Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 14 No 3, 651 doi: 10.2166/wcc.2022.279

Adaptation strategies for climate change impacts on water quality: a systematic review of the literature

Jenelle A. Bartlett[a] and Ayşın Dedekorkut-Howes[b,*]

[a] School of Environment and Science, Griffith University, G31, 3.05. Nathan Campus, Queensland 4222, Australia
[b] Cities Research Institute, Griffith University, G31, 3.05. Gold Coast Campus, Queensland 4222, Australia
*Corresponding author. E-mail: a.dedekorkut@griffith.edu.au

ADH, 0000-0002-3844-4796

ABSTRACT

Climate change will impact water bodies and create significant challenges for natural resource managers. Despite the increasing impacts of climate change on water quality, the development and implementation of long-term strategic adaptation measures are seldom governmental priorities. So far, research has mainly tended to focus on the availability and volume of water rather than the quality. Comparatively fewer studies have considered adaptation strategies that deal with the uncertainties of the impacts of climate change on the quality of water bodies. This paper reports the results of a systematic review of literature on adaptation options and the barriers and drivers that can exert a positive or negative influence on their implementation. Findings suggest that there has been and continues to be a cautious approach to a growing concern for a natural resource of utmost necessity. Most of the strategies mentioned in the literature use coping or incremental approaches. However, adaptation strategies offering low levels of resilience for addressing water quality may not be up to the challenge of significant future climate changes.

Key words: adaptation strategies, barriers and drivers, climate change, systematic review, water quality

HIGHLIGHTS

- The impacts of climate change on water quality are increasing at an alarming rate.
- Still, most research is focusing on impacts on water supply, disregarding water quality.
- Similarly, there is an emphasis on adaptation strategies that address water security, with much fewer addressing water quality.
- Many of the adaptation strategies for water quality use coping or incremental approaches with scant evidence of transformational adaptation.

1. INTRODUCTION

There is consensus between scientists and policymakers that human-induced climate change is occurring, with substantial unavoidable impacts despite future reductions in greenhouse gas emissions (IPCC 2022). The consequences of climate change are geographically complex and are manifesting at regional and local scales. To reduce or prevent these consequences, we must lower our emissions. Such actions are referred to as *mitigation strategies*. However, climate change impacts are irreversible, and as we experience these effects, we must adapt to the new conditions. The IPCC (2022) describes these measures as *adaptation strategies* that must work across scales and address both the opportunities and risks arising from climate change. As mitigation responses have so far been limited, adaptation strategies have gained importance to respond to climate change and the impacts that it will have on local communities (Baker *et al.* 2012).

Water is a complex resource that not only supports human and ecosystem health and is essential for food and energy production and transportation services, but also provides cultural, aesthetic, and recreational values (Miller & Belton 2014). Khaniya *et al.* (2021) concur that water is central to the wellbeing of mankind and the functioning of sustainable ecosystems, and as such, any variations in climate can negatively impact the quality and availability of water resources. Therefore, as Cross & Latorre (2015) emphasise, it is important to develop necessary response mechanisms to protect public health and the environment.

To date, research has predominantly focused on the climate change impacts on the availability of water rather than its quality, despite the mounting evidence that water quality issues are of equal significance and concern (Coffey *et al.* 2014). While the availability of water is undoubtedly an important issue, there is also a need to direct attention to impacts on source water quality. Water quality compromised by climate change-related meteorological events can hinder the ability of conventional treatment systems to provide communities with quality drinking water (Levine *et al.* 2016).

As climate change impacts increasingly stress natural resources, water quality requires additional attention, as long-term strategies for preserving environmental services and public health fail to gain traction. To address this gap in the literature, this research aims to understand how we can better deal with the impacts of climate change on water quality and focuses on best practice adaptation strategies to the impacts of climate change on water quality in the peer-reviewed literature. Water quality is impacted not only by climate change but also by urban development and increasing population; however, it is almost impossible to separate the contribution of each. Regardless, the scope of this research is limited to climate change impacts. As such, strategies developed for holistic water management were excluded from this review in favour of those with a specific focus on water quality.

After briefly describing the methods used in this systematic review, we present the results. To assess adaptation strategies for climate change impacts on water quality, one must first identify the risks posed by climate change. So, we first examined how water will anticipate, absorb, adapt to, or recover from future climate change scenarios. Secondly, we distinguished the broad approaches to building resilience to climate change impacts as coping, incremental, or transformational to determine the level of foresight involved. Then, we studied each adaptation strategy in detail to categorise its approach and identify best management practices for water quality. Finally, we identified the factors that positively and negatively influence the implementation of these strategies to gauge a measure of potential implementation success. We anticipate that the identification of broad adaptation strategies may aid their translation to specific tangible actions at the local level.

2. METHODS

The key methodology we used is a Systematic Quantitative Literature Review (SQLR), following the procedures recommended by Pickering & Byrne (2014), a method used in similar research focusing on adaptation to sea-level rise and coastal flooding (Dedekorkut-Howes *et al.* 2020) and public engagement in climate adaptation (Khatibi *et al.* 2022). The review followed the protocols of the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) by Moher *et al.* (2009). A PRISMA Statement identifying the steps taken in the SQLR is summarised in Figure 1.

The Google Scholar and Scopus online databases were used to search English language, peer-reviewed academic literature, using the keywords 'climate', 'adaptation', and 'water quality' to identify relevant articles. In Google Scholar, the first 120 records of the 284,000 hits were screened for publication type excluding book chapters and grey literature. The contents of the selected records were then skimmed to determine their relevance to the topic, resulting in 39 papers selected for detailed assessment. A second Google Scholar search was undertaken with the same keywords in the title of the articles resulting in five additional papers. The Scopus database search of article title, abstract, and keywords produced 620 hits. The first 160 records by relevance were screened for publication type following the same procedures, resulting in 51 papers. A second Scopus search was undertaken limiting the search to the article title only adding another three papers to the database.

An initial review of the identified records showed that many lacked adaptation strategies. As a result, additional searches were undertaken in both databases using the search string ('climate' AND 'adaptation' 'water quality' '(strategies OR measures)'). These searches identified not only relevant literature on how water quality will be impacted by climate change but also adaptation strategies or measures.

After identification, screening, and assessment of eligibility, the records identified through the six different searches were amalgamated and duplicates removed. The resulting 111 records were then assessed in detail with only 78 identified as directly relevant to the research questions. These articles were coded in NVivo qualitative analysis software and are listed in the Supplementary Material.

2.1. Challenges

Discovering research that not only focused on impacts of climate change on water quality, but also recommended adaptation strategies, has proved challenging. At times, it was impossible to separate the impacts of other factors such as urban development and population growth. Furthermore, much research aggregates data on water availability with the quality of the

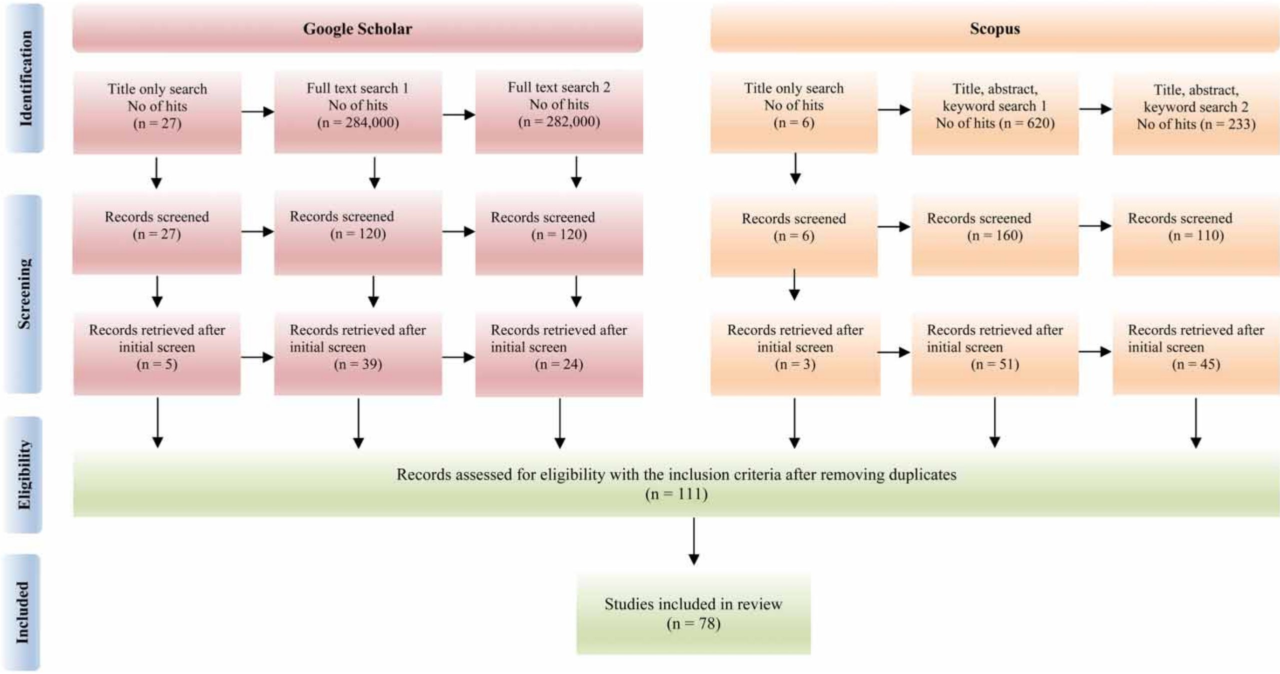

Figure 1 | PRISMA statement.

water. In the scant literature that focused on impacts of climate change on water quality, the emphasis was often on the data rather than recommended adaptation strategies. These factors significantly limited the literature relevant to this review. Due to the dearth of literature on the topic, the review was not limited geographically, temporally, or thematically. Water quality was examined holistically without differentiating the physical, chemical, and ecological indicators. The research also did not distinguish between the various types of water bodies and includes surface water, such as lakes, rivers, streams, and reservoirs, as well as groundwater.

3. RESULTS

The amount of research on climate change impacts on water quality has been gaining momentum in recent years. The SQLR identified the most concerning climatic changes anticipated to impact water quality, the approaches to building resilience to these impacts, and the adaptation strategies being proposed or adopted. Finally, it also discovered some of the barriers and drivers of the implementation of these adaptation strategies that would influence their measure of success.

3.1. Overview of the literature

The 78 articles included in the review were published in 50 different journals, as listed in the Supplementary Material. The majority of the articles were contained in meteorological journals (31%), followed by science journals (28%), environmental studies (12%) and geography (10%) journals. Environment and agriculture journals and environment and sustainability journals published 5% of the articles each, followed by urban planning and mathematics journals with 3% each. Only one article relevant to the review was published in a civil engineering publication.

The oldest paper in the review dated back to 2004 (Chang 2004), with most of the articles (79%) published post 2012. Figure 2 indicates a generally increasing trend over the years, demonstrating that the impacts of climate change on water quality are gaining attention. While the reviewed articles do not identify reasons for peaks in 2012 and 2015, the 2015 date coincides with the publication of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) in 2014 (United Nations Climate Change 2022).

The locations studied in the articles indicate that research on the impacts of climate change on water quality is predominantly conducted in developed countries (58%), with the USA leading (27%) followed by Europe (17%), the UK (7%), and Australia (6%) as seen in Figure 3. This result may be attributed to the review being confined to English language literature.

