Understanding knowledge needs for Scotland to become a resilient Hydro Nation: Water stakeholder perspectives

Citation for published version:
Adams, KJ, Metzger, MJ, Macleod, CJA, Helliwell, RC & Pohle, I 2022, 'Understanding knowledge needs for Scotland to become a resilient Hydro Nation: Water stakeholder perspectives', *Environmental Science & Policy*, vol. 136, pp. 157-166. https://doi.org/10.1016/j.envsci.2022.06.006

Digital Object Identifier (DOI):
10.1016/j.envsci.2022.06.006

Published In:
Environmental Science & Policy

Environmental Science and Policy 136 (2022) 157–166

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Understanding knowledge needs for Scotland to become a resilient Hydro Nation: Water stakeholder perspectives

Kerr J. Adams[a,b,*], Marc J. Metzger[a], Christopher (Kit) J.A. Macleod[b], Rachel C. Helliwell[b], Ina Pohle[b]

[a] School of Geosciences, Institute of Geography, Drummond Street, Edinburgh, EH8 9XP, Scotland, UK
[b] The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland, UK

ARTICLE INFO

Keywords:
Freshwater resilience
Stakeholder participation
Systems-thinking
Future change
Policy

ABSTRACT

Freshwater resources provide ecosystem services that support human prosperity and development. Future changes in climate, land-use, and population could lead to detrimental impacts on freshwater quality and quantity, threatening drinking water, irrigation and energy production. To increase resilience there is the need to better understand the possible impacts of future changes on freshwaters. We use Scotland – and its legislative agenda 'Scotland: The Hydro Nation' – to understand the knowledge needs of water stakeholders as a first step in building freshwater resilience. By interviewing water stakeholders across Scotland, we found an overarching 'knowledge need' for a greater understanding of the cumulative impacts on freshwaters associated with the interactions between multiple climatic and socio-economic drivers and their associated pressures. Stakeholders also identified five specific 'knowledge need' themes; large-scale land-use change, future water demands, water value, integrated development planning and water asset conditions. We identify a willingness of stakeholders to participate in systems-thinking approaches to address these 'knowledge need' themes. The 'knowledge needs' can be used to inform research priorities to support water-related policy in Scotland. We propose that participatory methods should be applied following the Driver Pressure State Impact Response (DPSIR) framework to address 'knowledge need themes' to identify and appraise adaptive management and policy options. Our methods used to identify stakeholder knowledge needs are a time, cost and environmentally effective way for collecting rich data. Methods can be replicated in other regions and water policy contexts to understand where increased knowledge is required to help build future resilience.

1. Introduction

Freshwater resources provide vital ecosystem services that support human health and wellbeing, socio-economic growth and the natural environment (Rockström et al., 2014). The international importance of freshwater is highlighted by its direct relationship to two of the United Nations (UN) Sustainable Development Goals (SDGs): Clean Water and Sanitation (SDG6) and Life on Land (SDG15) (Schönhart et al., 2018). Freshwaters are also of indirect importance to other goals: No Poverty (SDG1), Zero Hunger (SDG2), Health and Wellbeing (SDG3) and Climate Action (SDG13) (Sprague, 2019; Bhaduri et al., 2016). The rooted significance of freshwaters within these goals emphasise their importance to human development from social, economic and environmental perspectives. Yet, growing demand for freshwater to enable prosperity and development has often resulted in the physical alteration of watercourses and the overconsumption of water resources (Cosgrove and Loucks, 2015). In the European Union (EU), around 60 % of surface water bodies fail to achieve good ecological status set by the EU Water Framework Directive (WFD) (Carvalho et al., 2019).

Future changes in climate, land-use, and population are likely to increase pressures on freshwater ecosystems to deliver vital ecosystem services. The water-energy-food (WEF) nexus approach describes the interactions between climate and socio-economic drivers and how they can affect freshwater environments (Endo et al., 2017). Failure to consider the interactions between climatic and socio-economic drivers could lead to over or under-estimations of their impacts on the water environment (Holman et al., 2016). Efforts to understand climate change impacts on freshwater should therefore be considered within the

* Corresponding author at: School of Geosciences, Institute of Geography, Drummond Street, Edinburgh, EH8 9XP, Scotland, UK.
E-mail addresses: kerr.adams@ed.ac.uk (K.J. Adams), marc.metzger@ed.ac.uk (M.J. Metzger), kit.macleod@hutton.ac.uk (C.(K.J.A. Macleod), rachel.helliwell@hutton.ac.uk (R.C. Helliwell), ina.pohle@hutton.ac.uk (I. Pohle).

https://doi.org/10.1016/j.envsci.2022.06.006
Received 19 February 2021; Received in revised form 11 January 2022; Accepted 6 June 2022
Available online 18 June 2022
1462-9011/

context of wider socio-economic and political changes. This requires a holistic evaluation of environmental impacts from multiple drivers, such as the Driver-Pressure-State-Impact-Response (DPSIR) Framework (EEA, 1999). DPSIR conceptualises the complexity of interactions between global change drivers and direct pressures on the environment – including freshwater – and has been used successfully to model global change impacts and adaptation options (Kagalou et al., 2012).

To plan for – and cope with – the potential future impacts on freshwater resources, policy and management solutions will have to be resilient (Escribano Francés et al., 2017). Resilient water management allows freshwater systems to bounce back and adapt to variability, uncertainty and transformation (Brown, 2015). As such, resilience refers to the capacity of a system to absorb disturbance and re-organise while undergoing change to retain the same function, structure, identity and feedbacks (Walker et al., 2004). For freshwater systems, this requires high levels of adaptability from stakeholders with a responsibility to manage the system. Stakeholder participation is therefore a fundamental requirement when considering how to increase the resilience of a system (Aldunce et al., 2016), and has the advantage of increasing the likelihood of adopting the policy options or management strategies (Conallin et al., 2017). There is a recognised need for better engagement practices to understand stakeholder needs when considering adaptive environmental management (Gramberger et al., 2015; Hewitt and Macleod, 2017). Despite the advantages of stakeholder participation their involvement in decision making is often limited to a consultative capacity during implementation stages (Reed, 2008), rather than taking into account their needs during problem framing or design stages.

To address this limitation, we aim to understand the knowledge water stakeholders need to increase the resilience of freshwater resources to the impacts of future change. We use the case study of Scotland to provide a national context of the importance of freshwater resilience in achieving relevant policy ambitions, with specific relevance to its legislative agenda, 'Scotland: The Hydro Nation'.[1] However, our methods and findings will be relevant for other regions wanting to increase the resilience of their water management in the face of global change.

2. Scotland the Hydro Nation

In 2013 the Scottish Parliament introduced the legislative agenda 'Scotland: The Hydro Nation' to support the Scottish Government's vision of Scotland as a leader in sustainable water resource management (Greig and Rathjen, 2021). The agenda aims to maximise the value of freshwater resources for the benefit of both the Scottish economy and the natural environment.

Scotland's freshwaters provide drinking water, irrigation for food production, cooling for distilling Scotch Whisky, habitats for iconic wildlife and intrinsic scenic landscapes which all contribute to the economic development, health and well-being, natural environment and cultural identity of the nation. The Hydro Nation agenda recognises the existing challenges for Scotland's 3,169 water bodies to achieve Good Ecological Status (GES) status under the EU WFD – for now still a requirement despite the UK's exit from the EU – and the increased emerging global change pressures impacting freshwater resources.

One of the key pressures is the increased frequency of flood events which have been attributed to increasing numbers of intense rainfall events due to climate change (Werritty et al., 2006). Annual rainfall increased by 27 % between 1961 and 2011, with average winter rainfall in the north of Scotland increasing by 51 % during the same period (ClimateXChange, 2017). Changes in land management, including agricultural intensification, have also contributed to increased flood events in the UK, e.g. by increasing soil compaction, and removing hedgerows and vegetation in upland regions, resulting in faster surface drainage of water run-off into river systems (O'Connell et al., 2007; Alaoui et al., 2018).

