligning these 4 concepts using systems thinking we would be able to analyse the water management system so that unintended consequences could be discovered and systemic solutions implemented. We refer to the concept as **systems water management** (SYWM), *‘which provides a framework for holistic understanding and structuring of components relevant for sustainability of coupled human-natural water systems’.* We define water management system sustainability as its ability to function well over a long period of time. Its application to analyse key catchment water management feedbacks through a generic water management system archetype is referred to as the **SYWM meta-model**.

3.2.1 SYWM components

The SYWM framework is based on 2 hypotheses. The first is that the key driver of development is to achieve a ‘good local quality of life’ (QoL). A focus here on the locality is very important. It implies that water management and other relevant decisions are typically aimed at maximising activities and behaviour that benefit people living in the country or a particular region, even at the expense of impacts on the wider environment and distant ecosystems. ‘Local’ implies that we are focusing on water management system components that we can control through decisions and regulation. Decisions could also support the local economy, and if the economic activities significantly contribute to the total GDP, then there will be a pressure at the national level to maximise the ecosystem services provision supporting these activities. This pressure, however, will not necessarily come with any appreciation of the need or value of the long-term sustainability of the ecosystem service provision being exploited.

The second hypothesis is that localism also allows for the state of the environment to be explicitly included in the QoL evaluation. We argue that if the feedback from ‘the environment’ to development were assessed, communicated and used for infrastructure planning and water management decisions, then the system would avoid resource overuse and long-term environmental degradation. Nationally and regionally, this could give an indication of the level of growth that a local environmental system can support, and steer the development towards regions that have the highest levels of functioning environment.

We first define 7 SYWM components and their elements that align with existing water management and sustainability concepts. In describing each element of the framework, we will emphasise components that were assumed to be outside of the current description of the system and if and how they can be added.

Catchment state

Catchment state defines biophysical systems as basic components for analysing natural processes and water balance. Their function results from the hydrological processes (soils, land and processes such as infiltration) and their behaviour, and can be described by measuring key state variables or signatures [41]. Hydrology system signatures mainly describe characteristics of streamflow (for example, flow duration and flood frequency curves), but they can also be used to quantify the role of other system state variables such as soil moisture and water quality. Catchment state defines the fundamental supporting hydrological ES, that is the water quantity and quality in the freshwater (surface and groundwater) system, whose regeneration capacity fundamentally depends on the regional climate processes [42].

The catchment state is also defined by land use, which we link with the natural capital (NC) concept. We define NC stock as a function of the holistic system use, and we distinguish between 2 types of NC assets. Natural habitats (forest and grassland) are assumed to be **critical NC assets** because of their role in defining hydrological processes and, therefore, water management system regeneration, as well as for their role in providing land for conservation and habitats to support biodiversity [43]. In addition to their life-supporting role, natural land habitats have a role in supporting raw material and energy production and cultural ES. This work does not consider marine and other habitats (for example, deserts and tundra) however, but they can be added as additional concepts.

Human habitats are divided into 2 large categories: agricultural and built-upon land. Human habitats are assumed to be **essential NC assets** because they define productive capacity of land that underpins the economy and supports growth [44]. Agricultural land supports food production (crops and livestock), while built-upon land is essential for residential and commercial development and transport infrastructure.

We conceptualise system use through the concept of catchment services [45], which are defined as benefits that are supplied by catchments for humans and ecosystems. This concept is closely linked with the concept of hydrologic ecosystem services, which can be broadly categorised as water supply, damage mitigation and water-related cultural and supporting services [46]. To emphasise the role of local environment planning, we categorise catchment services into environmental and human made ES.

Environmental services

The environmental services (ENS) component defines those ES that are provided by local natural systems and cannot be imported. As such, they are crucial elements that define the local quality of life [43]. In this category, we include in-situ water use, which accounts for ES benefits for humans (supporting navigation, recreation and fishing) and ecosystems (environmental flows). The provision of ENS will directly depend on 3 aspects of the system – catchment state defined by levels of water abstractions and pollution, as well as local climate.

The ENS category also considers the role of NC assets in preventing erosion and reducing run-off and the level of water pollution, which, in turn, reduces the risk of flooding and improves the state of the environment. Those ENS that are provided without human intervention are referred to as **critical ENS**. This way we explicitly separate the functioning of the environment and its role in ES generation [47].

Human impacts

The concept of human impacts recognises the role resource demand and activities play in changing the natural system in the context of water management [48], [49]. We define ‘direct impacts’ as those that result from water and land pollution activities such as fertiliser use in agriculture [50], untreated run-off pollution from cities and transport [51] and pollution from wastewater [13]. Other sources of pollution such as from abandoned mines [52] and industry processes [53] should be taken into account if the values are significant for a study region. In addition, physical modifications of the system should also be considered, for example, changes in the natural river channel that could significantly contribute to the build-up of sediments [54]. All these activities will have significant water management impacts, such as reducing environmental flows and/or increasing the risk of flooding and impacts on water quality, as well as wider ecological impacts, such as loss of habitat.

We consider the impact of water abstractions through human made services (see definition below) to emphasise the focus of the work on the main water management decisions of how much water should be taken out of the natural system and when. The impacts of human activities through greenhouse gas emissions and ultimately climate change is not directly taken into account. We recognise a need for that aspect to be added, in particular, if the impacts beyond the economic and environmental domains, such as direct and indirect impacts on health are to be analysed.

Finally, we recognise the need to explicitly account for land use decisions when defining the water management problem. Explicit accounting for critical and essential NC has significant implications for defining feedback loops and controlling processes. At a catchment level, any increase in the size of essential NC assets (agricultural and urban land) to support economic growth will directly decrease the size of critical NC assets and related ENS generation.

Human made services

We define human made services (HMS) as provisional ES that are linked directly to water management by altering water flows through water abstractions, irrigation, reservoir management [55] and flood protection [56], and indirectly through any activity (for example, food production and land management) that changes the integrity of an ecosystem [43]. The human made services subsystem also recognises the role of infrastructure in providing water and food, flood protection and other human activities. This subsystem provides a key link between the potential and desirable functioning of the water management system.

Water consumption is analysed per sector. This includes irrigation water for perennial and annual crops, livestock and human population. Globally, thermal power water consumption accounts for only 1% of total use. In contrast, reservoir management water consumption in the form of water use via evaporation represents 21% of total use [8]. These reservoirs are primarily designed for hydropower, irrigation and flood control, and emphasise the key role of water infrastructure in managing water flows for water storage when water is seen as an economic good [57].

Water supply is directly linked with the need to provide wastewater infrastructure that will minimise the impact of pollution on the water environment. Aspects such as wastewater network connectivity and misconnections [58], combined sewer overflows [59] and wastewater treatment technology [60] need to be taken into account, as well as flood infrastructure and its role in impacting the water environment [61].

The role of land management is analysed through crop production and livestock farming activities [62], as well as any other activities that may impact on water quality and quantity. These may include forestry practices [63] and management of urban parks [64]. Finally, the role of ‘built-upon’ land needs to be taken into account by analysing the role of transport [65], housing [66], service [67] and industry [68] sector infrastructure in changing the water environment.

Local demand-supply

From water systems analysis and engineering perspectives, we are interested in the design of the infrastructure that can support provision of human made services. A sustainability focus suggests that we are interested in both technical and ecosystem infrastructures and processes that provide ES for human needs [69], such as the optimal combination of grey and green infrastructure in cities [70]. In the context of SYWM, this implies that human needs such as water or food provision define the demand function and use of the system. By using functional organisational analysis, infrastructure design can be imposed on a natural catchment form to achieve the required ES [71].

A concept of satisfying demand-supply balance is closely linked with the water security paradigm, extends the sustainability focus to include welfare, equity and water-related risks, as well as policy and adaptation aspects. This results in attempts to take a systems perspective on water security, which mainly utilises a well-established driver-pressure-state-impact-response (DPSIR) framework [72]. The DPSIR framework was used in the context of adaptive water management [73], as well as for analysing the impacts of human activities on a system [74], [75]. In the SYWM concept, we recognise the role of infrastructure planning in formulating controlling processes as feedback loops between the demand and availability aspects of a water management system.

Finally, the demand-supply balance will depend on the way people use water, their food and products consumption patterns and activities preferences. Water conservation behaviour can greatly contribute to residential water savings [76], while a shift to plant-based diets could have a positive impact on water quality through reduction in the use and excretion of nutrients [77]. In addition, farmers’ choices such as the source of water supply and irrigation water use [78], as well as water companies' decisions on water abstractions and allocation will play a key role in understanding the water management system [79].

Local economy

Ecological and water footprints define a level of system use, which is linked with economic activities. The water ES represent either a necessary resource for production processes, such as irrigation water use [80] that is categorised as HMS, or service delivery, such as water quality for recreational activities [81] that represents ENS. The functioning ecosystems and the level of ES provision provide a direct or indirect benefit to all system users. However, the same provision is limited by the level of system use. From the SYWM perspective, this creates a direct link between water management and land decisions and the need to understand the role of key economic sectors and implications of their activities for system biocapacity.

Discussion about ES provision also opens a debate about the value of water and ecosystem services through the NC concept. Various methodologies have been discussed on how to monetise the ES value [82]. Following a NC concept of system actors, a SYWM approach supports the argument that explicitly including providers, users and beneficiaries, as well as their interactions with respect to driving the demand and creating pressures on water and land environment [83] will make value intrinsic to ES [98]. Final benefits and the value they provide are directly linked with individual sectors in the system through the local economy. Understanding these interdependences will define the underlying drivers of the system change.

Quality of life

The concept of quality of life (QoL) is closely linked with the notion of sustainable development. Sustainable development concepts such as the steady-state economy [84] and 'safe and just' development space [3] recognise that achieving a high QoL is often in contradiction with stabilising critical environmental resources. Moreover, human wellbeing has globally increased, while, at the same time, a decline in most ES provision has been recorded [85].

To try to understand this paradox, we argue that the QoL that is defined by the level of economic growth and demand-supply balance indirectly supported by human made services is directly influenced by ENS that define the functioning of the changed local environment. This development is defined as a change in the quality of life, which implies that the local economy cannot increase at the expense of environmental degradation. If a region overuses its NC, it will have a development path that ultimately diminishes ENS. If it uses its NC in such a way that ecosystems continue to produce ENS, it will increase the quality of life in the long term.

Finally, while it is clear that the natural environment provides benefits for catchment users either directly though ENS or supported by built infrastructure, when designing regional development plans it is important to identify which ES are essential for the analysed catchment. This will allow interventions to be prioritised and trade-offs to be discussed between those ES that are critical for regional development (for example, biodiversity, pollution and flood control) compared to those that affect the quality of life but could potentially be imported from regions with less environmental pressures (for example, food supply). This links 2 key decisions that need to be balanced in regional planning – the land use decision, which defines the balance between critical and essential NC assets, and an infrastructure planning decision, which supports HMS provision. Analysing economic development of a region will have a crucial role in understanding which ES need to be provided locally, and how the economic growth can be supported by a functioning environment as a measure of local quality of life.

The list of second-tier variables, extracted from the literature review, is summarised in Table 3.

Table 3 Concept second-tier variables in the SYWM framework for analysing a water management system

Catchment state (CS)	**Environmental services (ENS)**	**Human impacts (HI)**
CS1 – Hydrological processes CS2 – Climate processes CS3 – State of water (water quantity and quality) CS4 – State of land (natural and human habitat capital)	ENS1 – Water availability ENS2 – Environmental flows ENS3 – Water purification capacity ENS4 – Flood regulation capacity	HI1 – Water pollution (treated and untreated discharges) HI2 – Land impacts (sedimentation, erosion) HI2 – Physical modifications HI4 – Ecological (land) footprint
Human made services (HMS)		
HMS1 – Water abstractions HMS2 – Water supply infrastructure HMS3 – Wastewater infrastructure HSM4 – Flood infrastructure	HMS5 – Crop production HMS6 – Livestock farming HMS7 – Natural land management HMS8 – Recreational land management	HMS9 – Urban land management HMS10 – Urban infrastructure HMS11 – Service infrastructure HSM12 – Industry infrastructure
Local demand-supply (LDS)	**Quality of life (QoL)**	**Local economy (LE)**
LDS1 – Population growth LDS2 – Water and food demand LDS3 – Infrastructure planning or land development LDS4 – Human behaviour and decisions	QoL1 – Regional sustainable development QoL2 – Economic growth QoL3 – Role of imports and exports QoL4 – Local development plans	LE1 – Economic activities and sectors LE2 – Employment LE3 – Providers, users and beneficiaries LE4 – Embodied environmental impacts

3.3 The SYWM meta-model

The SYWM meta-model is aimed at supporting understanding, providing structure and informing discussions about water management decisions at a catchment scale. The work translates conceptualisation in the SYWM framework into a SYWM meta-model that defines relationships between defined components in the form of feedback loops. The SYWM meta-model conceptualisation is based on the assumption that integrated water management can be analysed by identifying 3 key fundamental feedback loops that affect emergent properties of a water environment system (Figure 4):

- The perception of a QoL through the level of economic development creates a reinforcing development loop (R1), which increases system use through local demand-supply balance and economic activities. This loop is supported by evidence that high-income, emerging economies enable good living standards and high QoL [3].

- In a self-organising system proposed here, a degradation of environment and catchment state through human impacts, which results in decrease in ENS generation would directly lead to transition of economic activities and reduction in system use by matching resource demand with the available supply, resulting in environmental improvement monitored by ENS indicators. This is controlled by the environmental balancing loop (B).
- However, through HMS and infrastructure provision, the development R1 loop can continue to be supported regardless of the level of environmental change, creating an infrastructure reinforcing loop (R2). This explains why QoL indicators could continue to rise despite the fact that environmental state variables keep declining - the system 'overuse' is compensated by the provision of HMS through built infrastructure [86].

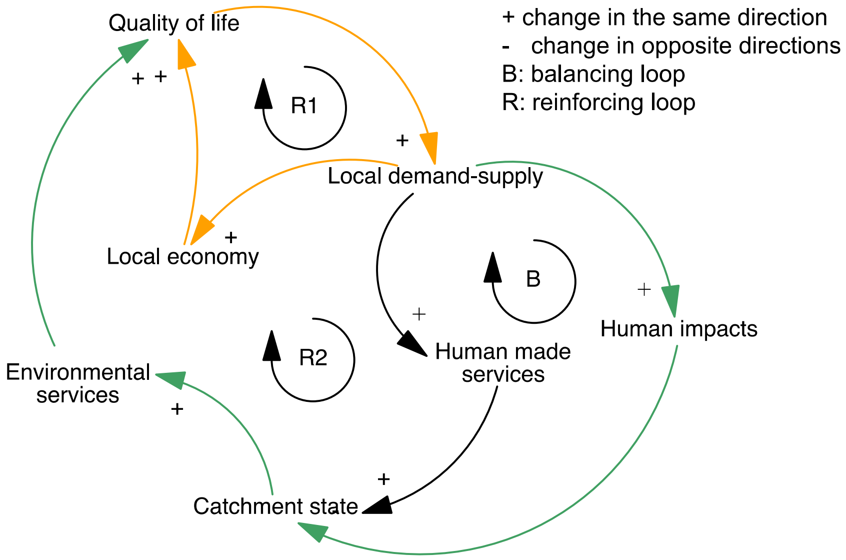


Figure 4 The SYWM meta-model for analysing water management sustainability from systems perspective

The understanding of catchment water management using the SYWM meta-model provides a new perspective on its purpose. We argue that the fundamental purpose of water management is to find a balance between economic development supported by the local environment, which accounts for human impacts and footprint, and indirect provision of ES through built infrastructure. This can be achieved by strengthening the environmental balancing loop B so that this feedback informs development: (i) either through providing information about the catchment state to economic sectors so that their operations could be altered and/or profits could be reinvested for environmental management, or (ii) by initiating a transition of local economic activities so that their direct or indirect impacts on the environment are minimised. It should be noted that the proposed meta-model only partially takes into account exogenous factors (see Table 3). The consequences of trade and embedded resources is accounted for in the human impacts component through the concept of ecological footprint. In future work, this component could be expanded to consider environmental impacts such as air pollution [87]. Finally, the impact of climate change should be taken into account through the catchment state subsystem.

