Water Resilience Assessment Framework

Guidance for Basin Managers and Planning Authorities

PACIFIC INSTITUTE

UN GLOBAL COMPACT CEO WATER MANDATE

BHP

Water Resilience Assessment Framework: Guidance for Basin Managers and Planning Authorities

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Guidance Authors

Ashok Chapagain
Gregg Brill
CEO Water Mandate; Pacific Institute
www.ceowatermandate.org
www.pacinst.org

Jed Youngs
BHP
https://www.bhp.com/

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Project Partners

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Stakeholder Advisory Group

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Project Overview
The project was launched in 2019, with seed funding from BHP, initially to develop a common water accounting framework. The scope evolved to speak more directly to climate change and focus on water resilience, given the urgent and critical need to build long-term resilience in basins around the world.

The Water Resilience Assessment Framework was launched in 2021. For more information and to download the framework, guidance documents and associated tools for implementation, please visit https://ceowatermandate.org/resilience-assessment-framework/.

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Glossary

Basin: A basin or river basin follows the same principles as a catchment (see below) of capturing water across a geographical zone, however at a wider scale.

Catchment: The geographical zone in which water is stored, flows through and is eventually discharged at one or more points.

Resilience: The ability of an individual, institution or system to respond to shocks and stresses and survive and thrive despite the impacts of those shocks and stresses.

Resilience strategy: A systematic approach to enhance resilience by understanding and addressing shocks and stresses. Resilience strategies fall into three categories: persistence, adaptation and transformation.

Resilience characteristics: Specific aspects of resilience to be considered to ensure resilient actions align and support the selected resilience strategy.

Resilience indicators: Qualitative and/or quantitative metrics to track the impacts of the actions on the resilience of the system and/or stakeholder(s).

Resilience actions: Interventions made by stakeholders to enhance the resilience strategy.

Stakeholder: A stakeholder can be a person, group, sector, company, agency, community or organization that influences or is influenced by the use and governance of a common set of resources. Ecosystems can also be stakeholders, though they may need to be represented by a proxy, such as via expert opinion or a legal representative.

Stress test: The process of assessing the impact of actions intended to build resilience under a range of plausible future scenarios. The stress test clarifies how well the actions respond to shocks and stresses and supports the goals of the selected resilience strategy.

System: The catchment and the interconnected components that influence the functioning of components. The system components are further categorized as socio-economic, institutional, governance, infrastructure, management and biophysical components (including ecosystem functions) that influence that catchment. It is defined not only by hydrological boundaries but also the administrative/political boundaries.

System boundary: The spatial and temporal limits of the water system, as defined through stakeholder goals and interests.

System scale: Water systems are not uniform, and they differ in size and scope. The spatial, temporal and institutional elements that are included in the system inform the scale of the system. A system scale can range from the individual or institution - such as a company, organization, community or utility - to a catchment and beyond to key elements of that system that may exist outside of a catchment - such as the data, electrical and water grids, supply chain networks and distribution networks. Impacts at different scales can affect the resilience of stakeholders and systems.

System status: The historic and current water status in the system is defined through qualitative and quantitative variables, such as water quantity and quality, storage, uses and other eco-hydrological characteristics. Water accounting is the core process in establishing the water status of the system.

System trends: The course of future water status, predicted using quantitative or qualitative approaches, based on ongoing or projected drivers impacting water status.

Abbreviations and Acronyms

AWE	**Agency for Water and the Environment**
BMPA	**Basin Managers and Planning Authorities**
DEM	**Department of Environmental Management**
IWRM	**Integrated Water Resource Management**
NBS	**Nature-based solutions**
ReST	**Resilience Scoring Tool**
SC	**Steering Committee**
WG	**Working Group**
WRAF	**Water Resilience Assessment Framework**

To thrive in times of uncertainty, water systems must cultivate and enhance their core resilience characteristics to achieve the goals of water security, sustainability and beyond.

Executive Summary

The world is facing a critical water crisis. This crisis is impacting social, economic and natural systems globally. Climate change is further exacerbating the magnitude and scale of the crisis, and immediate action is needed to build long-term water resilience. Climate change demands immediate changes in how we govern and manage water. While acknowledging the need for adaptation is common, translating this into concrete action within water management remains a challenge. This is where the Water Resilience Assessment Framework (WRAF) enters the picture, offering a practical guide for navigating these complexities.

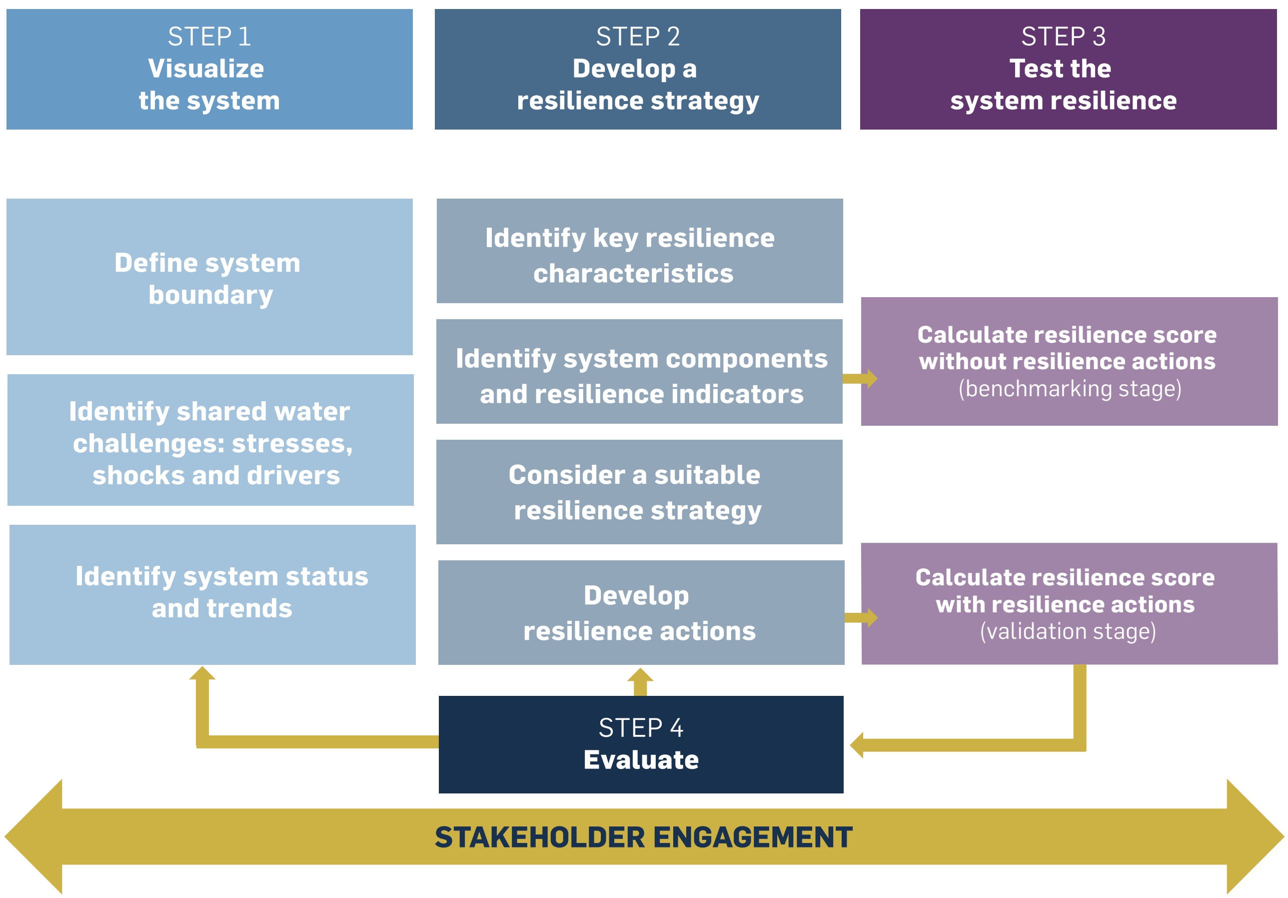
Building resilience in these systems begins with understanding the challenges they face. Water systems are vulnerable to both long-term incremental stresses like gradual temperature changes and droughts and urgent shocks like floods, coastal storms, cyberattacks and major earthquakes. To develop appropriate resilience strategies and actions, we must understand what drives these shocks and stresses that water systems may experience. These drivers, which can be global, regional or local, encompass factors like climate change, population growth, water withdrawals, land-use changes and governance issues. Identifying these drivers exposes vulnerabilities and highlights the need for resilience across socio-economic, institutional and biophysical components.

Basin managers and planning authorities (BMPA) play a critical role in navigating these challenges. Basin managers work at the regional or watershed level, overseeing water allocation, conservation and distribution while balancing the needs of diverse stakeholders. This balancing act demands an understanding of both immediate water needs and the long-term health of water systems. Planning authorities work alongside them, developing and implementing long-term water resilience strategies through data analyses, demand forecasting and policy design. Both parties play a vital role in steering water management towards sustainability for future generations. This guide is intended to support these efforts.

Effective decision-making in an uncertain future necessitates a resilient mindset. This goes beyond simply bouncing back from challenges to adapting and transforming. When uncertainties shift targets and decision-making processes, resilience becomes a critical tool for survival. This is where the WRAF comes in, offering practical actions and strategies along with tools to measure and monitor progress. By providing an overarching framework to build resilience across all stakeholder levels within a water system, the WRAF for BMPA (see figure below) empowers decision-makers with the tools they need to navigate an uncertain future and safeguard this finite resource for generations to come.

The management of a river basin can be a complex process and varies depending on the country or region. The specific roles and responsibilities of the entities involved will also vary. However, all entities play an important role in ensuring the sustainable management of river basins.

BMPA (Basin Managers and Planning Authorities) is a generic term used in this guidance to refer to the agency or agencies that develop policies and plans for water resources and governance of these and implement actions as part of their responsibility and authority in the basin's context. A few examples of BMPA are national, federal, state and provincial water and environmental authorities, catchment authorities (local, national, transboundary), river basin commissions/authorities and regional and national planning commissions/authorities. For more examples, see section: Step in Practice.



By fostering smarter resilience strategies, effective actions and clear monitoring, this document empowers BMPA in building systemwide resilience in three ways:

1. This guidance sheds light on how water resilience is interconnected across the entire basin. This shift from siloed solutions to a broader understanding guides the development of better strategies, plans and policies. This holistic approach also clarifies limitations, ensuring everyone aligns their efforts with shared goals.

2. This guidance equips BMPA to pinpoint actions that truly strengthen water resilience. By understanding the real impact of these actions, BMPA can focus on making a significant difference, avoiding wasted effort.

3. This guidance provides the tools to choose and track the right indicators, measure the state of resilience and keep everyone informed about progress in resilience planning and implementation. This transparency fosters accountability and collaboration, ensuring stakeholders are engaged and empowered.

The impact of this document extends far beyond BMPA themselves. Researchers, water professionals and even community groups can leverage it to develop better tools and best practices for building resilient water systems everywhere. Local stakeholders and Indigenous Peoples can use it to advocate for water resilience at the basin level, ensuring all voices are heard.

Resilience Approach in Planning and Managing a Basin

THE NEED FOR BUILDING SYSTEM RESILIENCE

Compounding pressures from population growth, intensifying climate impacts, and increasing demand for a finite resource are pushing the world towards a critical water scarcity tipping point. Alarming statistics paint a stark picture: 26% of the global population lacks safely managed drinking water. Since 1970, we have lost 35% of the world's wetlands (Convention on Wetlands, 2021). Climate change's impact on water resources is undeniable. Between 2000 and 2019, water-related extremes like floods and droughts dominated natural disasters, affecting more than 3 billion people and causing $780 billion in economic losses (CRED and UNDRR, 2020). These events, amplified in both frequency and intensity, accounted for 75% of all disasters, displacing 1.65 billion people and impacting an additional 1.43 billion others.

The impacts of climate change and other human activities have led to a high degree of unpredictability in ecological, social and economic systems[1], which impedes the ability of these systems to thrive. Water systems in particular face increased levels of vulnerability, which can be and have been further exacerbated by unprecedented social and economic shocks, such as a pandemic or economic crises. Impacts on water systems also follow varying temporal scales and intensities - extreme heat, long-term droughts and over-extraction can cause incremental impacts, while events like wildfires, floods and chemical spills can cause sudden impacts. Clean water plays a critical role in providing health and wellbeing to nature and society, thus there is an urgent need to address the long-term viability of our water systems.