The frequency of droughts are expected to increase in certain regions of Scotland, particularly centrally and in the east, due to a combination of decreasing precipitation and increasing temperatures (Gosling, 2014). Increased air temperatures result in less snow accumulation, which also contributes to increasing water temperatures due to declining cooling properties of snowmelt (Pohle et al., 2019). The combination of higher water temperature and lower water flow results in a lack of dilution of elements and chemicals entering freshwater sources, resulting in lower concentrations of dissolved oxygen which negatively impacts freshwater ecology (Mosley, 2015; Nilsson and Malm-Renöfält, 2008). Furthermore, reduced water availability during periods of low flows and increased river temperatures can impact industrial, domestic and agricultural sectors (Middelkoop et al., 2001).

Point source and diffuse pollution are pressures on Scotland's freshwater environment. Point sources of pollution to water environments in Scotland come from wastewater, mining, industry, agricultural and fish farm discharges (Marsden and Mackay, 2001). Diffuse pollution sources mainly stem from agricultural land in the form of fertiliser and pesticide run-off and agricultural animal waste. Future changes in land-use could have an important influence on changes in diffuse pollution (Dunn et al., 2012). Both point and diffuse pollution can have detrimental impacts on water quality through the addition of heavy metals, pathogens, pharmaceuticals and macronutrients such as nitrogen and phosphorus. The introduction of these elements can be toxic to aquatic species (Luo et al., 2015) and result in the decrease of dissolved oxygen due to higher biological oxygen demands (BOD) (Ansari et al., 2010).

The intensity and severity of environmental changes are projected to increase in the future (Brown et al., 2011b; Dunn et al., 2012; Werritty and Sugden, 2012). If the Hydro Nation agenda is to achieve its aim of maximising the value of Scotland's freshwaters, it must recognise that freshwaters will need to be resilient to the impacts of future change to continue providing their valuable ecosystem functions.

Applying a proactive approach in understanding and resolving emerging issues, the Hydro Nation agenda aims to work collaboratively with water sector stakeholders and academia to co-construct and identify relevant research to develop water policy. To support the Hydro Nation agenda, our research aims to understand the knowledge needs of water sector and academia stakeholders. By understanding stakeholder knowledge needs our goal is to inform the identification of relevant research required to help achieve a resilient Hydro Nation.

3. Methods

3.1. Stakeholder interviews

We conducted stakeholder interviews to understand the knowledge needs of individuals with a relevant interest in Scotland's freshwater resources. We invited sixty-two stakeholders to participate in our interview process, of which twenty-seven (44 %) completed an interview, twenty-four (39 %) did not respond, five (8 %) rejected the request, four (6 %) provided a response which could not be included in the data analysis – including written responses or technical faults during interview recording – and two (3 %) declined but suggested an alternative stakeholder contact. Of the twenty-seven completed interviews, twenty-four individual interviews were carried out, while two interviews involved more than one participant from the same organisation. We conducted twenty-four (89 %) interviews via telephone interview and three (11 %) via face-to-face interview. The average recording time for the interviews was thirty-three minutes, the shortest interview lasted twenty minutes and the longest was eighty-three minutes.

[1] Further detail on the Scotland's Hydro Nation strategy can be found on the Scottish Government website: https://www.gov.scot/policies/water/hydro-nation/

A snowballing technique, where interview participants were asked to recommend stakeholders who may have been missed in the initial desk-based research, was used to identify and increase the number of relevant interview participants (Durham et al., 2014). The twenty-seven participating stakeholders represented a range of backgrounds associated with Scotland's freshwater resources, (Table 1), which are divided into seven categories and assigned unique identification codes based upon their responses when asked about their association with Scotland's freshwater landscape (Q2. Table 2). Please note that as Scottish Water, the main water utility in Scotland, is publicly owned and accountable to the Scottish Parliament, the knowledge needs of water utility stakeholders are represented in the water policy stakeholder category.

When possible, we conducted face-to-face interviews to build a rapport with the stakeholder, allowing for rich data to be collected (Irvine et al., 2013). But the majority of interviews were conducted by telephone as a time and cost-effective alternative (Novick, 2008), which we believed could increase the willingness of busy stakeholders to participate. Telephone and face-to-face interview methods followed the same questions and structure to achieve a consistent approach. Interviews followed a semi-structured process using a consistent set of interview questions (Table 2). A justification for selecting each question can be found in Supplementary Material (SMTable1).

When asking stakeholders to highlight the future drivers and pressures they believe will have the greatest impacts on Scotland's freshwater resources in the future (Q5 and Q6), the DPSIR framework was described to stakeholders as a structured way of considering potential future impacts (Henriques et al., 2015). We derived drivers from a review of peer-reviewed publications that detail the main drivers that lead to future uncertainties from environmental, ecological, governance and future business perspectives (Barthel et al., 2012; Alcamo et al., 2007; Lead et al., 2005; Wu et al., 2008; Dong et al., 2013; Haasnoot and Middelkoop, 2012; Henriques et al., 2015; Kebede et al., 2015; Zessner et al., 2017). From this literature review, we identified seven driver categories: economic, natural, social, governance & policy, technological innovation, land-use & management and population.

3.2. Data analysis

We transcribed interview recordings, which were then analysed using the qualitative data software package NVIVO (Bazeley and Jackson, 2013). Content analysis was conducted to identify knowledge needs following a three-stage inductive coding process (Fig. 1):

1. *Understanding context* **-** Initial coding of stakeholder roles (Q1), associations to Scotland's freshwater resources (Q2) and previous related research (Q3) to provide context to the response provided in later questions.
2. *Identifying knowledge needs* **-** Line-by-line coding of responses to the important research questions (Q4) and future scenario research (Q7). Coded responses were grouped to identify a set of knowledge need themes.
3. *Understanding knowledge needs* **-** Each knowledge need theme was then populated with relevant coded responses to questions: key drivers and pressures (Q5 & Q6), specific study area(s) (Q8) and time horizons (Q9). Populating the knowledge need themes allowed for a detailed interpretation of the individual knowledge needs.

Table 2
Stakeholder interview questions and their justification.

Question number	Question
Q1	Could you please detail your organisations association to Scotland's water resources?
Q2	Please describe the work you do that is relevant to Scotland's water resources?
Q3	Have you or your organisation worked, or are currently working, on scenario development? If so, please give details.
Q4	What are the important questions you believe need to be addressed to help Scotland's water resources become resilient to future change?
Q5	From the drivers provided, please tell me which three drivers you believe will have the greatest impact on Scotland's water resources in the future and why?
Q6	What are the pressures on water that will occur due to the top drivers you selected in the previous question?
Q7	What scenario research would you like to see conducted to better understand the future pressures on water you described previously? Please explain your response.
Q8	Do you believe the scenario research you describe should be carried out at a national or catchment scale? If catchment scale, could you suggest any Scottish catchments that would be suited for the future scenario research?
Q9	What time horizon do you believe to be most specific to scenario you describe?
Q10	Do you plan to use the new climate projections -UKCP18? If so, please explain how you plan on using them? If not, how would you like to see them used?

Stages 2 and 3 passed through three iterations by the author team to increase validity of the content analysis process (Graneheim and Lundman, 2004). The first iteration was conducted on an individual basis then presented to the author team. Second, the author team provided feedback on the first iteration and contributed findings of their own analysis during a content analysis workshop. Feedback and new findings were combined to finalise the analysis.

4. Results

One overarching 'knowledge need' and five more specific 'knowledge needs' were identified, as described in the sections below and illustrated with relevant coded quotes from the interviews. A full list of coded responses for all stakeholder 'knowledge need' themes can be found in Supplementary Material (SMTable 2). A network diagram illustrating the link between the overarching 'knowledge' need theme,

Table 1
Categories and unique identifiers for participating stakeholders.