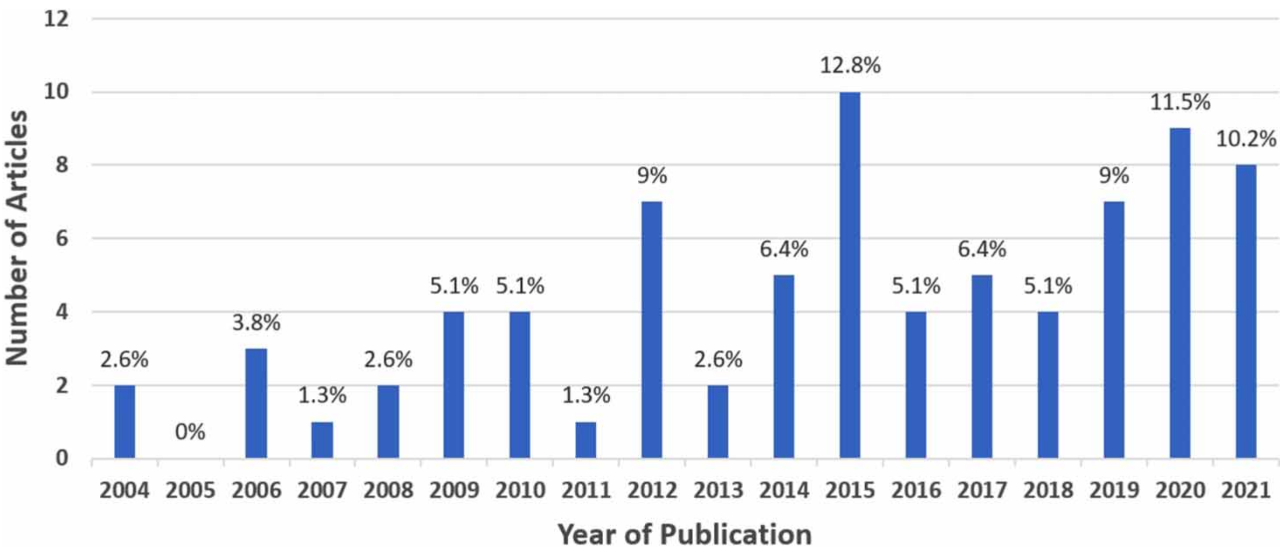

Figure 2 | Volume of scholarly articles on climate impacts on water quality included in the review across time.

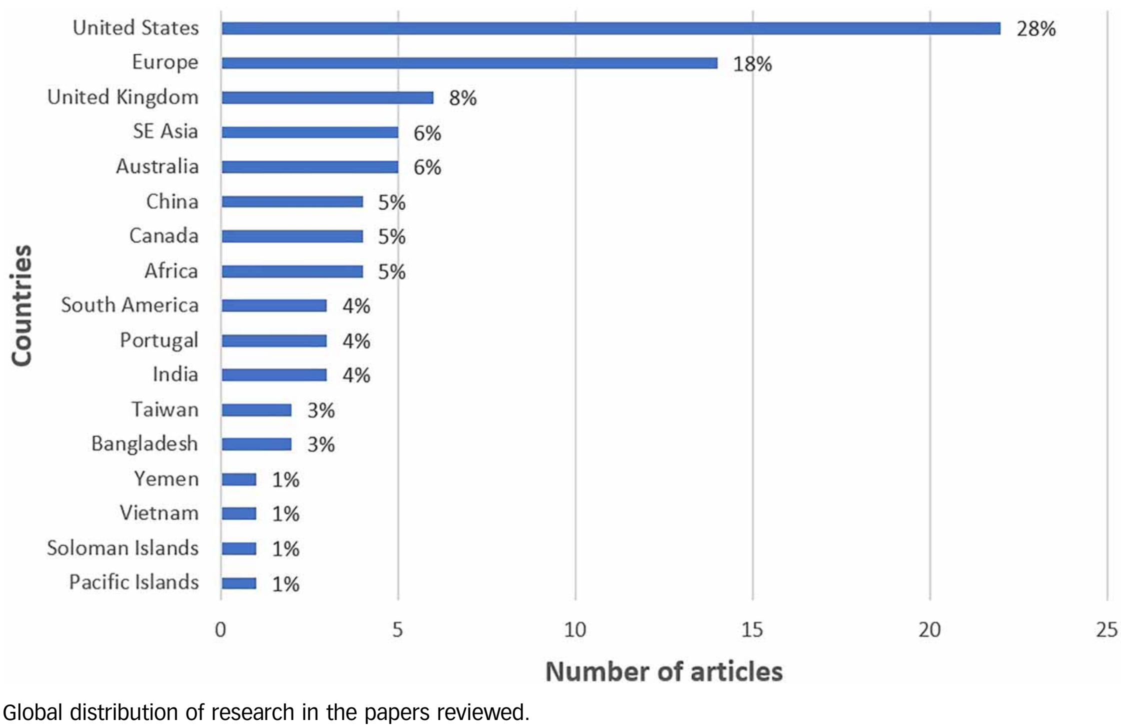

Figure 3 | Global distribution of research in the papers reviewed.

A small number of papers covered research in more than one country, such as Chaubey *et al.*'s (2016) review of the papers presented at the 2015 ASABE 1st Climate Change – Adaptation and Mitigation Symposium. A similar number of articles explored the topic without reference to a specific location. Kashyap (2004), for example, discussed the need for water governance to develop the adaptive capacity to incorporate climate variability and change.

3.2. Climate impacts on water quality

While the responses to global warming have historically been the mitigation of greenhouse gas emissions through national and international initiatives, the consequences of climate change are manifesting at regional and local levels (Baker *et al.*

2012). It is anticipated that climate change will affect the quality of water in local and regional areas through a number of different climate-related pathways, including drought, increased rainfall, higher temperatures, and more frequent and severe natural disasters (Bates *et al.* 2008). The IPCC (2022) notes that climate change will impact water quality through increases in stream temperatures and nitrogen loading in rivers. The articles reviewed indicate that, of the climate impacts, increases in temperature and changes to precipitation patterns will have the most significant effect on water quality.

3.2.1. Increase in temperature

Because the surface water temperature is largely dependent on ambient air temperature, an increase in temperatures under a warmer climate will result in changes to water temperatures (Palmer *et al.* 2009; Whitehead *et al.* 2009a, 2009b; Alam *et al.* 2013; Coffey *et al.* 2014; Chang *et al.* 2015; Anisha & Yunus 2016; Shannon *et al.* 2019). Bi *et al.* (2018) state that water temperature changes will result in significant disruptions to the normal aquatic ecological balance through changes in water density, surface tension, and viscosity. The most significant impacts on water quality are the changes to water chemistry and thermal stratification. An increase in water temperature can increase the risk of degraded water chemistry and anoxic conditions (Shannon *et al.* 2019). This can lead to water contamination through increases in pollutants, microorganisms, and bacteria (Thorne & Fenner 2008; Delpla *et al*. 2011; Coffey *et al.* 2014; Boholm & Prutzer 2017; Ekstrom *et al.* 2017). A degradation of water quality will put additional pressure on water treatment systems to ensure that the public is not exposed to contaminated drinking water (Boholm & Prutzer 2017).

Abdel-Fattah & Krantzberg (2014), Ekstrom *et al.* (2017), and Magee *et al.* (2019) agree that more frequent algal blooms can also result from increases in temperatures, complicating water treatment processes and creating toxic conditions for users of the water bodies (Ekstrom *et al.* 2017) such as recreational users, fish species, and livestock that graze in the area.

Both Chang *et al.* (2015) and Feldbauer *et al.* (2020) discuss the thermal stratification caused by rising temperatures and the detrimental impact it has on water quality. Thermal stratification not only increases the probability of oxygen depletion in deeper layers of water increasing the risk of algal blooms (Chang *et al.* 2015), but can also have a significant impact on drinking water production (Feldbauer *et al.* 2020). Drinking water reservoirs have outlet structures from which water is withdrawn at different depths and variable rates. Stratification and temperature influence the bio-geo-chemical processes and therefore water quality (Feldbauer *et al.* 2020).

3.2.2. Precipitation

Research indicates that climate change will also result in subsequent effects on regional precipitation, including the occurrence of droughts and floods (Bi *et al.* 2018). Water quality will be impacted by changes in precipitation patterns, intensity, and duration (Astaraie-Imani *et al*. 2012; Jin *et al*. 2012; Cross & Latorre 2015; Qiu *et al.* 2019). Not only will heavy rainfall increase contaminants in water bodies (Cross & Latorre 2015), but also droughts can result in reduced dilution of pollutants through lower flow rates (Coffey *et al.* 2014).

Rodriguez & Delpla (2017) argue that heavy rainfall will have the greatest impact on water quality. Many concur that more intense rainfall and storms result in increased pollutant concentrations (Abdel-Fattah & Krantzberg 2014; Coffey *et al.* 2014; Staben *et al.* 2015; Boholm & Prutzer 2017; Rodriguez & Delpla 2017; Bi *et al.* 2018; Shannon *et al.* 2019). There is also much evidence to demonstrate that high rainfall will lead to a degradation of water quality due to an increase in surface runoff, sedimentation, and nutrient inflow (Abdel-Fattah & Krantzberg 2014; Bi *et al.* 2018; Magee *et al.* 2019; Qiu *et al.* 2019; Wardropper & Rissman 2019). Coffey *et al.* (2014), Rodriguez & Delpla (2017), and Staben *et al.* (2015) emphasise that the impacts of precipitation changes will not only apply to surface water but also to groundwater systems.

The changes in precipitation patterns may result in flood and drought events. During flood events, water treatment facilities can become inundated, contaminating both overland and subsurface water (Coffey *et al.* 2014; Boholm & Prutzer 2017; Parkinson *et al.* 2021). Drought events particularly impact groundwater by concentrating contaminants and degrading the water quality (Tung *et al.* 2012; Coffey *et al.* 2014; Ekstrom *et al.* 2017).

3.3. Approaches to developing climate change adaptation strategies

The adaptation of water supply systems to new climate realities is core to sustainability and resilience (Levine *et al.* 2016). The European Environment Agency (EEA) (2016) places adaptation approaches to building resilience to climate change along a spectrum that ranges from coping with the changes to transformational adaptation (Figure 4). *Coping mechanisms* deal with the consequences of disaster events in the short term (low resilience), such that water quality is maintained. *Incremental adaptation* not only provides coping mechanisms but also implements medium-term strategies that improve the risk level.

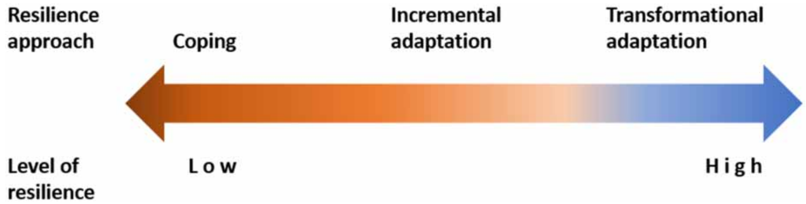

Figure 4 | The climate resilience spectrum.

Transformational adaptation includes long-term innovative approaches that aim to provide a high level of resilience. The analysis of approaches identified in the literature reviewed based on the resilience spectrum indicates that transformational adaptation is extremely rare.

3.3.1. Coping

Most of the strategies identified in this review fall under short-term coping mechanisms. Often the water bodies and catchment areas are already under stress from the impacts of climate change and the strategies proposed are short-term reactive options such as the adaptation of withdrawal depth (Feldbauer *et al.* 2020); improving or increasing water treatment levels (Levine *et al.* 2016; Garnier & Holman 2019); and river restoration projects (Palmer *et al.* 2009).

Some of the coping mechanisms could be modified to adapt to medium-term climate change impacts as well (Ekstrom *et al.* 2017; Feldbauer *et al.* 2020). Ekstrom *et al.* (2017) recommend changes in organisations and infrastructure to support deeper transformative changes, and Feldbauer *et al.* (2020) suggest dynamic water withdrawal depth and timing become an integral part of future reservoir management strategies.

3.3.2. Incremental adaptation

Effective adaptation requires proactive strategies that anticipate change and adapt water management to changing circumstances. Despite research indicating extensive use of modelling of future climate change scenarios, the literature reviewed includes few proactive strategies. While the risk management approach put forward by Cross & Latorre (2015) predominantly includes preventative actions, it can be adapted to identify appropriate control measures that respond to long-term climate change impacts affecting the supply chain. The modelling implemented by Chiang *et al.* (2012) uses future climate mitigation scenarios to determine an optimal suite of best management practices and will benefit water quality goals within the watershed. Similarly, Salerno *et al.* (2018) use modelling to determine the level of reduction of impervious surfaces required to prevent the future impacts of climate change.

Palmer *et al.* (2009) recommend modelling to anticipate the implications of climate-related hydrological and land-use changes to enable decision-makers to plan for variable river flows, as this is a fundamental trait of natural systems. They also recommend increasing the adaptive capacity of aquatic fauna species; restoring floodplains and setting back levees to prepare for future drought and flooding; and re-evaluating institutional mechanisms that govern water use and management to ensure they are flexible and have a strong awareness of ecological issues.