In the past, policymakers and advocates have used the concepts of water security and water sustainability to address many water-related challenges. The term 'water security' was originally conceptualized to acknowledge that water scarcity risks fueling violent geopolitical and transboundary conflicts. The term 'water sustainability' refers to the ability of a community or natural system to meet present water needs without compromising the ability of future generations to meet their own needs. Water sustainability takes a more holistic, systems-based approach that acknowledges the role water plays in providing ecosystem goods and services, supporting biodiversity, increasing climate mitigation and adaptation and underpinning sustainable development. Water sustainability is broadly recognized as a long-term goal achieved by meeting economic, social and environmental objectives for water that includes notions of inter- and intra-generational equity (Pacific Institute, 2021).

However, for a system to thrive in times of uncertainty, it must develop characteristics that achieve the goals of water security, sustainability and *beyond* (Pacific Institute, 2021). The emerging concept of resilience focuses on strengthening those core concepts of security and sustainability while also maintaining and enhancing system functioning to ensure that the system can withstand and rebound from shocks and stresses.

1 Functioning of the interconnected and interdependent interacting parts of the Earth, including the atmosphere, hydrosphere, geosphere, cryosphere and biosphere.

Resilience can also help policy- and decision-makers with competing objectives to develop or adapt policies and practices in an equitable and just manner. Water systems are dynamic and interconnected and fundamentally influence the environmental, social and economic sectors. As such, a resilience approach is crucial for maintaining such a system so that disturbances do not impact long-term stability.

Resilience as a concept is not a new idea. However, resilience in and of water systems is still nascent and beginning to gain attention in water resources management practice, decision-making, policy and scholarship (Miralles-Wilhelm *et al.*, 2022). Several academic publications highlight resilience thinking focused specifically on watersheds (Wilson and Browning, 2012; Baird *et al.*, 2016; Koebele, 2020), but efforts have been mostly compartmentalized and divided into ecological resilience, social resilience or engineering resilience. As knowledge and awareness of resilience increases, there is a need to have a comprehensive system-wide approach that aligns and brings together the different siloed approaches across multiple scales.

Ecological resilience is the foundation for building resilience across social and economic systems. An ecosystem can absorb disturbance and reorganize while undergoing change to retain essentially the same function, structure, identity and feedback. Ecological resilience is important to broader system resilience because it helps to buffer the system against shocks and stresses. When an ecosystem is resilient, it is more likely to be able to recover from a disturbance without major changes to its function or structure. This can help to protect the ecosystem from collapse and can also help to protect the goods and services that the ecosystem provides to humans and nature. Resilient ecosystems provide us with clean air, water, fuel, fiber and food. They also help to regulate the climate and protect us from natural disasters. When ecosystems are resilient, they are more likely to be able to provide these essential services to humans (Walker *et al.*, 2004)

WATER RESILIENCE ASSESSMENT FRAMEWORK

The Water Resilience Assessment Framework (WRAF) provides a practical means for stakeholders and water users to understand and improve the resilience of their water systems in the face of increasing levels of uncertainty and vulnerability (Chapagain *et al.*, 2021; 2022). The WRAF supports the development of strategies and actions to build and enhance long-term water resilience and is intended to inform resilient decision-making that prevents isolated shocks and stresses from becoming unmanageable crises. The WRAF emphasizes water as the keystone of resilience because water is vital for life and is embedded in the economy as processes, products, institutions and sectors in ways we often cannot see and do not think about regularly. As such, the WRAF is a method to be used either individually or collectively along with existing risk-management and water-management approaches to gain insight into how we measure progress towards resilience.

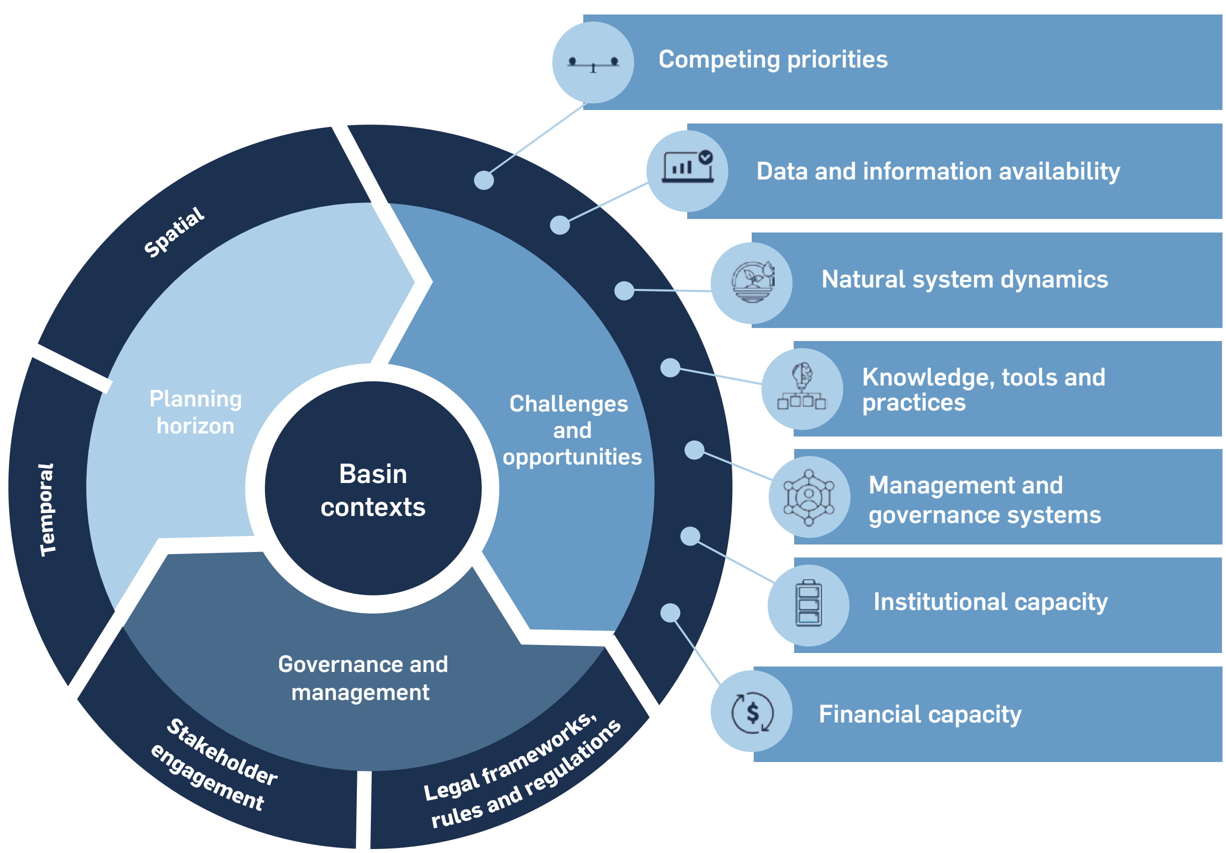
The WRAF builds on existing approaches and practices such as Integrated Water Resource Management (IWRM), water accounting and risk assessments. For example, common water accounting methodologies traditionally identify the connections among the dynamic hydrologic, economic and social components that make up a basin-scale water system to enable effective, meaningful action for water security for all. These approaches are mostly based on historical data and modeling and do not provide a forward-facing approach that allows for shifts in policies and actions as the overall system changes. The WRAF provides the flexibility to expand the scope of these approaches and practices by helping select appropriate actions and strategies while monitoring and evaluating the impacts of these efforts over time.

BASIN-SPECIFIC CONTEXTS IN BUILDING RESILIENCE

Basin managers and planning authorities (BMPA) are tasked with the critical responsibility of ensuring sustainable water management at the regional or watershed level. They must balance the demands of diverse stakeholders, including agriculture, industry and communities, while simultaneously safeguarding the environment. To achieve this balance, they employ long-term water resilience strategies, which involve analyzing data, forecasting demands and designing policies to address existing and future water challenges. By prioritizing water resilience, basin managers and planning authorities can avert water scarcity, environmental degradation and socio-economic disruptions. Their proactive approach to sustainable water management ensures the continued availability of this precious resource for generations to come.

However, BMPAs face unique and complex challenges in managing water resources compared with corporations or utilities. These challenges vary depending on the country or region. The specific roles and responsibilities of the entities involved also vary. For successful implementation of the WRAF at the basin level, it is crucial to understand the basin contexts (Figure 1) which can be broadly categorized into three areas: governance and management, planning horizon and direction and challenges and opportunities.

FIGURE 1. EXAMPLES OF BASIN-SPECIFIC CONTEXT CATEGORIES, CHALLENGES AND OPPORTUNITIES



Governance and management: River basin governance is a complex process that requires the engagement of multiple stakeholders and the consideration of a variety of legal frameworks and rules and regulations. A successful river basin management plan will balance multiple goals and objectives, such as providing water for human use, protecting ecosystems and biodiversity and reducing flood and drought risk. Many countries have complex legal frameworks for water management that are often guided by national or international framework directives. These legal frameworks underpin basin governance and management, guiding decisions on resilience actions and strategies. Effective stakeholder engagement requires political support from multiple levels of Government, a dedicated budget, open lines of communication and transparency in decision-making.

Planning horizon: BMPA must anticipate changes in water systems in terms of time and space to plan effectively. The nature and duration of these changes will determine whether BMPA should prepare for continuity, gradual shifts or abrupt transitions. These insights guide the selection and implementation of appropriate strategies. To develop resilience strategies, BMPA can consider different planning horizons. Resilience planning typically operates on long-term temporal scales, allowing for the consideration of future needs and the development of gradual management strategies. When working at the basin scale, temporal and spatial planning is crucial. Resilience planning typically requires working with long-term temporal scales; this allows planners and managers to consider the basin's future needs by assessing potential problems and opportunities and thus develop management strategies that are designed to address those issues over time. Spatial planning is also key to successful resilience planning, given that basins often cross political boundaries, which can have a significant impact on decision-making in basin management.

Challenges and opportunities: Operationalizing the WRAF at the basin level can be challenging, but it can also provide opportunities to enhance the resilience of the overall system. The key challenges include meeting conflicting priorities of different organizations or communities operating in the basin, data and information availability, understanding of natural system dynamics, level of existing knowledge, tools and practices, level of maturity of the management and governance systems, limited institutional capacity and financial capacity. Despite these challenges, operationalizing the WRAF can provide opportunities to enhance system-wide resilience by providing a framework for holistically managing water resources, improving data and information collection and management, promoting the use of adaptive management and supporting the development of institutions and partnerships.

A detailed explanation of these contexts is presented in Appendix A.

OBJECTIVES OF THE GUIDANCE

The WRAF provides a systematic approach to addressing water management challenges by considering three components of the water system: socio-economic, institutional and biophysical. This holistic approach fosters a comprehensive understanding of the basin context, challenges and opportunities, and it enables BMPA to develop effective strategies for building long-term water resilience. This detailed guidance on the application of the WRAF is for BMPA interested in understanding and improving the resilience of the water system for all users and the environment. It can be equally useful for community groups, Indigenous Peoples and other local stakeholders looking to understand and advocate for water resilience at the basin level or to help lead resilience planning, particularly in situations where catchment management is immature or ineffective.

The guidance aims to provide:

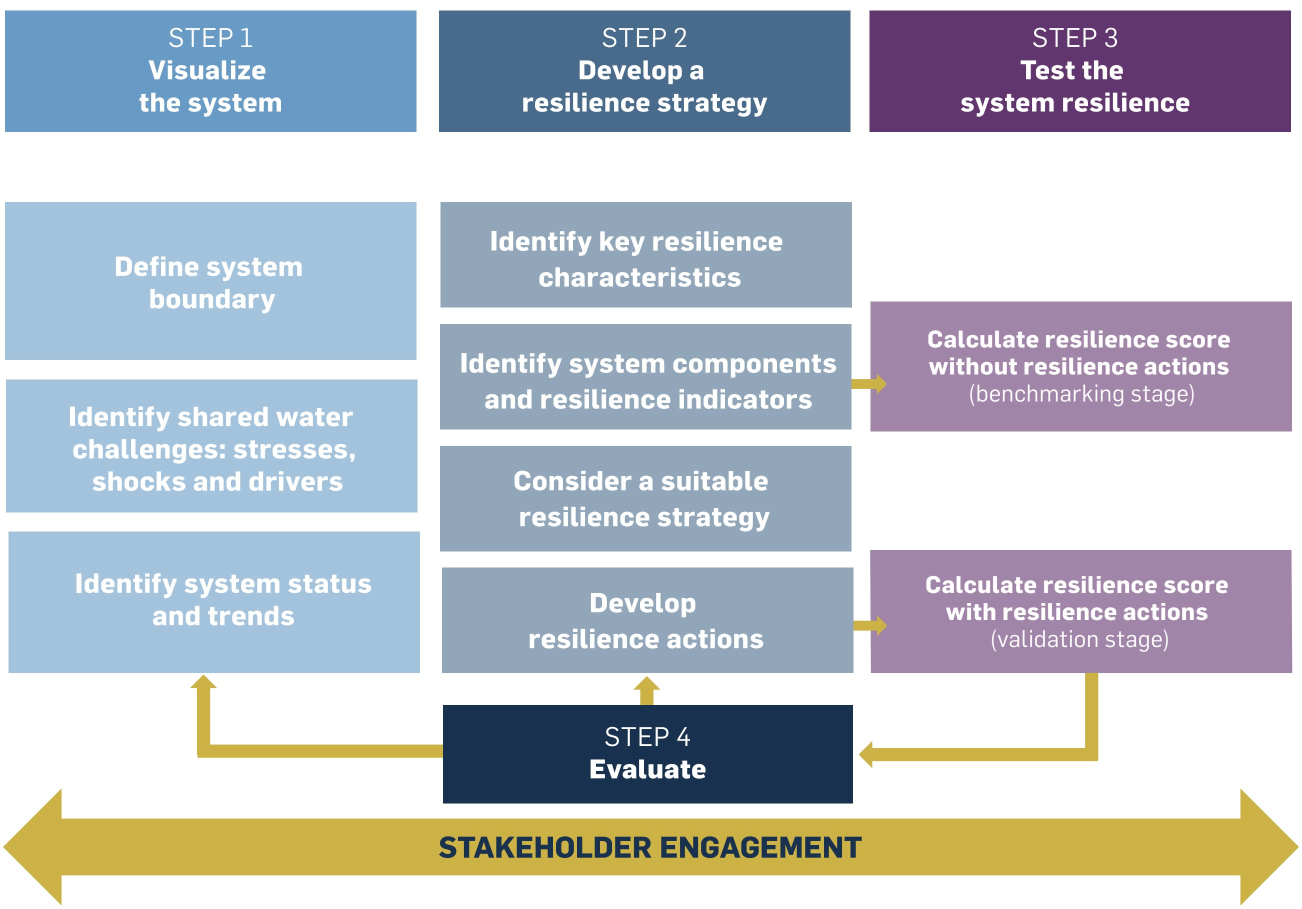
- A **clear and comprehensive explanation of the framework** for different authorities and key stakeholders relevant to basin management and governance**.**
- An outline and elaboration of the **key steps in WRAF** to understand system resilience with examples and case studies to help users apply the framework.
- A logical framework to **develop resilience actions** for a selected set of resilience goals.
- Resources to perform the various steps of the WRAF, including **resilience indicators, actions, relevant tools and methods**.

The WRAF is further elaborated in two specific sectors with practical guidance on how to implement: WRAF for corporates (or, more broadly, water users), and WRAF for utilities (or, more broadly, water suppliers). The current guidance is the third in the series and focused on decision-makers and planners at the system level, such as river basin managers, regional and national planners, policymakers, etc.

Operationalizing the Water Resilience Assessment Framework

The WRAF provides an overarching modular approach to building resilience across different scales. This practical guidance presents the steps of the Framework (Figure 2, adapted from Chapagain *et al.*, 2021). Although it is suggested to follow the steps sequentially, due to the inherent characteristics of a basin and multiple decision-making agencies involved, individual authorities may perform substeps concurrently or in a different order depending on their priorities, resources and capacity. In the following sections, we elaborate on all the steps in the WRAF in detail and provide a hypothetical example from a river in the United Kingdom (Step in Practice).

FIGURE 2. WATER RESILIENCE ASSESSMENT FRAMEWORK FOR BASIN MANAGERS AND PLANNING AUTHORITIES



Stakeholder engagement is essential throughout the WRAF process. The following are the various basin stakeholders that BMPA can engage in the WRAF process:

- **Water users:** Households, businesses, farmers, local communities and other organizations that use water.
- **Government agencies:** Local, state and federal agencies that have a role in water management.
- **Environmental groups:** These groups are concerned with protecting the environment and ensuring that water resources are used sustainably.
- **Indigenous communities:** These communities have a long history of living in the basin and have a deep understanding of the water resources.
- **Research institutions:** These institutions can provide scientific expertise in water resources management.
- **Private sector:** This includes businesses that are involved in water-related activities, such as water utilities, water treatment companies and water bottling companies.

The specific stakeholders that need to be engaged will vary depending on the specific application of the WRAF. However, it is important to engage a broad range of stakeholders to ensure that the process is inclusive and meets the needs of all water users. A few examples of stakeholder engagement processes are:

- **Public meetings:** This is a traditional way to engage stakeholders. Public meetings can be held to present the WRAF application process and various steps involved and to gather feedback from stakeholders.
- **Online surveys:** This is a way to engage stakeholders who may not be able to attend public meetings. Online surveys can be used to gather feedback on the WRAF processes and to identify the priorities of stakeholders.
- **Focus groups:** This is a way to engage stakeholders in a more in-depth discussion of the WRAF processes. Focus groups can be used to gather feedback on specific aspects of the plan and to identify potential solutions to problems.
- **Workshops:** This is a way to engage stakeholders in a collaborative process to develop the WRAF processes. Workshops can be used to bring together stakeholders from different backgrounds to work together to develop a plan that meets the needs of all water users.

Most BMPA can easily identify the relevant stakeholders within the hydrological and\or political boundaries. However, other stakeholders external to these boundaries, who are influenced or impacted by what happens in that catchment, should also be included in the process.

Some organizations looking to implement the WRAF may look to set up a steering committee, working group or similar structure to engage stakeholders and create a mechanism for overall decision-making and governance in the project, including planning and development of the project phases, budgeting, resource allocation, communications and stakeholder engagement.

The WRAF process should be inclusive and transparent, and all stakeholders should have a voice in the development of the plan. By engaging and sharing a common goal and understanding the risks of transformation, many groups can align their efforts and investments in building long-term water resilience in the basin.

STEP 1: VISUALIZE THE SYSTEM

Every water system holds a unique set of opportunities and challenges in building resilience depending on the local context and underlying processes, functions and conditions of the landscape. Assessing resilience begins with understanding the system boundaries, current and potential challenges, trends and status of a particular water system. This also includes identifying and engaging key stakeholders. The system refers to interconnected socio-economic, institutional and biophysical components that function as a whole. Connections among different parts of that system may not be obvious or intuitive which, in itself, is an important insight.

This section presents the initial steps to visualize the different attributes of the system as needed in operationalizing the WRAF for BMPA. This step also structures how to collect data and information to update the current status and trends of the challenges, stresses, shocks and drivers.

1.1 DEFINE SYSTEM BOUNDARY

The first step for visualizing the system involves defining its boundary. For the WRAF, the demarcation of the system boundary is guided by who is making decisions and managing the system. These system boundaries may not fully align with the hydrological boundaries. Hydrological boundaries are physically defined by hydrological parameters that can be delineated using models, tools or other approaches (e.g., HydroSHEDS, DHI's Global Hydrological Model, etc.). However, the system boundaries can also be defined by administrative jurisdictions. For example, BMPA may be able to make decisions at a regional basin level or across multiple basins including transboundary basins, whereas district-level Government officers or local sub-basin managers may only be able to operate at local levels. For the BMPA, the system boundary could encompass the whole basin under their jurisdiction, whereas for the local authority, it may only be a district, city or village. Beyond hydrological or administrative requirements, there may be other considerations in defining the system boundaries, such as Aboriginal or Indigenous rights to water, access to land or sovereignty.

Importantly, and regardless of the hydrological or jurisdictional boundaries, the system also implies a set of interconnected socio-economic, institutional and biophysical components that influence and impact the selected area (see Step 1.3). Additionally, a broad range of stakeholders should be engaged to ensure that their perspectives and values are considered when demarcating system boundaries. These additional considerations may inform the governance and management of resources within the system, which will ultimately define the system boundary considered in the WRAF.

Shared values: A value represents something of significance and meaning to an individual or organization. A 'shared value in a river basin" represents a critical concept in the context of sustainable water resource management. It signifies a specific aspect of the river basin that holds significance and meaning for more than one individual or organization. Examples of shared water values include clean and safe drinking water, water for irrigation and agriculture, water for industrial use, water for hydropower generation, water for ecosystem health and recreational and cultural values. These values can encompass environmental, cultural, economic and social aspects. A shared water challenge arises when multiple stakeholders recognize that a particular value is under threat or when stakeholders' activities are perceived to conflict with one another.

The concept of shared water values was first introduced by the Global Water Partnership (GWP, 2000). The GWP defines shared water values as 'those values of water that are shared by multiple stakeholders in a river basin and that are essential for the sustainable development and management of the basin. These values could be highly context specific though share similar aspects. One example of such shared value identification is presented in 'Water Resources Situational Analysis for the Central Queensland Region' (WRSA, 2023) which identified eight high-level water resource-related value categories in the Fitzroy River Basin in Central Queensland, Australia:

- Healthy aquatic ecosystems
- Abundant and diverse native aquatic and riparian flora and fauna
- Cultural and spiritual connections with Land and Sea Country
- Water for safe human consumption
- Water for primary industries and industrial water
- Safe recreational waters and amenity
- Water security for future livelihoods
- Equity in decision-making and ensuring Traditional Owners Rights

Delineating the hydrological boundaries helps understand the system's water status such as quantity, quality and accessibility of water resources, prediction of water flows and other hydrological variables in the system. Delineating the jurisdictional boundaries helps identify relevant stakeholders, coordinate water management efforts, develop and enforce rules and regulations, etc. Ultimately, defining a system boundary helps BMPA identify the key drivers influencing the shocks and stresses experienced in a system, articulate the relevant system components and evaluate the water status and trends of the system.

1.2 IDENTIFY SHARED WATER CHALLENGES: STRESSES, SHOCKS AND DRIVERS

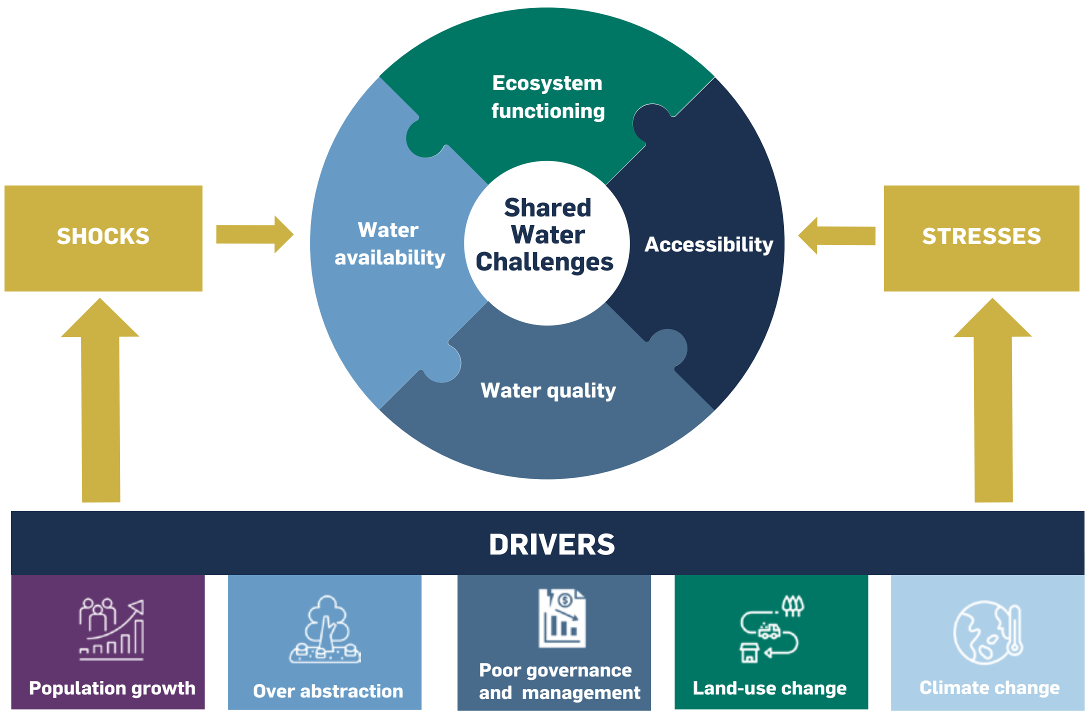
Once the system boundaries and components have been delineated, the next step is to identify the current and anticipated challenges in the system.

A shared water challenge arises when more than one stakeholder identifies that a value is being threatened or that a stakeholder's activities are seen to compete with the protection of a value (WRSA, 2023). In the Fitzroy River Basin in Central Queensland, Australia, the shared water challenges identified by WRSA are:

- Lack of integrated water resource planning and management
- Limited participation and access of First Nations to Land and Sea Country
- Limited water for economic and social wellbeing
- Limited data confidence and knowledge
- Poor water and catchment quality e.g., lack of sufficient water to support ecosystems, coral bleaching, rising salinity levels, increasing sediment loads, excessive toxicants, chemicals, fertilizers, etc.