Stakeholder Category	Category Definition	#	Abbreviated Category ID	Unique Stakeholder ID
Flood Risk Planning	Involvement in the development and implementation of flood plans to minimise risk.	2	FRP	FRP1, FRP2
Freshwater Management	Direct management of freshwaters, e.g. infrastructure and restoration.	3	FWM	FWM3, FWM4, FWM5
Freshwater Protection	Protecting and conserving freshwaters, e.g. monitoring and compliance.	7	FWP	FWP6, FWP7, FWP8, FWP9, FWP10, FWP11, FWP12
Land-Use Management	Active involvement in land-use activities that influence freshwaters.	3	LUM	LUM13, LUM14, LUM15
Water Industry	Reliance on freshwater to provide a good or service.	2	WI	WI16, WI17
Water Policy	Involved in setting and engaging with relevant freshwater policy.	5	WP	WP18, WP19, WP20, WP21, WP22
Water Research	Involvement in research projects related to freshwaters.	5	WR	WR23, WR24, WR25, WR26, WR27

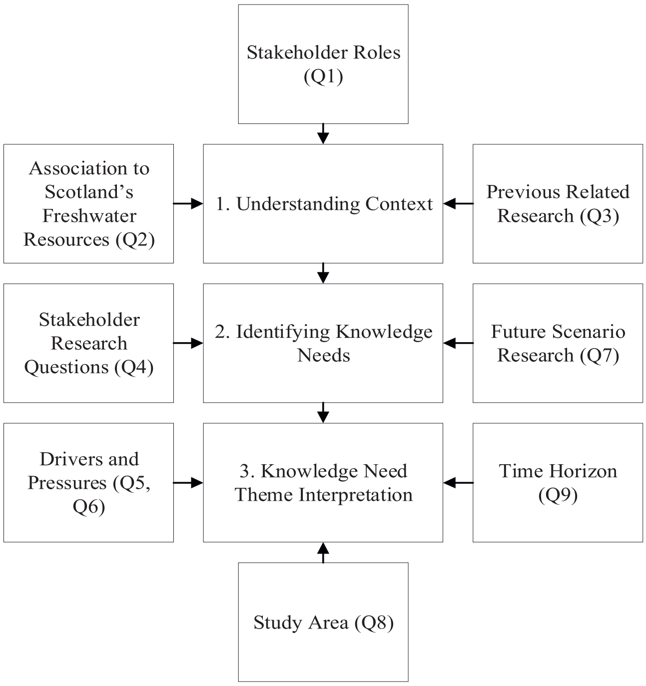


Fig. 1. Data analysis process, consisting of three stages: (1) Understanding context, (2) Identifying knowledge needs, and (3) Understanding knowledge needs.

the specific 'knowledge need' themes and the related drivers and pressures are provided in Fig. 2.

4.1. *Influence of multiple drivers overarching 'knowledge need'*

The need to better understand how the cumulative impacts of interactions between multiple future change drivers could influence freshwaters was identified as an overarching knowledge need, mentioned by 18 participating stakeholders in 37 coded responses. The impacts of individual drivers for change (e.g. the impacts of climate change on both future flood and drought events) are being addressed. But stakeholders highlighted the need to better understand the interaction between combinations of both climatic and socio-economic drivers and their cumulative impacts on Scotland's freshwaters, as exemplified by the following coded response:

> *"Of course, we have a load of systemic problems with climate change itself, we've done scenario testing on what we think catchments will do, what we think individual rivers will do, how surface water will change in terms of the intensity of storms into the future. What we're trying to do is bring an understanding of all those things together, to think each of those things won't be felt equally and getting you head around what all that means individually is quite difficult, but how those things interact with each other is more complicated.". -FRP1.*

4.1.1. *Large scale land-use change specific 'knowledge need'*

The need to better understand the impacts of large-scale land-use changes on flooding, water quality and water availability was mentioned by 15 stakeholders in 50 coded responses. Interactions between natural (climatic) and land-use change pressures including flooding, water pollution and water availability were identified. The investigation of land-use scenarios that encourage the re-introduction of more natural management options, such as the planting of riparian woodlands to attenuate flows and reduce water temperature, was highlighted as a knowledge need at a large catchment scale over long time-horizons of 50–80 years to reflect the time taken for natural processes to occur, for example, tree growth.

> *"It's all too easy to make generalisations about different land-use, habitats and land-cover and make general comments about what impact that might have on water quality, flow rates or water storage. We need more evidence to demonstrate on a big scale" -LUM15.*

4.1.2. *Future water demands specific 'knowledge need'.*

The need to better understand how future water demand might be

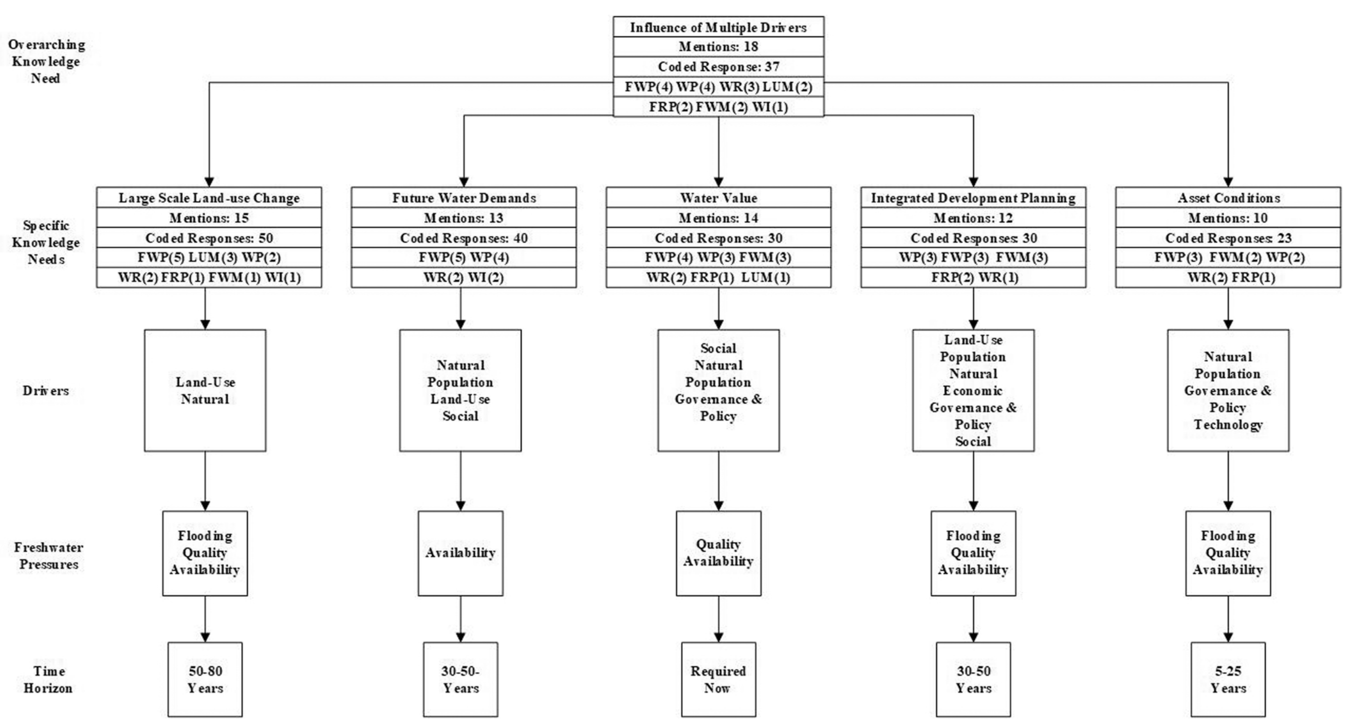


Fig. 2. Network diagram summarising the knowledge needs identified by stakeholders.

influenced by changes in multiple drivers was mentioned by 13 stakeholders, in 40 coded responses. Stakeholders described water demands as being influenced by multiple future changes such as climate, population and land-use, which could exacerbate the projected increased frequency of future drought events, particularly in summer months. Scenarios to understand how future water availability will change and how this will influence water allocations across competing industries are suggested. Understanding this need is required at the catchment scale in drought-prone areas of North East Scotland over a medium time-horizon of 30–50 years.

"we don't really have a picture of what future demands might look like and what new water use activities might be taking place here, that's important because it's telling you if there is going to be competition for something at the moment you think is quite plentiful." -WI17.