3.4 Case studies and SYWM framework application

The developed theoretical framework and the SYWM meta-model were applied to 2 selected case studies to conceptualise and analyse the water management systems.

The regional (multiple catchments) water management system case study was analysed from a planning perspective, and developed regional water management (RWM) systems map for England were used to analyse systems-level challenges and opportunities in the context of urban water management.

The catchment case study focused on a catchment-level management perspective of a water environment system in the Windermere and River Leven catchment and addressed discussions with the CCP. Based on initial insights from the CCP workshop in spring 2018 [37] and conversations with the CCP Environment Agency team throughout the project, it was decided to focus on the Windermere lake water quality systems analysis. This work particularly helped to integrate tourism and recreation elements with traditional water management aspects related to agriculture and urban environments.

The case studies were analysed through a defined 3-step process, which included system understanding, systems map structuring and water management analysis. The process is summarised in Table 4.

Table 4 The applied CASYWat 3-step process for case study analysis

Steps	**Regional water management system**	**Lake water quality system**
1. Understanding: Review of high-level information, scientific papers and reports to understand…	…the overall context of the water management system	…the specific selected environmental problem (for example, lake water quality)
2. Structuring: Defining second-tier variables and their links to create systems map that…	… will give a high-level structure of the interdependences that influence water management	…will contain the same information as the high-level regional systems map, but with more detail linked to the specific problem analysed
3. Analysing: Mapping the feedback loops and finding patterns defined by the SYWM meta-model to…	… discuss management goals and understand which processes need to be coordinated to enable the agreed systems level water management balance	… map a range of possible systems level interventions (leverage points) that could enable local development without environment degradation

In step 1, we are interested in 3 aspects: (i) What is the overall state of the environment from land, water and climate perspectives, and what are the direct impacts on the water environment that could affect the quality of life (QoL); (ii) What is a high-level socio-economic structure that defines the QoL and demand for water and food resources; and (iii) What is a high-level state of water infrastructure provision and what is the role of ENS in supporting local wellbeing and QoL. This information should be collected through a participatory process in a series of workshops using approaches such as participatory system mapping [88]. The recent Defra Systems Analysis for Water Resources study provides a good example of participatory mapping approach application [89]. In the

CASYWat study, although originally planned as a fully co-development process, the relevant information was primarily collected through a range of scientific literature and published reports (see Appendices B and C). Although this implies that produced maps are a view of a system that results from integrating multiple general perspectives from a range of case studies and applications, we believe that they provide the basis to showcase the SYWM concept and analysis and can be used as a starting point for discussions with local stakeholders and decision makers.

In step 2, elements of systems maps and their structures were defined using the literature review from Appendix B (England regional system) and Appendix C (Windermere catchment system). In particular, the list of second-tier variables defined for each concept within the SYWM framework (Table 3) was used to select the elements relevant for 2 case studies. This process results in a high-level water management systems map, which could be used for, and validated through, discussions with relevant stakeholders. In a systems map, the link between variables is defined as either positive or negative. Positive links mean that the change in the value of one variable (for example, increase in urban water use) will result in the same-directional change of the value of the linked variable (for example, increase in water abstractions). Negative links imply the interaction between 2 variables in the opposite direction (for example, decrease in water quality due to increase in fertiliser use). While in this study we do not specify the types of the proposed links, they can be broadly classified into physical links (for example, link between the groundwater and surface water flow), information/evaluation links (for example, link between service sector and GDP) and decision links (for example, link between urban land and housing infrastructure).

In step 3, keys aspects of a water management system are analysed by defining feedback loops as proposed by the SYWM meta-model. In the analysis of possible water management options, both from a perspective of system coordination (regional scale) and system interventions (catchment scale), we have used the concept of ‘leverage points’. These leverage points are ranked based on a systems ladder as defined by [22] that ranks the levels of intervention based on their order of effectiveness from a whole-system perspective.

It should be noted that if the system boundary was expanded beyond the inland catchment water management system, aspects such as marine and forestry ecosystems from the production perspective (that is, supply of wood material in addition to impacts of forested land impacts of water processes), as well as environmental impacts of manufacturing and finance sectors could be analysed. We also acknowledge that analysing the link between water and energy systems through CO_2 emissions and impacts of climate change are very important given the UK government’s net zero carbon by 2050 ambition [90], and could be added in future analysis. The same applies for addressing links between water systems and ecology and human health, both of which are necessary to have a more complete representation of systems level interdependences. All of these aspects should be added in any future work that builds on the SYWM analysis principles developed in this study.

4 The water management system maps

4.1 Regional water management systems map for England

Following the steps described in Chapter 3, a preliminary version of a regional water management (RWM) systems map for England has been developed. This is shown in Figure 5. The map shows that the proposed high-level subsystems as defined by SYWM are aligned with the more detailed representation. For a detailed description of interactions, feedback loops and a full version of the map readers are referred to Appendix B.

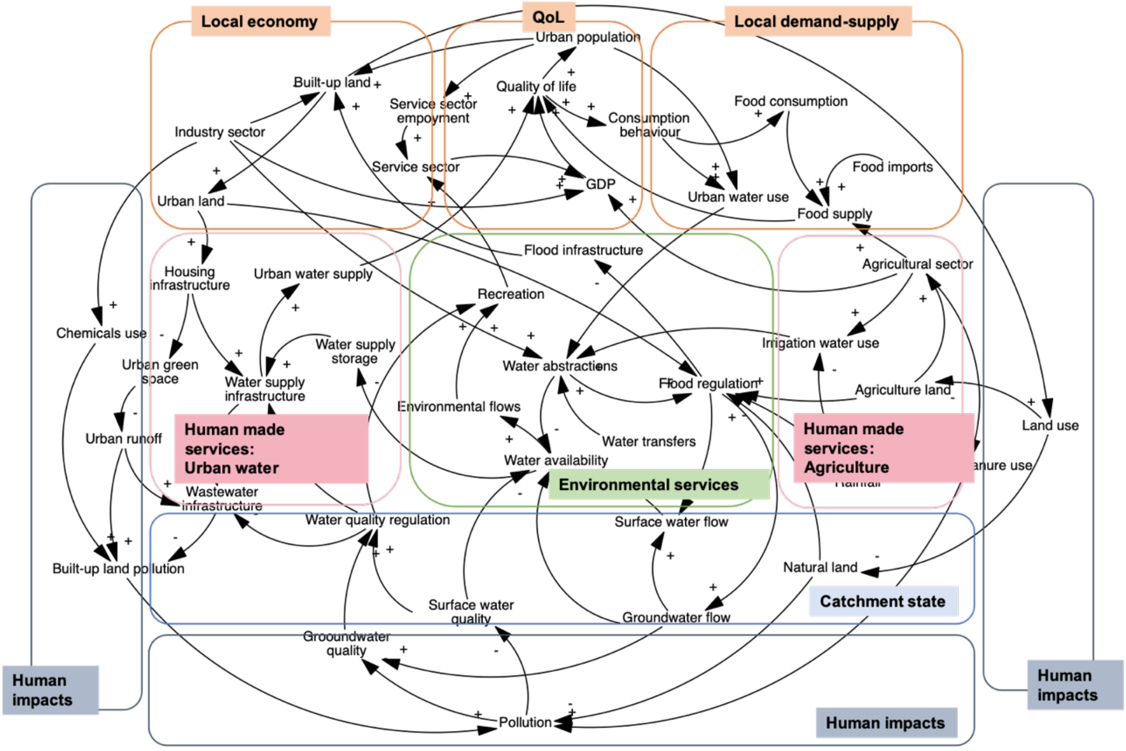


Figure 5 High-level version of a regional water management systems map for England. The cluster colours correspond to defined SYWM subsystems: Local economy, Local demand-supply and QoL (orange), Human impacts (dark grey), Catchment state (blue), Human made services (pink) and Environmental services (green).

The RWM systems map reveals a fundamental issue of the water management system. From the perspective of water management decisions, which include water abstractions, flood management and water quality regulation (pink and green clusters), it is clear that any interventions linked to the physical side of the system through HMS could be relatively insignificant at a systems level if the underlying drivers defined through development subsystems, including local economy, local demand-supply and QoL (orange clusters) keep increasing the pressure and impacts on the environment through human impacts (dark grey clusters).

In the SYWM conceptualisation, land use defined though the human impact subsystem (right grey cluster in Figure 5) has a central role in driving the overall system dynamics as it provides a link that propagates impacts from development subsystems back into the environment. This has 3 significant implications for the concept of natural capital:

- **Revaluing of land-dependent and other economic sectors**. While the agricultural, forestry and fishing land is included in the natural capital analysis, their value needs to be directly linked with economic indicators such as GDP, so that the role of land-based sectors is aligned with their environmental footprint. Any redefinition of the contributions of other economic sectors (for example, service and industry) to GDP should be scaled by their impact on the environment in the form of water, land (and other) footprints. If we see the system in this way, we will be able to strengthen the link between natural environment and QoL as conceptualised in the SYWM meta-model, and more accurately estimate the value of the environment for development and growth.
- **Including built-up land in the natural capital analysis.** The highest value from the perspective of economy typically comes from urban-based service sectors. Therefore, in addition to urban green spaces, the value of the land that is allocated to urban development needs to be explicitly included in the analysis of natural capital. Firstly, the built-up land, if using principles of blue-green design [91] can also provide urban ES. In addition, the fact that the land is converted from a use that could provide services to a traditional grey design that only supports the economy could be accounted for through ES loss calculations, which could have significant implications for land use decisions. Concepts such as environmental net gain, promoted by the 25 YEP, could support this analysis.
- **Redefining the role of environmental services.** The RWM systems map reveals the role of the functioning environment (green cluster) to act as a component of the system that has the same function as the HMS – to provide a link between development and the environment and enable economic growth and QoL. While there has been a significant effort to, for example, emphasise the role of urban green spaces for water management and other ecosystem services [92] as well as to show the value of natural flood management for both flooding and water quality [93], land use decisions are still not seen as a high leverage point that could influence the planning and operation of water systems. It is, therefore, recommended that the state of environment is explicitly included as an indicator of the water management system performance and analyses for water infrastructure planning [94].

4.2 Implications for water management planning

The developed RWM systems management map was analysed to define components of the CASYWat meta-model feedback loops in the context of urban water management. By doing so, we aim to explain the systemic challenges and potential solutions for regional water management planning. The components of each mapped feedback loop are detailed in Table 10 (Appendix B). It should be noted that the loops defined as B1, R1 and R2 in this section capture the same dynamics as the SYWM meta-model loops with the same notation.

4.2.1 Role of water demand drivers for integrated planning

The first validation of the RWM map was done by mapping the current approach to urban water management in the UK (Figure 6). Two reinforcing loops dominate the system: the R1 feedback loop between water and housing sectors and the R2 loop between water demand and supply. The R1 loop emphasises the increasing need for water supply infrastructure through increasing urbanisation and housing growth, while R2 loop maps the increasing need for additional water storage and/or water supply infrastructure (for example, need for increased water treatment) due to increased water use driven either by population growth or a change in water use behaviour. Consequently, water abstractions would increase, which leads to decreased capacity of the environment system to provide regulating ecosystem services (for example, water quality regulation). The solution is then provided through the provision of wastewater infrastructure through the balancing B1 loop. However, from a systems perspective, upgrades of wastewater infrastructure are considered as a relatively low level of intervention, which addresses only local issues rather than systemic causes at a systems level.

From a systems water management perspective, the following aspects are emphasised:

- Currently in practical water management the R1 feedback loop ‘does not see’ the wastewater side of the system, which reflects the lack of systems level coordination between water resources and drainage and wastewater planning in the UK. Furthermore, the need for coordination between the water and housing/urban planning sectors is evident, as any decision to increase housing will have implications across the whole water management system. Over a decade ago, the Environment Agency tried to address this challenge from a systems perspective through the concept of **water neutrality** [95]. We recommend that this approach should be revisited and developed further from a whole-water system perspective.

  While the R2 loop is defined as reinforcing because of its impact on increasing water abstractions, the same loop could become balancing if water use was changed towards water savings. This emphasises the usefulness of systems level analysis to find the loops with negative impacts on the system and analyse which components of the loop could be influenced to change the system dynamics. The analysis confirms the **role of urban water use** as a high point of intervention in the system [96]. We recommend that the **link between the quality of life and consumption behaviour** is added in detail in further developments of this work.

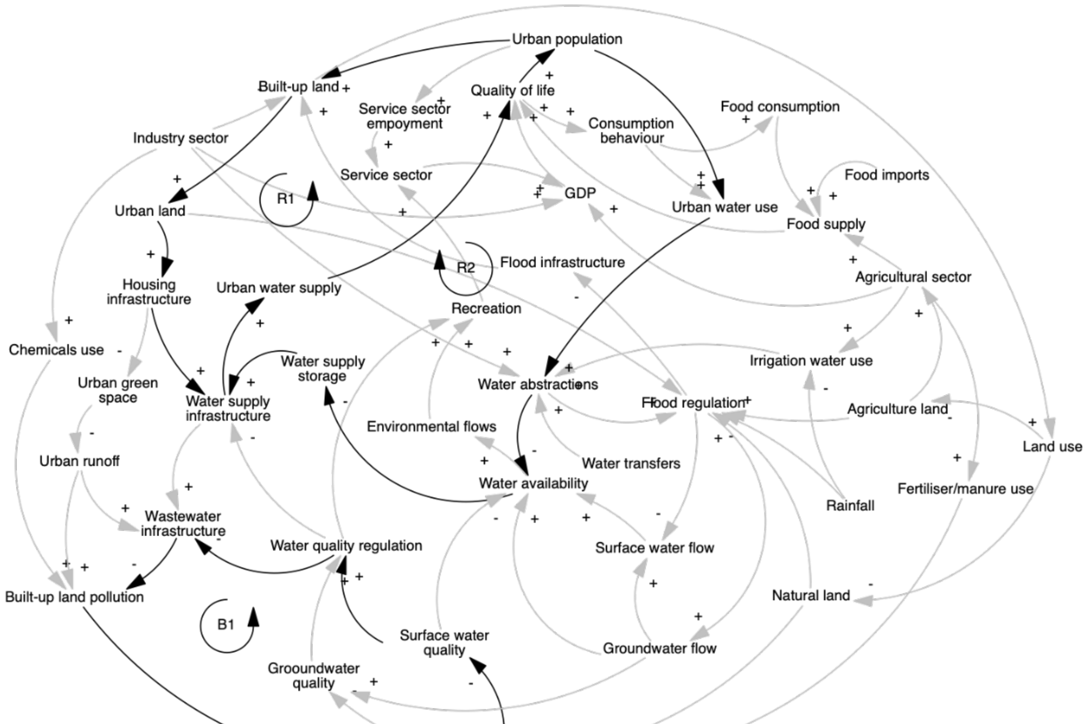


Figure 6 RWM systems map: role of water demand drivers

4.2.2 Opportunities for water planning decisions coordination

Analysis of the RWM systems maps can also be used to define positive balancing feedback loops, which have the function of propagating information through a system and ensure that the unintended consequences are considered in planning decisions. These loops link at least 2, but very often multiple, concepts of SYWM and emphasise the need and opportunities for integration and coordination of decisions.

In the context of urban water management, 3 feedback loops are mapped (Figure 7). The B2 loop shows the need for, and value from, coordination of operational and planning decisions between the water supply and wastewater infrastructure systems. Within the loop, pollution is a controlling variable, which creates links between abstractions, discharges and the urban water network. The B3 loop is an example of a cross-sector balancing process. The loop links urban and catchment scale processes through the link between built-upon land pollution, water quality and water availability. This impact is then propagated to the economy through environmental flow impacts on human activities such as recreation. It should be noted that this is only one of the numerous cultural ecosystem services that are provided by a functioning environment and should be added in future studies. In future work, the environmental flow component could be also used to link the ecology and biodiversity subsystem to the current RWM systems map.