The magnitude, likelihood and frequency of shared water challenges in a particular water system will be influenced by existing and anticipated incremental stresses and shocks, which are in turn further influenced by the nature of the drivers. Understanding the key drivers, shocks and stresses can help us better visualize the shared water challenges of the system (Figure 3). Drivers influence and exacerbate the shocks and stresses in a system. These shocks and stresses further influence the magnitude, frequency and likelihood of shared water challenges. It is an important step of the WRAF to identify all these interrelated topics.

FIGURE 3. INFLUENCE OF DRIVERS, SHOCKS AND STRESSES ON CHALLENGES IN A WATER SYSTEM



Many of the drivers, shocks and stresses (existing or anticipated) could be identified during risk assessments or adaptation planning. These exercises may already be a part of operational and management practices and processes, whereas in some cases, specific risk assessments may need to be undertaken. Importantly, resilience goes beyond typical risk assessments and helps build long-term, systemic mitigation and adaptation approaches through resilience actions and strategies. Wherever possible, the WRAF calls on existing data gleaned from these approaches.

Stresses are incremental changes in the system, such as gradual changes in temperature and precipitation, sea-level rise and long-term droughts. Shocks are sudden changes in the system, such as rapid changes in temperature and precipitation, flooding, coastal storms, earthquakes, fire, cybersecurity breaches, terrorism, violent conflict and epidemics/pandemics. Drivers are the external factors, such as climate change, demographic change, economic trends and regulatory shifts that influence the magnitude, frequency and likelihood of impacts from shocks and stresses.

The identification of drivers, shocks and stresses can be informed by the outcome of Step 1.3 where the data on current water status, trends and predicted changes are collected. As Step 1.3 (water status and trends) is directly linked to the identification of the key water challenges of the system and the current and anticipated stress and shocks (Step 1.2), there could be multiple iterations of the substeps in Step 1.

1.3 IDENTIFY SYSTEM STATUS AND TRENDS

System status refers to the current and historic state of a water system, while trends reflect predicted changes in the system due to ongoing, planned or probable shifts in the policies or activities impacting the system. Once the system status has been established, it is important to understand how it is changing (or anticipated to change) temporally, spatially and across different system components. Trends can be identified using quantitative and qualitative data sources. For example, if BMPA want to understand how certain stresses, such as surface water scarcity/availability, are influencing the challenges in the watershed, they need to know if water availability is improving, worsening or unchanged.

The WRAF proposes a sliding scale to assess shifting trends in the attributes of the system – going from 'worsening' to 'no change' to 'improving.' For example, due to increasing water scarcity, the supply of household water could be under stress. The increase in urbanization and economic activities may further increase the demand for potable supplies. Hence, the trend in this case is 'worsening'.

System status and trends can be used to understand how the system is responding to stresses and shocks and to identify potential vulnerabilities. They can also be used to predict or understand key water challenges and their state and to help visualize the system. This process can help BMPA to further identify or prioritize new shared water challenges in the basin (revisit Step 1.2).

STEP 2: DEVELOP RESILIENCE STRATEGY

In this step, BMPA implementing the WRAF should aim to identify the key resilience characteristics (Step 2.1) relevant to the system components and subcomponents that were identified in Step 1. Additionally, they should select appropriate resilience indicators to measure, assess and track the progress in building these resilience characteristics of the system (Step 2.2), select a suitable resilience strategy (Step 2.3) and develop specific resilience actions to support the selected strategies (Step 2.4).

Once Step 2 is complete, managers and planners will have a baseline state of resilience of the system and a feasible set of resilience actions to improve long-term water resilience across the different system components and subcomponents.

2.1 IDENTIFY KEY RESILIENCE CHARACTERISTICS

Two central tenets of the WRAF are (a) resilience must be able to be measured to know if progress is being made, and (b) traditional sustainability measures are probably not useful for measuring resilience. Resilient systems exhibit specific characteristics that aid in assessing their resiliency. The WRAF identifies six resilience characteristics that can help track, measure and assess the status of the resilience of the water system (Chapagain *et al.*, 2021).

- **Robustness:** The system is designed to perform at or beyond the levels of high-confidence, low-uncertainty risks.
- **Redundancy:** The system has spare capacity intentionally created to accommodate disruption, extreme pressures or demand surges.
- **Flexibility:** The system can be altered and adapted in response to potential shocks and stresses or adjusted to take advantage of opportunities.
- **Integration:** The system components are linked and coordinated while also able to be isolated.
- **Inclusiveness:** The system has effective mechanisms for broad consultation and engagement of individuals and communities, including the most vulnerable.
- **Justice and Equity:** The system ensures that all stakeholders within a system are provided with equitable water access, rights and allowances.

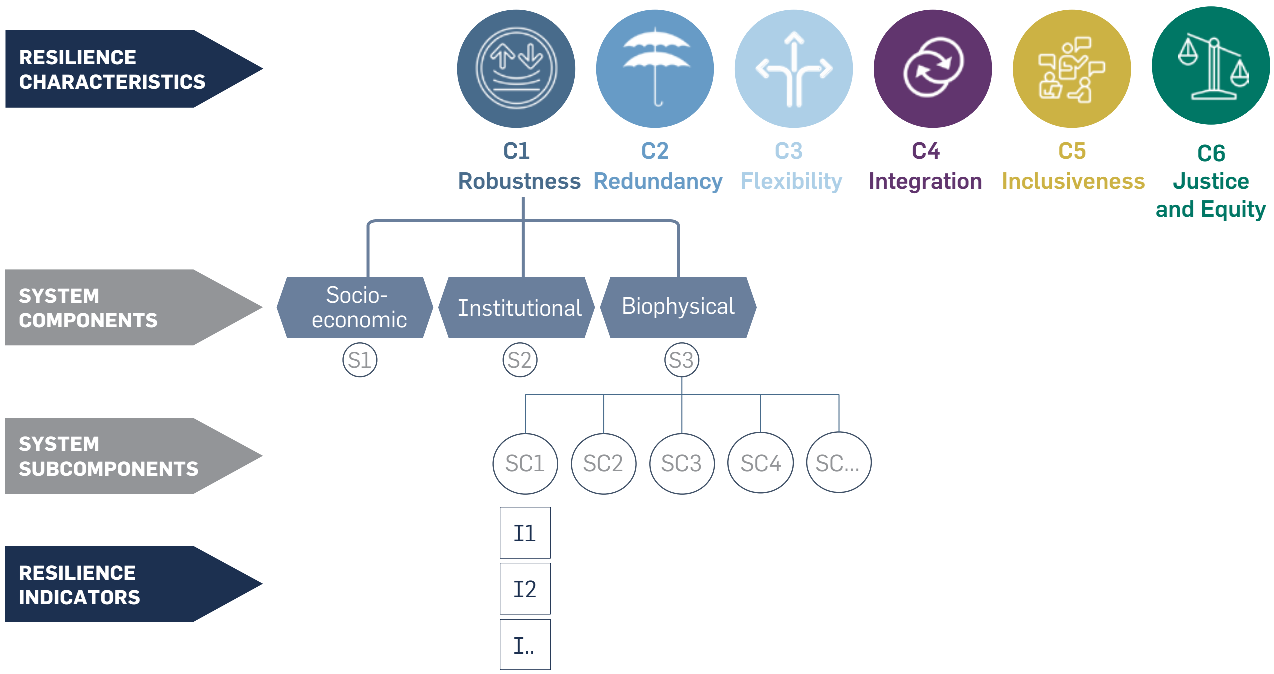
BMPA wishing to undertake a comprehensive resilience analysis should plan to review all six characteristics to produce long-term, system-wide resilience. However, it is possible to start the WRAF process by only focusing on a few characteristics that are considered a priority. For example, in a system with a history of limited stakeholder trust and poor governance, BMPA can consider focusing efforts towards the 'Inclusiveness' and 'Justice and Equity' characteristics.

The information from Step 1 will inform the selection of the appropriate resilience characteristics. The priority water challenges in the system, and the current status and trends, will point to which characteristics require greater attention and more active intervention. The WRAF is designed to be iterative, so this step can be revisited after reviewing subsequent steps or updated as the WRAF is repeated later.

2.2 IDENTIFY SYSTEM COMPONENTS AND RESILIENCE INDICATORS

To strengthen the selected resilience characteristics of the system, BMPA can examine it at a more granular level by breaking it down into smaller, more manageable parts. This will help them better understand the system and identify areas where it can be improved. The components and subcomponents of the system can be selected based on how they influence the selected resilience characteristics (Figure 4).

FIGURE 4. PROCESS FLOW TO SELECT SPECIFIC RESILIENCE INDICATORS TO MEASURE RESILIENCE CHARACTERISTICS



Note: Includes an example from resilience characteristic 'Robustness' (C1) for system component 'Biophysical' (S3) and subcomponent 'SC1.'

2.2.1 Identify system components

The resilience characteristics identified in Step 2.2 need to be examined and strengthened for each system component. To fully understand how the system functions and the elements present in the system, we need to define and understand system components. The WRAF broadly delineates three interrelated system components: socio-economic, institutional and biophysical. Each system component comprises various system subcomponents (Table 1). The identification of a particular system component or multiple components is based on the challenges identified in Step 1.2 as well as the other considerations listed below.

- Roles and responsibilities of the BMPA
- Strategic goals and mandate of the organization/collective group
- Management and governance structures
- Selected temporal and spatial scales
- Data availability
- Stakeholder preferences and levels of engagement
- Financial aspects

TABLE 1. EXAMPLES OF SYSTEM SUBCOMPONENTS ACROSS SYSTEM COMPONENTS

Socio-economic	Institutional	Biophysical
• Access to funds/ resources • Access to services • Demand management • Knowledge systems • Available capacity • Cultural and Indigenous knowledge systems	• Economic ability (affordability) • Governance (financial ability, willingness, competency, transparency, trust, accountability, maturity, environmental justice, etc.) • Operations/system management (decision-making, flexibility, etc.) • Regulations (practicality, maturity, compliance, etc.) • Built and/or natural infrastructures (policies/ mechanisms) • Legal frameworks (allocation, operation and management) • Corruption, accountability and transparency	• Supply (types, reliability in quantity and quality, adequacy, interconnections and independence) • Built infrastructure (suitability, capacity to operate, technology, reliability and capacity of structures, etc.) • Natural infrastructure (capacity, connectedness, quantity and quality) • Operations/system management (access to technology and tools) • Biodiversity (aquatic and terrestrial)

Not all system components will be relevant across all contexts. Similarly, some subcomponents may be mutually exclusive, whereas others will be interconnected. For example, 'demand management' under the socio-economic component will be heavily influenced by many of the subcomponents under the institutional and biophysical components. BMPA should select and prioritize as many subcomponents as needed to reflect the nature of the system(s). The selection of system components and subcomponents could be further revisited following subsequent steps in the WRAF.

2.2.1 Identify resilience indicators

With the resilience characteristics selected and system components identified, BMPA should identify relevant resilience indicators to measure these characteristics (Figure 4). This guidance provides two tiers of resilience indicators (Appendix B, also captured in the Resilience Scoring Tool (ReST).

The ReST is a user-friendly tool that can be used to select key resilience indicators, based on relevant system components and subcomponents under each of the resilience characteristics (Chapagain and Brill, 2024). This tool follows a traffic-light scoring system - green indicates a high or good score; yellow indicates an average score; red indicates a low or poor score. Based on expert knowledge and available metrics, appropriate score ranges for each indicator are built into the tool. Users will select the score that best represents the outcomes from their benchmarking or validation stress tests. The tool can be used for both Tier 1 and Tier 2 resilience assessments, depending on the needs of the users.

Tier 1 provides snapshot indicators that can be used to assess a resilience characteristic at a high level (Table 2). Tier 2 indicators allow BMPA to undertake a more granular assessment of the selected characteristics for each relevant system component and subcomponent (Appendix B). The list of Tier 1 and Tier 2 indicators is illustrative and ultimately should be tailored based on the local context as identified in Step 1.