4.1.3. Water value specific 'knowledge need'

The need to better understand how the people of Scotland value their water resources was mentioned by 14 stakeholders in 30 coded responses. Due to the nature of the Scottish public water supply – where water supply and wastewater services are priced at a fixed rate, rather than metered – it is suggested that the people of Scotland might not be fully aware of the impacts their behaviours have on the water environment. The key driver for change was social interactions which lead to pressures on water quality and availability. The water value research should be carried out at a national scale and is not appropriate for a time-horizon as it should be carried out now the help guide future understanding.

"In terms of the important questions we believe need to be addressed, they all relate to how we use our water environment, how we use that resource and how we value it" -FWP6.

4.1.4. Integrated development planning specific 'knowledge need'.

The need to better understand how a more integrated approach in planning and design of urban areas can be achieved was mentioned by 12 stakeholders in 29 coded responses. An integrated development planning approach would involve increased partnership working between organisations involved in water management, infrastructure planning and investment planning. The main concern for stakeholders is the threat of flooding due to developments in flood plains as a consequence of future changes in land-use, population and climate. Scenarios of integrated development plans which consider flood risk and natural surface water run-off treatment options are suggested for urban catchments over a medium to long-term time-horizon of 30–50 years to reflect population and climate projections.

"coming together of different organisations and taking away our blinkers of our own infrastructure and thinking about how we work for Scotland plc and join that thinking together. Be creative and innovative, how can we actually create much better resilience within the Scottish infrastructure" -FWM5.

4.1.5. Asset condition specific 'knowledge need'

The need to better understand the resilience of the water industry and associated infrastructure assets to the impacts of multiple drivers was mentioned by 10 stakeholders in 23 coded responses. Changes in climate, population and land-use in urban areas could create stress on the water asset capacity, in both high-intensity rainfall and low-flow conditions, while the emergence of new water contaminants were identified as the key drivers and pressures. Scenarios to test how assets respond under intense changes to future conditions under differing investment options were described. The need to understand asset conditions in densely populated urban catchments at incremental short-term to medium-term 5–25 year time horizons was identified.

"The first thing is the actual supporting infrastructure, there are questions around how that needs to be re-designed in the future to build resilience" -WR26.

4.2. Drivers and their associated pressures

Stakeholders were asked about the pressures (Q6) and the associated drivers (Q5) they believe will have the greatest influence on Scotland's water resources in the future (Fig. 3, Table 3). The majority of responses considered water availability as a key future pressure mentioned by 12 stakeholders (17 coded responses) which is associated with natural (7), economic (4), population (2), land-use and management (1), social (2) and technological (1) drivers. Flood risk was mentioned by nine stakheolders (15 coded responses), associated with natural (7), land-use (4), population (3) and social (1) drivers. Water pollution was metioned by 10 stakeholders (14 coded responses), which was associated with land-use (6), natural (4), population (1), and economic (1) drivers. Other pressures include public awareness mentioned by five stakeholders (6 coded responses)) and investment in assets and research mentione bv five stakeholders (5 coded responses). Five stakeholders also considered positive impacts of future changes, including working with nature (5 coded responses) which are considered a potential opportunity to improve both water quality and quantity. Each of the key pressures mentioned by stakeholders are considered to result from multiple associated drivers for future change, emphasising the need to better understand the influence of future changes in combination, rather than in isolation. Coded responses for each of the pressures are provided in Supplementary Material (SMTable 3).

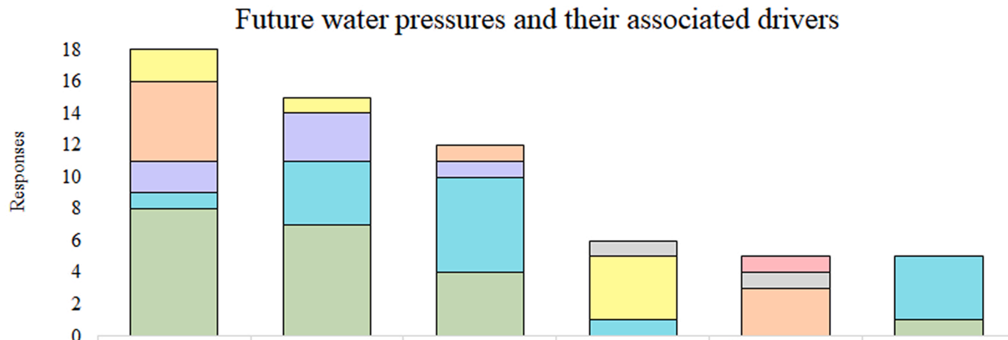
5. Discussion

During content analysis, the overarching 'knowledge need' – the need to better understand the cumulative impacts of the interactions between multiple climatic and socio-economic drivers – was identified by stakeholders. The 'knowledge need' is described as an overarching 'knowledge need' because the theme was discussed by stakeholders when describing the five specific 'knowledge need' themes. The consistent reference to the overarching knowledge need prompted the decision that inductive thematic saturation had been achieved and no new themes would be identified by conducting further interviews (Saunders et al., 2018).

The overarching 'knowledge need' is also evident when asking stakeholders to describe the key future change drivers and their associate pressures. For each of the three most frequently mentioned pressures – water availability, flood risk, and water pollution - multiple future change drivers are identified as a cause of the pressure. The association of multiple future change drivers emphasises the drivers interact to influence freshwater resources. It is the cumulative impacts of often complex interactions between future change drivers that stakeholders seek to better understand. Increasing knowledge of the cumulative impacts would assist stakeholders when identifying adaptive management and policy options to increase the resilience of freshwaters.

In the specific 'knowledge need' to further investigate the role of large-scale land-use change and the potential benefits of working with nature on larger scales, interactions between water pressures are evident (see SMTable2, Section 2). Restoring natural processes, such as increased forest cover to attenuate flows to enhance resilience to drought and flooding, at a large catchment scale was identified as a potential resilient solution to water availability, water pollution and flood risk pressures. Burton et al. (2018) discuss the benefits of woodland expansion for flood control, while appropriate management of riparian zones can improve stream water quality.

Interview responses (see SMTable 2, Section 3) related to the future water demands 'knowledge need' demonstrated that the influence of multiple drivers and their influence on future water demands was a



	Water Availability	Flood Risk	Water Pollution	Public Awareness	Investment in Assests & Research	Working with Nature (Positive)
Technology	1	0	0	0	1	0
Governance & Policy	0	0	0	1	1	0
Social	2	1	0	4	0	0
Economy	5	0	1	0	3	0
Population	2	3	1	0	0	0
Land-use	1	4	6	1	0	4
Natural	8	7	4	0	0	1

Pressure

Natural Land-use Population Economy Social Governance & Policy Technology

Fig. 3. Future water pressures and their associated drivers identified by stakeholders.

concern for several stakeholders. The future water demands 'knowledge need' relates to the pressure on water availability, which is often attributed to low-flow or drought events. Drought is considered to be a result of an increased frequency of extreme dry - due to a deficit in precipitation (meteorological), inadequate soil moisture (agricultural), or low surface and groundwater flow (hydrological) - which are projected to increase in Scotland due to climate change (Gosling, 2014). In addition to the influence of climate change, stakeholders identified the need to better understand how water demand would change with increased competition between industries and sectors that rely on freshwater resources for economic growth. Changes in climate and land-use are projected to change the demand and supply of water resources in Scotland (Allan et al., 2020; Brown et al., 2011a). Stakeholder responses also referenced changes in societal attitudes and population growth in terms of overconsumption of water could potentially exacerbate water availability issues (Dawadi and Ahmad, 2013; Dessai and Sims, 2010).

Multiple drivers for future change are also considered within the 'knowledge need' to achieve a more integrated development planning system. Pressures related to the current methods for development planning include the risk of increased flood events and poor water-use efficiency (see SMTable 2, Section 5). With the Scottish population expected to grow by 2.5 % by 2043 (NRS, 2019), the potential of 350 000 new homes by 2037 and the increasing intensity and severity of storm events, the number of homes at risk of flooding is predicted to increase (Rowland et al., 2019). Urban development and planning were identified as influencing pressures on water resource availability and the demand for water from both industrial and domestic sectors (Holman et al., 2016).