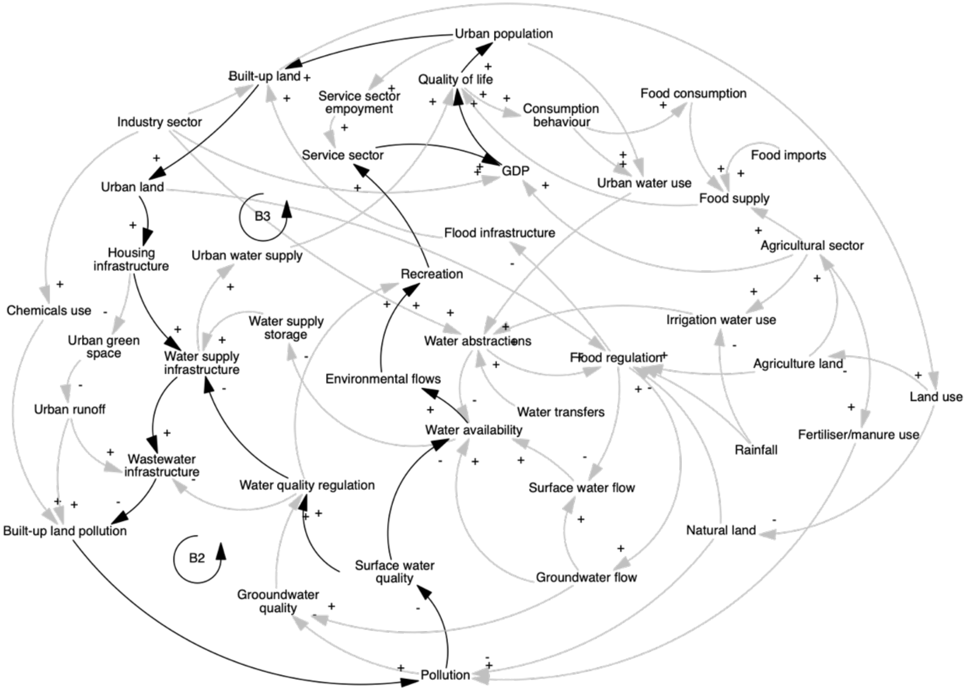


Figure 7 RWM systems map: opportunities for water planning coordination

The following recommendations are made based on the analysis of the B2 and B3 balancing loops:

- The B2 loop can be used for the operational coordination and integrated planning of the water infrastructure system, as it provides informational links between water abstractions, availability, reservoir levels and surface water quality. The key state variable that could be used to inform water infrastructure planning decisions is the surface water quality, as shown in the proof-of-concept work on the London water management system [94]. We recommend that water planning regulation should consider **dynamic water quality indicators** to support fully integrated water infrastructure operation and planning.

- The interdependences mapped by the B3 loop strengthen the argument that environmental services need to be considered as an integral part of water management decisions and solutions. The work on the London case study has shown that novel water management options between supply and wastewater, which explicitly account for the role of the flow in the river to dilute incoming pollution such as the proposed abstraction-effluent dilution, could provide up to £200 million worth of equivalent infrastructure in river quality improvements with minimal impact on the reliability of water supply [94]. It is, therefore, recommended that water infrastructure planning decisions are supported by **systems level evaluation** of integrated water management benefits.

4.2.3 Mapping unintended consequences

Systems level analysis is particularly useful in mapping possible unintended consequences (phenomena) of water management decisions (see Table 6 in Appendix A and examples in [97]). Here, we map 2 of those phenomena (Figure 8). Loop R3 shows the well-known flood management rebound effect, where the construction of flood infrastructure leads to higher level of protection of urban environments. This, in turn, results in increased urbanisation and a decreased capacity of the system to attenuate high intensity rainfall events (decrease in environmental services).

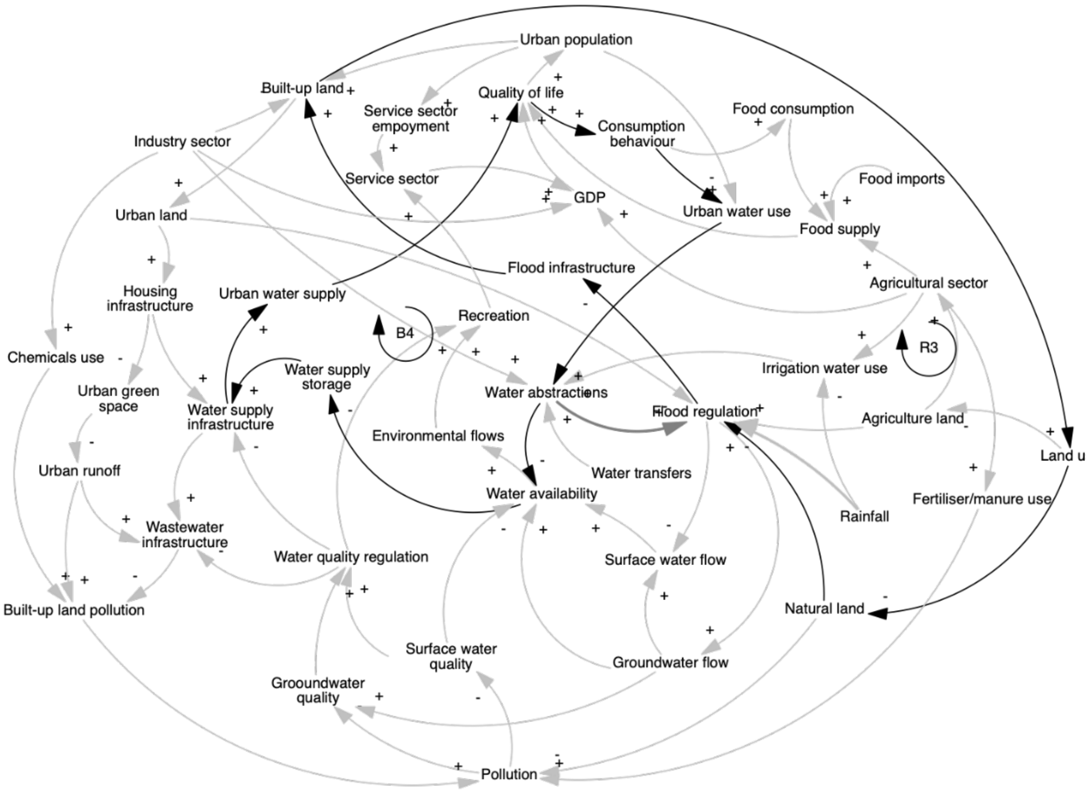


Figure 8 RWM systems map: possible unintended consequences

What may happen, at the same time, is that people become more environmentally aware regarding water consumption, transforming the negative reinforcing R2 loop into a balancing B4 loop (note the change of the direction of the link between ‘Consumption behaviour’ and ‘Urban water use’ from positive to negative in Figure 8), which could result in decreased water abstractions. More water in the system would result in higher environmental flows, while improved water quality could increase the value of the system for recreation, create benefits for service sectors (for example, tourism) and ultimately for the local QoL. However, a decrease in abstractions would further decrease the natural environment flood regulation capacity, potentially leading to increases in regional flood risk. We, therefore, recommend that the **use of systems maps** should be an integral part of discussions between relevant stakeholders to conceptualise a range of potential feedbacks within the system that, if unnoticed, would shift the burden and solve one problem while creating another.

4.2.4 Towards classification of roles in the RWM systems

The RWM systems map can also be used to analyse the role of key players in the water management process. Several questions arise from the previous analysis:

- What is the role of the agriculture sector in supporting other sectors (and ecosystem services) and, therefore, how much of the environmental impact should be redistributed (and therefore % of the GDP) based on the sectors' interdependences?
- How should water utilities, as key water providers of water supply and wastewater infrastructure, balance their role in water service provision and environmental protection with economic targets?
- What is the role of service sectors in a water management system, as the highest contributors to GDP, in particular large services sectors, such as tourism and housing? Both sectors either directly (via number of visitors) or indirectly (via resources use) are heavily reliant on the functioning environment.
- How can we make citizens an integral part of the water management system?

A way forward could be to explicitly define roles from a systems water management perspective. Here, we propose the classification shown in Figure 9. The sectors that are primarily responsible for HMS delivery are defined as 'Providers'. In the context of this work, they include farmers and landowners who are responsible for agricultural systems (including cropland and grazing land) and water utilities. Their decisions have a direct impact on the environment either through their land footprint or water abstractions and pollution.

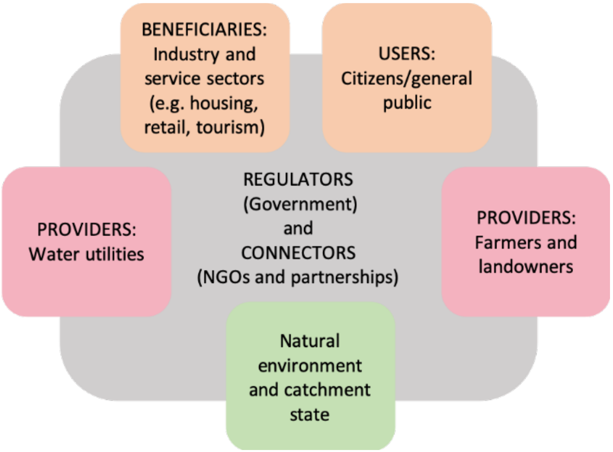


Figure 9 Proposed classification of roles in RWM system

Two groups of actors are relevant from the water demand and land use perspectives. The first group is defined as 'Beneficiaries'. This includes industry and services sectors, including, among others, retail, housing and tourism sectors. These sectors directly depend on the environment through resource use. Their financial performance depends on a functioning environment and can be significantly impacted by floods, droughts and water pollution incidents. The second group includes citizens/general public. They have a non-profit role in the system, however, they benefit from HMS provision in the form of a good quality of life. Nevertheless, any deterioration in the environment manifested through a decline in HMS provision would be primarily perceived as a failure of the water utilities operations, rather than as a consequence of systemic causes that could play a significant role.

The government is fundamentally interested in a functioning environment as it impacts both society and the economy and, therefore, it has a role as a regulator. A large amount of environmental funding also comes from multiple governmental departments. The government may 'profit' from a functioning environment if the public perceives the quality of life resulting from a high level of environmental services and HMS as valuable. This, in turn, could affect their election voting decisions. Organisations such as catchment partnerships and NGOs provide an invaluable link between all key players in the system, and, as such, they are seen as 'Connectors'.

While this work does not explicitly cover governance analysis, we argue that both **beneficiaries and users** need to be involved **in all water management decisions and future governance arrangements**. Their role within the system needs to be explicitly considered. This could be done through concepts of water and land footprints and/or by working with sectors in developing 'shared value' [98]. The recently published Natural Course study provides insights into water governance across England, with more detailed analysis of the governance in Cumbria [99]. Relevant aspects related to understanding catchment development pathways and complex behaviour linked to farming systems through participatory approaches can be found in Systems Analysis for Water Resources study [89].

4.3 Catchment systems map for Windermere lake water quality

The insights gained from the analysis presented in Appendix C can be summarised in the preliminary high-level lake water quality (LWQ) systems map shown in Figure 10. In a similar way to regional water management systems representation, the LWQ systems map integrates multiple perspectives on the system, including catchment state and human made services through agriculture and urban water sectors. Specific aspects of the Windermere system are represented through mapping the tourist sector, together with high-level representation of consumer behaviour and transport and housing aspects. Detailed description of interactions, management interventions and a full version of the LWQ systems map is presented in Appendix C.

It should be noted, however, that not all perspectives have been developed with the same level of detail, and that aspects such as explicit accounting for flood management need to be added in future work. The proposed map should be also discussed, and detailed aspects of the Windermere systems should be validated through a participatory approach with local stakeholders. Finally, the map does not explicitly represent links between system components and regulation/policies. This will be discussed in the context of system control and management.

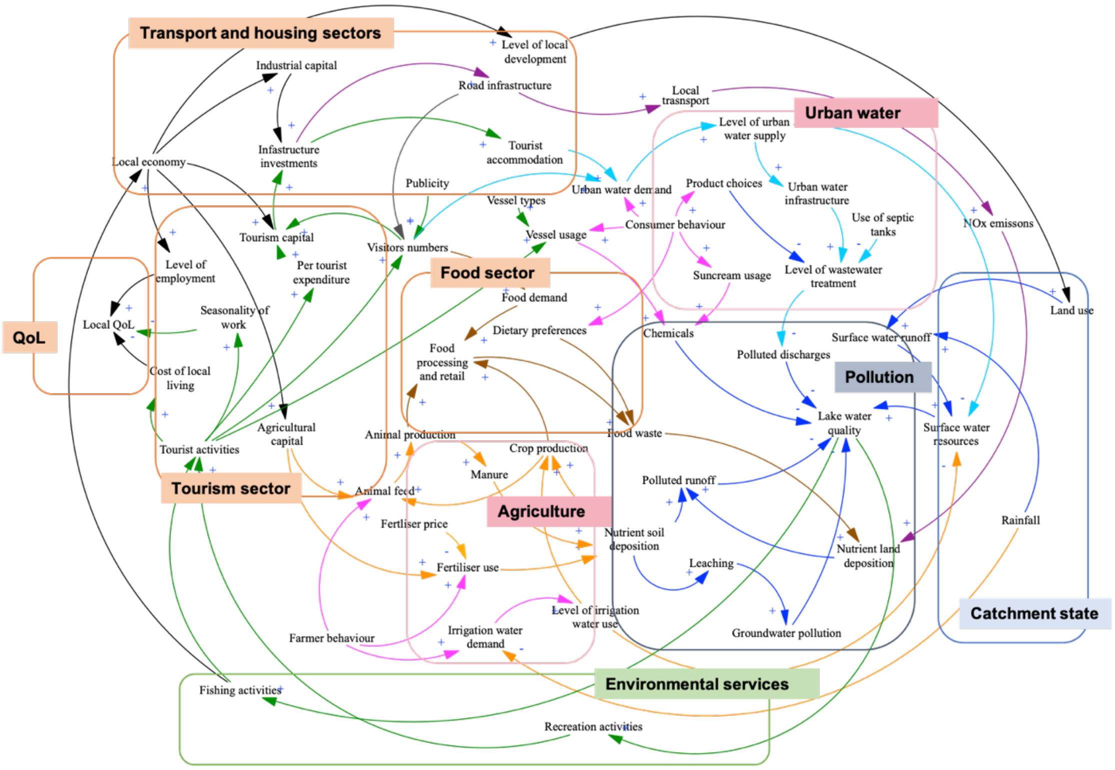


Figure 10 High-level version of a lake water quality systems map for Windermere. The cluster colours correspond to defined SYWM subsystems: Local economy and demand-supply (transport, housing, food and tourism sectors) and QoL (orange), Human impacts through pollution (dark grey), Catchment state (blue), Human made services including urban water and agriculture (pink) and Environmental services (green).

The map reveals the complexity of the LWQ system and the need to expand the boundary of analysis beyond individual system users. A range of important feedbacks within the system linked to lake water quality can be observed. While the problem with wastewater discharges is a clear direct driver of decreased water quality in the lake (see grey pollution cluster), 5 additional aspects should be considered:

- **The role of lake ecosystem services** (green cluster) in directly providing benefits for local tourism (orange cluster), and, therefore, the need to minimise impacts from the tourism business operation and activities, including transport, accommodation and recreation to maintain the future sustainability of the local environment. At the same time, a potential negative impact from economic growth, which is already observed in Windermere through high house prices, needs to be addressed. This emphasises the need for local collaboration and coordination between industry and service sectors (beneficiaries), visitors (users) and environmental regulators.
- **The link between the local food supply and use** (orange cluster) should be further explored, to understand the dependences of the interlinked sectors. The high reliance on the local resources (catchment state and agriculture) on one side supports the local economy and enables better system control. However, if the tourism sector is relying on food products produced elsewhere, and hence the link between the two sectors is weak, that could give a false view of environmental security. For example, if local tourism was impacted by pollution that results from the agricultural sector, while the food sector profited from tourists visiting, then there would be an incentive for both sectors to collaborate and find optimal solutions for environmental management of the natural system they share.