3.4. Strategies for adapting to climate change impacts on water quality

This review identified numerous adaptation strategies for overcoming climate change impacts on water quality. The strategies were classified using nine categories. In addition to the four categories established by the United States Environmental Protection Agency (U.S. EPA) in their *Adaptation Actions for Water Quality* (U.S. EPA 2021a) – modelling, natural infrastructure, building staff capacity, and green infrastructure – five further categories including policy and management frameworks, agricultural practices, technology, alternative water sources, and stormwater management were created. Most of the articles reviewed mentioned multiple adaptation strategies. As each mention of each strategy was coded and counted, theoretically a particular article can be counted towards all categories. Of these nine categories, policy and management frameworks are the most mentioned category in the literature reviewed (45%), followed by modelling (22%), agricultural practices (21%), and natural infrastructure (19%) (Figure 5). Building staff capacity and technology both feature in 15% of the articles, with alternative water sources, green infrastructure, and stormwater management in 12% or less each. Before the overview of the findings for each of these categories, we present Table 1 which includes a summary of all identified

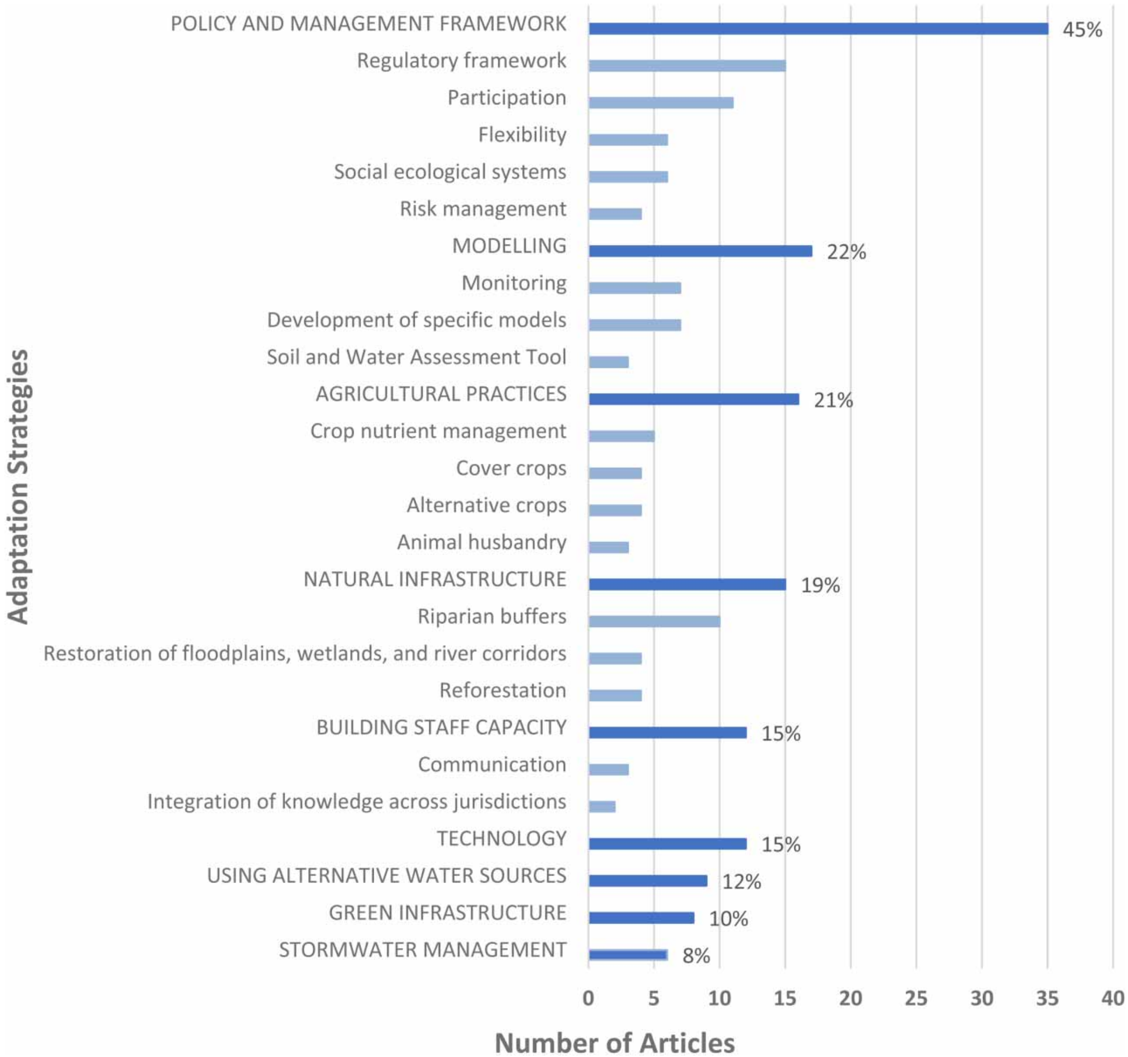

Figure 5 | The frequency of adaptation strategies for climate impacts on water quality.

adaptation strategies and the climate impacts they address. As most actions provide multiple benefits, many strategies are repeated across the table.

3.4.1. Policy and management frameworks

Policy and management framework strategies featured prominently in the reviewed articles, constituting 45% of the articles reviewed. Policy, governance, or managerial frameworks that decision-makers use to address water quality in a changing climate often already exist requiring little effort to adopt them, perhaps explaining their prominence among the strategies identified through the review.

The adaptation strategies in the policy and management framework category share common themes of flexibility, participation, regulatory framework, risk management, and social–ecological systems. Modifications or improvements to regulatory frameworks, with the encouragement of a participatory approach were widespread common elements in the strategies identified. Flexibility and social–ecological approaches were mentioned in six articles, while risk management appeared only in four articles.

The majority of policy and management strategies identified proposed new regulatory frameworks or the adaptation of existing ones. This included strengthening licencing arrangements (Palmer *et al.* 2009; De Smedt 2010; Garnier & Holman 2019); integrating water management policies into other inter-related planning policies and programmes

Table 1 | Summary of adaptation strategies and the impacts of climate change they address

Impacts of climate change	Impacts on water quality	Adaptation strategies
Wholistic strategies that address multiple impacts		Strengthening environmental flow programmes and water use permit conditions (PM) Integration of water management policies (PM) Reviewing existing regulations (PM) Investing in policies and education programmes (PM) Multi-disciplinary approach (PM) Transdisciplinary and integrated (top-down and bottom-up) approach (PM) Multi-criteria decision analysis strategy (PM) A flexible governance and management framework (PM) Integrated social–ecological systems (PM) Risk management approach (PM) Modelling of climate and land-use data (M) Watershed modelling (M) Hydro-physical modelling (M) Integrated water resource modelling (M) Physical and biogeochemical modelling (M) Flexible modelling systems (M) Soil and Water Assessment Tool (SWAT) (M) Improving communications among stakeholders (BSC) Multidisciplinary research (BSC) Development of programmes in coordination with local communities (BSC) Development of community capacity (BSC) Technical assistance with modelling (BSC) Building of knowledge capacity (BSC)
Temperature		
Increased water temperatures	Disruptions to normal aquatic ecological balance	Strengthening environmental flow programmes and water use permit conditions (PM) Alternative crops (diverse) (AP) Restoration of floodplains, wetlands, and river corridors (NI) Reforestation Artificial aeration (T) Permeable pavements, rain gardens, bioswales, green roofs, and infiltration trenches (GI)
	Changes in water density, surface tension, and viscosity	Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI) Artificial aeration (T)
	Degraded water chemistry and anoxic conditions	Hydro-physical modelling (M) Upgrading of treatment plants (T) Improvements to water treatment processes (T) Increasing chemical dosing (T) Artificial aeration (T) Alternative water sources (AWS)
	Contamination through increased in pollutants, microorganisms, and bacteria	Watershed modelling (M) SWAT (M) Alternative crops (AP) Riparian buffers (NI) Reforestation (NI) Restoration of floodplains, wetlands, and river corridors (NI) Construction of wetlands to treat wastewater (GI) Upgrading of treatment plants

(*Continued*.)

Table 1 | Continued

Impacts of climate change	Impacts on water quality	Adaptation strategies
		Improvements to water treatment processes Increasing chemical dosing
Thermal stratification	Oxygen depletion in deeper layers of water	Hydro-physical modelling (M) Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI) Upgrading of treatment plants (T) Improvements to water treatment processes (T) Increasing chemical dosing (T) Artificial aeration (T) Alternative water sources (AWS)
	Influences bio-geo-chemical processes	Hydro-physical modelling (M) Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI) Artificial aeration (T)
Algal blooms	Complicating water treatment processes	Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI) Upgrading of treatment plants (T) Improvements to water treatment processes (T) Increasing chemical dosing (T)
	Creates toxic conditions for users of the water bodies	Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI)
Precipitation		
Intense rainfall and storms	Increases pollutant concentrations	Watershed modelling (M) SWAT (M) Crop nutrient management (AP) Alternative crops (AP) Cover crops (AP) Controlling animal husbandry (AP) Riparian buffers (NI) Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI) Principles of ecohydrology (NI) Upgrading of treatment plants (T) Improvements to water treatment processes (T) Increasing chemical dosing (T) Permeable pavements, rain gardens, bioswales, green roofs, and infiltration trenches (GI) Construction of wetlands to treat wastewater (GI) Slowing road surface drainage (SM) Permeable pavements (SM) Runoff attenuation features (SM)
	Increase in surface runoff	Watershed modelling (M) SWAT (M) Alternative crops (diverse) (AP) Cover crops (AP) Riparian buffers (NI) Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI) Principles of ecohydrology (NI)

(*Continued.*)

Table 1 | Continued

Impacts of climate change	Impacts on water quality	Adaptation strategies
		Upgrading of treatment plants (T)
		Improvements to water treatment processes (T)
		Increasing chemical dosing (T)
		Permeable pavements, rain gardens, bioswales, green roofs, and infiltration trenches (GI)
		Construction of wetlands to treat wastewater (GI)
		Slowing road surface drainage (SM)
		Permeable pavements (SM)
		Runoff attenuation features (SM)
	Sedimentation and nutrient inflow	Watershed modelling (M)
		SWAT (M)
		Crop nutrient management (AP)
		Alternative crops (AP)
		Cover crops (AP)
		Controlling animal husbandry (AP)
		Riparian buffers (NI)
		Restoration of floodplains, wetlands, and river corridors (NI)
		Reforestation (NI)
		Principles of ecohydrology (NI)
		Upgrading of treatment plants (T)
		Improvements to water treatment processes (T)
		Increasing chemical dosing (T)
		Permeable pavements, rain gardens, bioswales, green roofs, and infiltration trenches (GI)
		Construction of wetlands to treat wastewater (GI)
		Slowing road surface drainage (SM)
		Permeable pavements (SM)
		Runoff attenuation features (SM)
Droughts	Reduced dilution of pollutants through lower flow rates	Strengthening environmental flow programmes and water use permit conditions (PM)
		Watershed modelling (M)
		SWAT (M)
		Riparian buffers (NI)
		Upgrading of treatment plants (T)
		Improvements to water treatment processes (T)
		Increasing chemical dosing (T)
		Alternative water sources (AWS)
	Concentration of contaminants	Watershed modelling (M)
		SWAT (M)
		Crop nutrient management (AP)
		Alternative crops (AP)
		Controlling animal husbandry (AP)
		Riparian buffers (NI)
		Restoration of floodplains, wetlands, and river corridors (NI)
		Reforestation (NI)
		Principles of ecohydrology (NI)
		Upgrading of treatment plants (T)
		Improvements to water treatment processes (T)
		Increasing chemical dosing (T)
		Permeable pavements, rain gardens, bioswales, green roofs, and infiltration trenches (GI)
		Construction of wetlands to treat wastewater (GI)
		Slowing road surface drainage (SM)

(*Continued.*)

Table 1 | Continued

Impacts of climate change	Impacts on water quality	Adaptation strategies
		Permeable pavements (SM) Runoff attenuation features (SM)
Floods	Inundation of water treatment facilities	Upgrading of treatment plants (T) Improvements to water treatment processes (T) Increasing chemical dosing (T) Alternative water sources (AWS) Construction of wetlands to treat wastewater (GI) Slowing road surface drainage (SM) Permeable pavements (SM) Runoff attenuation features (SM)
	Contaminating waters	Watershed modelling (M) SWAT (M) Riparian buffers (NI) Restoration of floodplains, wetlands, and river corridors (NI) Reforestation (NI) Principles of ecohydrology (NI) Upgrading of treatment plants (T) Improvements to water treatment processes (T) Increasing chemical dosing (T) Permeable pavements, rain gardens, bioswales, green roofs, and infiltration trenches (GI) Construction of wetlands to treat wastewater (GI) Slowing road surface drainage (SM) Permeable pavements (SM) Runoff attenuation features (SM)

(PM) Policy and management frameworks (NI) Natural infrastructure (AWS) Alternative water sources (M) Modelling (BSC) Building staff capacity (GI) Green infrastructure (AP) Agricultural practices (T) Technology (SM) Stormwater management

(De Smedt 2010; Boholm & Prutzer 2017); reviewing existing regulations that were drafted under different conditions (Cross & Latorre 2015); and investing in policies and education programmes (Kopprio *et al.* 2015). Palmer *et al.* (2009) propose strengthening environmental flow programmes and water use permit conditions in an effort to maintain natural flow conditions, ensuring that flows support ecosystems, protect river health, and promote natural flows under a changing climate. Alternatively, Miller & Belton (2014) propose an approach designed to support climate policy planning by incorporating a multi-criteria decision analysis, enabling a whole system perspective and encouraging the identification of climate policies and measures that are low cost, environmentally effective, and consistent with national development goals. These adaptation strategies are all designed within existing policy and management frameworks.