Considering the 'knowledge need' to understand the resilience of water assets to the interactions between future drivers was identified by stakeholders (see SMTable 2, Section 6). Determining how assets and infrastructure respond during extreme events, such as high-intensity rainfall events, needs to be assessed and the re-design of more resilient infrastructures considered. Extreme hydrological events pose a significant risk to critical infrastructure (McGrane et al., 2018) and investment is required to ensure their resilience to change. Stakeholder responses suggested levels of investment in water infrastructure may change in the future due to demands in different sectors, which could influence the resilience of assets. For emerging issues, such as new contaminants in water and wastewater, technological innovations were considered by stakeholders as potentially having a positive influence on alleviating pressures and are described in the literature as a key characteristic of adaptation (Heikkila et al., 2013).

For all the previously discussed specific 'knowledge needs', a catchment scale systems-thinking approach is recommended by stakeholders, which is evident in coded responses provided in results Section 4.1 by stakeholder FRP1 and results in section 4.2.4 by stakeholder FWM5. The desire for a systems-thinking approach is also evident in the Supplementary Material (SMTable 2), for example, coded responses 13.1-13.5 in Section 1 and coded response 4.1 in Section 5. Coded responses suggest the current management and planning carried out by stakeholders to address water issues are often done in isolation and more holistic systems thinking approaches are required to address catchment scale specific 'knowledge needs'. At the catchment scale, water is shared between competing stakeholders often dependant on access to quality water for activities such as food production and drinking water supply. Aquatic ecosystems also rely on quality water to function (Falkenmark et al., 2003). The interrelationships between competing stakeholders and ecological processes create complex socio-ecological systems.

Achieving a holistic systems-thinking approach involves engaging with and understanding the complexity of socio-ecological systems. Resilience has developed into a process for understanding socio-ecological system complexity, while measuring the capacity of the system to adapt and transform in the face of diverse pathways (Folke, 2016). Systems-thinking approaches are a method of engaging with complex interrelationships within socio-ecological systems, while also seen as critical in identifying resilient solutions that solve water resource problems (Aldunce et al., 2016; Falkenmark, 2017; Mirchi et al., 2012). We argue that research methods to address the stakeholder 'knowledge needs' should therefore adopt frameworks such as the WEF nexus and the DPSIR framework, which enable stakeholder participation in systems-thinking approaches and inform collaborative identification of adaptive management and policy options.

We recognise that holistic participatory approaches are often challenging to implement, particularly when regarding the conflicting

Table 3
Description of pressures and associated stakeholder responses.

Pressure	Description	Illustrative quote	Mentions
Water Availability	Future water scarcity from low-flow/drought events and the impacts this would have on competition between water-using sectors.	"Increased demand on water resources during drier periods when you've got less supply anyway. There's going to be increasing rationing of the resource between competing grants''-FWP7.	12
Flood Risk	Increasing flood risk is highlighted as a pressure due to concerns regarding the increasing frequency of extreme hydrological events, while the loss of natural land was also considered to have an impact on increasing flood risk.	"In terms of the impacts of flooding, regardless of what else you do, those numbers are pretty full-on, pretty scary where they're going. So that's one." -FRP1.	9
Water Pollution	Diffuse pollution from intensive agricultural processes. New or increased contaminants and the treatment costs to address these pollutants. Increasing water temperature was also considered as a potential source of pollution, which is also linked to water availability.	"….diffuse pollution next, in that we've obviously got clear targets at the moment for key delivery and in Scotland and elsewhere there are large parts of Scotland where there are adverse impacts from diffuse pollution." -WR27.	10
Public Awareness	The level of awareness and understanding the public of their impacts on freshwater resources and their awareness of future risks to freshwaters.	"Then also social is probably the one we should put further up our agenda because to the extent people don't perceive a problem they don't do anything about it. I think there is much more to do in the social space and I know Scottish Water is doing quite a bit of research. Why people use the water they do and the trends and the fact they don't know what the impacts are of their behaviour, there's a lot more in there to do."-WP22.	5
Investment in Assets & Research	Levels of investment in water industry assets, infrastructure technologies and research to address future impacts are described as potential pressures. Lower levels of investment due to the resourcing of other competing issues were a cause for future concern.	"Ensuring that there are funds available to address Scotland's water resources in the future, that's been a challenge anyway, so I think that's only going to get more difficult as there is going to be more demands on what we actually need money for."-FWP9.	5
Working with Nature (Positive)	Restoring natural processes and increasing natural areas is described as an indirect pressure to address potential pressures such as water pollution and flooding.	"we're keen to help rivers adapt to climate change by encouraging establishing and extending riparian woodland to some of our vulnerable watercourses to reduce temperature peaks and restore natural processes"-FWP10.	5

interests of stakeholders (Voinov and Bousquet, 2010). For successful implementation, participatory methods must demonstrate a change in stakeholder understanding and enable participating stakeholders to recognise their role and interactions with other stakeholders within the socio-ecological system (Reed et al., 2010). To overcome the challenges of implementation, we propose the application of combining participatory scenario development and modelling processes to address the overarching 'knowledge need' of stakeholders. The participatory methods would provide a common flexible framework for stakeholders to share knowledge and education, which is key when assessing complex socio-ecological systems (Macleod and Haygarth, 2010) and overcoming conflicting interests.

Our findings in Fig. 3. and Table 3 demonstrate that following the DPSIR framework helped stakeholders articulate and identify key pressures on water and their associated drivers. To build on this, we propose participatory scenario development - used to support adaptive decision-making within complex systems (Kebede et al., 2018) – as a structured method for engaging with the complex interactions between future change Drivers and Pressures. Within scenarios, the importance of considering both socio-economic and climatic change factors can be achieved by coupling both Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) (Holman et al., 2016). RCPs consider possible climate futures (Van Vuuren et al., 2014), while SSPs describe plausible changes in society (O'Neill et al., 2017). Methods for combining RCPs and SSPs include the scenario framework matrix described by Van Vuuren et al. (2014) which can be followed with diverse groups of stakeholders and scaled to create plausible catchment-specific scenarios. Creating plausible scenarios would provide a structured way for considering uncertainty associated with future pathways and allow stakeholders to address the overarching 'knowledge need' to better understand the cumulative impacts of the interactions between multiple climatic and socio-economic drivers. The participatory process would enable stakeholders to understand pressures on other stakeholders within the socio-ecological system, while also recognising shared pressures with others.

Participatory modelling processes can consider the State and Impact aspects of the DPSIR framework. Analytical tools such as System Dynamics, Bayesian Networks, Fuzzy Cognitive Mapping and Agent-based modelling can each support stakeholders in mapping, knowledge sharing and understanding complex systems (Voinov and Bousquet, 2010). Modelling the impacts of the multiple pathways on socio-ecological systems would lead to the identification of new knowledge regarding changing states and identified impacts. We propose participatory modelling as the identification of new knowledge could lead to attitude shifts and a more enriched understanding of shared future impacts with other stakeholders, providing stakeholders with their desired holistic systems-thinking approach.

The generation of new knowledge, the increased awareness of the interactions with other stakeholders and an understanding of shared issues would inform the Response aspect of the DPSIR framework. Modelling outputs would allow stakeholders to appraise adaptive management and policy solutions required to address future impacts and build resilience. Informed by the DPSIR framework, the participatory methods can invoke a change in stakeholder attitudes and facilitate the identification of adaptive management and policy options, increasing the likelihood of their adoption as described by Conallin et al. (2017).

Despite discussion of the overarching and previously identified specific 'knowledge needs' being in a Scottish context, the inherent need to better understand the cumulative impacts of multiple factors for global change can be applied internationally. Participatory scenario development and catchment modelling could also be applied internationally. Encouraging stakeholder participation and collaboration supports the findings of previous studies (Aldunce et al., 2016; Durham et al., 2014; Williams, 2011) who champion the importance of stakeholder engagement when co-designing projects and building resilience.