Business models that incentivise the use of local products in food sector retail could strengthen the link between the local economy and the environment.

- **The role of consumer behaviour** (urban water pink cluster) in both driving the demand for food and influencing tourist activities. This aspect links back to issues of food production and retail sectors as important elements in the system. The use of products that could have impacts on water quality as well as activities such as boat use could significantly contribute to pressures on lake water quality.
- **The role of coordinated management** to match the high seasonal demand (tourism orange cluster) and pressures on the system with natural availability of water supply. This aspect is closely linked with another important feedback - the role of water abstractions (urban water pink cluster) in influencing water levels in the lake, and, therefore, the ability of the lake to self-purify. This is particularly important when water abstractions are used for supply outside the system, which is the case in Windermere, therefore, decoupling impacts and benefits from the local catchment system.
- **The link between local economy and land decisions**, which fundamentally defines hydrologic ecosystem services. Any expansion of the tourism sector, with potential benefits for the local economy, would need to be linked with coordinated improvements in water infrastructure and management (pink clusters), as well as ensuring the transition of sectors such as agriculture and transport towards sustainable operation (orange clusters).

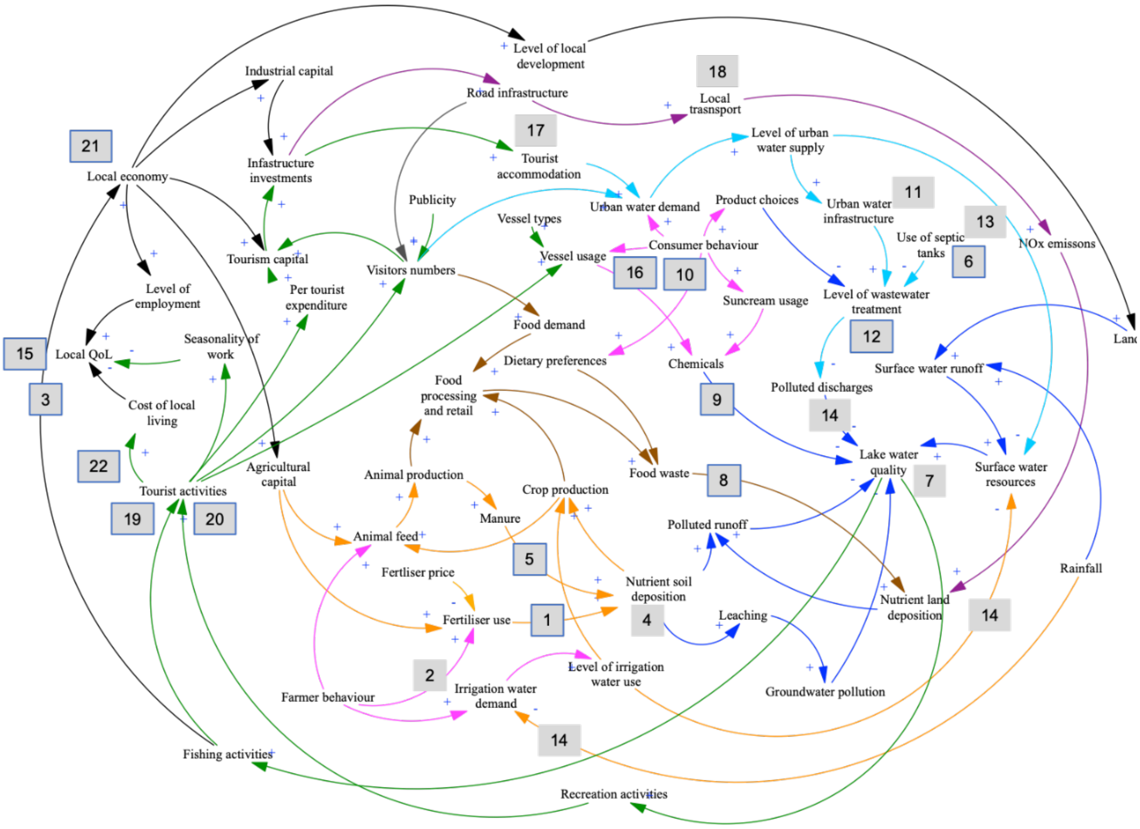


Figure 11 High-level version of a lake water quality systems map for Windermere including selected intervention measures. The numbers in the figure correspond to those listed in Table 12 in Appendix C. Boxes with an outline correspond to structural, informational or policy interventions, while those without an outline represent technological and infrastructure solutions

4.4 Implications for water quality management and control

By combining our new understanding of the LWQ system with intervention measures for water quality management and control (Table 12) described in detail in Appendix C, we can add them to the systems map (Figure 11) to enable the clustering and ranking of leverage points. The mapping and ranking of LWQ management and control interventions was based on the leverage point hierarchy defined by [22], which considers proposed solutions based on their effectiveness at a systems level.

The results summarised in Table 5 highlight 4 system water management aspects:

- Traditional ways of addressing water quality issues by either limiting pollution load or increasing wastewater treatment capacity and upgrading septic tanks (levels 9-11), while efficient in dealing with local issues, will not address the problem of systemic pressures that increase the system use. It is, therefore, recommended that **land use and economic decisions** that could have indirect implications on the lake water quality are **aligned with the water infrastructure system capacity** to manage the pollution load.
- Systems theory promotes the role of timely information to influence drivers of demand on the water management system. In the context of Windermere lake water quality, measures such as **food labelling and educational activities** (levels 7-8) should be included in the portfolio of LWQ management options, as a way of providing a necessary link between system use and environmental state, and, therefore, indirectly increasing the value of environmental services.
- Interventions at level 5-6 that are intended to either change the structure of the system (such as **wastewater recycling**) or account for system level impacts (for example, **catchment-level nutrient balance analysis**) could potentially make significant contributions to lake water quality improvement. While requiring more significant effort to be designed and implemented, both interventions should be considered in a portfolio of future water quality management options.
- Lastly, levels 3-4 provide 2 options for **whole-system restructuring**. While the system could be controlled through new environmental policies and taxes, it is equally recommended that participatory systems level coordination and governance frameworks are developed to support coordination of decisions between relevant stakeholders and system users. The SYWM framework could provide a basis for discussions around such a collaborative arrangement.

Table 5 Ranking of LWQ management and control interventions based on the leverage point hierarchy [22]

Level	Type of intervention in the system (in increasing order of effectiveness)	Application for the LWQ management and control	Intervention/policy option [numbers correspond with notation from Table 12 in Appendix C]
11	Introducing new standards	Managing direct impact on lake water quality	Limit pollution loads [1, 8, 9]
10	Increasing buffering capacity	Adding new elements in the system that increase the system capacity to manage pollution	Increase wastewater treatment capacity, reduce direct pollution or enhance

			self-purification [2, 4, 5, 6, 7, 12]
9	Changing the system structure	Adding new elements in the system that reduce/minimise environmental impacts	Upgrade of septic tanks, adopting green infrastructure, N recycling, sustainable transport and green hotels [11, 13, 17, 18]
8	Providing timely information	Information that can positively influence consumer behaviour change	Food labelling and promoting local consumption [10, 16]
7	Designing positive feedback loops	Maximising the link between the local environment and people who live there and care about it	Education activities and local employment [19, 20]
6	Reducing the strength of the reinforcing loop	Multifunctional solution that targets multiple stocks and flows in the system	Wastewater recycling and reuse [14]
5	Enhancing information flows	Providing information at a system level that can be used for collaborative decisions	Develop nutrient-balance programmes and participatory approaches [3, 15]
4	Changing the system rules	Direct impact on all components in the system	Introduce new environmental and visitor taxes [21,22]
3	Improving the system's capacity to self-organise	Shifting the decision focus onto the local quality of life and adjusting the local economy to the level of local ESS provision	Participatory integrated catchment management [15]
2	Changing mindsets	Societal agreement that there is a need for urgent action and system change	For example, climate emergency [100]
1	Charging paradigm	New economic system that enables sustainable development at global scale	For example, Green New Deal [101]

While different programmes and information sharing could have a significant impact on overall LWQ system dynamics, 2 things could fundamentally change the way the system behaves (levels 1-2). The first aspect is linked to the collective mindset change, which is usually triggered by global crises. We have seen a glimpse of that process through the current COVID pandemic, where people have realised the value of nearby outdoor green spaces and adjusted their consumption and entertainment habits. It could be argued that the climate emergency [100] should provide a similar incentive to the COVID crisis. However, we are yet to see if the general public will take this issue seriously enough. Developing approaches to visualise and communicate the potential impacts of the QoL resulting from the collapse of the natural environment could contribute to the much-needed mindset change.

Finally, we need to keep reminding ourselves that the way we evaluate the system and the whole of the nation's economy is a virtual concept that could be changed overnight (although its implementation would take a bit longer!), if there was a critical mass of highly influential individuals that would have the power to change the current growth paradigm. This way of thinking is behind the Green New Deal proposal, however, we are yet to see how this highly ambitious concept could be implemented in reality [101].

5 Summary and conclusions

The SYWM approach developed in this work, which proposes mapping, structuring and analysis of a water management system through a SYWM framework and meta-model, provides a first step towards increased understanding of water management system complexity. The proposed framework, which explicitly accounts for water management, natural capital, ecosystem services and footprint concepts, has shown that most (if not all) water management critical interactions could be analysed by mapping 3 key feedback loops and 7 high-level components.

The approach provides a hierarchical view of the water management system, where second-tier variables are defined to support the water management systems maps structuring. Finally, by representing system links to account for water management decisions and information flows, as well as physical processes in the system, the SYWM framework lays foundations for an operational approach to understand system-level interventions through causal relationships analysis.

A number of recommendations arose from this work. From a regional water management perspective, the challenge of water planning coordination could be addressed by revisiting the concept of water neutrality to strengthen the link between water and housing (and other infrastructure) sectors. The role of urban water use as a high leverage point has been reinforced, as well as the need to link drivers of the consumption behaviour with the QoL indicators. The role of environmental services, and in particular surface water quality, is proposed as a state variable that should be used to coordinate water supply and wastewater infrastructure planning and operation. This analysis should be supported by a water management model that can quantify impacts from proposed interventions across the system as a whole. Finally, the study recommends the use of the developed RWM systems map (in current or revised version) as a starting point for open discussions with local stakeholders about the water management system and communication of key feedbacks that may lead to unintended consequences. This is demonstrated by the interactions between flood management, urbanisation and consumption behaviour, potentially leading to an increase in flood risk if water demand reductions result in decreased abstractions and increased environmental flows. A range of relevant stakeholders should be included in these discussions, with beneficiaries and users being an essential part of the water management governance system.

Analysis of the water quality system of Lake Windermere in Cumbria confirmed the need to account for activities resulting from service and industry sectors, and tourism in particular, in defining the possible measures for water pollution management. The focus on mapping of leverage points revealed that most infrastructure and technological solutions, unless implemented across the system as a whole, will not contribute to solving the systemic causes of Windermere lake water pollution. The role of information sharing as well as high-level structural changes such as wastewater recycling and reuse are likely to provide more significant systems-level water quality benefits. The role of coordination and environmental regulation, in particular linked to a visitor economy was emphasised as a high leverage point. Finally, global trends such as the climate emergency and Green New Deal are mentioned as ways of fundamentally changing how we think about and evaluate complex human-natural water systems.

This work, while covering multiple water management aspects, is by no means fully comprehensive. Various concepts relevant for water management decisions, such as ecology and biodiversity, cultural ecosystem services, marine ecosystems and other industry (for example, mining) and service sectors (for example, energy and transport) should be added in potential future studies. The SYWM framework, however, provides a basis to which all these and any other components could be added in future work through further socio-economic, behavioural and environmental analysis. Finally, there is a need to refine and expand the high-level maps with stakeholders as part of an interactive participatory process. This will help to promote systems thinking and create a sense of map ownership for those stakeholders who are directly involved in water management decisions. Finally, we hope that this work will help promote systems thinking in the context of catchment water management and that the SYWM framework and meta-model will be used for analysing, modelling and assessing water management systems, thereby creating a range of case studies to validate SYWM thinking.

Appendix A: Review of theoretical concepts

A.1 Introduction to key concepts

Traditionally, water management has been a process of planning, operation, use and protection of water, which is defined by policy and regulation. The outcome of water management was primarily aimed at satisfying human needs and addressed from multiple perspectives. It focused on problems of too much (flood management), too little (water resources management), or too polluted water. Alternatively, it started from individual goals and disciplines that, in isolation, addressed urban and catchment water management challenges, and partially included environmental, engineering, social and economic aspects in the evaluation process [102].

As the world became more integrated through industrialisation and urbanisation, it became clear that managing water for people and nature would need to go beyond satisfying current human needs. A goal to maintain and improve the state of environmental resources for future generations, which has been changed by human activities has broadened the scope of water management from a mainly technical to a socio-ecological-technological challenge [103]. The interactions between human use of nature and the impacts it poses on ecosystems has become a focus of integrated catchment management [55]. Concepts such as natural capital [104] and ecological [105] and water [106] footprints have been introduced to emphasise the need for environmental management to support sustainable development. In addition, certain aspects of ‘water environment management’ such as the hydro-morphological dynamic interactions of watercourses with floodplains and the wider catchment have been seriously neglected [107].

However, much-needed integration of concepts beyond the water system into water management analysis has not yet been fully achieved. On one hand, the scientific community is still trying to decide how to comprehensively represent and assess the role of humans within the hydrological cycle [108], how to categorise water use for improved management [8] and how to understand the limits of that use [109]. At the same time, from a long-term perspective, many policies and interventions have been shown to lead to undesired outcomes or intended consequences [103] and a range of socio-hydrological phenomena [97].

It has been argued that one of the possible reasons why we cannot solve water management problems is because the relevant methodologies have been guided by linear engineering approaches and principles of system control [103], [110]. The lack of understanding of water management as a complex social, ecological, technological and political problem with interdependent causes has resulted in numerous examples of unforeseen impacts of proposed policies and interventions (Table 6), also known as a ‘socio-hydrological phenomenon’ [97].

Table 6 Examples of unintended consequences of policies and interventions

Policy/intervention	Unintended/undesired impact
Expansion of reservoirs to cope with drought conditions [111]	- Increase in water demand and vulnerability due to increased water use - Drying of lakes and wetlands due to increased irrigation supplied by reservoirs

Introduction of irrigation efficiency through advanced technologies to reduce the irrigation water use and increase availability of water for other sectors and the environment [112]	- Reduction in recharge and surface run-off on a catchment scale impacting water resources - Increase in water use at the farm scale due to the farmers choosing more water-intensive crops
Implementation of flood control through structural flood protection measures, including levees and flood-control reservoirs [15]	- Intensive urbanisation in the protected area leading to higher exposure and the need for increased protection standards - Higher protection standards increasing a sense of complacency, leading to increases in vulnerability

As a way of improving understanding of the water management challenge, the scientific and management community has seen a need to extend its theory to include principles of systems thinking [113]. Approaches to address water management from a complexity perspective have been proposed, which include multisector and trans-boundary decision-making, adaptive management and self-organisation and incorporation of natural capital in markets [110], [114]. Despite efforts to apply integrated approaches in informing water policy, the evidence shows that water management is still far from being sustainable [115].