Numerous articles in the review referred to adaptation strategies that involve a participatory approach and encourage coordination and cooperation between a variety of stakeholders. Abdel-Fattah & Krantzberg (2014), Cross & Latorre (2015), and Staben *et al.* (2015) all recommend multi-stakeholder strategies, and similarly, Poudel & Duex (2017) suggest an initial multi-disciplinary approach for solving complex water resource management issues. Kumar *et al.* (2020) propose a transdisciplinary and integrated (top-down and bottom-up) approach for avoiding disconnects and redundancies when dealing with water quality issues.

A number of researchers proposed the incorporation of flexibility in the policy and management frameworks. Cross & Latorre (2015), Kashyap (2004), Miller & Belton (2014), and Peirson *et al.* (2015) identify the need for flexibility within the strategy to allow for different outcomes and to cope with the challenges of unpredicted climate changes. The multi-criteria decision analysis strategy proposed by Miller & Belton (2014) relies on the ability of the framework to take into consideration various values, vulnerabilities, and ecosystem services that the policy may affect. The governance and management framework recommended by Peirson *et al.* (2015) relies on flexibility to accommodate the different outcomes resulting from the analysis of the uses, values, and goals of the various stakeholders.

Another common theme within the policy and management category of adaptation strategies reviewed was the interrelationships between society and environmental systems. In particular, Kopprio *et al.* (2015) identify the importance of building social–ecological resilience for climate change adaption. Peirson *et al.* (2015) also support this theory through their development of a governance and management framework which recognises integrated social–ecological systems to encourage transformative adaptation to climate change.

The risk management approach addresses the changing climatic conditions as a threat to water quality, and as such, the process involves identifying hazards, assessing risks, and determining appropriate control measures along the supply chain from the catchment to the end use for water. Cross & Latorre (2015) recommend a proactive risk management approach, in which resilience is built into water safety planning in an effort to absorb climate change impacts. This preventative and flexible management framework that evaluates and addresses risks is also supported by Khan *et al.* (2015) and Rosenzweig *et al.* (2007). Urama & Ozor (2010) go further in their recommendation of providing training to those involved to increase their skills and knowledge in climate risk management, empowering them to scale up or replicate adaptation strategies as required.

3.4.2. Modelling

Modelling using climate and land-use data to inform decision-making was mentioned in 22% of the articles reviewed. U.S. EPA (2021a) lists the collation of existing data sets, the development of regional scenarios, the mining of existing data sources, and the use of data to demonstrate historical and future trends as strategies that use climate and land-use data to inform the decision-making process.

One of the main modelling strategies includes the analysis and evaluation of climate and land-use data for monitoring water quality. Approximately one-third of the articles mentioning modelling in the review discussed the gathering and modelling of data to monitor climate change and other stressors on water quality to provide early warning indicators. This can lead to a more resilient decision-making framework and more effective climate adaptation strategies and forecasting (Levine *et al.* 2016). It can also allow local jurisdictions to respond to specific local needs (Palmer *et al.* 2009).

The review revealed that a variety of models are implemented to determine the potential effects of alternative actions on water quality. Chiang *et al.* (2012) and Coffey *et al.* (2014) both discuss the use of watershed modelling; however, the former used the modelling to comparatively analyse a suite of best management practices and determine the combination that would meet water quality goals, whereas the latter used watershed models for informing pollution control measures. Feldbauer *et al.* (2020) used hydro-physical models to determine withdrawal strategies in thermally stratified reservoirs. Kumar *et al.* (2020) reviewed the use of integrated water resource models to address key decision choices and facilitate targeted intervention, and Magee *et al.* (2019) discussed physical and biogeochemical models that were used to broaden the understanding of uncertainties in responses and mechanisms. Pouget *et al.* (2012) and Wilby *et al.* (2006) both highlight the benefits of a flexible modelling system, in which a range of models can be linked and then automatically exchange information. Carnohan *et al.* (2021) use modelling to facilitate participatory processes.

A commonly used hydrological model is the Soil and Water Assessment Tool (SWAT) (Bi *et al.* 2018; Rocha *et al.* 2020; Wu *et al.* 2021). It is a physically based model capable of simulating the impacts of land management practices on water, sediment, and agricultural chemical yields in watersheds (Arnold *et al.* 2012). It can be used to simulate different ecohydrological scenarios and responses under both current and future climate conditions to inform decision-making.

3.4.3. Agricultural practices

As crop production and animal husbandry are prominent land uses in catchment areas, agricultural practices have a significant impact on water quality (Mehdi *et al.* 2015; Nunes *et al.* 2017). Strategies involving modifications to agricultural practices were almost as prominent as modelling, mentioned in 21% of the articles in the review. The adaptation strategies in agricultural practices involve crop nutrient management (mentioned in 6% of articles), the use of cover crops or consideration of alternative crops (5% of articles), and improved grazing management in animal husbandry (4% of articles).

Shannon *et al.* (2019) propose avoidance or reduction in the use of organic supplements, nutrients, and chemical delivery to areas near waterbodies. Many others (Whitehead *et al.* 2006; Chiang *et al.* 2012; Ha & Wu 2017; Salila *et al.* 2020) support crop nutrient management to reduce pollutant loading in the waterways.

The review identified a variety of strategies related to crop management for improving water quality. For example, Ebert *et al.* (2009) recommend the replacement of vulnerable monocultures with more diverse crops. This not only provides a more sustainable ecosystem service but also benefits grazing and other local industries. Godebo *et al.* (2021) and Salila *et al.* (2020) propose improved crop choices, while Whitehead *et al.* (2009a) recommend crops that are better suited to the climatic conditions. Cherkauer *et al.* (2021), Wardropper & Rissman (2019), Whitehead *et al.* (2006), Giri *et al.* (2020), and Ha & Wu (2017) recommend the use of cover crops which can reduce soil erosion and absorb the nutrients remaining in the soil.

Controlling animal husbandry to reduce the impacts of livestock on waterbodies can be achieved through a variety of strategies. Whitehead *et al.* (2006) recommend the use of off-stream watering without fencing the livestock to reduce stream bank erosion and pollution from livestock defaecation. Boholm & Prutzer (2017) suggest the protection of water quality by controlling livestock – limiting grazing animals near water supply areas, controlling animal health, and keeping track of the location of the animals.

3.4.4. Natural infrastructure

Natural infrastructure includes the natural physical systems that support life and examples include the planting of trees, controlling stream bank erosion, controlling soil erosion in the watershed, and controlling stormwater runoff (U.S. EPA 2021a). Natural infrastructure strategies were reported in 19% of the articles reviewed. The common natural infrastructure adaptation strategies include the implementation of riparian buffers (two-thirds of the reviewed papers); the restoration of floodplains, wetlands, and river corridors; and the reforestation of critical areas (four articles each).

Riparian buffers were identified as a common strategy for reducing sediments, nutrients, and pesticides from surface runoff and therefore improving water quality (Lukasiewicz *et al.* 2016; Ha & Wu 2017). These buffer strips adjacent to streams, lakes, and rivers may be vegetated with native grasses (Chaubey *et al.* 2016), switchgrass (Ha & Wu 2017), and shade trees (Shannon *et al.* 2019). However, Wilby & Wood (2012) identify potential issues with woody debris, channel roughness, and localised flooding. Wu *et al.* (2021) conclude that while a riparian buffer will reduce sediment outputs, its reduction is not sufficient to fully offset the impacts of climate change.

Khaniya *et al.* (2021) define reforestation as the planting of new trees within an existing forest area, whereas afforestation is the planting of new trees in a new or fresh area. Both Khaniya *et al.* (2021) and Salila *et al.* (2020) recommend the use of reforestation as a strategy for improving water quality. Additionally, Shannon *et al.* (2019) and Wilby & Wood (2012) recommend afforestation for the purposes of shading the water to offset warming temperatures.

The restoration of floodplains, wetlands, and corridors are recommended strategies put forward by Ebert *et al.* (2009), Iacob *et al.* (2014), Magee *et al.* (2019), and Palmer *et al.* (2009). Such restoration work is expected to create more robust and dependable freshwater ecosystem services.

Kopprio *et al.* (2015) suggest a robust strategy for climate adaptation that uses the principles of ecohydrology. This strategy is based on the use of aquatic biota as water management tools and involves the redesign of wetlands (preservation, restoration, and creation) to protect them from erosion and improve water quality through the removal of excess nutrients and pollutants. Natural and social sciences are complementary, and therefore, the integration of both can represent a powerful climate change adaptation tool in complex human–natural systems (Kopprio *et al.* 2015).

3.4.5. Building staff capacity

Building staff capacity through the engagement of new staff with appropriate experience, the provision of staff training, and the encouragement of the use of appropriately qualified contractors and engineers can be an important adaptation strategy (Jun *et al.* 2010; U.S. EPA 2021a) and was mentioned in 15% of the reviewed articles.

The review identified the need to bridge the gap between the research available and local communities' capacity to address water sustainability and climate change adaptation (Palmer *et al.* 2009; Poudel & Duex 2017; Magee *et al.* 2019). Magee *et al.* (2019) discuss the importance of communication as a key strategy for local communities to address the climate change impacts on water quality for Wisconsin lakes. This includes improved communication between management and stakeholders regarding requirements for high water quality; between businesses and other stakeholders; and between lake associations and local community members. Poudel & Duex (2017) propose comprehensive multidisciplinary research, the development of programmes in coordination with local communities, and the development of community capacity to address water sustainability. Palmer *et al.* (2009) identify the need for affordable tools in regions with few resources. Technical assistance with modelling that demonstrates potential climate change impacts within specific watersheds can be provided to build human resource capacity. However, small communities may not have the resources to access Geographic Information Systems (GIS) or modelling tools. More user-friendly low-cost tools need to be explored.

Cross & Latorre (2015) and Kalafatis *et al.* (2015) both hail the merits of the Great Lakes Water Quality Protocol and its ability to integrate knowledge across jurisdictions and decision-making scales. The binational regional network binds parties and shares information in a timely and comprehensive manner. The protocol is implemented and enforced by an International Joint Commission, which works in cooperation with local authorities and the public to build their understanding of the water cycle and the climate change pressures it is under. Kalafatis *et al.* (2015) propose a conceptual model in which knowledge capacity is built up between climate information at the regional level and specialised networks that function like communities of practice. This will enable the two networks to span the boundary between knowledge production and its use.

3.4.6. Technology

Strategies that involve the use of technology including advances in engineering and improvements to water treatment processes and technologies were fewer than anticipated and were mentioned in only 15% of the articles reviewed. The research undertaken did not reveal significant breakthroughs in technology or engineering advancements. The strategies proposed were predominantly short-term coping mechanisms. Abdel-Fattah & Krantzberg (2014), Garnier & Holman (2019), Rodriguez & Delpla (2017), and Staben *et al.* (2015) mentioned upgrading treatment plants, improvements to water treatment processes and technologies, and increasing chemical dosing to accommodate the anticipated reductions in water quality as a result of future climate change impacts. And similarly, Magee *et al.* (2019) proposed artificial aeration to prevent anoxic conditions.

Feldbauer *et al.* (2020) and Shannon *et al.* (2019) discuss the strategy of dynamic withdrawal to overcome the issues associated with thermal stratification. As rising air temperatures impact the thermal stratification of water bodies, the withdrawal depth within reservoirs will need to be adapted. The differing depths and variable rates of withdrawal will depend on the properties of the reservoir; however, this strategy is not expected to be able to fully compensate for the negative impacts of climate change (Feldbauer *et al.* 2020).