TABLE 2. TIER 1 RESILIENCE INDICATORS AND MEASURES FOR BASIN CONTEXT

Resilience characteristic	Tier 1 Resilience indicator	Measure	Score range
Robustness	Percentage of time that the basin provides the required volume of water to meet environmental flow requirements and to meet the needs of all water users in the system	Low Medium High	Low (<70%) Medium (70-79%) High (>80%)
	Percentage of time that the basin maintains required water quality levels to meet environmental flow requirements and to meet the needs of all water users in the system	Low Medium High	Low (<70%) Medium (70-79%) High (>80%)
Redundancy	Percentage of time the backup, supplementary and/or alternative replacement components of the system can support key functions	Low Medium High	Low (<2%) Medium (2-5%) High (>5%)
	Capacity of the backup, supplementary and/or alternative components to meet critical functions	Low Medium High	Low (<5%) Medium (5 - 25%) High (>25%)
Flexibility	Ability of the system sub-components to be adapted or shifted to meet critical functions	Low Medium High	Qualitative assessment/ value judgment
Integration	Degree that sub-components within the system are linked and coordinated	None Minimal Sufficient	Qualitative assessment/ value judgment
Inclusiveness	Level of inclusion of diverse stakeholders in decision-making of the system	Low Medium High	Qualitative assessment/ value judgment
Justice and equity	Degree of provision of fair and equitable water-related services for all users in the system	Low Medium High	Qualitative assessment/ value judgment

After selecting indicators, BMPA should conduct an initial stress test (Step 3) using the ReST to assess the current state of resilience in their system (benchmarking stage). The outcome of the 'benchmark stress test' should indicate the state of resilience of the system components under each selected resilience characteristic. Attention should be paid to the indicators receiving the lowest or weakest scores (red) as these indicators will best inform the selection of a suitable resilience strategy and appropriate actions to improve overall resilience. An example of a benchmarking test, for the resilience characteristic 'Robustness', is presented in Table 6 in the Step in Practice section.

2.3 SELECT A RESILIENCE STRATEGY

The WRAF proposes three resilience strategies: persistence, adaptation and transformation. These strategies can be applied independently at multiple levels starting from the subcomponent level to component level for each resilience characteristic through to a broader resilience strategy at the organizational level.

RESILIENCE STRATEGIES

Persistence: A *persistence* strategy expects the functioning of the system to return to its original or near-original state following a disturbance or shock. There may be shocks and stresses that temporarily disrupt ordinary functions, but these are short-lived and after these disturbances, the system returns to business as usual. A *persistence* strategy emphasizes shoring up key weaknesses against shocks but does not radically re-envision current operating practices.

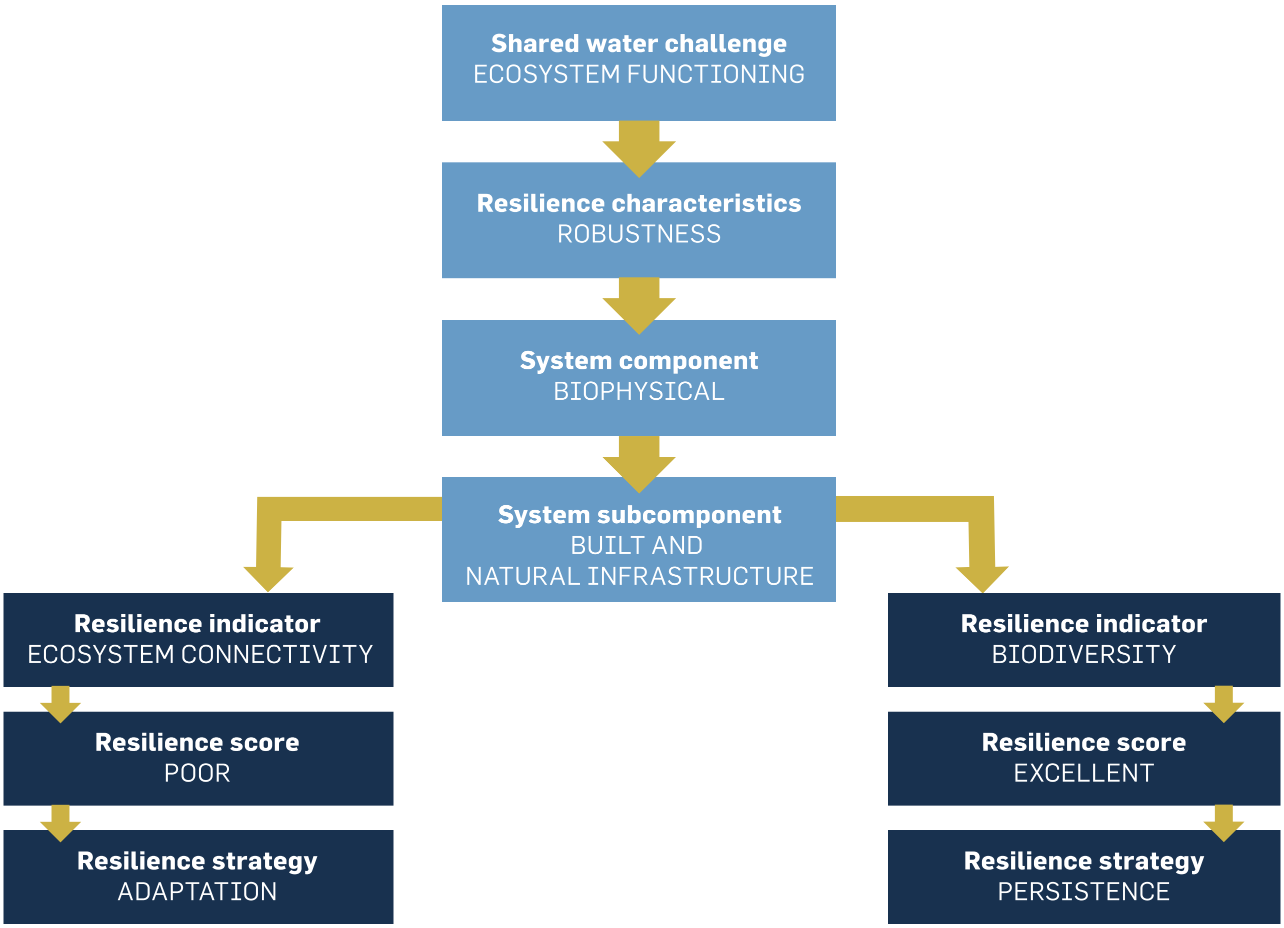
Adaptation: An *adaptation* strategy expects that the system will face a future that is substantively different from the status quo. These changes occur gradually but meaningfully eliminate the status quo as viable in the future. An a*daptation* strategy emphasizes maintaining current needs while simultaneously preparing for more drastic future changes.

Transformation: A *transformation* strategy expects the system to face major, unrecognizable future conditions. The system is reorganizing itself with new eco-hydrological characteristics, which could come suddenly and dramatically or, following a gradual accrual like sea-level rise, reach a tipping point of more systemic and sweeping adjustments. Drastic changes in the context have already occurred and are expected to accelerate. A *transformation* strategy emphasizes reconsidering at a fundamental level the management and operation of the system and may require new technological and socio-economic structures.

Choosing a resilience strategy requires careful consideration of various factors. While some systems may exhibit strong robustness and only require *persistence*, others may necessitate transformative approaches to enhance resilience characteristics such as 'Inclusiveness'. Stakeholder priorities may conflict, necessitating tailored strategies for different system components and subcomponents to address the diverse needs of stakeholders. Adopting an inappropriate resilience strategy can have detrimental consequences for a basin. The impact of major investments, such as infrastructure development, on resilience enhancement may not be apparent until the opportune window for action has passed. For instance, if BMPA selects a *persistence* strategy amidst ongoing climate change, the system's functioning could be severely disrupted, potentially stranding vital assets over time.

The selection of resilience strategies for different system components should be guided by local priorities. For instance, if 'ecosystem functioning' is identified as the primary shared water challenge, and the goal is to enhance system robustness, particularly in terms of the built and natural infrastructure of the biophysical system component, two distinct strategies could be employed based on specific resilience indicators (Figure 5). An *adaptation* strategy could be implemented to address broken or weak ecosystem connectivity. Conversely, a *persistence* strategy might be more suitable if the system exhibits satisfactory biodiversity richness.

FIGURE 5. AN EXAMPLE OF THE PROCESS OF SELECTING APPROPRIATE RESILIENCE STRATEGIES



Importantly, a strategy that is suitable now or under current conditions may become ineffective or inappropriate should the system cross a certain tipping point (threshold) or if conditions change significantly. Therefore, a regular revisit of the WRAF process is recommended.

The dynamics of human-natural systems are complex to understand. Although there are efforts to develop integrative models to study these interactions (energy-water-land-economy-climate change), the development of suitable basin-level resilience strategies can only be approached through combined modeling scenarios and data analytics (Miralles-Wilhelm *et al.*, 2022).

To guide the selection of resilience strategies and the combination of multiple strategies for different system subcomponents, BMPA should ask a series of questions to ascertain their resilience goals, system functions, available resources, capacity and other key factors. Some sample questions to support the selection of an appropriate resilience strategy are presented in Table 3 (adapted from Chapagain *et al.*, 2022; Miralles-Wilhelm *et al.*, 2022).

TABLE 3. SAMPLE QUESTIONS TO SUPPORT THE SELECTION OF AN APPROPRIATE RESILIENCE STRATEGY

Key focus	Questions
Resilience goals	• What are the resilience goals or priorities of the BMPA? • Do these goals also support ongoing efforts for building resilience for communities and the environment? If not, what would need to change so that they align with organizational goals and deliver multiple benefits to communities and nature?
Managing system functioning, resilience variables and their interactions	• What are the current and future status and trends of the system? • Should we maintain existing flows despite climate change? Revert to past flows? Anticipate or track emerging trends? • Which resilience strategy is the most suitable to select based on the status and trends of the system? • What are the drivers and the associated risk of actions (or inaction) on the resilience of a basin? • How will anticipated shocks and stresses influence the status and trends, or how will these affect the management and operations in the basin? • To what degree can resilience be managed as past conditions, tracking change through time or for potential future states?
Leveraging natural properties and processes	• Which resilience characteristics can be strengthened through nature-based solutions (NBS)? • How effective are NBS in basins on multiple spatial and temporal scales? • What are the trade-offs, externalities, uncertainties and potential negative impacts of NBS on other ecosystem services and specific communities? What can be adjusted to mitigate these impacts upfront? • How do the stacked NBS benefits and enhancements on ecosystem services and community/social outcomes influence basin resilience?
Integrative monitoring, modeling and data analysis	• Can resilience strategies be developed based on available data and scenarios? • What are new methods in data-driven and physically based modeling that are needed to quantify outcomes across the wide variety of resilience variables (status and trends)? • Can modeling help understand spatial and temporal dimensions of the system's persistence, adaptation and transformation phases? • Are advanced methods available to better integrate socio-economic, institutional and biophysical components assessing the impact of resilience actions? • Following the benchmarking stress test, which resilience characteristics and system components and subcomponents are performing poorly? • How can scenario planning be effectively integrated into basin resilience assessments?
Developing a resilience focus on adaptive watershed management	• Which resilience strategy can boost the ecosystem services for nature and people? • Which resilience strategy is best suited to planning conducted with traditional engineering or ecological management approaches? • Which resilience strategy best suits the underlying social factors or drivers (e.g., attitudes, behavior and standard institutional processes)? • Which resilience strategy best supports the outcome of monitoring, evaluation and learning processes? • Are there already existing suitable strategies that can be scaled and transferred between basins?
Institutional elements	• How much control does the BMPA have in implementing the selected strategy on its own? • What is the required level of engagement to work collectively with other stakeholders? • What is the level of complexity and fragmentation in decision-making organizations? • What are the complementary and conflicting policies across different decision-making organizations? Which resilience strategy best aligns with the current or anticipated regulatory requirements?

Following the selection of a resilience strategy, the BMPA can start developing resilience actions to improve overall resilience across selected characteristics and components as indicated in the stress test at the benchmarking stage.

2.4 DEVELOP RESILIENCE ACTIONS

Following the selection of an appropriate resilience strategy, resilience actions must be developed such that the selected resilience characteristics are improved. While the resilience scoring tool and strategy direct actions, the following considerations can support the action development and selection process:

- If the resilience score at the benchmarking stage is poor or low regarding one or more specific indicators (red at Tier 2), authorities should prioritize immediate improvement in these areas.
- If the resilience score at the benchmarking stage is moderate or good (yellow at Tier 2), it may require improvements to address current and future challenges.
- If the resilience score at the benchmarking stage is excellent or high (green at Tier 2), BMPA may develop actions to future-proof themselves based on prioritized resilience characteristics or operational mandates. An organization should endeavor to have resilience actions in place to be proactive rather than reactive.
- As water policies evolve, resilience actions must be continuously evaluated and adapted to ensure effectiveness.
- An unexpected shock or challenge is experienced and needs to be addressed.

Those responsible for WRAF implementation can start the development of resilience actions by looking into the existing policies, practices and plans to manage their system, the available resources and capacity, etc. This will help prepare an initial portfolio of feasible resilience actions that can be implemented. This could be done in multiple steps: internal assessment, engaging with external parties (stakeholder surveys, workshops) and gathering expert knowledge. Additional opportunities to engage with relevant actors should be explored along the WRAF process to ensure that all opportunities to build appropriate resilience actions are considered.

BMPA can compile a list of existing and potential resilience actions they could undertake to address the shared water challenges identified (Table 4). These high-level actions can be used to inform the more specific actions developed to improve the performance of the indicators used in the benchmarking stress test.