A.2 Water management concepts

The theory of water management that investigates physical flows as an ultimate constraint on system performance generally comes from 4 complementary research fields. Hydrologic theory quantifies the behaviour of a catchment related to its physical connectivity with surface and subsurface systems [45] and as altered by human activities [108]. Water resources systems analysis studies water and society and practical issues of water management [48], while engineering theory focuses on the design of human-environment-infrastructure systems [116]. Meeting societal demands, however, must consider ecological aspects and the needs of aquatic species and ecosystems that depend on the same resources [117]. More recently, a field of socio-hydrology has emerged as an attempt to address the complexity of human and natural system interactions [118], complemented by a sustainable engineering concept that introduces ecological, economic and social aspects in the system design [69].

Based on these new insights, water management concepts have changed over time. The current focus (Figure 12) is on the premise of water security as a major goal of water management [102], [119] and adaptive water management as a key concept to address the need for changing water management practices based on new information that becomes available, either through evidence or insights [73], [120].

It is clear that existing theories and concepts address much of the water security challenges we are facing, including water resources (quantity and quality) management and flood protection. However, a common practical evaluation framework for water management that could facilitate comparative analysis, in a systemic way, across different perspectives on water security is still missing [121]. If such a framework were based on assessments of system state variables, it would provide a way forward for consolidation and advancement of the fundamental research and findings across the water management scientific community and practice [48].

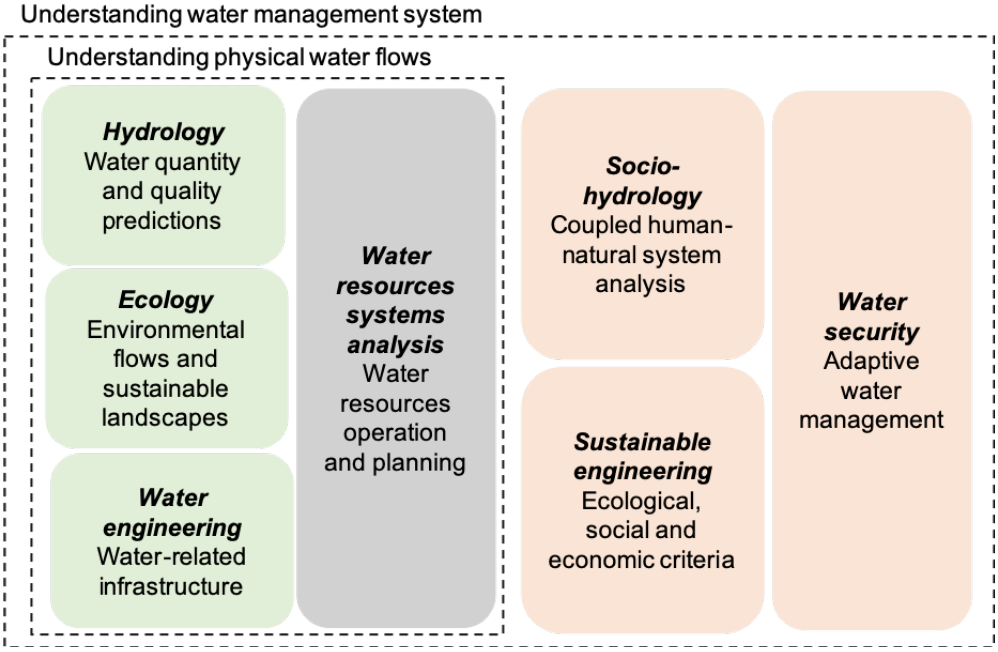


Figure 12 Water management concepts for system understanding

One way towards systems level assessment is to introduce a value chain between natural assets and the benefits they provide for humans and ecosystems through the natural capital approach. Expanding on the premise of integrated environmental resources management, the natural capital thinking has posed an argument that unless we are fully aware of our dependence on (and therefore the value of) the natural environment, we will not be able to develop mechanisms to maintain or enhance that value for future generations of human and non-human species.

A.3 Natural capital and ecosystem services concepts

The natural capital (NC) concept is fundamentally based on systems thinking (Figure 13). It is defined as any stock of natural resources or environmental assets (for example, ecosystems) such as water, forests or agricultural land that contribute to the generation of goods and services of value for people [122]. As such, NC provides an inherently anthropocentric view of the natural environment. Ecosystems provide and sustain benefits for people through ecosystem service (ES) flows. The ES provide direct benefits such as carbon sequestration (regulating ES), or intermediate benefits, supporting final services such as generating water resources for human consumption (provisioning ES) and recreation (cultural ES) [123]. Maintaining NC is essential for supporting ES (for example, water cycle), which supports sustainable development and future flows of ES [104].

Although the NC concept has been widely discussed in the scientific literature, its implementation in practice to inform planning and management decisions still faces multiple challenges. In particular, this includes implementing practical NC approaches in the context of systems thinking. Although critical in providing the potential benefits of a NC approach, there is a serious risk that application of a systems understanding framework is not realised in practical management of natural capital [34]. The NC concept is intrinsically linked with socio-economic systems and other forms of capital such as human-made stocks [124]. However, in practice, NC accounting is mainly done in isolation [123]. Some approaches, such as the inclusive wealth concept, aim to holistically assess sustainability by aggregating values of all capital assets: human, manufactured and natural [125]–[127]. However, we still need to better understand complex human-natural system dynamics, and how any changes in the system could affect NC and the future provision of ES.

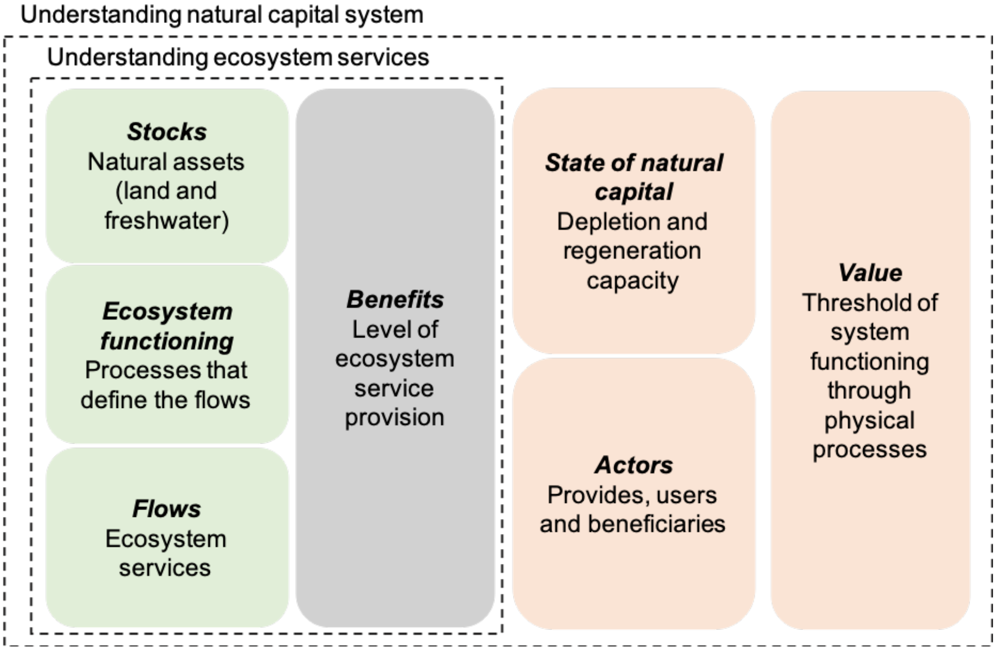


Figure 13 Natural capital concepts for system understanding

Two key interdependences define a NC system. To understand how natural ecosystems generate ES we need to explicitly represent natural processes (such as water) that create ES flows [47]. This creates a link between processes and benefits [128] and defines ecosystem-capacity approach to NC accounting [129]. We argue that this conceptualisation will bring us closer to understanding the limits of ecosystem functioning and how much development the world can cope with before we reach irreversible tipping points [130].

We also need to understand the role of different economic sectors and users in producing and using ES [46]. Analysis of a range of case studies focused on ES use for human wellbeing has shown that trade-offs between multiple services and ES benefits distribution are likely to occur, in particular when at least one of the stakeholders is involved with provisioning ES [131] or managing key ecosystem properties [83]. We argue that explicit representation of ecosystem functioning and players in a NC system will allow us to measure the level of human consumption of natural assets, represented by depletion of NC stocks and the use of ES flows. That way, we can better understand indicators that define threshold values of natural system functioning, how the value of NC may differ depending on the state of the NC, and how far it is from its threshold for renewable production.

A.4 Environmental footprint concepts

Human impacts on the environment are primarily manifested through the use of natural resources (for example, water and land) for production and services. From a catchment water management perspective, impacts can be broadly categorised as land use change, water abstractions and water pollution [132]. Concepts such as ecological and water footprint analysis can translate these impacts into natural resource use and help us understand the role of multiple stakeholders within the water environment system (Figure 14). Ecological footprint (EF) analysis helps us to understand the human need for land resources defined as biologically productive areas and measured in global hectares. The EF assesses the use of 5 different categories of land: cropland (crops for food, feeding and other uses), grazing land (to support food production), fishing grounds (fish harvest for human consumption), forest (resources to support manufacturing) and built-up area (to support infrastructures and service sectors). In addition, EF assessment accounts for the forest area capacity for carbon sequestration through the concept of 'carbon land' [105].

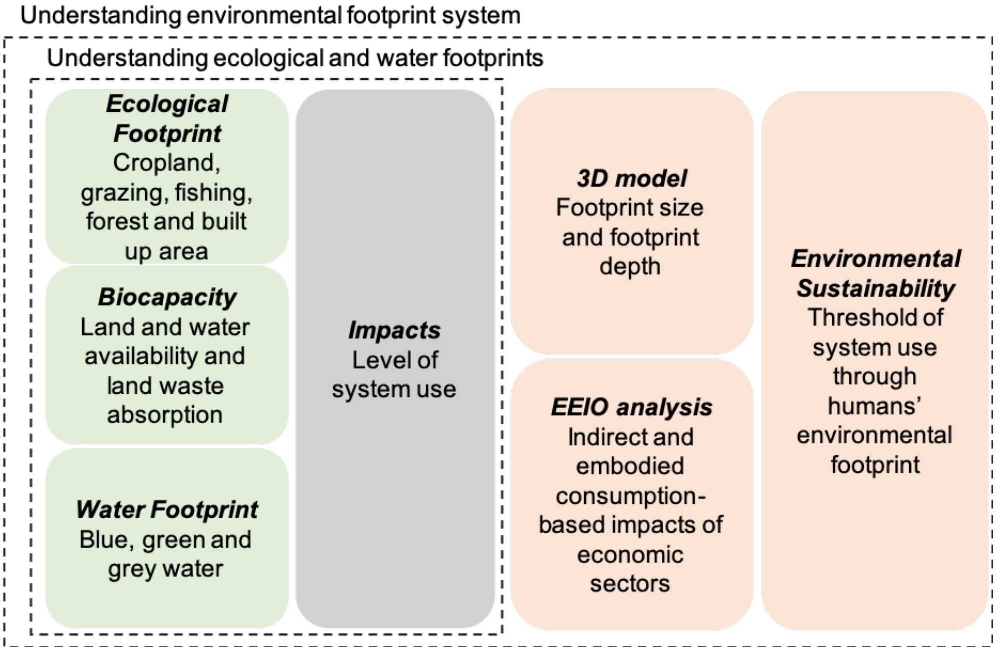


Figure 14 Environmental footprint concepts for system understanding

To assess the sustainability of an EF system, the use of resources is linked with the availability of resources assessed through the concept of biocapacity (BC). It defines the biological capacity of ecosystems to either produce resources or absorb waste generated by human activities [105]. A fraction of 12% of the overall biocapacity is assumed to be a minimum value required for biodiversity and ecosystem functioning [133]. The remaining capacity can then be compared with the EF, leading to either the state of 'ecological overshoot' when the use of resources exceeds regenerative capacity of the assets or 'ecological surplus', which indicates a sustainable use of the resources. EF analyses are typically done at a national level [134], although examples can be found for regional [135] and city levels [136], [137] or local scale analysis [138].

A link between EF and NC accounting has been proposed through the concept of the 3D footprint model [139]. The model introduces a footprint size as a measure of the NC stock extent that cannot go beyond the system capacity and a footprint depth, which if larger than one, represents an extra demand on land required to meet human needs, resulting in depletion of the NC stock [140]. However, a clear distinction between the use of NC stocks compared to the use of ES flows and the impacts on NC evaluation is still part of scientific debate [141], [142].

Freshwater as a resource is not directly represented in the EF. However, a similar water footprint (WF) methodology exists to account for the level of human interactions and water resources [106]. The WF accounts for freshwater demand for any goods and services produced, either as a direct demand (blue water) or water available through rainfall and related processes (green water). The capacity of a freshwater system to assimilate pollutants due to goods and services production is assessed through a greywater footprint. A distinction between local (actual) and global productivity is accounted for through the virtual water concept. This represents the amount of water used to produce a commodity or service [143]. Concepts of EF and WF have been regarded as complementary, both from the perspective of critical factors that influence land development and as estimates for assessing the sustainable use of NC [144].

Unsustainable increases in the scale of environmental footprints highlight a need to understand linkages between economic consumption activities and drivers of downstream environmental issues [145]. A possible way to evaluate hidden, indirect or embodied environmental impacts associated with consumption activities is to apply environmentally-extended input-output (EEIO) analysis [146]. The approach uses nationally developed input-output (I-O) tables that describe the economic relationships between producers and consumers within an economy to calculate the so-called ‘Leontief inverse matrix’ [147]. This can be used to redistribute environmental footprints from production to a range of dependent consumption sectors. Examples of EEIO studies for both EF and WF can be found for both national and regional level analysis [135], [148], [149].

Appendix B: Review of a water management system in England

To understand the issues of regional (multiple catchments) water management from a systems perspective, we start with an overview of the overall quality of life and how it links with the key high-level indicators related to water environment management. The overview is undertaken based on the SYWM concepts defined in the theoretical framework described in Chapter 3. We specifically comment on the issue of scale and how perspectives on water management can change by using information at various spatial levels of aggregation.

B.1 England and water management

Overall, relative to many other countries, evidence suggests life indicators for the UK are good. In 2018, the UK had a Human Development Index (HDI) of 0.92 [150]. Considering that the HDI can vary within a range 0-1, this implies that, on average, people in the UK score extremely high on the global socio-economic wellbeing scale. This result is replicated in a study exploring quality of life linked to planetary boundaries, where the UK scores for 2014 are >1 (that is, above the defined minimal threshold) for 7 out of 10 analysed social indicators [3]. In the study, aspects of infrastructure included within indicators relevant for this report give the UK the high scores of 1.71 on nutrition availability and 1.06 on access to sanitation.

The situation however, is significantly different if we look at the biophysical indicators [3]. Within that group, the UK scored particularly high (>1, meaning that the system is operating outside the defined thresholds for its biophysical capacity) for a range of indicators, including CO_2 emissions (7.48), nitrogen (8.19) and phosphorus (5.86) per capita use and ecological footprint (2.41). At the same time, the results showed that blue water consumption, defined as withdrawal of water from rivers, reservoirs, lakes, and aquifers, is significantly lower than the use boundary (0.42).

From the SYWM perspective, although indicators imply that the UK has significant problems with water quality due to nutrient pollution, at a national level, issues related to water supply have not been detected in some measures as indicated above. In addition, the possible signal of environmental degradation is not reflected in the measure of the quality of life. However, more detailed analysis of the system components reveals a different picture. We discuss this through analysing high-level concepts and interdependences defined by the SYWM meta-model.

B.2 Water management from a systems perspective

B.2.1 Environment and human impacts

High water availability could be justified up to a certain level by the very high mean value (1.62) of the UK's Aridity Index [151]. The index represents the ratio between precipitation and reference evapotranspiration during the period 1970 to 2000, with all regions with a value >0.65 classified as humid.