3.4.7. Alternative water sources

Alternative water sources were mentioned in 12% of the articles in the review as essentially a risk management strategy and include reducing reliance on one major supply source and allowing the use of different water qualities for different purposes. Alternative water sources can be used for maintaining water quality in future climate scenarios. Boholm & Prutzer (2017) identified the risk of relying on only one major supply source for drinking water and propose a risk management strategy, in which the raw supply is derived from multiple sources. Cross & Latorre (2015) recommend revising the regulations around water quality, allowing different water qualities for different uses to ensure there is a more efficient use of water. Yang *et al.* (2010), Kim & Chung (2015) and Trinh *et al.* (2013) all propose the reuse of treated wastewater for uses such as irrigation in the agricultural sector. It is anticipated that the wastewater, when used for agricultural purposes, would not need to be treated in expensive tertiary treatment systems, reducing treatment costs. If the wastewater is reused, and not directed to waterways, this will improve water quality management. The challenge to this strategy is how the wastewater is collected, treated, and then distributed for use, without increasing health risks to the population (Trinh *et al.* 2013).

3.4.8. Green infrastructure

The U.S. Water Infrastructure Improvement Act (U.S. EPA 2021b) defines green infrastructure as 'the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters'. Green infrastructure includes retention ponds for managing stormwater, bioretention to collect stormwater runoff, blue roof to hold rainwater, permeable pavements, and extended detention wetlands to reduce flood risk (U.S. EPA 2021a). Adaptation strategies involving green infrastructure were identified in only 10% of the reviewed articles.

Green infrastructure mimics natural habitat and is a natural solution implemented to provide ecological, economic, and social benefits (EEA 2014). It can be implemented as a strategy for protecting water quality against the impacts of climate change. Salerno *et al.* (2018) recommend the implementation of permeable pavements, rain gardens, bioswales, green roofs, and infiltration trenches, as these practices will protect the quality of water in natural water bodies by slowing and filtering the water flows. They anticipate that a 15% reduction in imperviousness would be sufficient to prevent the negative impacts of future climate changes.

Magee *et al.* (2019) and Ricart & Rico-Amoros (2021) recommend the construction of wetlands to treat wastewater as an alternative to wastewater treatment plants (grey infrastructure). Constructed wetlands are a cost-effective strategy for protecting water quality, with the additional benefits of flood risk mitigation, stormwater management, and additional water supply. Depending on their design, they can also provide recreation, aesthetic values, and landscaping (Ricart & Rico-Amoros 2021).

3.4.9. Stormwater management

Stormwater management strategies prioritise and direct the flow of water in catchment areas and were mentioned in only 8% of the reviewed articles. The strategies involved increasing vegetation, implementing permeable pavements (Abdel-Fattah & Krantzberg 2014), and slowing road surface drainage to reduce sedimentation (Shannon *et al.* 2019). Wilby & Wood (2012) promote the use of low-cost soft engineering solutions, such as runoff attenuation features that slow, store, and filter runoff to mitigate the potential effects of flooding.

3.5. Barriers and drivers of adaptation strategy implementation

Klein *et al.* (2014) identify eight types of barriers and drivers that can exert a positive or negative influence on the planning or implementation of adaptation actions. These categories have been adopted for this review and include governance and institutional; financial; knowledge, awareness, and technology; physical; social and cultural; human resource; economic; and biological. Acting as barriers, these factors can significantly reduce the range of adaptation options and opportunities. On the other hand, as drivers they can positively influence the success of adaptation measures.

This literature review has identified barriers and drivers in all categories but one: biological factors. The results demonstrate a broad range of factors influencing the success of adaptation strategies implemented to address the impacts of climate change on water quality (Table 2).

The most commonly reported factors were governance and institutional barriers and drivers, followed closely by financial and knowledge, awareness, and technology factors. The physical, social and cultural, and human resource barriers and drivers are also featured in a significant number of the articles reviewed. There were relatively few economic factors identified.

3.5.1. Governance and institutional factors

Governance and institutional barriers and drivers were identified in 18% of the articles reviewed. Klein *et al.* (2014) describe how societal institutions can support or hinder climate change adaptation measures through the mobilisation of resources, decision-making, and the implementation of specific policies. The success of adaptation can also be influenced by the complexities of governance networks, coordination among the various actors who will likely have different objectives, jurisdictional authority, and levels of power and resources. The influence that the inter-related themes of governance and institutions have on water quality adaptation strategies was prevalent in the papers reviewed. The institutional barriers and drivers identified predominantly relate to regulatory systems, while the governance factors relate to the cooperation and coordination of the various players involved.

Regulatory systems can hinder climate change adaptation strategies through their inflexibility, insufficient attention to detail, and the lack of coordination between jurisdictions. Cross & Latorre (2015) and Ebert *et al.* (2009) both identify issues with flexibility in existing regulatory systems. Strict regulations can prevent timely responses (Cross & Latorre

Table 2 | Barriers and drivers of adaptation identified in the literature

Adaptation barriers and drivers	Number of articles	Percentage
Governance and institutional	14	18
Financial	13	17
Knowledge, awareness, and technology	11	14
Physical	5	6
Social and cultural	5	6
Human resource	4	5
Economic	2	3
Biological	0	0

2015) and thwart individual efforts through the imposition of institutional processes, regulatory structures, property rights, and social norms (Ebert *et al.* 2009). Cross & Latorre (2015) also acknowledge the risks of too-flexible regulations as the high costs of ensuring compliance and the determination of tolerable risks. Azhoni & Goyal (2018) and Crabbe & Robin (2006) found that existing regulatory systems were insufficient for monitoring and addressing the changing climate patterns. However, the most significant issue with regulatory systems revealed through the review was a lack of coordination between government levels and differing policies. Both Crabbe & Robin (2006) and Jordan (2020) discuss the difficulties with federal intervention or lack of leadership at the local government level. Boholm & Prutzer (2017) mention disparate roles and responsibilities within existing regulatory systems. De Smedt (2010) explains how other policies, such as spatial policies and land-use practices, can interfere with water quality management, making some ecosystems more vulnerable and less capable of adapting.

Governance issues such as the cooperation and coordination between stakeholders, the complexity of the authorities and agencies involved in the decision-making process, political interferences, and interactions with institutional frameworks were also mentioned (e.g. Carvalho *et al.* 2019). Boholm & Prutzer (2017) discuss the importance of cooperation and positive interactions between public and private actors, including non-government organisations, stakeholders, and the public. This was supported by Ricart & Rico-Amoros (2021). Boholm & Prutzer (2017) also identified the complexity of governance structures as an obstacle to the success of adaptation strategies, admitting that interdisciplinary collaboration and better integration with authorities are not easily achieved. Jordan (2020), Parkinson *et al.* (2021), and Ricart & Rico-Amoros (2021) all discussed the barriers that institutional frameworks can have on good governance. They identified institutional fragmentation, asymmetric power dynamics, and inadequate human and financial resources as the issues that may hinder effective water governance. The political issues that can disrupt good governance were identified as a lack of political engagement (Boholm & Prutzer 2017) and political pressure that can be exerted by influential stakeholders with short-term interests (Ebert *et al.* 2009).

3.5.2. Financial factors

Klein *et al.* (2014) describe financial constraints on adaptation as the impacts that access to financial capital (credit, insurance, tax revenues, and earnings of individual households or private entities) can have on specific adaptation strategies and options. Financial barriers and drivers were identified in 17% of the articles reviewed.

Financial resources can be both an impediment to and a driver of the implementation of water-related adaptation strategies. Almost half of the articles that identified financial resources as a relevant factor in implementing adaptation strategies cited the impact of high costs (e.g. Mukheibir 2008; Nagy-Kovács *et al.* 2018; Mi *et al.* 2020). In particular, Cross & Latorre (2015) discussed the low rates of the application of adaptation strategies when there are high costs associated with ensuring compliance. Ebert *et al.* (2009) found that even when cost–benefit analyses are favourable, there are often hidden financial barriers such as transaction costs and compensatory measures. Adaptation strategies that involve changes to agricultural practices often financially impact farmers unfairly. Particularly in developing countries, farmers do not have access to credit or savings to improve their crop varieties (Godebo *et al.* 2021). Xu *et al.* (2019) identified adaptation strategies that would lead to farm-level cost-savings; however, Ricart & Rico-Amoros (2021) argue that such strategies often involve high investment costs and are influenced by unpredictable behaviour of the food market. While the majority of adaptation strategies were impeded by the availability of financial resources, De Smedt (2010) and Khaniya *et al.* (2021) proposed cost-effective eco-based adaptation strategies. They concurred that water quality strategies that work with nature's capacity to control or absorb impacts can offer consistent financial benefits over the long term.

3.5.3. Knowledge, awareness, and technology

Knowledge-, awareness-, and technology-related barriers and drivers were identified in 14% of the articles reviewed. IPCC Assessment Report 4 concludes that knowledge gaps and impediments to the flow of information can impede adaptation, yet knowledge itself is not sufficient to drive adaptative responses (Adger *et al.* (2007) as cited in Klein *et al.* (2014)). More information can support decision-making processes and build capacity through education, training, and information access to provide valuable opportunities for adaptation. Boogaard *et al.* (2020) conclude that fundamental change is only possible through knowledge and awareness.

Among barriers to effective adaptation related to the lack of knowledge and information, four articles discussed the impacts of a deficit in climate change data. Azhoni & Goyal (2018) and Godebo *et al.* (2021) both acknowledge a lack of reliable historical data on projected weather and climate conditions as key challenges. Crabbe & Robin (2006) identify the need for information to be consistent, credible, and downscaled to the local level.

Ricart & Rico-Amoros (2021), Jordan (2020), and Garnier & Holman (2019) all cite the lack of scientific knowledge as a significant constraint on adaptation capacity. Ricart & Rico-Amoros (2021) mention the impacts on farmers, whereas Jordan (2020) discusses the need for up-to-date scientific information to help manage risks and forecast conditions. Garnier & Holman (2019) identify a significant gap between the scientific knowledge of climate change impacts and the adaptation capacity at the local level.

3.5.4. Physical factors

Klein *et al.* (2014) describe physical factors that can constrain adaptation as the physical environment including the climate itself, geographical features, soil conditions, and anthropogenic land uses. Physical barriers and drivers were identified in only 6% of the articles reviewed.

Of the reviewed articles that identified physical barriers to adaptation strategies, two discussed land-use issues. Kim *et al.* (2021) claim that Korean farmers were impeded in dealing with climate change adaptation because they feel they have already maximised the productivity of their lands with an intensive input of resources, machine farming, and the use of freely available water. Magee *et al.* (2019) also discuss challenges with land use, as the restrictions proposed for watershed lands were often controversial and difficult to implement. The only other physical barriers identified in this review were the limited capacity of reservoirs to support climate change adaptation measures (Rocha *et al.* 2020) and the challenges of capturing sufficient rainwater of acceptable quality (Chan *et al.* 2020).

3.5.5. Social and cultural factors

The social and cultural factors associated with our values, world views, and cultural norms and behaviours can influence the choice of adaptation options and the perceptions of associated risks (Klein *et al.* 2014). Social and cultural factors were identified as barriers or drivers of adaptation in 6% of the articles reviewed.

Ebert *et al.* (2009) and Kopprio *et al.* (2014) both identify socio-economic factors as barriers to adaptation. While the former points to the challenges of changing the uses of privatised lands, the latter discusses how socio-economic constraints can hinder the use of technology in developing countries. Social and cultural factors can also be used to drive adaptation strategies. Magee *et al.* (2019) suggest that changes will have more opportunities for success if local community values are used to inform adaption approaches.

3.5.6. Human resource factors

Klein *et al.* (2014) identify humans as the primary agents of change and therefore pivotal in the effectiveness of our efforts to adapt to climate change. Of the articles reviewed, only 5% indicated the influence of human resources as significant barriers or drivers.

Water quality is generally the responsibility of local authorities or municipalities. This level of government often lacks the necessary human resources for developing robust climate change adaptation strategies (Palmer *et al.* 2009; Boholm & Prutzer 2017; Azhoni & Goyal 2018). Experts from a variety of science fields will be required to contribute knowledge to water, natural resources, urban planning, crises, and disaster management domains, enabling the information to be linked to effective decision-making processes (Boholm & Prutzer 2017). Interestingly, Crabbe & Robin (2006) note that external consultants are often engaged due to a lack of internal human resources. This then leads to an overreliance on technological strategies rather than managerial solutions. While several articles cite the limits of human resources as a significant obstacle to the implementation of adaptation strategies, Palmer *et al.* (2009) propose adaptation actions that take into consideration the challenges of limited financial and human resources.