Water value was the only 'knowledge need' where a national scale study was mainly encouraged by stakeholders. The methods used to address the water value ‘knowledge need’ would therefore require a Scotland-specific approach. Social drivers and the way people interact with freshwater resources were identified by stakeholders as influencing both water quality and quantity (see SMTable 2, Section 4). Examples include poor water-use efficiency in the household, or poor waste disposal leading to water pollution. Stakeholders highlighted a combination of future changes could increase these impacts; such as the interaction between population growth and climate change resulting in increasing volumes of domestic water usage for recreational purposes during warmer summers (Dessai and Sims, 2010). Understanding how people value Scotland’s freshwater resources was seen as a potential way of identifying policy and management initiatives that increase awareness and influence a change in behaviours in water use to improve both quality and quantity. Stakeholders suggested that due to the majority of the Scottish population being charged for their water services at a fixed rate, how people in Scotland value their water resources may be different to populations who are charged at a metered rate. Although the fixed pricing method is not unique to Scotland, methods to address the water value ‘knowledge need’ would be best applied to the Scottish context only.

To address the water value ‘knowledge need’, we recommend a national scale mixed-method approach aimed at understanding household behaviour towards both domestic water resource consumption and wastewater services. Participants would be first asked to complete a questionnaire to gauge: (1) household understanding of tap water and wastewater life cycles, (2) estimates of their current water and wastewater consumption, (3) understanding of the impacts of their consumption and (4) how their demand for water services might change in the future. Following the questionnaire, participants would be asked to complete a water use calculator, following a similar process to the calculator used by Scottish Water.[2] The questionnaire and water usage calculator approach could help identify the nature of management or policy action required to improve household water resource efficiency and wastewater disposal. Comparing responses from the questionnaire and calculator concerning consumption would allow for investigation into disparities between perceived and actual household usage. Any disparities between perceived and actual water consumption could provide insight into user value of the water resource consumed at home, while identifying where increased user knowledge is required.

Our findings can be considered a first step in building resilience, as the ‘knowledge needs’ can be used to set research and funding themes in Scotland. Within the Scottish context, the Scottish Government use the Strategy for Environment, Natural Resources and Agriculture Research to fund a 5-year strategic research programme. Scotland’s Centre of Expertise for Waters (CREW) is an example of a research hub funded by the 5-year strategic research programme. CREW coordinates research activities across Scotland’s Higher Education Institutes, government and the water sector to support the development of water policy in Scotland (Greig and Rathjen, 2021). Our identified ‘knowledge needs’ can be used to inform research themes within research hubs such as CREW and funding bodies such as the Scottish Government. We therefore support the Hydro Nation agenda by co-constructing and identifying relevant research themes with water sector stakeholders, which can be used to inform water-related policy to help achieve a resilient Hydro Nation agenda.

By identifying the willingness of stakeholders to participate in holistic systems-thinking approaches we propose a process of participatory methods that should be inherent in addressing the ‘knowledge need’ themes identified. Responding to stakeholder ‘knowledge needs’ using our suggested participatory methods can support freshwater managers in bouncing back and adapting to variability, uncertainty and transformation caused by the cumulative impacts of future change leading to resilient freshwater management as described by (Brown, 2015). Research findings can inform and shape water policy to ensure a resilient Hydro Nation agenda that recognises the need for freshwaters to absorb the impacts of future change to continue providing their valuable functions.

Aspects of the specific ‘knowledge needs’ are considered in other policy contexts. In the latest call for ideas to inform the Scottish National Planning Framework, responses include the role of maximising nature-based solutions and achieving a more collaborative approach regarding both infrastructure planning and understanding infrastructure capacity (Scottish Government, 2020). Scotland’s National Water Scarcity Plan, which supports The Water Resources (Scotland) Act 2013, aims to strike the correct balance between competing resources, highlighting the importance of system resilience and the requirement of stakeholder collaboration in ensuring the availability of water resources (SEPA, 2020). The overarching ‘knowledge need’ can therefore be considered in future funding and research themes related to each of the mentioned policies.

Our methods used to identify specific stakeholder ‘knowledge needs’ can be replicated in other regions. Combining desk-based research with a snowballing technique was effective in identifying interview participants from a range of water stakeholder categories, achieving a 44 % response rate to interview invites. With the desire of many stakeholders to reduce carbon footprints to address the global climate emergency and our findings demonstrate that the use of telephone interviews is a time, cost and environmentally effective method for collecting rich data. Content analysis increased the validity of the results by having multiple investigators conduct their own separate analyses (Bengtsson, 2016). A process of member checking to increase the trustworthiness of results could have also been added to the data analysis process, such as methods used by (Behmel et al., 2018) to elicit water quality monitoring needs from stakeholders. Using a combination of semi-structured interviews and content analysis formed a systematic approach for understanding the ‘knowledge needs’ of stakeholders. Semi-structured interviews were important when building rapport with stakeholders to understand stakeholder ‘knowledge needs’, making interviews a preferable method in comparison to methods such a stakeholder surveys and stakeholder document analysis. By identifying stakeholder ‘knowledge needs’, we address the requirement for stakeholder engagement that facilitates and promotes the knowledge needs of stakeholders described by Hewitt and Macleod (2017) and Gramberger et al. (2015).

6. Conclusions

Our study supports the Hydro Nation agenda by co-constructing and identifying relevant research themes with water sector stakeholders and academia. Through 27 stakeholder interviews, we identified the overarching ‘knowledge need’ for greater understanding the cumulative impacts on freshwaters due to the interactions between future drivers and pressures. Five further specific ‘knowledge need’ themes identified were: large-scale land-use change, future water demands, water value, integrated development planning and asset conditions. The ‘knowledge need’ themes identified can be used to inform future policy relevant research. Stakeholders demonstrated a desire for improved systems-thinking approaches to better understand complex socio-ecological systems and enable knowledge sharing with other stakeholders. Participatory scenario and model development methods that follow the DPSIR framework and involve stakeholders at all stages of the decision-making process can play a significant role in responding to stakeholder calls for holistic systems-thinking approaches. Participatory approaches outlined can be applied to address stakeholder-identified research themes to inform the identification of adaptive water management and policy options to ensure a resilient Hydro Nation agenda. Our methods used to identify stakeholder ‘knowledge needs’ are time, cost and

[2] The Scottish Water, Water Usage Calculator can be found via the following link: https://www.scottishwater.co.uk/your-home/water-usage-calculator-page

environmentally effective and can be replicated in other regions as an initial step in identifying stakeholder knowledge needs to support the formulation of adaptive water-related management and policy options.

Ethics approval and consent to participate

All procedures performed in studies involving human participants were in accordance with the ethical standards were reviewed and accepted by the School of Geoscience Research Ethics and Integrity Committee at the University of Edinburgh. All participants consented to participate in the interview process and that their anonymised responses are made available through academic publication. Care has been taken to ensure that information in the manuscript and Supporting material does not reveal participant identity or information.

Funding

Scottish Funding Council, Hydro Nation Scholars Programme, 2018.

CRediT authorship contribution statement

Kerr J. Adams: Conceptualization, Methodology, Software, Resources, Data curation, Investigation, Writing – original draft, Project administration **Marc J. Metzger:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Christopher (Kit) J. A. Macleod:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision, Funding acquisition. **Rachel C. Helliwell:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Ina Pohle:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study is supported by the Hydro Nation Scholar Programme and funded by the Scottish Funding Council. The authors would like to thank the stakeholders who shared their knowledge and valuable time by kindly participating in the official interview process. We also give thanks to those who participated in the methods trial.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.06.006.

References

Alaoui, A., Rogger, M., Peth, S., Blöschl, G., 2018. Does soil compaction increase floods? a review. J. Hydrol. 557, 631–642. https://doi.org/10.1016/j.jhydrol.2017.12.052.

Alcamo, J., Florke, M., Marker, M., 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrol. Sci. J. 52, 247–275. https://doi.org/10.1623/hysj.52.2.247.

Aldunce, P., Beilin, R., Handmer, J., Howden, M., 2016. Stakeholder participation in building resilience to disasters in a changing climate. Environ. Hazards 15, 58–73. https://doi.org/10.1080/17477891.2015.1134427.