TABLE 4. AN ILLUSTRATIVE LIST OF RESILIENCE ACTIONS PER TYPICAL SHARED WATER CHALLENGE

Shared water challenges	Example list of resilience actions
Water Availability & Accessibility	• License review and modification: BMPA can review and modify abstraction licenses to protect the environment or ensure there is sufficient water available. They assess the licenses' impact on the environment and consult with stakeholders to make necessary changes. • Restrictions and bans: During times of water scarcity, BMPA may apply restrictions or bans on water abstraction to conserve water resources. • Diversification of water sources: BMPA can work with water companies and communities to diversify water sources by exploring alternatives such as desalination, water recycling and rainwater harvesting to reduce reliance on traditional surface and groundwater sources during times of water scarcity.
Water Quality	• Pollution reduction strategies: BMPA can work with stakeholders to reduce pollution through stricter regulations on industrial discharges, optimal/reduced use of chemical fertilizers and pesticides in agricultural fields, agricultural runoff management and sewage treatment plant upgrades in urban and agricultural areas in a basin. • Infrastructure additions and upgrades: Building or upgrading new sewage or wastewater treatment plants, treatment wetlands and stormwater storage tanks can help reduce sewage overflows into the river during heavy rainfall events, thereby improving water quality.
Flooding	• Flood management: BMPA plays a critical role in managing flood risk by implementing mitigation measures such as building flood defenses, dredging rivers and developing floodplain management strategies (such as planning guidance, permits restricting development and other activities impacting floodplains). • Data monitoring and forecasting: Investing in advanced data monitoring and forecasting technologies can help BMPA anticipate and respond to water challenges more effectively. Real-time data on river levels, water quality and weather conditions can enable proactive decision-making and early-warning systems for floods and pollution events. • Climate adaptation: To adapt to the expected increase in flooding due to climate change, BMPA can focus on measures such as enhancing early warning systems and promoting sustainable land-use practices in flood-prone areas.
Ecosystem Functioning	• Habitat restoration: BMPA can invest in habitat restoration projects to address negative impacts on ecosystem functioning, such as restoring wetlands, reconnecting floodplains and protecting key wildlife habitats. • Biodiversity conservation: BMPA can support initiatives to protect and restore biodiversity-rich areas in the basin.

Besides the targeted resilience actions per challenge, the BMPA can look into other resilience actions such as raising public awareness and education to create a culture of water stewardship, building strong partnerships, engaging in climate change mitigation efforts, supporting research and innovation in water management, advocating for necessary regulatory reforms, supporting the development of appropriate legislation and by-laws, developing and regularly updating emergency response plans, engaging in long-term planning and collaborating with neighboring countries and international organizations.

Within temporal and spatial considerations, BMPA may look to NBS and the role that green infrastructure can play in meeting key objectives or mandates. NBS are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits (IUCN, 2016). A few examples of resilience actions that BMPA can consider are:

- Protecting ecosystems to improve water quality, enhance biodiversity and reduce flood risk.
- Investing in green infrastructure to mimic the natural water cycle and manage water sustainably.
- Removing alien vegetation to improve water availability, quality and reduce flood risk.
- Implementing aquifer recharge measures to increase water availability and reduce drought risk.
- Restoring habitats and conserving biodiversity to improve water quality, reduce flood risk and increase ecosystem resilience to climate change.

These green interventions have been shown to complement investments in grey infrastructure and often come with lower costs and higher returns on investment. (Brill *et al.*, 2023).

Stakeholder engagement is a key part of all steps of the WRAF. However, in selecting the most appropriate resilience actions, engagement is particularly important as external stakeholders may have greater insight into the feasibility and consequences of different actions. Stakeholders who would either be beneficial in the development and implementation of actions or who stand to be impacted by actions should be consulted. These stakeholders may include government agencies, other businesses, NGOs, local communities, academic institutions, funding agencies, etc. At the system level, well-developed resilience actions will frequently take the form of collective action rather than just one stakeholder implementing them independently.

STEP 3. TEST IMPACT OF RESILIENCE ACTIONS ON RESILIENCE CHARACTERISTICS

Stress tests reveal how well a system, institution or sector may perform under different conditions. These tests help to determine the current state of a system's resilience and the predicted impact of resilience actions under a range of scenarios. The stress test clarifies how well the resilience actions do or could respond to shocks and stresses as well as how effectively they support the goals of the selected resilience strategy. The stress test can also be used to compare and evaluate different actions to determine which produces the most effective results.

Stress testing is done in two stages: benchmarking (Step 3.1) and validation (Step 3.2).

3.1 BENCHMARKING STAGE

In the benchmarking stage, BMPA assess their current level of resilience. This is done by using appropriate resilience indicators to estimate or measure how the system is performing with respect to the selected resilience characteristics for the selected system components and subcomponents. A sample baseline assessment from the first stress test (benchmarking stage) may yield a series of low or average results (Table 4), indicating areas for improvement. Areas that receive high scores indicate that they should be monitored and reassessed in the future, but no immediate actions are required. BMPA should continuously look for opportunities to improve their overall resilience, despite scoring green across certain indicators or characteristics. Stress testing may be quantitative or qualitative and should be performed for each resilience action.

Step 3.1 is carried out immediately after Step 2.3 (Identify system components and resilience indicators), whereas the validation stage only comes after Step 2.4 (Develop resilience actions). See Step in Practice section for an example.

3.2 VALIDATION STAGE

During the validation stage, utilities can test the impact of resilience actions or different scenarios to determine how the actions proposed will improve (or worsen) the selected resilience characteristics for the selected system component or subcomponent and ultimately the system resilience.

The success of selected resilience actions can be determined by the scores produced in the validation stage of stress testing. An example of the result of such stress tests for the resilience characteristic 'Robustness is presented in Table 4. Here, the system will see a significant improvement across most indicators, across both Tier 1 and Tier 2. The result of the second stress test shows that additional or revised actions are still needed for some subcomponents.

STEP 4. EVALUATE

In this step, the overall process of the WRAF is evaluated to examine how the resilience of a particular site, the organization and the system has been improved. The WRAF evaluation can be done in two stages:

1. **Immediately after the stress test (Step 3):** If the selected resilience strategy and associated actions fail to achieve the desired outcome, BMPA can immediately evaluate the WRAF decisions by revisiting some or all the steps, from visualizing the system to developing and stress-testing resilience strategies and actions. BMPA can consider re-visiting the WRAF steps as:

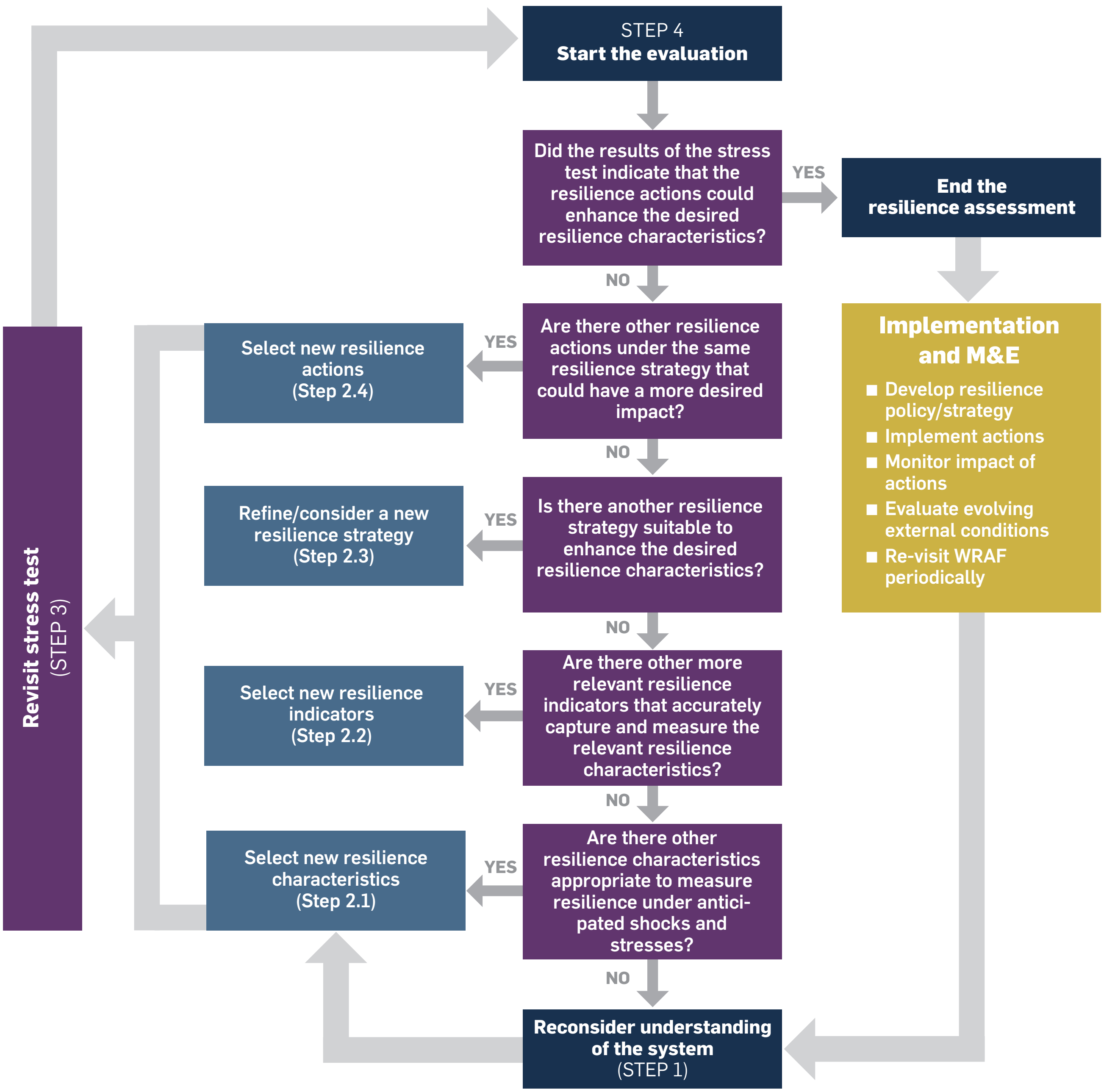
   - **Re-visualizing the system:** Review how the system has been defined and consider if it has been scoped too narrowly or broadly. If so, BMPA may need to reconsider how the system has been defined if the system has greater exposure than was accounted for or develop multiple resilience strategies.
   - **Identifying challenges, shocks and stresses:** Pinpoint events that significantly impacted or caused infrastructure or system features to fail. process of understanding whether an event was a primary driver, a contributing stress, or a sudden shock will help BMPA identify the most appropriate actions to adapt or mitigate the negative consequences.
   - **Selecting resilience characteristics, indicators and resilience strategy/strategies:** Based on the outcome, BMPA can select additional or alternate resilience characteristics and indicators to meet the additional resilience needs of the selected system components and subcomponents.

2. **At regular intervals after implementing the selected resilience strategy/strategies:** Evaluating a resilience strategy is an ongoing process that should be adapted to the specific context and scenario. It is challenging because it is difficult to say whether the degree of resilience achieved will be enough in the future, as water systems are dynamic and can change significantly over time. There is no specific recommended timeline for repeating resilience assessments/evaluations, as this will be context- and scenario-specific. The evaluation should be undertaken when there are:

   - **Changes in shared water challenges:** New information or issues may emerge that require changes to the resilience strategy. For example, climate change may impact water availability or new water allocation schemes may be implemented.
   - **Changes in shocks and stresses:** The environment is constantly changing, resulting in new acute or chronic shocks and stresses, such as earthquakes, floods or other sudden events. The resilience actions and strategies should be evaluated to ensure these are still appropriate under new conditions.
   - **Changes in resilience goals:** After implementing a resilience strategy, BMPA may reconsider resilience goals based on new information or changing conditions.
   - **Changes in internal factors:** Internal factors such as staffing, budget or technological capabilities may also change over time, necessitating a re-evaluation of the resilience strategy.

A decision tree (Figure 6) can be used to evaluate which parts of the overall resilience assessment need to be evaluated and adjusted (adapted from Chapagain *et al.*, 2022). While a sequential application of the steps in the decision tree is desirable, BMPA may find it easier to do several steps in parallel or prioritize certain substeps based on resources available. The WRAF evaluation should conclude with BMPA implementing the most appropriate resilience actions and monitoring impact. Stakeholder engagement will be a key consideration during the evaluation step, as the impact of resilience actions should be assessed across all sectors and communities where possible.

FIGURE 6. EVALUATION AND FEEDBACK STEPS IN THE WATER RESILIENCE ASSESSMENT FRAMEWORK



Step in Practice

This section provides a simplified example of applying the WRAF to the hypothetical River Mile in the United Kingdom (UK). It highlights key steps in the WRAF process to guide practitioners through its implementation.