The mean annual rainfall of approximately 600 to 1,500 mm/year is transformed into surface and subsurface fluxes over 241,278 km^2 of land. According to 2017 data, most of the land in England is 'developed' (92%), and the biggest land use is agriculture (63%) [152]. Transport and utilities take the largest share of the developed category (4%), and only 1% of total land area in England is used for housing. These data are supported by values from the Land Atlas of the United Kingdom [153] shown in Table 7.

Table 7 Land area, ecological footprint, biocapacity, water abstractions and human impacts per land use type

Land use type	**Total UK area (km^2)**	**Ecological footprint (EF) (global Mha)**	**Biocapacity (BC) (global Mha)**	**Freshwater abstractions (Mm^3/year)**	**Issues impacting water state (frequency of occurrence)**
Cropland	67,306	43.4	28.2	1.5	1,983
Grazing land	128,786	15.6	7.5		
Forest	23,704	30.2	7.9		
Fishing ground	1,209	4.9	19.4	5.5	0
Built-up	20,273	8.7	8.7	795.7	3,103

These data, however, provide a rather different view from the one we get when analysing the UK's economic system and ecological footprint. The UK's total gross domestic product (GDP) value in 2018 was 2.85 trillion USD, with the highest added value of 70.5% coming from the service sector [154]. The industry and construction sectors contribute an 18% GDP share, while the % GDP of the land-based sectors has decreased since 1990, with the current share at only 0.57%.

If we compare this data with the analysis of the UK ecological footprint globally for 2016 (Table 7), which measures human demand on nature [155], an interesting fact becomes apparent. While <1% of the UK's GDP comes from the land-based sectors (agriculture, including cropland and grazing land, forestry and fishing), they contribute 91% of the total EF. On the other hand, the service and industry sectors worth approximately 2.5 trillion USD are almost invisible in the EF, with a share of only 9%. Finally, the agricultural and forest sectors are currently operating way beyond the biophysical limits of the system, with 53 to 282% overuse, defined as the difference between biocapacity and ecological footprint (Table 7).

B.2.2 Demand, supply and economic sectors

The demand side of the water management system needs to consider UK demographics and employment. The current UK population of around 67 million people has significantly increased from ~52 million in 1960 [154]. More than 80% of people live in urban areas, with the highest level of employment in England in the service sectors (>90% of jobs) and <1% jobs related to the agricultural based activities [156].

To better understand the link between the agricultural sector and demand, global food analysis has shown that the UK is primarily a net food importer [157]. Results have shown that out of 3,426 kcal/cap/d that the UK was consuming in 2005, which is classified as high supply, only 1,973 kcal/cap/d were locally produced, which is classified as low production compared to global values. Almost 1,500 kcal/cap/d (42% of total supply) related to food energy supply has been imported, which puts the UK at the boundary between moderate and high net importers. Similar trends have been shown in analysis of countries' potential to become food self-sufficient, taking into account water and land constraints [158]. The study, however, showed that even if the UK wanted to become fully reliant on local food supply, based on current consumption patterns, the expansion in cropland necessary could not fulfil the production requirements.

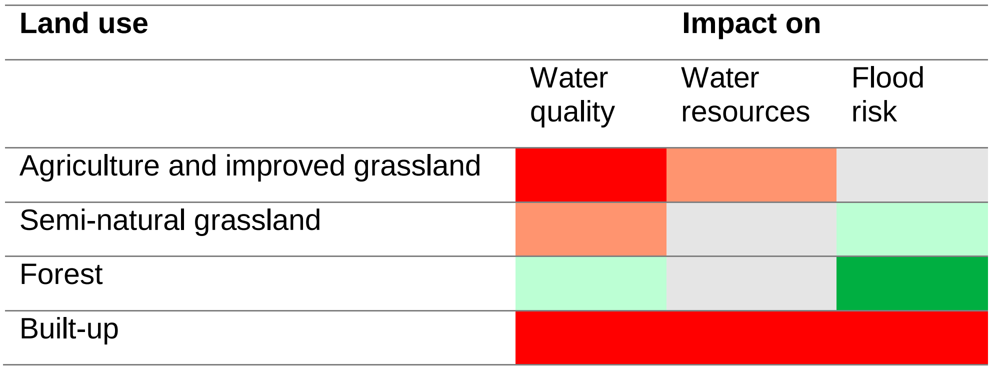
Water abstractions data for England (Table 7) show the impact of urban water demand [159]. Based on the 2013 data, most water use was allocated to built-up land as a proxy for service sectors, with public water supply being responsible for 48.5% of abstractions (389.5 Mm^3/year). The second largest water users are the electricity and gas (276.5 Mm^3/year) and chemical manufacturing (90.3 Mm^3/year) sectors. The majority of abstraction is from surface water (~80%), while groundwater resources contribute to 20% of supply. Groundwater resources also provide a significant contribution to baseflow [160]. In the case of increased groundwater abstraction, resulting decrease in streamflow could potentially have a disastrous impact on environmental flows and river ecosystems.

B.2.3 Environmental services and development

Only around 25 to 30% of rivers and lakes, and less than 60% of groundwater achieve Water Framework Directive ‘good status’ [161]. In addition to abstractions and flow, chemicals, fine sediment, nitrate and phosphorus have all been identified as significant water management issues, with both agricultural and service sectors contributing to the impact (Table 7). It is also worth mentioning that compared to other countries globally, the UK’s water quality standard is within the top category, with 92% success in meeting established water quality criteria with respect to dissolved oxygen, electrical conductivity, pH, and total phosphorus and nitrogen [162].

The role of environmental services in the UK to regulate water quality, provide water resources and manage flood risk has been analysed in the context of land use [163]. Results summarised in Table 8 confirm the previously mentioned trends. Agricultural land contributes most significantly to poor and bad river water quality ecological status and puts pressure on water resources. The impact of woodland is mainly positive, in particular with respect to water quality and flood risk management. Finally, we see again an overall high negative impact of built-up land, which poses huge pressures on the water environment.

Table 8 Summary of relative land use impacts on environmental services based on data in [163]; red implies high negative impact; grey: overall neutral impact and green: high positive impact



Land use	Impact on		
	Water quality	Water resources	Flood risk
Agriculture and improved grassland	🟥	🟧	⬜
Semi-natural grassland	🟧	⬜	🟩
Forest	🟩	⬜	🟩
Built-up	🟥	🟥	🟥

Finally, we look at the state of water infrastructure in the UK. While more than 99% and 95% of people in the UK have access to water supply and sanitation, respectively [154], the UK water infrastructure sector faces many challenges. On the water supply side, the National Infrastructure Commission has set a target of 1,300 Ml/day additional water supply by 2030, while leakage should be reduced by 50% [164]. Drainage and wastewater systems are under increased pressure from housing development, ageing infrastructure and limited space for the expansion of wastewater treatment works [165]. Similar questions have been posed by UK Water Industry Research (UKWIR) in the context of water industry sustainability, emphasising the need to achieve zero uncontrolled discharges from sewers by 2050 [166].

B.2.4 High-level dynamics and water management imbalance

To understand key high-level dynamics in the regional water management (RWM) system, the reviewed information was summarised to emphasise the link between economy, environment and pressures (Table 9). Land-based indicators were recalculated using values from Table 7 and risk categories from Table 8, assuming that industry and construction takes approximately 80% of the built-up land. Data presented in Table 9 were then scaled to calculate the percentage impact from economic activities, shown in Figure 15.

Table 9 High level evaluation of socio-economic and environmental indicators per economic sector

Indicator [reference]	**Sector**		
	Agriculture, forestry and fishing	Industry and construction	Services
% GDP [154]	0.57	18.0	70.5
% employment [156]	0.94	7.5	91.6
Ecological footprint % (global Mha) [155]	94.1	6.96	1.74
Water abstractions (Mm^3/year) [159]	7.0	90.3	705.4
Water pollution (frequency of occurrence) [161]	1,983	2,482	621
Flood generation (level of risk scaled by the land area, 0-5) [163]	2	5	3

Analysing the data presented in Figure 15, the following observations can be made:

- There is a significant difference between the roles of the 3 analysed sectors in the UK economy, which is dominated by service activities primarily linked with the built-up land and urban environments.
- The trend of service sector economic dominance is not reflected in the water footprint analysis, with <10% impact contribution. Built-up land has the highest water abstraction levels, as well as having direct impacts on water pollution and flood generation.
- Finally, the agricultural sector dominates in the overall ecological (land) footprint, which has indirect implications for all components in the system. The fact that its contribution to the UK's GDP is small compared with other sectors opens up questions around possible repositioning of the sector to match its value with the pressure it places on the environment.

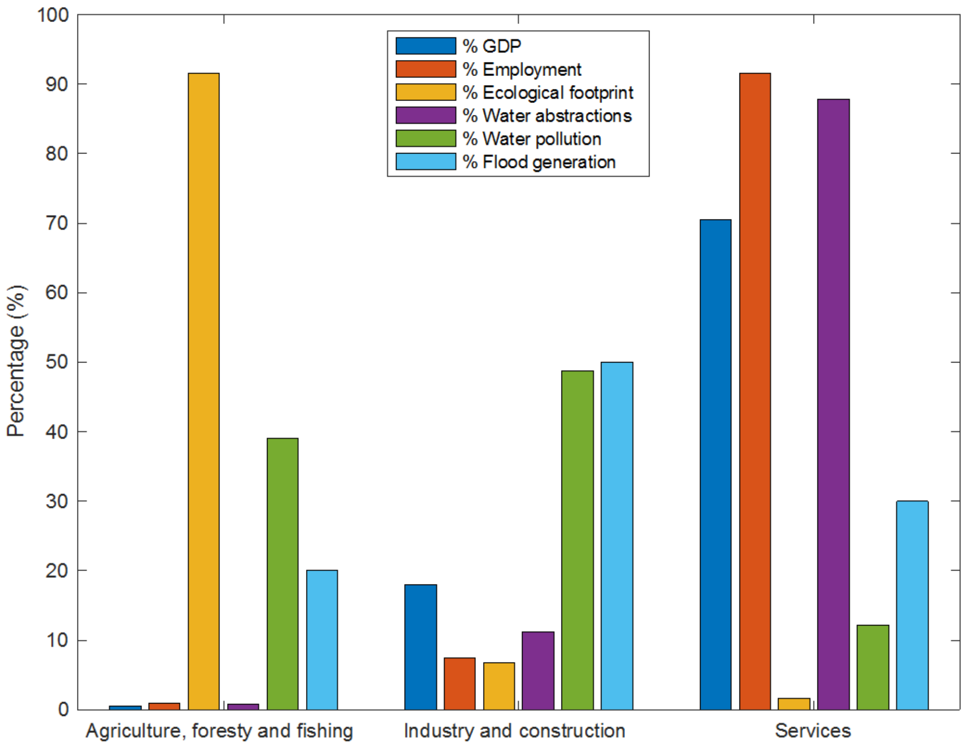


Figure 15 Distribution of approximated economic value and environmental pressures in a regional water management system

B.3 High-level regional water management systems map

Based on the above analysis and steps explained in Chapter 3, a preliminary version of the England's water management systems map shown in Figure 16 was developed. The map is used to identify feedback loops (Table 10) that are used for systems analysis presented in Chapter 4.

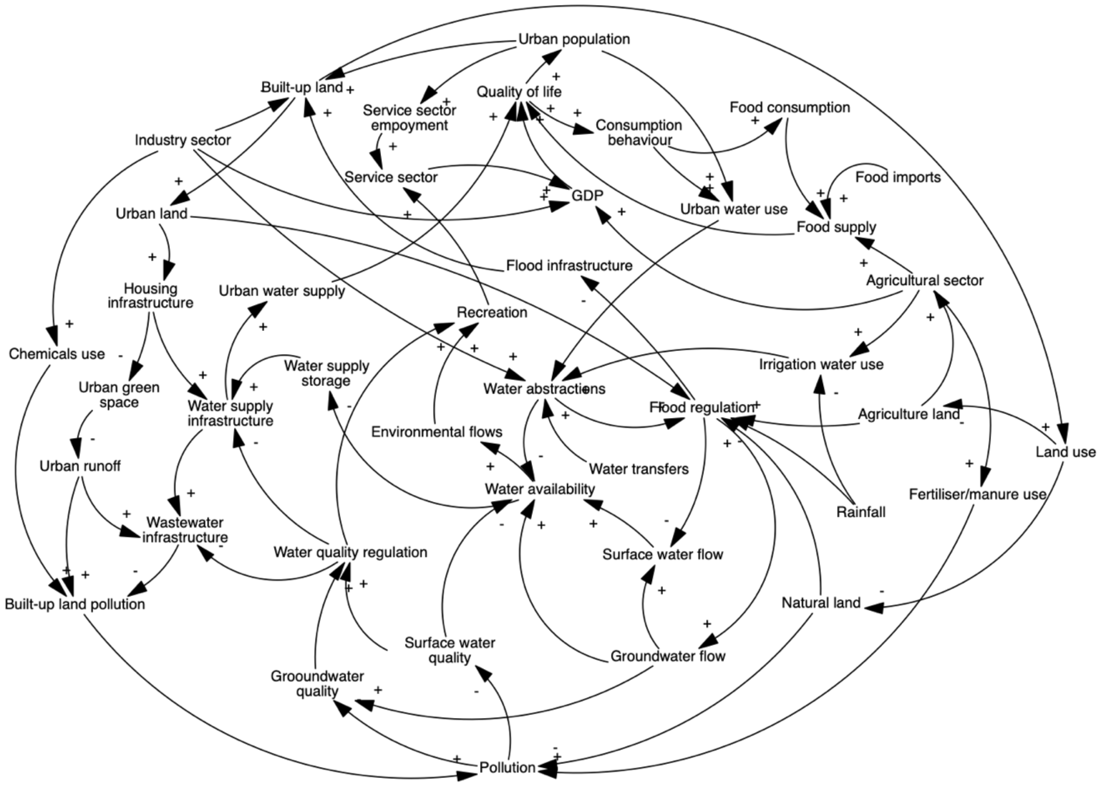


Figure 16 High-level version of a regional water management systems map for England

Table 10 The list of identified feedback loops in the regional water management system

Loop	Components
Role of water demand drivers	
B1	Pollution - Surface water quality - Water quality regulation - Wastewater infrastructure - Built-upon land pollution - Pollution
R1	Water supply infrastructure - Urban water supply - Quality of life - Urban population - Built-upon land - Housing infrastructure - Water supply infrastructure
R2	Water supply infrastructure - Urban water supply - Quality of life - Urban population - Urban water use - Water abstractions - Water availability - Water supply storage - Water supply infrastructure
Opportunities for water planning coordination	
B2	Water supply infrastructure - Wastewater infrastructure - Built-upon land pollution - Pollution - Surface water quality - Water quality regulation - Water supply infrastructure
B3	Water availability – Environmental flows – Recreation – Service sector GDP – Quality of life - Urban population - Built-upon land - Urban land - Housing infrastructure - Water supply infrastructure - Wastewater infrastructure - Built-upon land pollution - Pollution - Surface water quality - Water availability
Mind the unintended consequences	

R3	Flood regulation – Flood infrastructure - Built-upon land – Land use – Natural land - Flood regulation
B4	Water availability - Water supply storage - Water supply infrastructure – Urban water supply – Quality of life – Consumption behaviour – Urban water use – Water abstractions – Water availability

Appendix C: Review of the Lake Windermere water quality system

One of the key issues in the Windermere and River Leven catchment selected for analysis was problems with lake water quality and subsequent impacts on the local economy. There is strong evidence that the main sources of lake pollution are discharges from wastewater, particularly in the South Basin. The overall impacts have been linked with the increase in tourism, primarily though population increase in catchment urban areas and the resulting increase in wastewater discharges. While the upland part of the catchment is primarily grassland used for sheep grazing and cattle farming and the lowland areas have been exposed to agricultural intensification and increases in livestock density, the impact of diffuse pollution in the catchment seems not to be significant compared to point-source inflows.