Allan, G.J., McGrane, S.J., Roy, G., Baer, T.M., 2020. Scotland's industrial water use: understanding recent changes and examining the future. Environ. Sci. Policy 106, 48–57. https://doi.org/10.1016/j.envsci.2020.01.005.

Ansari, A.A., Singh, G.S., Lanza, G.R., Rast, W., 2010. Eutrophication: Causes, Consequences and Control. Springer. https://doi.org/10.1007/978-94-007-7814-6.

Barthel, R., Reichenau, T.G., Krimly, T., Dabbert, S., Schneider, K., et al., 2012. Integrated modeling of global change impacts on agriculture and groundwater resources. Water Resour. Manag. 26, 1929–1951. https://doi.org/10.1007/s11269-012-0001-9.

Bazeley, P., Jackson, K., 2013. Qualitative Data Analysis with NVivo. Sage Publications Limited.

Behmel, S., Damour, M., Ludwig, R., Rodriguez, M.J., 2018. Participative approach to elicit water quality monitoring needs from stakeholder groups – An application of integrated watershed management. J. Environ. Manag. 218, 540–554. https://doi.org/10.1016/j.jenvman.2018.04.076.

Bengtsson, M., 2016. How to plan and perform a qualitative study using content analysis. Nurs. Open 2, 8–14. https://doi.org/10.1016/j.npls.2016.01.001.

Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., et al., 2016. Achieving Sustainable Development Goals from a Water Perspective. [Review]. Front. Environ. Sci. 4 (64) https://doi.org/10.3389/fenvs.2016.00064.

Brown, I., Dunn, S., Matthews, K., Poggio, L., Sample, J., et al.,. 2011a. [Online]. Mapping of water supply-demand deficits with climate change in Scotland: land use implications. Centre of Expertise for Waters (CREW) Report: James Hutton Institute, Aberdeen, Scotland. Available:⟨https://www.crew.ac.uk/sites/www.crew.ac.uk/files/sites/default/files/publication/Climate_change_and_water_demand-supply.pdf⟩.

Brown, I., Poggio, L., Gimona, A., Castellazzi, M., 2011b. Climate change, drought risk and land capability for agriculture: implications for land use in Scotland. Reg. Environ. Change 11, 503–518. https://doi.org/10.1007/s10113-010-0163-z.

Brown, K., 2015. Resilience, Development and Global Change. Routledge.

Burton, V., Moseley, D., Brown, C., Metzger, M.J., et al., 2018. Reviewing the evidence base for the effects of woodland expansion on biodiversity and ecosystem services in the United Kingdom. For. Ecol. Manag. 430, 366–379. https://doi.org/10.1016/j.foreco.2018.08.003.

Carvalho, L., Mackay, E.B., Cardoso, A.C., Baattrup-pedersen, A., Birk, S., et al., 2019. Protecting and restoring Europe's waters: An analysis of the future development needs of the water framework directive. Sci. Total Environ. 658, 1228–1238. https://doi.org/10.1016/j.scitotenv.2018.12.255.

Conallin, J.C., Dickens, C., Hearne, D., Allan, C., 2017. Stakeholder Engagement in Environmental Water Management. In: Horne, A.C., Webb, J.A., Stewardson, M.J., Richter, B., Acreman, M. (Eds.), Water for the environment. Academic Press. https://doi.org/10.1016/B978-0-12-803907-6.00007-3.

Cosgrove, W.J., Loucks, D.P., 2015. Water management: current and future challenges and research directions. Water Resour. Res. 51, 4823–4839. https://doi.org/10.1002/2014WR016869.

Dawadi, S., Ahmad, S., 2013. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. J. Environ. Manag. 114, 261–275. https://doi.org/10.1016/j.jenvman.2012.10.015.

Dessai, S., Sims, C., 2010. Public perception of drought and climate change in southeast England. Environ. Hazards 9, 340–357. https://doi.org/10.3763/ehaz.2010.0037.

Dong, C., Schoups, G., Van De Giesen, N., 2013. Scenario development for water resource planning and management: a review. Technol. Forecast. Soc. Change 80, 749–761. https://doi.org/10.1016/j.techfore.2012.09.015.

Dunn, S.M., Brown, I., Sample, J., Post, H., 2012. Relationships between climate, water resources, land use and diffuse pollution and the significance of uncertainty in climate change. J. Hydrol. 434–435, 19–35. https://doi.org/10.1016/j.jhydrol.2012.02.039.

ClimateXChange. 2017. Precipitation Headlines [Online]. ClimateXChange. Available: ⟨https://www.climatexchange.org.uk/media/1918/precipitationreport_cxc.pdf⟩.

Durham, E., Baker, H., Smith, M., Moore, E. & Morgan, V. 2014. *The BiodivERsA Stakeholder Engagement Handbook*. BiodivERsA, Paris (108pp).

EEA 1999. Environmental indicators: Typology and overview. Technical report No 25. [Online]. EEA, Copenhagen: European Enviornmental Agency. Available: ⟨https://www.eea.europa.eu/publications/TEC25⟩.

Endo, A., Tsurita, I., Burnett, K., Orencio, P.M., 2017. A review of the current state of research on the water, energy and food nexus. J. Hydrol.: Reg. Stud. 11, 20–30. https://doi.org/10.1016/j.ejrh.2015.11.010.

Escribano Francés, G., Quevauviller, P., San Martín González, E., Vargas Amelin, E., 2017. Climate change policy and water resources in the EU and Spain. a closer look into the water framework directive. Environ. Sci. Policy 69, 1–12. https://doi.org/10.1016/j.envsci.2016.12.006.

Falkenmark, M., 2017. Water and human livelihood resilience: a regional-to-global outlook. Int. J. Water Resour. Dev. 33, 181–197. https://doi.org/10.1080/07900627.2016.1190320.

Falkenmark, M., Folke, C. & Falkenmark, M. 2003. Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges. 358, 2037–2049.

Folke, C. 2016. Resilience (Republished). *Ecology and Society,* 21.

Gosling, R., 2014. Assessing the impact of projected climate change on drought vulnerability in Scotland. Hydrol. Res. 45, 806–816. https://doi.org/10.2166/nh.2014.148.

Gramberger, M., Zellmer, K., Kok, K., Metzger, M.J., 2015. Stakeholder integrated research (STIR): a new approach tested in climate change adaptation research. Clim. Change 128, 201–214. https://doi.org/10.1007/s10584-014-1225-x.

Graneheim, U.H., Lundman, B., 2004. Qualitative content analysis in nursing research: concepts, procedures and measures to achieve trustworthiness. Nurse Educ. Today 24, 105–112. https://doi.org/10.1016/j.nedt.2003.10.001.

Greig, B., Rathjen, J., 2021. Scotland the 'Hydro Nation': linking policy, science, industry, regulation in Scotland and internationally. Handb. Catchment Manag. 2e, 339–358. https://doi.org/10.1002/9781119531241.ch13.

Haasnoot, M., Middelkoop, H., 2012. A history of futures: a review of scenario use in water policy studies in the Netherlands. Environ. Sci. Policy 19–20, 108–120. https://doi.org/10.1016/j.envsci.2012.03.002.

Heikkila, T., Gerlak, A.K., Bell, A.R., Schmeier, S., 2013. Adaptation in a transboundary river basin: linking stressors and adaptive capacity within the Mekong River

Commission. Environ. Sci. Policy 25, 73–82. https://doi.org/10.1016/j.envsci.2012.09.013.

Henriques, C., Garnett, K., Weatherhead, E.K., Lickorish, F.A., Forrow, et al., 2015. The future water environment — using scenarios to explore the significant water management challenges in England and Wales to 2050. Sci. Total Environ. 512–513, 381–396. https://doi.org/10.1016/j.scitotenv.2014.12.047.

Hewitt, J.R., Macleod, J.A.C., 2017. What do users really need? participatory development of decision support tools for environmental management based on outcomes. Environments 4. https://doi.org/10.3390/environments4040088.

Holman, I.P., Harrison, P.A., Metzger, M.J., 2016. Cross-sectoral impacts of climate and socio-economic change in Scotland: implications for adaptation policy. Reg. Environ. Change 16, 97–109. https://doi.org/10.1007/s10113-014-0679-8.