SIP STEP 1: VISUALIZE THE SYSTEM

The River Mile is 400 km long and flows through several major cities, including a large metropolitan city. The basin, in which the river flows, covers more than 15,000 km^2 and is home to more than 12 million people.

This river is a vital water source for both people and wildlife. The basin is mostly rural to the west (upstream of the river) and very urban to the east (downstream of the river). About 25% of the river basin is urbanized and the remaining rural land is mainly arable, grassland and woodland.

During periods of heavy rainfall, the river can experience flooding, which can cause significant damage to infrastructure and property in the surrounding areas. The impact of climate change is predicted to lead to more frequent and severe flooding events in the region. To address these concerns, water management strategies are being developed to help reduce the risk of flooding and manage the water resources of the River in a sustainable manner.

STAKEHOLDER MAPPING

A critical starting point for any WRAF project is to identify and engage key stakeholders in the system. Water in the basin is managed through a combination of measures, including water abstraction, storage, treatment, distribution and conservation by several institutions with overlapping responsibilities requiring active coordination in managing the basin. Depending on who is applying the WRAF and at what scale, the system boundary could be drawn based on a variety or combination of hydrological and administrative boundaries.

The various institutions and their roles and responsibilities in the basin are:

- **The Agency for Water and the Environment (AWE):** This agency is responsible for managing water resources in the basin and works closely with water companies, farmers and local communities to ensure sustainable water use. The agency also monitors river levels, rainfall patterns and other factors to ensure that the basin's water resources are managed effectively and efficiently. The agency is not a part of any specific government department but reports directly to the national government.
- **NatureSave:** This organization works to protect and improve the natural environment in the region, including in the basin. NatureSave plays a key role in helping to manage the river in many ways, such as: protecting habitats and species found in and around the river, managing and restoring wetlands, improving water quality, protecting fish and other aquatic species, advising on development proposals and, promoting public access and recreation.

- **Department of Environmental Management (DEM):** Various policies and regulations are developed and implemented by the DEM to protect water quality and encourage sustainable water use including implementing the abstraction licensing system.
- **River Water Services:** This is the largest water and wastewater services provider in the basin. It is responsible for supplying potable water to customers and treating wastewater. This involves abstracting water from rivers, reservoirs and groundwater sources, treating it to remove impurities and distributing it through a network of pipes and storage facilities. River Water Services provides wastewater treatment services to more than 12 million customers, and it operates more than 375 sewage treatment works. This involves collecting wastewater through a network of pipes, treating it at wastewater treatment plants to remove pollutants and safely discharging the treated wastewater back into the environment. It also monitors water levels and flow rates in rivers and other sources and manages water resources to balance the needs of customers, the environment and other stakeholders.
- **Local Authorities:** Several local authorities in the basin have responsibilities for water management, such as managing drainage and flood risk. They also consider the impact of planning and development on the water and environment and support wastewater management in their local areas.
- **River Flood Watch:** This is a partnership of the AWE, local authorities and other organizations to reduce the risk of flooding in the basin. It involves various flood risk management measures, such as building flood walls and embankments.

To start planning the WRAF process, the AWE convened a multi-stakeholder workshop involving representatives of community board representatives, various local non-governmental organizations, academia, local businesses, utility providers, government institutes and internal stakeholders.

FORMULATING THE WRAF STEERING COMMITTEE AND WORKING GROUP

The AWE established a Steering Committee (SC) to represent all stakeholders and make recommendations to decision-makers. The SC is responsible for the strategic direction of the WRAF implementation. The SC formed a Working Group (WG) to help operationalize the WRAF. The WG includes representatives from multiple user groups, sectors, levels of government and other key stakeholders. The WG is responsible for implementing all stages of the WRAF and communicating the outcomes with all parties within the system regularly. The governance structure established for the WRAF implementation is presented in Figure 7.

FIGURE 7. GOVERNANCE STRUCTURE FOR THE WRAF IMPLEMENTATION

Agency for Water and the Environment

- Oversees water resources in the basin, collaborating with stakeholders to promote sustain-able water usage practices
- Monitors river levels, rainfall patterns, and other indicators to ensure effective and efficient water resource management
- Reports directly to the government, maintaining independence while ensuring accountability
- Oversees the WRAF process, establishes the Steering Committee

Steering Committee

- Represents all stakeholders and provides recommendations to decision-makers
- Oversees the strategic direction of WRAF implementation
- Establishes a Working Group to aid in the operationalization of the WRAF

Working Group

- Facilitates the strategic planning and operationalization of the WRAF
- Convenes monthly to discuss WRAF implementation steps
- Forms subgroups with composition tailored to the focus area

Stakeholders

- Community board representatives
- Local non-governmental organizations
- Academic institutions
- Local businesses
- Utility providers
- Government institutes
- Internal stakeholders

Based on the WRAF steps being explored and the duration of implementing the framework, the WG elected to meet monthly. Workshops are held at the offices of the AWE and are generally half- or full-day events. Various subgroups were also formed to dive deeper into different elements of the WRAF. These subgroups included members from different departments working directly on or responsible for decisions, managing and operating relevant system components. For example, engineers, hydrologists and plant operators comprised the subgroup to cover the 'Robustness' of the infrastructure, whereas the legal department and communication experts were included to cover the 'Inclusiveness' in the system.

The structure of the WRAF execution groups and subgroups will continue throughout the multiple WRAF iterations. The nature and scope of these groups will depend on the complexity of the organization or system.

Once the WG and subgroups were formed, their first task was to bring together all relevant stakeholders to plan the implementation of the WRAF process. To do this, the WG organized an onboarding workshop. At the workshop, key stakeholders were informed of the objectives of the project, the various tasks and their key responsibilities. The workshop also helped to gather preliminary information that was useful for starting the implementation phase of the WRAF, beginning with defining the system boundary.

SIP STEP 1.1 DEFINE SYSTEM BOUNDARY

The system boundary for the WRAF was established based on the goals and resources available to the AWE in building resilience. The potential application boundary of the WRAF in the basin is not limited to the local hydrological boundary and extends to multiple jurisdictional or administrative boundaries. These boundaries were selected based on the nature of the stakeholders involved in the basin, those responsible for developing policy, rules and regulation on use, monitoring and evaluation of the resource and the level of assessment. The workshop attendees decided to do a system-level resilience assessment. To do so, they overlapped the local hydrological and administrative boundaries.

SIP STEP 1.2 IDENTIFY WATER CHALLENGES: STRESSES, SHOCKS AND DRIVERS

The workshop attendees collectively identified three key shared water values in the basin, which are:

- Healthy natural ecosystem and thriving biodiversity
- Access to safe and adequate water for human consumption
- Safe recreational water in the river

These shared values helped define the shared water challenges (Step 1.2.1), which are exacerbated due to ongoing and anticipated stresses and shocks (Step 1.2.2) (Figure 9).

SIP Step 1.2.1 Identify shared water challenges

Following system boundary delineation, the WG prompted workshop attendees to consider the current and anticipated water-related challenges experienced within the system. In the workshop, several breakout tables were formed, where workshop attendees discussed and debated the most pressing water challenges. The workshop attendees collectively identified the following four key shared water challenges faced by AWE:

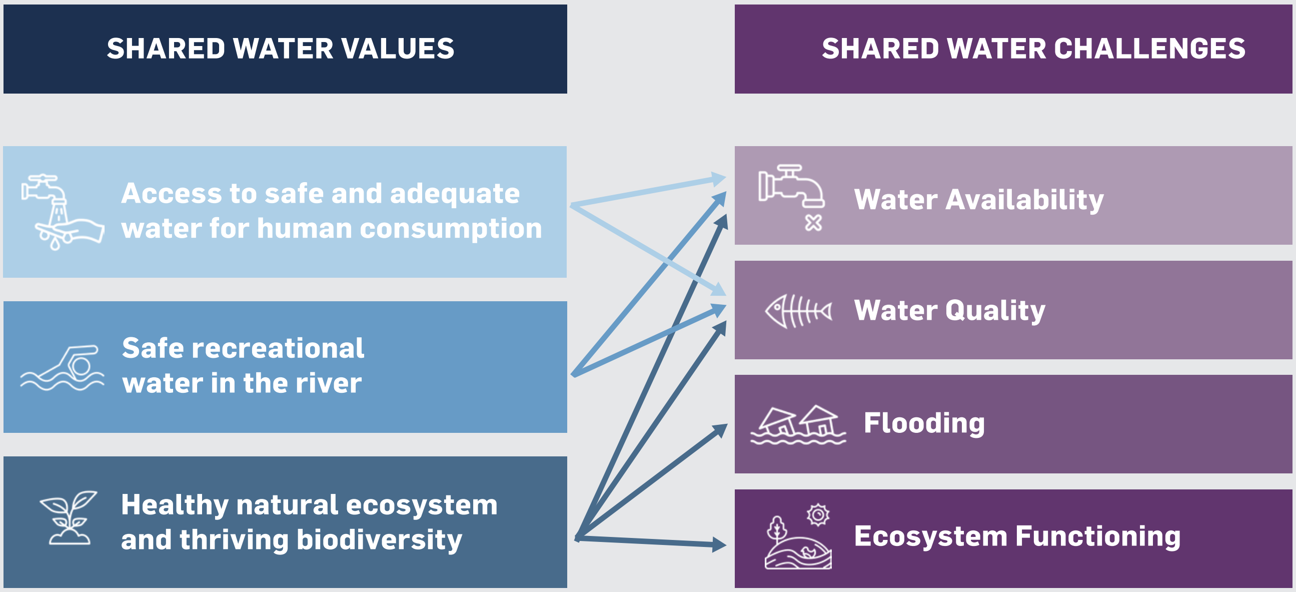
- **Water Availability:** There are various legal and institutional settings for water allocation in the region. For example, the DEM is responsible for water policy, while the AWE is the environmental regulator and delivery body involved with planning, assessing water availability, issuing licenses (entitlements), monitoring abstraction and enforcement. Across the region, water abstraction is regulated through a system of licenses. About 25,000 abstraction licenses enable the holders to draw water from surface and groundwater sources. During episodes of scarcity, the AWE can apply restrictions or ban abstraction to protect the environment. Water companies also have a variety of powers and mechanisms to address water scarcity. The AWE has the power to review and modify abstraction licenses if it is determined that the abstraction is causing environmental harm or if there is insufficient water available to meet the needs of all users. The AWE will typically consult with the license holders and other stakeholders, such as local authorities, water companies, and environmental groups, before deciding. The agency will also consider factors such as the need to protect the environment and other users, as well as the socio-economic impacts of any changes to the abstraction licenses.
- **Water Quality:** The basin has historically suffered from high levels of pollution due to a range of factors, including agricultural runoff, industrial discharges and sewage overflows. Sewage overflows are a particular concern for the river, with millions of cubic meters of raw sewage discharged into the river each year during heavy rainfall events. A range of measures has been implemented to tackle this issue, including the construction of new sewage treatment plants, the installation of stormwater

storage tanks and the implementation of pollution reduction strategies in urban and agricultural areas.

- **Flooding:** Due to the river's large catchment area and location in a low-lying region, flooding is one of the major issues in heavily populated areas downstream of the River Mile. The flooding also has severe impacts on the environment, including damage to wildlife habitats and erosion of riverbanks. Climate change is expected to exacerbate flooding.
- **Ecosystem functioning:** Ecosystems and their services are negatively affected by degradation of natural habitats, pollution of air, land and water, exploitation of terrestrial, marine and freshwater resources, invasive species and climate change. Research shows that over 30% of the services provided by aquatic and terrestrial habitat types and their constituent biodiversity in the region are in decline. These reductions are associated with declines in habitat extent or condition and changes in biodiversity. The expansion of urban areas has degraded the ecosystem services that regulate climate, hazards, soil and water quality and noise. Fragmentation and deterioration of wetlands, and particularly the separation of rivers from their floodplains, have compromised hazard (flood) regulation and many other ecosystem services. In recent years, abstraction from both groundwater bodies and surface waters was higher than sustainable levels.

The last element of this exercise was to overlay the shared water challenges with the shared water values to ensure that these aligned (Figure 8).