3.5.7. Economic factors

Economic factors defined by Klein *et al.* (2014) as macroeconomic constraints associated with broader macro-level driving forces were identified in only 3% of the articles reviewed. The articles reviewed identified economic factors as both a driver and a barrier for climate change adaptation. Ebert *et al.* (2009) suggest that the public were more supportive of strategies for improving water quality that improved their livelihoods and strengthened local economies. On the other hand, Parkinson *et al.* (2021) discuss the challenges of accessing funding for adaptation actions through the various levels of government.

4. DISCUSSION

This review sought to systematically evaluate peer-reviewed studies on adaptation strategies for protecting water quality from climate impacts to (i) determine the common climate-related pathways that will have a significant impact on water quality; (ii) identify the range of adaptation strategies for overcoming climate change impacts on water quality; (iii) evaluate the resilience approaches of the strategies to determine where they exist on the climate resilience spectrum; and (iv) identify the drivers and barriers of adaptation implementation. Figure 6 illustrates that the diverse and complex range of factors across seven themes, which may act as barriers or drivers of adaptation, affects the implementation of the strategies that protect water quality from climate change impacts. Which adaptation strategies from the nine categories are implemented and to what degree, in turn, determines the resilience approach used. Across the climate resilience spectrum, most adaptation strategies fall into low resilience coping and incremental mechanisms (warm colours – oranges and yellow) with very few transformational high resilience approaches (indicated by a cool colour – blue).

Four key themes have emerged from the review that require further attention due to the anticipated effects of climate change on water quality and the impacts that this will have on local communities. These include (i) the low level of attention given to climate impacts on water quality; (ii) the difficulty of differentiating the cause of water quality degradation; (iii) the reliance on coping approaches to adaptation which are unlikely to be sufficient; and (iv) the significant challenges to the planning and implementation of the adaptation strategies.

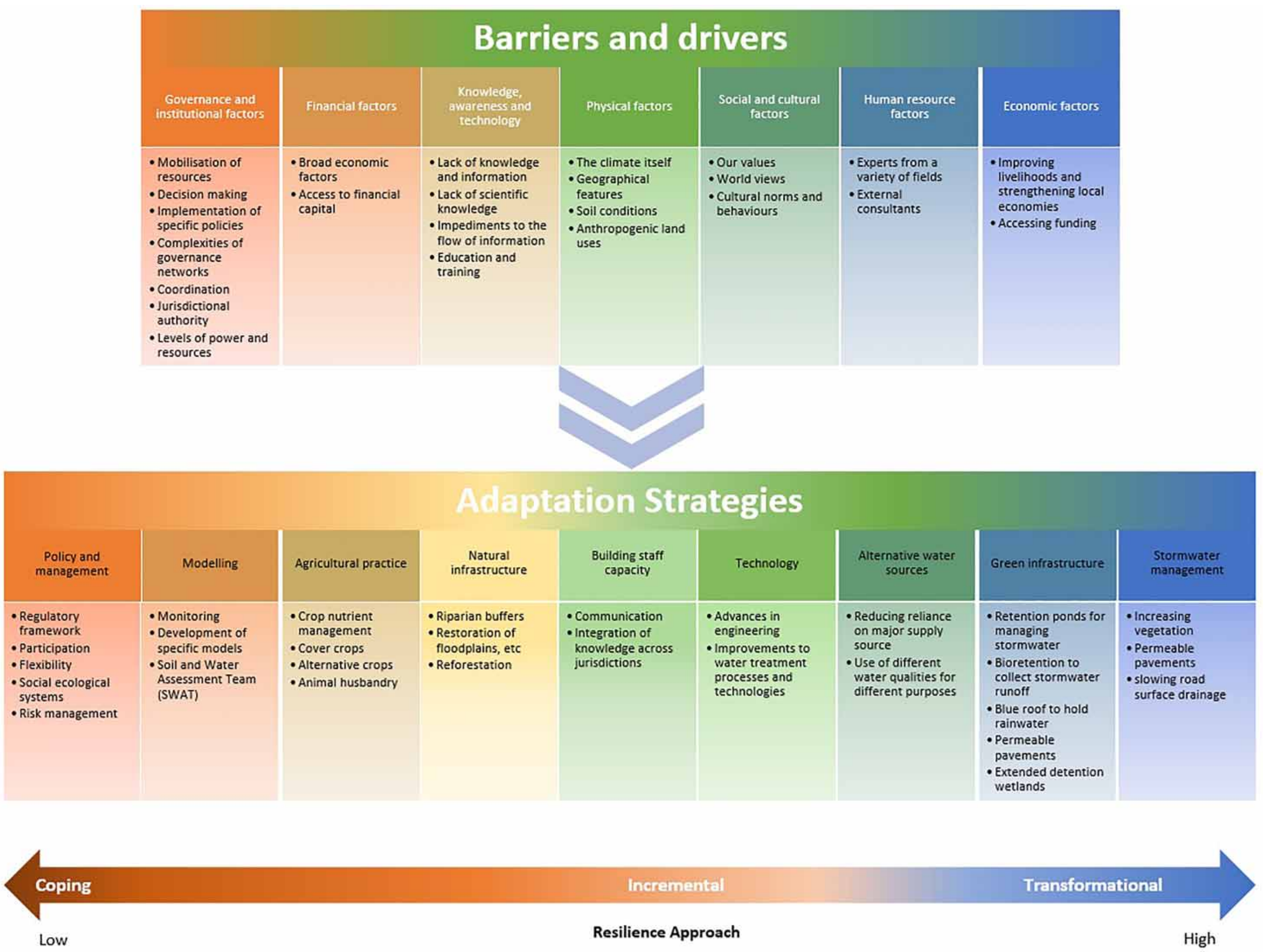

Figure 6 | Conceptual framework of adaptation to climate change impacts on water quality. Warm-coloured adaptation strategies (orange to yellow) correspond to coping approaches to resilience, whereas cooler colours (greens and blues) can be transformational. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wcc.2022.279.

4.1. Inattention to climate change impacts on water quality

There is a large body of literature that focuses on the impacts of climate change on water security. Much research also aggregates data on water availability with that of the quality of water. Identifying studies focusing on climate change impacts on water quality has been challenging.

Water security is undoubtedly a significant issue. The changing climate impacts the water cycle through droughts, floods, melting glaciers, sea-level rise, and storms with consequences on the availability of water in various locations throughout the world (International Union for Conservation of Nature 2022). However, as the IPCC (2022) acknowledges, there have been significant increases in climate-induced water quality degradation due to temperature increases or melting of the cryosphere.

As the number of articles identified for this review shows, the research on climate impacts on water quality is limited. Many studies are context-specific and have limited regional relevance. The review also shows that this limited body of literature often emphasises data accumulation rather than adaptation strategies. Further research is necessary not only on climate change impacts on water quality but also on strategies for developing resilience.

4.2. Differentiating the causes of water quality degradation

It is evident from the review that climate change is not the only source of water quality degradation. Degradation of water quality may also occur due to many other factors including water pollution resulting from human activities related to population growth and urban development. This degradation can result in environmental, social, and economic impacts on human health, food production, ecosystem functions, and economic growth (UNESCO 2021b).

However, the impacts of climate change on water quality are not insignificant. UNESCO (2021a) argues that policy discussions and scientific studies often overlook the significant links between water quality and climate change and this is supported by the dearth of studies focused on this specific linkage.

While water quality may be affected by regional and localised climatic effects, this review demonstrates that the changing climate patterns worldwide are continuing to shift, increasing the occurrence of extreme weather events, and are modifying the normal balance of water bodies and cycles, leading to the degradation of water quality. Reductions in water quality can not only affect economic and social welfare, but also critical environmental flows, ecosystems, and biodiversity. Further research is needed to understand the impacts that climate change will have on the physical, chemical, biological, and socio-economic systems related to our water resources (UNESCO 2021a).

4.3. The need for transformational adaptation approaches

Studies examining climate adaptation approaches often find most of the current approaches include coping or incremental strategies (O'Neill & Handmer 2012; Torabi *et al.* 2018; Fedele *et al.* 2020). The findings of this review are consistent with those. Of the 78 articles reviewed here, all adaptation strategies to water quality impacts fall under coping or incremental approaches on the resilience spectrum. As the loss and damage to water quality due to the impacts of climate change increase, the need for transformational adaptation strategies to provide major or fundamental changes is becoming more imperative for providing long-term benefits and addressing the root causes of vulnerability. The IPCC (2022) projects an increase in water quality degradation under climate change due to warming, enhanced floods, sea-level rise, droughts, and increased irrigation. The IPCC Assessment Report 6 confirms the need for transformational adaptation measures contrary to the many initiatives that prioritise immediate and near-term climate risk reduction reducing opportunities.

As Fedele *et al.* (2020) identify when social–ecological systems are impacted by climate change, responses tend to be coping and incremental adaptation strategies that aim to maintain the current social and ecological relationship, offering an immediate solution with short-term benefits. These strategies rarely address the root cause of the vulnerabilities and long-term sustainability issues. Transformational adaptation options are seldom considered or implemented, as they impact either the social or ecological system or the system dynamics and have the potential to influence long-term adaptation in other locations.

The IPCC (2022) also defines transformational adaptation in terms of social–ecological systems, stating that it changes the systems' fundamental attributes in anticipation of climate change and its impacts. As transformational adaptation generally includes adaptation at a greater scale or magnitude, it requires the introduction of new practices or technologies, the creation of new systems of governance, or shifts in the location of activities (Dinshaw 2014). While our review did not uncover concrete examples of transformational adaptation, there are a few examples in the broader literature. Kates *et al.* (2012) describe an ambitious transformational adaptation programme in the Netherlands. The Room for the River flood control programme is a major change from the traditional approaches of building levees and progressively increasing their heights over time. Rather, the extensive short-term projects are designed to adapt to the future impacts of climate change with a planning horizon of more than two centuries and provide an overall 10-fold level of flood protection. While the components of the programme may not all be new, they are considered transformational 'because of their enlarged scale, intensity, and integrated combinations of adaptations, and novel approaches, like artificial islands, evacuation of some areas, as well as new institutions and funding mechanisms' (p. 7157).

Many climate-related water quality issues can be traced back to land use in catchment areas. A case study of Canadian agriculture undertaken by Hadarits *et al.* (2017) examined the circumstances around which transformational adaptation would be adopted. For example, when faced with extreme drought conditions, an agricultural community would consider outmigration. Vermeulen *et al.* (2018) also identified examples of transformational adaptation in response to climate change, one such example being a Bangladesh farm impacted by the rising frequency and severity of floods reallocating land from crops to aquaculture.

4.4. Challenges to strategy implementation

The review identified significant challenges to the planning or implementation of adaptation actions. The barriers identified predominantly related to societal institutions and regulatory settings. Within the category of governance and institutional factors, the majority of issues were mentioned as barriers rather than providing a positive influence to support strategic actions. This finding highlights the importance of having sufficient and adequate regulatory settings, integrated and coordinated responses, and flexibility and sufficiently detailed policies.

5. CONCLUSION

This review has systematically evaluated peer-reviewed studies on adaptation strategies for climate impacts on water quality and the barriers and drivers that influence their implementation. At the beginning of this paper, we noted that there has been and continues to be a cautious approach to protecting our water quality from the impacts of climate change. Our review of the literature has confirmed these concerns but also highlighted the lack of attention to studies which focused on climate-impacted water quality adaptation strategies, the challenges in differentiating the sources of water quality degradation, the need for transformational adaptation strategies, and finding ways to overcome barriers to adaptation.

It was anticipated that the climatic conditions threatening water quality would be site-specific. However, while endemic weather patterns will play a significant role in levels of water quality, the review revealed common challenges of rising temperatures and variations in precipitation in a large proportion of the case studies from around the world. Rising air temperatures are intrinsically linked to water temperatures, and thus a warmer climate can lead to significant disruptions to the normal aquatic ecological balance. As a result, water quality is reduced through degraded water chemistry and anoxic conditions, resulting in implications for water treatment processes and increasing risks for users of the water bodies. Regional precipitation changes are increasing the occurrence of floods and droughts. Both of these extreme events lead to increased contaminants in the water, once again impacting water quality and putting increased stress on water treatment processes. While this study examined water quality holistically, there is an opportunity to focus future research on how impending climatic conditions impact the physical, chemical, and ecological indicators of water quality.