While focusing on point-source pollution helps us to analyse direct impacts, to understand the complexity of a lake water quality management from a systems perspective we expand a general overview to include multiple problem perspectives and links with the local economy. The understanding of a lake water quality system is then put in the context of Windermere water management by developing a high-level version of the lake water quality systems map. It should be noted that mapped system components and the strength of interactions between them needs to be validated by local stakeholders.

C.1 Windermere and water quality

In Windermere, there is evidence of a significant nutrient load coming into the lake. In 1991, the P budget analysis showed that 68% of the pollution entering the lake was from sewerage effluents [167]. In addition, 2 basins (North and South) have responded differently to the increased pressures. The North Basin was less affected due to less pollution load and lower exposure to tourism activities. Historical evidence also shows that the main nutrient causing eutrophication of the lake is phosphorus (P) rather than nitrogen (N). The response to this was to upgrade the wastewater treatment works to include a tertiary P stripping process [168]. More recently, evidence has shown that increased water temperatures due to climate change are potentially affecting lake plankton, along with the influence of large-scale patterns of ocean and atmospheric circulation [167]. The growth of tourism in the area has been identified as the most significant driver of changes in algal communities in the lake. This section gives an overview of the Windermere local economy, including tourism and agriculture, and key sources of point discharges into the lake.

C.1.1 Windermere local economy

The Windermere economy is currently driven by tourism. The population has increased by 6.1% since 2002, which follows the general England and Wales trend. Most residents (82.6% of 16 to 64-year olds) are economically active, which is high compared to the national average of 76.8%. Average house prices in Windermere are 9.6 times the local average household income [169]. A change in national economic policy context, which promotes strong commitment to devolution and customer choice in public services, poses new challenges to public sector agencies. They need to find new ways of working that will promote better relationships with citizens and business sectors, with potentially significant implications for local investment.

From the perspective of local business, 3 themes have emerged that could shape the future economic vision for Windermere [169]. These are (i) investment in infrastructure (for example, transport, broadband and affordable housing) for the visitor economy to facilitate economic growth, including actively promoting car alternatives, walking and cycling; (ii) development of the visitor economy to attract younger and higher spending visitors to stay longer. This includes investing in accommodation and local services and targeting expanding markets such as China, India and South America; and (iii) strengthening local social capital by retaining young people and families through affordable housing and sustainable employment and exploring partnership funding opportunities. The need to maintain good environmental status of the lake was also recognised in relation to the economic potential of the lake and multiple users.

The Windermere Lake Action Plan sets out a range of activities aimed at improving the local environment and visitor experience [170]. These actions, which support the future economic vision for Windermere, focus on improving visitor offers around the lake which do not require a car, improving access to the lake, managing lake swimming and improving resilience of public infrastructure and the state of natural capital. These actions were a direct response to address the vulnerability local business experienced after the 2015 flood events. In addition, low water levels during dry periods have affected the use of the lake for commercial and recreational boating, which has significant implications for the number of visitors. A change in demand from lake users has also been observed through the increase in swimming activities. Finally, there is a consensus across all local stakeholders that issues of water quantity (floods and droughts) and quality need to be addressed by increased resilience. From the perspective of water pollution, the remaining challenges include managing diffuse pollution, combined sewer overflows and seasonal variation of sewerage discharges due to the changing level of tourist visits.

While the highest income in Windermere comes from tourism, the agricultural sector and food production play their role in the local economy. The analysis of hill farms within the Lake District National Park has showed a decrease in the number of farms, while farms have increased in size [171]. Only 9% of land is arable and a further 9% is used for pigs, poultry and dairy farming, with predominant activities on 82% of land focused on livestock grazing (dairy cows, beef cows, breeding ewes and horses). A decline was observed in the sheep population, while the woodland area is still around 3% of agricultural land. Overall, a decline in stock numbers led to a significant decline in grazing intensity. The report emphasised that an increasing price of feed coupled with any further decline in the price of milk, as well as a potential increase in fertiliser price, could pose significant threats to farmers' income. The analysis showed that most hill farms are highly dependent on subsidy (Single Farm Payments[1]) with 50% of them losing money from their farming activities. The study has also emphasised the role of CARE (conservation, amenity, recreation and environment) payments[2] as a key income that supports farmers' livelihoods.

C.1.2 Impacts on Windermere lake water quality

The main source of lake pollution is assumed to come from sewage discharges. United Utilities (UU) has 9 wastewater treatment works (WwTW) and 2 pumping stations (PS) that are discharging directly or indirectly into Windermere [172]. Out of the 11 assets, Windermere WwTW (30% P load) and Glebe Road PS (27% P load) were estimated in 2013 to contribute more than a half of UU's phosphorus load to the lake. In total, UU's assets were estimated to contribute 56% of the total P load, compared to agricultural

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[1] Agricultural subsidy paid to farmers in the EU. The payment subsidies famers on a per-hectare basis.

[2] State subsidy aimed at producing CARE goods through funding to farmers/landowners.

(25%) and private (19%) discharges. In March 2020, UU completed major schemes at all 3 of its assets which discharge directly to the lake. These schemes were designed to reduce the phosphorus load to the North Basin by 22% and the South Basin by 65% in order to deliver satisfactory water quality. The Windermere Reflections project (2011 to 2014) encouraged residents, businesses and boating and physical land use conservation and education to reduce P load. In addition, measures have been implemented to address agricultural sources of P by a programme of farm visits in recent years. Finally, a range of interventions to address point sources of P across the catchment has been implemented, including additional monitoring to ensure permit compliance and septic tank upgrades and site connection to the sewer network. However, the report emphasises that in order for Water Framework Directive standards to be achieved, all sectors need to reduce their P contribution, including private discharges and agriculture.

C.2 Water quality from a systems perspective

To explore a range of additional options for addressing the lake water quality problem, we present here a systematic review and analysis of key factors that may influence the lake water quality. We include a range of scientific literature that, although not directly relevant for the Windermere lake system, gives us a broad overview of systems impacts and water quality management options that local stakeholders may want to explore in more detail in future studies.

C.2.1 Lake water quality and human impacts

The impact of nutrient loading on water quality is a well-known issue. Key pollutants to surface waters (lakes) are nitrogen (N) and phosphorus (P), both of which are exacerbated by human activities. As a result, a process of eutrophication occurs, leading to algal blooms, which have a significant impact on aquatic food systems and ecosystem service provision [50]. More broadly, it is important to emphasise the need to understand the N and P cycles holistically, that is the change of N and P loads in soils, air and water.

The main sources of N and P are human activities, such as farming, agricultural production and land use intensification [50]. Treated wastewater is also a common source of the pollution load. The increase in the N load in the aquifers draining from agricultural land, as well as releases of N and P from the bottom of sediment also provide sources of nutrients. Finally, run-off from urban areas and plantation forestry can add to total nutrient load. All this implies that it is necessary to understand natural and human processes that affect the transfer of pollution through the system (so-called ‘direct drivers). These include (i) fertiliser use on croplands, (ii) livestock and land management, (iii) industrial processes, (iv) wastewater management and (v) fossil fuel combustion.

Most applied fertiliser is typically absorbed by crops and removed when harvested, with around 20% being lost to the environment [173]. The excess nutrient flow from leaching and run-off from agricultural land varies greatly depending on the type of soil, with low rates of <5% for clay-loam soils up to a value of >80% for fields on clay soils. Waste from animal feeding, which provides a significant source of nutrients, is typically spread on agricultural fields or held in lagoons. At the same time, animal manure that could be used as a fertiliser has not been fully utilised due to the uncertainty in application timing and spread. Coupled with the low prices of synthetic fertilisers, this results in over fertilisation in the areas near animal feeding operations. The role of nutrient loading is particularly important at a global scale, where the highest food exporters (Brazil, China, India and the United States) account for more than 50% of the estimated global P and N use [174]. While this has significant consequences for local water quality in these countries, the pollution that results from food consumption and disposal could also have consequences for those countries importing food.

Fossil fuel combustion produces N in oxidised form, which is typically deposited onto the landscape as rain or dry deposition [173]. From there, through catchment land processes, the pollution is spread to surface water bodies and ultimately to lake and/or coastal regions. Data from California have showed that atmospheric depositions over natural land could be as high as 132 Gg N per year, which is almost 30% of the synthetic fertiliser use of 466 Gg N per year [175]. Most of this pollution comes from mobile sources, including transport and energy production. In addition, industrial activities could also significantly contribute to nutrient loading. The research focused on coastal zones in western and southern Europe showed that traditional processes used in textile and paper industries could have been one of the main sources of water pollution in coastal zones [176].

Key P flows from cities depend on the size, industry, infrastructure and stage of urban development, with discharges from wastewater being typically the largest part of the flow [13]. In addition, fossil fuel combustion deposition could play a significant role through road run-off [173]. Finally, aspects of food consumption need to be considered here too. Studies of 2 megacities in northern China found that between 64 and 72% of urban P flow is imported through food consumption and remains in the local system as sludge in landfills or organic fertilisers [177].

In many urban environments, septic tanks are used as an on-site sanitation option. In Hanoi, Vietnam, for example, septic tank effluents are discharged in the sewerage system, while the collected sludge is usually landfilled [178]. The study showed that replacing septic tanks with urine diversion latrines increases the percentage of P in waste products that could be recovered by food production by 27%, while the discharged P load reduces in the septic tank effluent. In addition, septic tanks could pose a significant impact on health due to the content draining into the surrounding areas, which is directly linked with the emptying, transportation and treatment of faecal sludge from latrines not being adequately managed [179]. In addition to new emptying technologies such as mechanical emptying services, the role of regulation in coordinating the services, and the need for monitoring and financial resources to support local authorities have been identified as necessary measures to improve the faecal sludge management in Bangladesh.

In addition to direct drivers of N and P increase in the catchment, it is important to understand the broader aspect of nutrient generation. This could be done by analysing nitrogen and phosphorous mass balances, which could help us to better understand the stocks and flows of nutrients within the analysed system [13], [180]. Taking a broader view on nutrient use problems shows that mining practices and dietary preferences (in particular meat and dairy products), and fundamentally population growth have a large impact on P use [13].

Finally, analysing the N cycle through a sequence of effects of the N cascade showed that as a result of human activities, approximately 15% of reactive nitrogen is emitted into the atmosphere. Food systems process around 75% of N, which is transferred either into the atmosphere or water systems or absorbed by food production and consumption. Finally, 10% of N is typically used in industrial processes [180]. This points to measures in both the food and energy sectors that may have a significant (positive or negative) impact on N propagation through the system, and the need to better understand underlying drivers of N and P pollution.

C.2.2 Water quality and economic activities

To understand the use of nitrogen and phosphorous in a system, in addition to direct drivers, we also need to identify underlying economic, political, technological and behavioural factors that influence the propagation of pollution within a catchment system. The assessment of N use decisions in California found that the global increase in food demand and per capita income has resulted in the expansion of agricultural production in the region, which mainly produces food for export [175]. Furthermore, the increase in fertiliser use has been linked with the long-term decline in fertiliser prices, while local population growth resulted in the increase of non-agricultural activities that contribute to the N load. Finally, the value of housing development caused changes in land use and prices, while targeted polices had a small effect on nitrogen flows. In the Windermere catchment, it has been shown that the growth of tourism in the area is the most significant factor influencing pollution increase and impact on algal communities in the lake [167].

Tourism and link to water management

As an economic sector tourism contributes significantly to the global economy. Data show that in 2015 tourism contributed 9.8% of global GDP (US$7.2 trillion), creating 9.1% of jobs worldwide. There is also evidence that developing an area for tourism benefits local people through the increase in public infrastructure investments and poverty alleviation [181]. It also inspires actions to minimise the impact on the environment though initiatives such as ecotourism [182]. A large part of tourist activities are linked with the emerging sector of nature-based tourism [183], which opens debate about the link between the economy and the environment.

Tourist activities, however, have a negative impact on the local vegetation landscape [184] and ecosystem service supply [81], some of which directly underpin tourism and other aspects of the regional economy [185]. Tourism could also have negative socio-economic aspects, in particular from the perspective of local residents. These include the seasonal nature of work and an increase in living costs [186]. Finally, the tourism sector is vulnerable to climate change, which could have significant consequences for future economic growth [187]. It is clear that achieving sustainable livelihoods in the tourism-based systems needs to ensure a balance between the number of visitors, economic benefits to the local population and environmental protection of the region [188]. The question remains how can we maintain economic benefits from this important economic sector, while minimising impacts on the local environment? Multiple tourism aspects can be linked with impacts on water quality, and more broadly other water management aspects (Table 11).

Table 11 Selection of factors linking tourism, lake water quality and other water management aspects

Ref.	Tourism aspect	Tourism demand
[81]	Cause/pressure	Annual visitation numbers; per tourist expenditure
	Impact/ consequence	Number of tourism attractions; investment in infrastructure; increase in per capita GDP
	Link to water quality	Increased demand for local food (crop and livestock) consumption and, therefore, pressure for agricultural pollution; increased demand for accommodation and, therefore, pressure from wastewater discharges
	Link to water management	Increased demand for local water resources, therefore, possible water stress; decrease in the level of system capacity to attenuate flow and capture CO_2 and, therefore, possible impact of flooding and CO_2 emissions
Ref.	Tourism aspect	Tourism activities
[189]	Cause/pressure	Tourist pressure index (TPI) as a function of accessibility to site and local facilities

	Impact/ consequence	Addition of nutrients and other chemicals; direct physical disturbance to sediment and vegetation
	Link to water quality	High TPI score relates to higher potential pressure from tourism (heavily visited systems), which increase tourism demand
	Link to water management	Potential implications for water abstractions
Ref.	Tourism aspect	Tourism activities
[67]	Cause/pressure	Swimming, fishing, motorised and non-motorised boating, snorkelling, sailing, diving, jet skiing and other
	Impact/ consequence	Motor emissions from marine motors (engine type); antifouling coatings on vessels; faecal matter and urine from humans and animals from boating; sun cream chemicals
	Link to water quality	Direct impact on lake water quality
	Link to water management	Potential implications for water abstractions
Ref.	Tourism aspect	Tourism water footprint at national level
[190]	Cause/pressure	Cross-sector interactions and supply chains in addition to direct water use and pollution
	Impact/ consequence	Tourism industries' direct water consumption; indirect consumption by domestic suppliers (for example, agriculture); embodied water through imports and trade
	Link to water quality	Indirect through embodied water use
	Link to water management	Important aspect of water footprint of domestic suppliers linked to water use

C.2.3 Lake ecosystem services and development

Lakes provide a range of ecosystem services (ES) directly supporting the tourism and recreation sectors, as well as other sectors and the general population [185]. Here, we briefly summarise the main ES and how they are linked with the problem of lake water pollution. We start with those directly linked to water management and expand to include a broader range of benefits for the environment and people.

In some parts of the world lakes provide a source of harvestable food, with a fisheries economy that could have a significant contribution to the local economy. Data from New Zealand show that this activity contributes around $200 million dollars a year [185]. The water in the lake has a capacity to mitigate some of the incoming contamination, in particularly nutrients, and lakes provide a range of hydrological regulation functions. Hydrological modification of rivers contributes to hydropower generation, while the stored water could equally be used as a source of water supply. Natural and artificial lakes in New Zealand are used for a variety of purposes, including aesthetic, flood control, urban stormwater control and recreation [185]. Lakes also provide benefits for biodiversity and climate change mitigation. All of these functions are significantly impacted by human activities, including land intensification, harvesting and modification of the hydrological regime. The lake environment is particularly important in terms of recreation, with activities that range from boating, swimming, kayaking and recreational fishing [185].

Modifications of the hydrological regime such as damming of lake outflows, diversion of water flowing into the lake and upstream abstractions can all have negative impacts on lake ES provision. In New Zealand, this is particularly linked with the expansion of the agricultural sector and dam construction for irrigation and water supply, emphasising the need for integrated catchment management.