Irvine, A., Drew, P., Sainsbury, R., 2013. 'Am I not answering your questions properly?'clarification, adequacy and responsiveness in semi-structured telephone and face-to-face interviews. Qual. Res. 13, 87–106. https://doi.org/10.1177/1468794112439086.

Kagalou, I., Leonardos, I., Anastasiadou, C., Neofytou, C., 2012. The DPSIR approach for an integrated river management framework. a preliminary application on a Mediterranean Site (Kalamas River -NW Greece). Water Resour. Manag. 26, 1677–1692. https://doi.org/10.1007/s11269-012-9980-9.

Kebede, A.S., Dunford, R., Mokrech, M., Audsley, E., Harrison, P.A., et al., 2015. Direct and indirect impacts of climate and socio-economic change in Europe: a sensitivity analysis for key land-and water-based sectors. Clim. Change 128, 261–277. https://doi.org/10.1007/s10584-014-1313-y.

Kebede, A.S., Nicholls, R.J., Allan, A., Arto, I., Cazcarro, I., et al., 2018. Applying the global RCP–SSP–SPA scenario framework at sub-national scale: a multi-scale and participatory scenario approach. Sci. Total Environ. 635, 659–672. https://doi.org/10.1016/j.scitotenv.2018.03.368.

Lead, C., Nelson, G.C. & Bennett, E. 2005. Drivers of change in ecosystem condition and services. *In: Ecosystem and Human Well-Being: Scenarios: findings of the scenarios working group*, 2, 172–222. Millenium Ecosystem Assessment, Island Press.

Luo, X., Yan, Q., Wang, C., Luo, C., Zhou, N., et al., 2015. Treatment of ammonia nitrogen wastewater in low concentration by two-stage ozonization. Int. J. Environ. Res. Public Health 12, 11975–11987. https://doi.org/10.3390/ijerph120911975.

Macleod, C.J., Haygarth, P.M., 2010. Integrating water and agricultural management under climate change. Sci. Total Environ. 408, 5619–5622. https://doi.org/10.1016/j.scitotenv.2010.02.041.

Marsden, M.W., Mackay, D.W., 2001. Water quality in Scotland: the view of the regulator. Sci. Total Environ. 265, 369–386. https://doi.org/10.1016/S0048-9697(00)00677-X.

McGrane, S.J., Allan, G.J. & Roy, G. 2018. [Online}. Water as an economic resource and the impacts of climate change on the hydrosphere, regional economies and Scotland. *Fraser of Allander Economic Commentary*, 42, 53–74. Available: ⟨https://strathprints.strath.ac.uk/66335/1/FEC_42_4_2018_McGraneSJAllanGJRoyG.pdf⟩.

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., et al., 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine Basin. Clim. Change 49, 105–128. https://doi.org/10.1023/A:1010784727448.

Mirchi, A., Madani, K., Watkins, D., Ahmad, S., 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour. Manag. 26, 2421–2442. https://doi.org/10.1007/s11269-012-0024-2.

Mosley, L.M., 2015. Drought impacts on the water quality of freshwater systems; review and integration. Earth-Sci. Rev. 140, 203–214. https://doi.org/10.1016/j.earscirev.2014.11.010.

Nilsson, C. & Malm-Renöfält, B. 2008. [Online]. Linking flow Regime and water quality in rivers: a challenge to adaptive catchment management. *Ecology & society*, 13, 18. Available: ⟨http://www.ecologyandsociety.org/vol13/iss2/art18/⟩.

Novick, G., 2008. Is there a bias against telephone interviews in qualitative research? Res. Nurs. Health 31, 391–398. https://doi.org/10.1002/nur.20259.

NRS 2019. Projected Population of Scotland 2018-based. [Online].]. National Records of Scotland. Available: ⟨https://www.nrscotland.gov.uk/files/statistics/population-projections/2018-based/pop-proj-2018-scot-nat-pub.pdf⟩.

O'Connell, P., Ewen, J., O'Donnell, G., Quinn, P., 2007. Is there a link between agricultural land-use management and flooding? Hydrol. Earth Syst. Sci. 11, 96–107. https://doi.org/10.5194/hess-11-96-2007.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., et al., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

Pohle, I., Helliwell, R., Aube, C., Gibbs, S., Spencer, M., Spezia, L., 2019. Citizen science evidence from the past century shows that Scottish rivers are warming. Sci. Total Environ. 659, 53–65. https://doi.org/10.1016/j.scitotenv.2018.12.325.

Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141, 2417–2431.

Reed, M.S., Evely, A.C., Cundill, G., Fazey, I., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C., Raymond, C., Stringer, L.C., 2010. What is social learning? Ecol. Soc. 15.

Rockström, J., Falkenmark, M., Folke, C., Lannerstad, M., Barron, J., Enfors, E., Gordon, L., Heinke, J., Hoff, H., Pahl-Wostl, C., 2014. Water Resilience for Human Prosperity. Cambridge University Press.

Rowland, C., Scholefield, P., O'Neil, A. & Miller, J. 2019. [Online]. Quantifying rates of urban creep in Scotland: results for Edinburgh between 1990, 2005 and 2015. Centre of Expertise for Waters (CREW): James Hutton Institute, Aberdeen, Scotland. Available: ⟨https://www.crew.ac.uk/sites/www.crew.ac.uk/files/publication/CRW2016_16_Urban_Creep_Main_Report.pdf⟩.

Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., et al., 2018. Saturation in qualitative research: exploring its conceptualization and operationalization. Qual. Quant. 52, 1893–1907. https://doi.org/10.1007/s11135-017-0574-8.

Schönhart, M., Trautvetter, H., Parajka, J., Blaschke, A.P., Hepp, G., et al., 2018. Modelled impacts of policies and climate change on land use and water quality in Austria. Land Use Policy 76, 500–514. https://doi.org/10.1016/j.landusepol.2018.02.031.

Scottish Government 2020. [Online]. National Planning Framework 4: Analysis of responses to the Call for Ideas. Scottish Government. Edinburgh, Scotland. Available: ⟨https://www.gov.scot/publications/npf4-analysis-reponses-call-ideas/⟩.

SEPA 2020. [Online]. Scotland's National Water Scarcity Plan. Scottish Environment Protection Agency. Available: ⟨https://www.sepa.org.uk/media/510820/scotlands-national-water-scarcity-plan-july-2020.pdf⟩.

Sprague, T., 2019. Building Resilience and Planning for Extreme Water-Related Events. Springer.

Van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., et al., 2014. A new scenario framework for climate change research: scenario matrix architecture. Clim. Change 122, 373–386. https://doi.org/10.1007/s10584-013-0906-1.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Softw. 25, 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007.

Walker, B., Holling, C.S., Carpenter, S.R. & Kinzig, A. 2004. [Online]. Resilience, Adaptability and Transformability in Social–ecological Systems. *Ecology and Society,* 9. Available: ⟨https://www.ecologyandsociety.org/vol9/iss2/art5/⟩.

Werritty, A., Sugden, D., 2012. Climate change and Scotland: recent trends and impacts. Earth Environ. Sci. Trans. R. Soc. Edinb. 103, 133–147. https://doi.org/10.1017/S1755691013000030.

Werritty, A., Paine, J.L., MacDonald, N., Rowan, J.S., McEwen, L.J., 2006. Use of multi-proxy flood records to improve estimates of flood risk: Lower River Tay, Scotland. CATENA 66, 107–119. https://doi.org/10.1016/j.catena.2005.07.012.

Williams, B.K., 2011. Adaptive management of natural resources—framework and issues. J. Environ. Manag. 92, 1346–1353. https://doi.org/10.1016/j.jenvman.2010.10.041.

Wu, S., Bates, B., Zbigniew Kundzewicz, A.W. & Palutikof, J. 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Zessner, M., Schönhart, M., Parajka, J., Trautvetter, H., Mitter, H., et al., 2017. A novel integrated modelling framework to assess the impacts of climate and socio-economic drivers on land use and water quality. Sci. Total Environ. 579 https://doi.org/10.1016/j.scitotenv.2016.11.092.