It became evident in this review that the literature on climate change impacts on the water is dominated by water security, with much less emphasis on strategies for the protection of water quality. Effective adaptation should be an intentionally planned process that responds to identified climate change impacts and vulnerabilities. The strategies developed need to adjust natural or human systems to minimise the harm from the changing effects of climatic elements (Wardropper & Rissman 2019). The strategies for protecting water quality identified in the reviewed articles include specific responses to local hydrology and ecology and within pre-existing management frameworks. Many are not necessarily significantly new measures or responses, but rather modifications implemented to contribute to an increase in resilience to climate change. Several authors concur that no one strategy can meet all future challenges, rather an integration of adaptation options tailored for different situations is necessary.

The approaches to adaptation for addressing climate-induced water quality challenges are predominantly reactionary, for example, simply altering the withdrawal depth for water treatment processes when thermal stratification occurs in water bodies. Some of the approaches are proactive, aiming to anticipate the changes and implementing preventative measures. The use of modelling to anticipate the implications of climate-related impacts on water quality is an example of incremental adaptation strategies. All adaptation strategies identified in the reviewed articles offer low to medium levels of resilience, with no examples of transformational adaptation necessary for high levels of resilience. Essentially, this lack of long-term adaptation strategies explains the current level of urgency assigned to climate change impacts by the majority of world leaders.

The review indicates the significance of societal institutions, governance networks, and decision-making frameworks on our ability to develop adaptation strategies to cope with the changing climate. As such, governance and institutional factors should be key considerations in determining appropriate strategies. Numerous examples of barriers and drivers in each of the other six categories identified by Klein *et al.* (2014) are also evident in the literature reviewed. A better understanding of these constraints and drivers can inform the selection of adaptation strategies or approaches.

Access to clean water is one of the most important human needs. Climatic changes are threatening the quality of our precious water resources, making it increasingly challenging to protect public health and water-reliant ecosystems. To date, research has focused on the volume and supply of water threatened by climate change, despite increasing evidence that the quality of water is of equal significance and concern. An improved understanding of the climate factors threatening water quality and the barriers and drivers of adaptation strategies will help unlock the innovative transformational solutions that will undoubtedly be required to protect our water quality in the future.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abdel-Fattah, S. & Krantzberg, G. 2014 A review: building the resilience of Great Lakes beneficial uses to climate change. *Sustainability of Water Quality and Ecology* **3–4**, 3–13.

Adger, W. N., Agrawala, S., Mirza, M. M. Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B. & Takahashi, K. 2007 Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson, eds.). Cambridge University Press, Cambridge, UK, pp. 717–743.

Alam, M. A., Badruzzaman, A. & Ali, M. A. 2013 Assessing effect of climate change on the water quality of the Sitalakhya River using WASP model. *Journal of Civil Engineering (IEB)* **41** (1), 21–30.

Anisha, N. F. & Yunus, A. 2016 Assessment of relationship of climatic, hydrologic and surface water quality parameters in Jamuna River. In: *8th International Perspective on Water Resources and the Environment American Society of Civil Engineers/Environmental and Water Resources Institute*, Colombo, Sri Lanka.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., Van Griensven, A., Van Liew, M. W. & Kannan, N. 2012 SWAT: model use, calibration, and validation. *Transactions of the ASABE* **55** (4), 1491–1508.

Astaraie-Imani, M., Kapelan, Z., Fu, G. & Butler, D. 2012 Assessing the combined effects of urbanisation and climate change on the river water quality in an integrated urban wastewater system in the UK. *Journal of Environmental Management* **112**, 1–9.

Azhoni, A. & Goyal, M. K. 2018 Diagnosing climate change impacts and identifying adaptation strategies by involving key stakeholder organisations and farmers in Sikkim, India: challenges and opportunities. *Science of the Total Environment* **626**, 468–477.

Baker, I., Peterson, A., Brown, G. & McAlpine, C. 2012 Local government response to the impacts of climate change: an evaluation of local climate adaptation plans. *Landscape and Urban Planning* **107**, 127–136.

Bates, B., Kundzewicz, Z., Wu, S. & Palutikof, J. 2008 *Climate Change and Water. Technical Paper VI*. Intergovernmental Panel on Climate Change (IPCC), Geneva.

Bi, W., Weng, B., Yuan, Z., Ye, M., Zhang, C., Zhao, Y., Yan, D. & Xu, T. 2018 Evolution characteristics of surface water quality due to climate change and LUCC under scenario simulations: a case study in the Luanhe River Basin. *International Journal of Environmental Research and Public Health* **15** (1724), 1–18.

Boholm, A. & Prutzer, M. 2017 Experts' understandings of drinking water risk management in a climate change scenario. *Climate Risk Management* **16**, 133–144.

Boogaard, F. C., Venvik, G., Pedroso de Lima, R. L., Cassanti, A. C., Roest, A. H. & Zuurman, A. 2020 Climatecafé: an interdisciplinary educational tool for sustainable climate adaptation and lessons learned. *Sustainability* **12** (3694), 1–19.

Carnohan, S. A., Clifford-Holmes, J. K., Retief, H., McKnight, U. S. & Pollard, S. 2021 Climate change adaptation in rural South Africa: using stakeholder narratives to build system dynamics models in data-scarce environments. *Journal of Simulation* **15**, 5–22.

Carvalho, M., Martins, B., Coelho, J. P., Brôco, N., Ribeiro, A. K., Magalhães, A. & Luís, A. 2019 Climate change adaptation: a pragmatic approach for assessing vulnerability. *Water Practice & Technology* **14** (1), 172–177.

Chan, T., MacDonald, M. C., Kearton, A., Elliott, M., Shields, K. F., Powell, B., Bartram, J. K. & Hadwen, W. L. 2020 Climate adaptation for rural water and sanitation systems in the Solomon Islands: a community scale systems model for decision support. *Science of the Total Environment* **714**, 136681.

Chang, H. 2004 Water quality impacts of climate and land use changes in Southeastern Pennsylvania. *The Professional Geographer* **56** (2), 240–257.

Chang, C. H., Cai, L. Y., Lin, T. F., Chung, C. L., Van der Linden, L. & Burch, M. 2015 Assessment of the impacts of climate change on the water quality of a small deep reservoir in a humid-subtropical climatic region. *Water* **7**, 1687–1711.

Chaubey, I., Bosch, D. D., Muñoz-Carpena, R., Harmel, R. D., Douglas-Mankin, K. R., Nejadhashemi, A. P., Srivastava, P. & Shirmohammadi, A. 2016 Climate change: a call for adaptation and mitigation strategies. *Transactions of the ASABE* **59** (6), 1709–1713.

Cherkauer, K. A., Bowling, L. C., Byun, K., Chaubey, I., Chin, N., Ficklin, D. L., Hamlet, A. F., Kines, S. J., Lee, C. I., Neupane, R. & Pignotti, G. W. 2021 Climate change impacts and strategies for adaptation for water resource management in Indiana. *Climatic Change* **165** (1), 1–20.

Chiang, L. C., Chaubey, I., Hong, N. M., Lin, Y. P. & Huang, T. 2012 Implementation of BMP strategies for adaptation to climate change and land use change in a pasture-dominated watershed. *International Journal of Environmental Research and Public Health* **9** (10), 3654–3684.

Coffey, R., Benham, B., Krometis, L. A., Wolfe, M. L. & Cummins, E. 2014 Assessing the effects of climate change on waterborne microorganisms: implications for EU and U.S. water policy. *Human and Ecological Risk Assessment: An International Journal* **20** (3), 724–742.

Crabbe, P. & Robin, M. 2006 Institutional adaptation of water resource infrastructures to climate change in Eastern Ontario. *Climate Change* **78**, 103–133.

Cross, K. & Latorre, C. 2015 Which water for which use? Exploring water quality instruments in the context of a changing climate. *Aquatic Procedia* **5**, 104–110.

Dedekorkut-Howes, A., Torabi, E. & Howes, M. 2020 When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding. *Journal of Environmental Planning and Management* **63** (12), 2102–2143.

Delpla, I., Baures, E., Jung, A. V., Clement, M. & Thomas, O. 2011 Issues of drinking water quality of small scale water services towards climate change. *Water Science and Technology* **63** (2), 227–232.

De Smedt, P. 2010 Water-related tools for climate change adaptation in the Flemish Region: the art of linking water quality standards to spatial planning. *Journal for European Environmental Planning Law* **7** (3), 287–301.

Dinshaw, A. 2014 *What Is the Role for Transformation in Adaptation?* Available at: https://www.wri.org/insights/what-role-transformation-adaptation (accessed 8 June 2022).

Ebert, S., Hulea, O. & Strobel, D. 2009 Floodplain restoration along the lower Danube: a climate change adaptation case study. *Climate and Development* **1** (3), 212–219.

Ekstrom, J., Bedsworth, L. & Fencl, A. 2017 Gauging climate preparedness to inform adaptation needs: local level adaptation in drinking water quality in CA, USA. *Climate Change* **140**, 467–481.

European Environment Agency (EEA) 2014 *Spatial Analysis of Green Infrastructure in Europe*. Available at: https://www.eea.europa.eu/publications/spatial-analysis-of-green-infrastructure.

European Environment Agency (EEA) 2016 *Urban Adaptation to Climate Change in Europe 2016, Transforming Cities in A Changing Climate*. EEA, Luxembourg.

Fedele, G., Donatti, C. I., Harvey, C. A., Hannah, L. & Hole, D. G. 2020 Limited use of transformative adaptation in response to social-ecological shifts driven by climate change. *Ecology and Society* **25** (1), 25.

Feldbauer, J., Kneis, D., Hegewald, T., Berendonk, T. U. & Petzoldt, T. 2020 Managing climate change in drinking water reservoirs: potentials and limitations of dynamic withdrawal strategies. *Environmental Sciences Europe* **32** (1), 1–17.

Garnier, M. & Holman, I. 2019 Critical review of adaptation measures to reduce the vulnerability of European drinking water resources to the pressures of climate change. *Environmental Management* **64**, 138–153.

Giri, S., Lathrop, R. G. & Obropta, C. C. 2020 Climate change vulnerability assessment and adaptation strategies through best management practices. *Journal of Hydrology* **580**, 1–19.

Godebo, T. R., Jeuland, M. A., Paul, C. J., Belachew, D. L. & McCornick, P. G. 2021 Water quality threats, perceptions of climate change and behavioral responses among farmers in the Ethiopian rift valley. *Climate* **9** (6), 92.

Ha, M. & Wu, M. 2017 Land management strategies for improving water quality in biomass production under changing climate. *Environmental Research Letters* **12** (3), 034015.

Hadarits, M., Pittman, J., Corkal, D., Hill, H., Bruce, K. & Howard, A. 2017 The interplay between incremental, transitional, and transformational adaptation: a case study of Canadian agriculture. *Regional Environmental Change* **17**, 1515–1525.

Iacob, O., Rowan, J. S., Brown, I. & Ellis, C. 2014 Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective. *Hydrology Research* **45** (6), 774–787.

Intergovernmental Panel on Climate Change (IPCC) 2022 *Climate Change 2022: Impacts, Adaptation and Vulnerability. Summary for Policymakers. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK and New York, NY, USA.

International Union for Conservation of Nature. 2022 *Water and Climate Change*. Available from: https://www.iucn.org/resources/issues-briefs/water-and-climate-change (accessed 8 June 2022).