C.2.4 Water quality management and control

A range of interventions to manage nutrient pollution can be broadly grouped into 2 categories: (i) technologies and practices, and (ii) policies and institutions. The nitrogen cascade approach has provided many useful insights into the possibilities for intervention in the system, including decreasing the rate of reactive N production and increasing its conversion to N [180], [191]. These include technologies for fossil fuel combustion process improvements, as well as the role of N efficiency in the food production process. They also include improved animal management strategies, nitrogen recycling, and providing incentives to reduce over fertilisation or nitrogen redistribution from high production to high consumption areas. Livestock and meat processing industries need to play their role in the N management system too. Finally, a change in people's eating habits, particularly the consumption of meat, would lead to reduced use of nitrogen for food production.

In California, management options included improvement in agricultural, industrial and transportation N efficiency, as well as manure management and improved monitoring [175]. From the policy perspective, a challenge of high (time and monetary) cost of technological practices was emphasised, as well as a need for cost-effective policies for N pollution reduction resulting from dairy operations. Finally, there is a need to better understand the level of economic benefits that would be achieved through nutrient emission reductions, the effectiveness of pollution control policies and the role of key non-agricultural economic sectors in the region. A range of different measures are discussed in more detail below and summarised in Table 12.

Table 12 Summary of selected measures to directly and indirectly manage lake water quality

No	Intervention	Example	Ref.
1	Limitation of P and N load	Nutrient load targets and aluminium sulphate dosing	[50]
2	Agricultural productivity and nutrient efficiency	Using soluble P spray and low P demand crops	[77], [192]
3	Improved animal management strategies	Preventing over fertilisation though nutrient balance programmes	[180], [191]
4	N recycling	Diversification of nutrient sources, leading to less dependence on global markets	[180], [191]
5	Incentives to reduce over fertilisation	Crop yield insurance	[193]
6	Ownership status of faecal sludge collection business	Public-private partnership	[194]

7	Geo-engineering	Intervening in the lake's internal biogeochemical cycles	[195]
8	Livestock and meat processing industries	Restricting P additive use in food products	[77]
9	Detergent industry	Reducing detergent P concentration	[77]
10	Changing society's eating habits	Reducing consumption of meat by food labelling and reducing food waste	[77]
11	Urban greening	Minimising fertiliser use, food and waste recycling and urban pollution purification	[77]
12	Wastewater treatment processes	Upgrading national standards to nutrient removal	[173]
13		Septic tank upgrade	[196]
14	Wastewater recycling	Wastewater reuse for crop irrigation	[197]
15	Sustainable recreation and tourism	Participatory integrated catchment management	[188]
16		Promotion of local consumption by tourism agencies	[198]
17		'Green' hotel construction	[199]
18		Use of transport run on biodiesel from locally sourced waste	[198]
19		Employment in local tourist businesses and cultural interactions with tourists	[182]
20		Education activities to enhance sustainable tour experiences	[200]
21		Environmental tax on pollution (air, water, waste)	[201]
22		Tourists' visiting and consumption tax	[201]

Direct interventions

Typically, the main way of controlling eutrophication is through the limitation of the P load. However, the dual limitation paradigm that advocates for both N and P limitation to phytoplankton growth has been tested and shown successful results for a case study of Lake Rotorua in New Zealand. The measures included catchment-wide interventions for nutrient load targets and aluminium sulphate dosing in 2 tributaries [50]. Analysing a range of mitigation measures to reduce diffuse agricultural nutrient loss in the UK emphasised the need for integrated direct measurements, nutrient budgeting and risk assessment and modelling to accurately assess the effectiveness of individual interventions. These measures included land use soil management, livestock, fertiliser and farm management, and farm infrastructure [62].

Nutrient application practices, such as spraying small quantities of soluble P may be more efficient than applying P to some soils [77]. In addition, using low nutrient demand crops such as genetically modified crops can significantly reduce the amount of pollution load [192]. While using these crops for food could pose significant challenges, they could be used as a source of biofuel production, therefore, contributing to energy security. Finally, voluntary mechanisms such as crop yield insurance may contribute to addressing the issue of over fertilisation near animal feed zones [193].

Research also shows that the success of common lake restoration measures (nutrient load reduction, lake flushing or biomanipulation) depend on the sources (spatial heterogeneity) in nutrient loading (point versus diffuse pollution) and hydrology (seepage versus drainage). Pollution load reduction has shown to be effective for all combinations of conditions, while biomanipulation success was constrained to seepage lakes with diffuse nutrient inputs. Flushing has proved to have a negative impact in lakes with nutrient point sources [202].

While the main approach to mitigating eutrophication is to reduce excessive external nutrient load, the research has shown that even if the measure was successfully implemented, the lake recovery process could be insignificant. A possible reason may be the internal cycling of P, for which the geo-engineering approach to intervene with biogeochemical cycles could be a way forward [195].

Most efforts to reduce P accumulation in the environment are focused on agricultural nutrient use efficiency and P recycling from waste. However, the research showed that population increase and eating habits, in particularly meat consumption, need to be addressed by encouraging behaviours that support low P lifestyles [77]. The measures could include food labelling information (products' P content or footprint) and promoting lower P diets by restricting P additive use by the food industry.

Urban sustainability will play a key role in sustainable nutrient management [77]. Urban greening should minimise fertiliser use, and green zones should be used as buffers for urban pollution run-off. At the same time, human and food waste can be used as a fertiliser in both urban and peri-urban zones. The discharges from wastewater treatment plants could be directly related to the amount of nutrient pollution by upgrading national standards of nutrient removal, potentially in catchment systems that significantly contribute to deterioration of water quality [173]. In systems with onsite sanitation systems, aspects of the faecal sludge collection business model have also been analysed in the literature. A particular area that was highlighted was the role of ownership status in business performance in Vietnam, which could affect sludge collection and transport service efficiency [194].

Finally, solutions such as wastewater recycling could directly contribute to the reduction of pollution load and provision of additional water supply. Four schemes, which combine wastewater for irrigation and nutrients at a regional scale with 3 sources of agricultural non-point source pollution, have shown that the combined recycling system satisfied irrigation water demand and significantly reduced the use of chemical fertiliser, while also achieving high removal efficiencies of pollutants [197]. Combined measures to improve the surface water quality were also tested in Cumbria, UK. These included constructing a small field wetlands system, together with improving a septic tank system [196]. Monitoring results showed that wetlands had an efficiency of 60% P removal, while the upgrade of septic tank systems reduced P and N fluxes within a range of 9 to 37%.

Indirect management options

From an ecosystem service perspective, it is clear that there is an obvious link between the health of the environmental system and the future prosperity of tourism and recreation. While this aspect adds additional complexity to the water management process, it also opens a range of opportunities for collaborative approaches that could be implemented to protect the catchment system from further degradation.

Research done in Canada focusing on the Lake Simcoe watershed environmental management proposed a 'Participatory Integrated Catchment Management' approach. This recommends that environmental considerations are fully integrated in tourism development practices, as well as impacts from tourism becoming part of environmental governance [188]. Their work identified some interesting results. In a set of online survey and interview questions, most local stakeholders that are linked to the tourism sector expressed a concern that government regulations made the business non-competitive. While they could clearly link the functioning environment with their business prosperity, they could give few examples of sustainability practices in their operations. The respondents saw solutions in low impact activities such as cycling, hiking and fishing. They also emphasised the role of current regulation that did not allow cottages on smaller plots to upgrade their septic tank systems because of the small property size. Finally, local stakeholders expressed the need for a sustainability practice toolkit supported by training for businesses. This would allow them to better understand how the interventions could both positively impact the environment and help their business.

From a tourism sustainability perspective, multiple approaches have been analysed. Ethical tourism focuses on influencing industry behaviour so that tourism management brings benefits to the local community [199]. Two aspects have been particularly emphasised – the role of travel operators and 'green' hotels. In the selection of destinations and marketing material holiday providers and tour operators should promote ethical consumption such as using local services, resources and products. In addition, the 'green' hotels, which encompass environmental principles such as interior design using recycled materials and reduction of energy and water consumption and waste, would, at the same time, have a positive impact on the environment and increase environmental awareness by influencing visitors' choices in local accommodation.

Similarly, the 'responsible tourism' concept promotes activities that enable economic growth while minimising impacts on the local environment [198]. Examples of initiatives that were awarded for their contribution to responsible tourism include responsible transport (bus services run on biodiesel from locally sourced waste cooking oil), tour operators promoting responsible tourism (employing local leaders and guides, and the use of small, local and family-run hotels, restaurants and facilities), carbon reduction initiatives by agencies (promoting direct flights and spending more days in destinations with lower carbon footprints), environmentally friendly accommodation (thermally insulated hotels that are heated with geothermal energy, also used to heat water and for flushing sanitation) [203].

Research has also looked at the link between ecotourism and conservation of ecosystem integrity [182]. While the concept promotes a minimal impact approach to tourism, success in the business has led to increased numbers of tourists and increased demand for agricultural land. At the same time, a positive link has been seen between direct employment in the tourism sector and environmental awareness, as well as indirect benefits associated with tourism such as cultural interactions with tourists and environmental awareness.

Visits by nature-based tourists can be particularly impactful on the local environment. This requires better understanding of the relationship between visitor usage, consequent impacts and management of that relationship [200]. In the context of regulating access to visitor areas, research shows that there is a need to better understand how to use resources sustainably while providing a satisfying visitor experience. Giving visitors an opportunity to participate in education activities has shown to be particularly successful in the context of sustainable tour experiences.

Finally, environmental taxation in China has proven to have a positive impact on the tourism economy and environmental management [201]. Environmental taxes are linked to criteria for air and water pollutants, solid wastes and noise. In addition, local government can collect tax for tourist scenic visitor locations and tourist consumption.

Tax collection is used as a mechanism to regulate profit of activities that put pressures on environment. Based on the argument that there is small demand price elasticity for most tourism. This implies that the potential increase in prices due to taxation will have a small effect on tourism demand. While potentially impacting short-term economic benefits, the regulation ultimately protects the local environment and, therefore, enables long-term business sustainability.

C.3 High-level water quality systems map

Based on the above analysis and steps explained in Chapter 3, a preliminary version of a lake water quality systems map for Windermere has been developed and is shown in Figure 17. The map is used for analysis of a range of potential interventions for lake water quality management presented in Chapter 4.

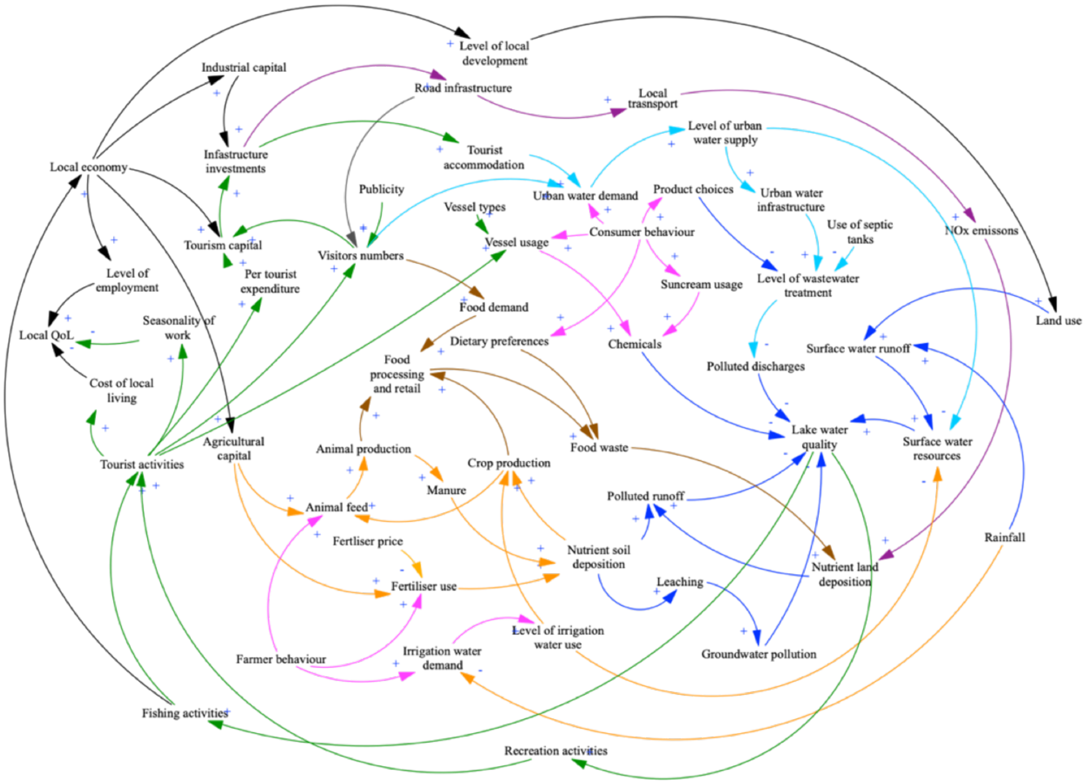

Figure 17 High-level version of the lake water quality systems map for Windermere

Abbreviations

25 YEP	25 Year Environment Plan
B	Balancing loop
BC	Biocapacity
CASYWat	Systems Water Management for Catchment Scale Processes
CCP	Cumbria Catchment Pioneer
CS	Catchment state
Defra	Department for Environment, Food and Rural Affairs
EEA	European Environment Agency
EEIO	Environmentally-extended input-output
EF	Environmental footprint
ENS	Environmental services
ES	Ecosystem services
GDP	Gross domestic product
HDI	Human Development Index
HMS	Human made services
HI	Human impacts
LDS	Local demand-supply
LE	Local economy
LWQ	Lake water quality
N	Nitrogen
NC	Natural capital
NERC	Natural Research Environment Council
P	Phosphorous
QoL	Quality of life
R	Reinforcing loop
RAE	Royal Academy of Engineering
RWM	Regional water management
SDGs	Sustainable development goals
SYWM	Systems Water Management
TPI	Tourist pressure index
UKNEA	UK National Ecosystem Assessment
UU	United Utilities
WF	Water footprint
WwTW	Wastewater treatment works

Glossary

Beneficiaries	Sectors directly depend on the environment through using resources. Their financial performance depends on a functioning environment and this can be significantly impacted by floods, droughts and water pollution.
Biocapacity	Defines capacity of a natural system to generate ecosystem services.
Catchment state subsystem	Defines the state of biophysical systems (water, land and climate) as basic components for analysing natural processes and water balance.
Ecosystem services	Ecosystems provide and sustain benefits for people through ecosystem service (ES) flows.
Environmental services subsystem (ENS)	Defines direct provision of ES through functioning of the local natural systems that cannot be imported.
Environmental footprint	Defines water and ecological (land) footprints as a measure of human demand on natural capital.
Human impacts subsystem	Defines the role of humans in changing the natural system in the context of water management.
Human made services subsystem (HMS)	Indirect provision of ES through infrastructure and land management.
Leverage points	Points of interventions in a system, including technological, management and policy, that create the biggest positive change in the system as a whole.
Local demand-supply subsystem	Defines demand for ES and use of the system through human needs such as water or food provision.
Local economy subsystem	Defines a direct link between water management and land decisions and the need to understand the role of key economic sectors and implications of their activities for system biocapacity.
Natural capital	Any stock of natural resources or environmental assets that contribute to the generation of goods and services of value for people.
Quality of life subsystem	Defines a direct driver of development as a combined effect of a level of economic growth and level of ENS provision.
Providers	Sectors that are primarily responsible for providing HMS.
SYWM framework	Holistic understanding of 7 subsystems (components) relevant for sustainability of coupled human-natural water systems.
SYWM meta-model	Core systems model that defines relationships between 7 SYWM components in the form of feedback loops.
Users	Citizens/general public that benefit from HMS provision in the form of a good quality of life and can be significantly impacted by floods, droughts and water pollution.

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