Jin, L., Whitehead, P. G., Futter, M. N. & Lu, Z. 2012 Modelling the impacts of climate change on flow and nitrate in the River Thames: assessing potential adaptation strategies. *Hydrology Research* **43** (6), 902–916.
Jordan, P. A. 2020 Hands across the water: climate change and binational cooperation in the Great Lakes Basin. *Climatic Change* **161**, 479–497.
Jun, X., I. A., Shubo, C., Xiuping, H. A. O., Rui, X. I. A. & Xiaojie, L. I. U. 2010 Potential impacts and challenges of climate change on water quality and ecosystem: case studies in representative rivers in China. *Journal of Resources and Ecology* **1** (1), 31–35.
Kalafatis, S. E., Lemos, M. C., Lo, Y.-J. & Frank, K. A. 2015 Increasing information usability for climate adaptation: the role of knowledge networks and communities of practice. *Global Environmental Change* **32**, 30–39.
Kashyap, A. 2004 Water governance: learning by developing adaptive capacity to incorporate climate variability and change. *Water Science and Technology* **49** (7), 141–146.
Kates, R. W., Travis, W. R. & Wilbanks, T. J. 2012 Transformational adaptation when incremental adaptations to climate change are insufficient. *PNAS* **109** (19), 7156–7161.
Khan, S. J., Deere, D., Leusch, F. D., Humpage, A., Jenkins, M. & Cunliffe, D. 2015 Extreme weather events: should drinking water quality management systems adapt to changing risk profiles. *Water Research* **85**, 124–136.
Khaniya, B., Gunathilake, M. B. & Rathnayake, U. 2021 Ecosystem-based adaptation for the impact of climate change and variation in the water management sector of Sri Lanka. *Mathematical Problems in Engineering* **2021**, 1–10.
Khatibi, F., Dedekorkut-Howes, A., Howes, M. & Torabi, E. 2022 Can public awareness, knowledge and engagement improve climate change adaptation policies? *Discover Sustainability* **2** (1), 1–24.
Kim, Y. & Chung, E. S. 2015 Robust prioritization of climate change adaptation strategies using the VIKOR method with objective weights. *JAWRA Journal of the American Water Resources Association* **51** (5), 1167–1182.
Kim, D. H., Jang, T., Hwang, S. & Jeong, H. 2021 Paddy rice adaptation strategies to climate change: transplanting date shift and BMP applications. *Agricultural Water Management* **252**, 106926.
Klein, R., J. T., Midgley, G. F., Preston, B. L., Alam, M., Berkhout, F. G. H., Dow, K. & Shaw, M. R. 2014 Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea & L. L. White, eds.). Cambridge University Press, UK and New York, NY, USA, pp. 899–943.
Kopprio, G. A., Freije, R. H., Arias-Schreiber, M. & Lara, R. J. 2014 An ecohydrological adaptive approach to a salt lake in the semiarid grasslands of Argentina: future management perspectives. *Sustainability Science* **9** (2), 229–238.
Kopprio, G. A., Biancalana, F., Fricke, A., Cardona, J. E. G., Martínez, A. & Lara, R. J. 2015 Global change effects on biogeochemical processes of Argentinian estuaries: an overview of vulnerabilities and ecohydrological adaptive outlooks. *Marine Pollution Bulletin* **91** (2), 554–562.
Kumar, P., Johnson, B. A., Dasgupta, R., Avtar, R., Chakraborty, S., Kawai, M. & Magcale-Macandog, D. B. 2020 Participatory approach for more robust water resource management: case study of the Santa Rosa sub-watershed of the Philippines. *Water* **12** (1172), 1–15.
Levine, A., Yang, Y. & Goodrich, J. 2016 Enhancing climate adaptation capacity for drinking water treatment facilities. *Journal of Water and Climate Change* **7** (3), 485–497.
Lukasiewicz, A., Pittock, J. & Finlayson, M. C. 2016 Are we adapting to climate change? A catchment-based adaptation assessment tool for freshwater ecosystems. *Climate Change* **138**, 641–654.
Magee, M. R., Hein, C. L., Walsh, J. R., Shannon, P. D., Vander Zanden, M. J., Campbell, T. B., Hansen, G. J., Hauxwell, J., LaLiberte, G. D., Parks, T. P. & Sass, G. G. 2019 Scientific advances and adaptation strategies for Wisconsin lakes facing climate change. *Lake and Reservoir Management* **35** (4), 364–381.
Mehdi, B., Lehner, B., Gombault, C., Michaud, A., Beaudin, I., Sottile, M. F. & Blondlot, A. 2015 Simulated impacts of climate change and agricultural land use change on surface water quality with and without adaptation management strategies. *Agriculture, Ecosystems and Environment* **213**, 47–60.
Mi, C., Shatwell, T., Ma, J., Xu, Y., Su, F. & Rinke, K. 2020 Ensemble warming projections in Germany's largest drinking water reservoir and potential adaptation strategies. *Science of the Total Environment* **748**, 1–12.
Miller, K. A. & Belton, V. 2014 Water resource management and climate change adaptation: a holistic and multiple criteria perspective. *Mitigation and Adaptation Strategies for Global Change* **19** (3), 289–308.
Moher, D., Liberati, A., Tetzlaff, J. & Altman, D. 2009 Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ* **339** (7716), 1–8.
Mukheibir, P. 2008 Water resources management strategies for adaptation to climate-induced impacts in South Africa. *Water Resources Management* **22**, 1259–1276.
Nagy-Kovács, Z., László, B., Simon, E. & Fleit, E. 2018 Operational strategies and adaptation of RBF well construction to cope with climate change effects at Budapest, Hungary. *Water* **10** (1751), 1–11.
Nunes, J. P., Jacinto, R. & Keizer, J. J. 2017 Combined impacts of climate and socio-economic scenarios on irrigation water availability for a dry Mediterranean reservoir. *Science of the Total Environment* **584–585**, 219–233.

O'Neill, S. J. & Handmer, J. 2012 Responding to bushfire risk: the need for transformative adaptation. *Environmental Research Letters* **7** (1), 014018.

Palmer, M. A., Lettenmaier, D. P., Poff, N. L., Postel, S. L., Richter, B. & Warner, R. 2009 Climate change and river ecosystems: protection and adaptation options. *Environmental Management* **44**, 1053–1068.

Parkinson, R. W., Seidel, V., Henderson, C. & De Freese, D. 2021 Adaptation actions to reduce impairment of Indian River Lagoon water quality caused by climate change, Florida, USA. *Coastal Management* **49** (2), 215–232.

Peirson, W., Davey, E., Jones, A., Hadwen, W., Bishop, K., Beger, M., Capon, S., Fairweather, P., Creese, B., Smith, T. F. & Gray, L. 2015 Opportunistic management of estuaries under climate change: a new adaptive decision-making framework and its practical application. *Journal of Environmental Management* **163**, 214–223.

Pickering, C. & Byrne, J. 2014 The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. *Higher Education Research and Development* **33** (3), 534–548.

Poudel, D. D. & Duex, T. W. 2017 Vanishing springs in Nepalese mountains: assessment of water sources, farmers' perceptions, and climate change adaptation. *Mountain Research and Development* **37** (1), 35–46.

Pouget, L., Escaler, I., Guiu, R., Mc Ennis, S. & Versini, P. A. 2012 Global change adaptation in water resources management: the water change project. *Science of the Total Environment* **440**, 186–193.

Qiu, J., Shen, Z., Leng, G., Xie, H., Hou, X. & Wei, G. 2019 Impacts of climate change on watershed systems and potential adaptation through BMPs in a drinking water source area. *Journal of Hydrology* **573**, 123–135.

Ricart, S. & Rico-Amoros, A. M. 2021 Constructed wetlands to face water scarcity and water pollution risks: learning from farmers' perception in Alicante, Spain. *Water* **13** (2431), 1–21.

Rocha, J., Carvalho-Santos, C., Diogo, P., Beça, P., Keizer, J. J. & Nunes, J. P. 2020 Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal). *Science of the Total Environment* **736**, 139477.

Rodriguez, M. & Delpla, I. 2017 Climate changes and drinking water in sustainable cities: impacts and adaptation. *WIT Transactions on Ecology and the Environment* **223**, 573–582.

Rosenzweig, C., Major, D. C., Demong, K., Stanton, C., Horton, R. & Stults, M. 2007 Managing climate change risks in New York city's water system: assessment and adaptation planning. *Mitigation and Adaptation Strategies for Global Change* **12**, 1391–1409.

Salerno, F., Gaetano, V. & Gianni, T. 2018 Urbanization and climate change impacts on surface water quality: enhancing the resilience by reducing impervious surfaces. *Water Research* **144**, 491–502.

Salila, E., Sharma, M. P. & Singh, R. 2020 Climate change impacts on water quality of water bodies – a review. *International Journal of Environment and Climate Change* **10** (3), 26–37.

Shannon, P. D., Swanston, C. W., Janowiak, M. K., Handler, S. D., Schmitt, K. M., Brandt, L. A., Butler-Leopold, P. R. & Ontl, T. 2019 Adaptation strategies and approaches for forested watersheds. *Climate Services* **13**, 51–64.

Staben, N., Nahrstedt, A. & Merkel, W. 2015 Securing safe drinking water supply under climate change conditions. *Water Science and Technology: Water Supply* **15** (6), 1334–1342.

Thorne, O. & Fenner, R. 2008 Modelling the impacts of climate change on a water treatment plant in South Australia. *Water Science & Technology: Water Supply* **8** (3), 305–312.

Torabi, E., Dedekorkut-Howes, A. & Howes, M. 2018 Adapting or maladapting: building resilience to climate-related disasters in coastal cities. *Cities* **72**, 295–309.

Trinh, L. T., Duong, C. C., Van Der Steen, P. & Lens, P. N. 2013 Exploring the potential for wastewater reuse in agriculture as a climate change adaptation measure for Can Tho City, Vietnam. *Agricultural Water Management* **128**, 43–54.

Tung, C.-P., Lee, T.-C., Liao, W.-T. & Chen, Y.-J. 2012 Climate change impact assessment for sustainable water quality management. *TAO: Terrestrial, Atmospheric and Oceanic Sciences* **23** (5), 565.

UNESCO 2021a *Water Quality and Climate Change*. Available from: https://en.unesco.org/waterquality-IIWQ/activities-projects/water-quality-climate-change (accessed 8 June 2022).

UNESCO 2021b *International Initiative on Water Quality (IIWQ)*. Available from: https://en.unesco.org/waterquality-iiwq/wq-challenge (accessed 8 June 2022).

United Nations Climate Change 2022 *The Fifth Assessment Report of the IPCC*. Available from: https://unfccc.int/topics/science/workstreams/cooperation-with-the-ipcc/the-fifth-assessment-report-of-the-ipcc.

United States Environmental Protection Agency (U.S. EPA) 2021a *Adaptation Actions for Water Management and Ecosystem Protection*. Available from: https://www.epa.gov/arc-x/adaptation-actions-water-management-and-ecosystem-protection#:~:text=%20Adaptation%20Actions%20for%20Water%20Management%20and%20Ecosystem,other%20federal%20resources.%20%20…%20%20More%20.

United States Environmental Protection Agency (U.S. EPA) 2021b *What is Green Infrastructure?* Available from: https://www.epa.gov/green-infrastructure/what-green-infrastructure.

Urama, K. C. & Ozor, N. 2010 Impacts of climate change on water resources in Africa: the role of adaptation. *African Technology Policy Studies Network* **29**, 1–29.

Vermeulen, S. J., Dinesh, D., Howden, S. M., Cramer, L. & Thornton, P. K. 2018 Transformation in practice: a review of empirical cases of transformational adaptation in agriculture under climate change. *Frontiers in Sustainable Food Systems* **2** (65), 1–17.

Wardropper, C. B. & Rissman, A. R. 2019 Adaptations to extreme storm events by conservation organizations. *Climate Change* **152** (1), 85–101.

Whitehead, P. G., Wilby, R. L., Butterfield, D. & Wade, A. J. 2006 Impacts of climate change on in-stream nitrogen in a lowland chalk stream: an appraisal of adaptation strategies. *Science of the Total Environment* **365** (1–3), 260–273.

Whitehead, P. G. Wilby, R. L., Battarbee, R. W., Kernan, M., & Wade, A. J. 2009a A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* **54** (1), 101–123.

Whitehead, P., Wade, A. & Butterfield, D. 2009b Potential impacts of climate change on water quality and ecology in six UK rivers. *Hydrology Research* **40** (2–3), 113–122.

Wilby, R. L. & Wood, P. J. 2012 Introduction to adapting water management to climate change: putting our science into practice. *Area* **44** (4), 394–399.

Wilby, R., Whitehead, P. G., Wade, A. J., Butterfield, D., Davis, R. J. & Watts, G. 2006 Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology* **330**, 204–220.

Wu, C.-L., Herrington, S. J., Charry, B., Chu, M. L. & Knouft, J. H. 2021 Assessing the potential of riparian reforestation to facilitate watershed climate adaptation. *Journal of Environmental Management* **277**, 111431.

Xu, Y., Bosch, D. J., Wagena, M. B., Collick, A. S. & Easton, Z. M. 2019 Meeting water quality goals by spatial targeting of best management practices under climate change. *Environmental Management* **63** (2), 173–184.

Yang, Y. J., Restivo, A., Jun, Y. S., Schupp, D. A., Mash, H. & Krishnan, E. R. 2010 Aquifer storage and recovery as a viable climate change adaptation technique: sustainable development under the current regulatory framework. In: *World Environmental and Water Resources Congress 2010: Challenges of Change* (R. N. Palmer, ed.). American Society of Civil Engineers, Reston, VA, pp. 144–153.

First received 29 July 2022; accepted in revised form 16 December 2022. Available online 26 December 2022