FIGURE 8. SHARED WATER VALUES AND SHARED WATER CHALLENGES IN THE MILE RIVER BASIN

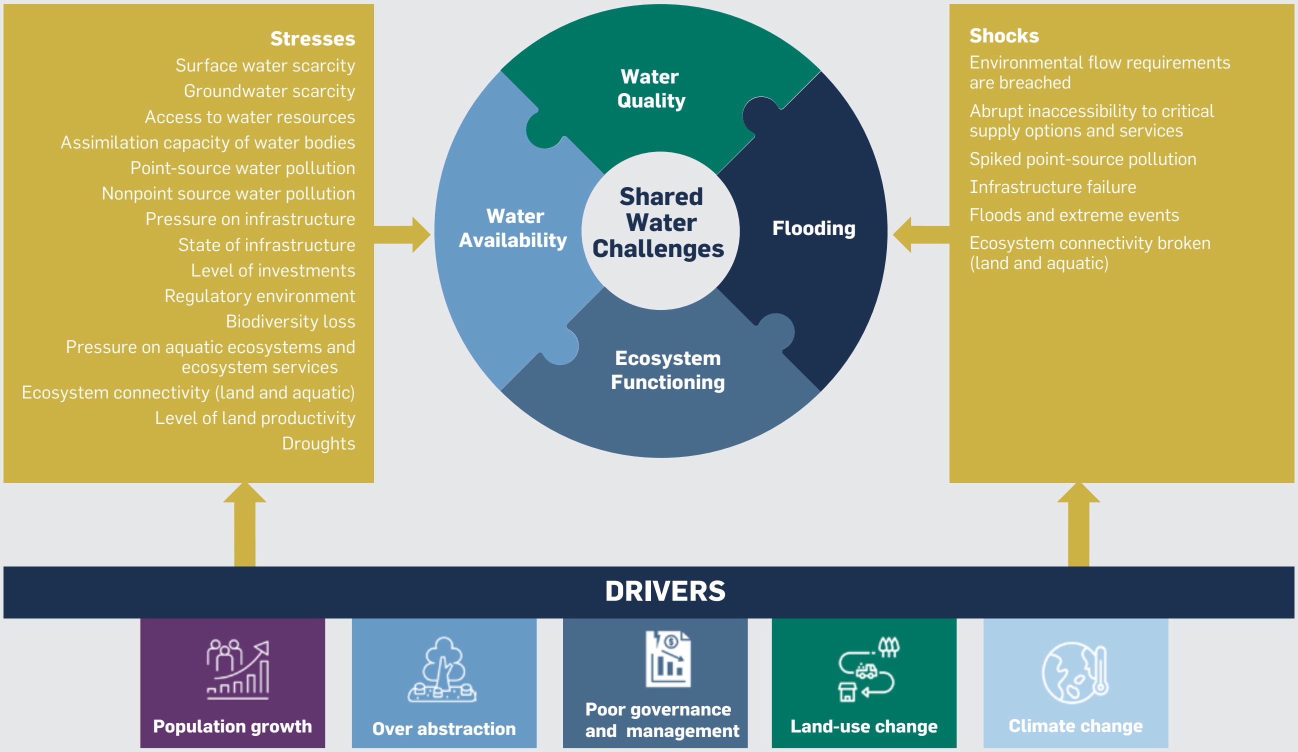


SIP Step 1.2.2 Drivers, stresses and shocks

After the workshop, the WG, through the respective sub-groups, compiled a list of ongoing and anticipated stresses and shocks and their relevance to the challenges identified in the workshop. The impact of these shocks and stresses can be influenced by several drivers. The key drivers identified in this case study were population growth, over-abstraction, poor governance and management, land-use change and climate change. Most of these drivers influence more than one stress or shock, although to varying degrees. Drivers are also not mutually exclusive, as some drivers may influence others (e.g., population growth impacts the nature of land-use change and over-abstraction).

Figure 9 presents a sample list of drivers and their impact on the various shocks and stresses identified in the basin. The impact of these drivers on shocks and stresses could vary widely, but all contribute to the overall shared water challenges present in the system. The WG prioritized them to align with other initiatives related to the shared water challenges in the basin.

FIGURE 9. SHARED WATER CHALLENGES, STRESSES, SHOCKS AND DRIVERS IN THE MILE RIVER BASIN



SIP STEP 1.3 IDENTIFY SYSTEM STATUS AND TRENDS

At the workshop, attendees identified data available to measure and assess the magnitude of current challenges, ongoing stress and, the direction of change as well as the impact of various drivers identified in Step 1.2.2. They also discussed how the data on the system status (includes key attributes of socio-economic, institutional and biophysical system subcomponents such as water quality, quantity, accessibility, current uses, service levels, biodiversity, etc. were collected and identified the responsible departmental units and institutes.

SIP Step 1.3.1 System status

The AWE normally collects data on a range of water quality and quantity parameters, including flow rates, dissolved oxygen levels, nutrient levels and levels of pollutants and other contaminants. They also collect data on weather patterns and develop scenario modeling to forecast the status of and trends in the water system. NatureSave monitors the river's habitats and species, while local authorities monitor water quality and quantity in specific areas within their jurisdiction. The WG gathers the required data from different sources and analyzes these data to establish the status of the water system.

The status of the drivers is established using primary data collected by the AWE and others in the basin.

- **Population growth:** The population in the basin is expected to increase by 2.5 million people by 2060. This represents a growth of 12%, which is higher than the projected growth rate for the region (8%). This will put additional pressure on water resources, water quality and the environment. It is also reported that urbanization and economic activities have a significant impact on the environment in the basin. Urban areas are often polluted with runoff from roads and roofs, and industrial activities generate waste and pollution that regularly enters water courses. This impacts water quality and biodiversity.
- **Over-abstraction:** Current abstraction licensing practices, based on historical water availability, are failing to address the pressing challenges of rising water demand and over-abstraction. The consequences of over-abstraction are far-reaching and include increased water scarcity, stress on aquatic ecosystems, and declining groundwater levels. Additionally, it exposes water systems to acute shocks such as breaching environmental flow requirements and triggering regulatory shifts in abstraction licenses.
- **Poor governance and management:** This set of drivers is related to how the system is operated, maintained and regulated. For example, due to weak regulations on discharging wastewater to water bodies, during heavy rainfalls the wastewater is directly discharged without any treatment into the river streams, intensifying a range of stresses related to water pollution.
- **Land-use change:** The current land-use composition in the basin shows agriculture (50%), urban/built environment (25%) and natural habitat (25%). There is a higher degree of urbanization and potential changes in the land-use patterns, with agriculture and urban areas increasing at the expense of natural habitats. This land-use change is impacting water quality, biodiversity and flood risk.
- **Climate change:** Water scarcity is increasing, and droughts are occurring more frequently with longer durations. In the longer term, climate change could have a bigger impact on available water resources than population growth could in the region.

SIP Step 1.3.2 Trends

At the workshop, attendees decided to identify the status and trends of each shock, stress and driver. The granularity of this assessment was important for this utility but may not be necessary for all contexts.

The workshop attendees identified a range of relevant data and information for each challenge category. They also discussed how to collect further data and information for each challenge, stress, shock and driver to update the current status and trends of the system after the workshop (Table 5).

This work will be further elaborated on by the WG after the preliminary assessment that occurred during the workshop.

TABLE 5. STATUS AND TRENDS IN THE WATER SYSTEM PER SHARED WATER CHALLENGE CATEGORIES

Shared water challenges	System attributes	Status and trend	Trend Increasing / Declining
Water availability	Surface water availability	Reduction in quantity and accessibility	Declining
	Ground water availability	Lowering groundwater tables	Declining
	Assimilation capacities of water bodies	Reduced volumes of freshwater	Declining
	Droughts	Frequency and duration	Increasing
	State of infrastructures	Poor maintenance and aging	Declining
Water Quality	Point source pollution	Increase in frequency and magnitude	Increasing
	Non-point source pollution	Fertilizers and pesticides runoffs	No significant change
	Water quality standards breached	Increase in frequency and magnitude	Increasing
Flooding	Land area submerged	Area, depth and frequency of submergence	Increasing
	Number of people displaced	More frequent displacement	Increasing
	Number and duration of flood events	Greater flood frequency and magnitude	Increasing
Ecosystem functioning	Biodiversity	Stable biodiversity status	No significant change
	Pressure on aquatic ecosystem	Ecosystem threatened	Increasing
	Ecosystem connectivity	Duration and frequency of connectivity broken	Increasing
	Level of land productivity	Stable land productivity	No significant change

SIP STEP 2: DEVELOP RESILIENCE STRATEGY

SIP STEP 2.1 IDENTIFY KEY RESILIENCE CHARACTERISTICS

The WRAF process helped the WG identify the key resilience characteristics of the water system. To address the challenge of increasing water availability during droughts, the WG prioritized 'Robustness' as the main resilience characteristic to target first. They also identified other key characteristics to be strengthened for long-term resilience.

SIP STEP 2.2. IDENTIFY SYSTEM COMPONENTS AND RESILIENCE INDICATORS

SIP Step 2.2.1 Identify relevant system components

The WG used the ReST to identify the different system components and subcomponents for the selected characteristic 'Robustness'. The WG undertook an assessment of the components and subcomponents that make up these characteristics. This more granular approach will help them better understand the elements of the system in smaller, more manageable pieces. The system components and subcomponents are selected based on how they influence the robustness of the system (Table 6).

TABLE 6. SYSTEM COMPONENTS, SUBCOMPONENTS AND RELEVANT STRESSES, SHOCKS AND DRIVERS IN BUILDING SYSTEM ROBUSTNESS

System component	System subcomponent	Stresses	Shocks	Drivers
Socio-economic	Access to funds	Declining O&M funds Declining investment in new infrastructures	Financial crash or downturn with no O&M investment funds available	• Population growth • Poor governance and management
Institutional	Regulation	Discriminatory policies Inappropriate policies	Limiting/halting abstraction or use of resources (e.g., hosepipe ban, no new abstraction licenses)	• Poor governance and management • Over-abstraction
	Demand management	No/poor demand management tools and practices	Limiting/halting abstraction or use of resources (e.g., hosepipe ban, no groundwater abstraction, no new abstraction licenses)	• Population growth • Over-abstraction
	Operations/system management	Poor O&M practices	Failure of critical maintenance practices Essential worker strike	• Poor governance and management
Biophysical	Supply	Low availability Competition for resources	Access to critical supply options and services not available	• Population growth • Over-abstraction • Poor governance and management
	Built and natural infrastructure	Poor O&M practices	Failure of critical maintenance practices Essential worker strike	• Poor governance and management
	Built and natural infrastructure	Reduced environmental flows	Environmental flow requirements are breached	• Land-use change • Poor governance and management • Over-abstraction
	Built and natural infrastructure	Ongoing droughts, floods and other extreme events	High-intensity events (droughts, floods and other extreme events)	• Climate change • Poor governance and management • Land-use change
	Biodiversity	Ongoing point-source pollution	Spiked point-source pollution	• Land-use change • Poor governance and management

SIP Step 2.2.2 Identify key resilience indicators

The WG identified resilience indicators for each system subcomponent, such that the performance of these indicators under shocks and stresses reflects the strength of the resilience characteristic ('Robustness' in this example) for the selected system subcomponent.

At this stage, the WG moved to Step 3.1 to conduct a benchmark resilience assessment. The WG used expert knowledge, existing system performance assessment results, staff/expert group surveys and other methods to score each indicator to understand the current state of resilience for the selected resilience characteristics.

The WG started by assessing the system at a high level using Tier 1 indicators. This assessment provided insight into how the system was performing under current conditions with respect to 'Robustness'. This characteristic scored 'Medium' with respect to both the following two Tier 1 resilience indicators selected:

- Percentage of time that the basin provides the required volume of water to meet environmental flow requirements and to meet the needs of all water users in the system.
- Percentage of time that the basin maintains required water quality levels to meet environmental flow requirements and to meet the needs of all water users in the system.

The WG decided that the resilience assessment using Tier 1 resilience indicators only was not enough to understand, develop and implement practical resilience actions. They decided to undertake a Tier 2 resilience assessment using the ReST. The specific Tier 2 resilience indicators used in the stress tests are presented in Table 7. This benchmark resilience assessment provided a 'resilience scorecard' that helped the WG identify which resilience indicators are performing well and where they need to prioritize certain actions per system subcomponent. The stress test using Tier 2 resilience indicators highlighted that while several indicators are currently performing well, a few are exhibiting moderate performance and four are performing very poorly.

TABLE 7. BASELINE RESILIENCE STRESS TEST (BENCHMARKING STAGE) USING TIER 2 RESILIENCE INDICATORS FOR RESILIENCE CHARACTERISTIC 'ROBUSTNESS'

System component	System subcomponent	Tier 2 resilience indicator	Benchmark resilience score (without resilience actions)
Socio-economic	Access to funds	Economic ability to finance/fund existing/ planned operations and system maintenance	**Good**
		Economic ability to finance/fund new or enhanced system infrastructure	**Good**
Institutional	Regulatory	Level of regulatory compliance	**High**
		Ability of regulatory, policy and legal frameworks to enable new operational and infrastructure solutions	**High**
		Maturity of the legal and policy frameworks	**High**
		Practicality and applicability of the legal and policy frameworks	**High**
	Governance	Degree that investment in infrastructure operations and maintenance is prioritized	**High**
		Degree that investment in new infrastructure development is prioritized	**Low**
		Degree of authority over water infrastructures and services	**Medium**
	Operations/system management	Capacity to operate the available technology reliably and effectively	**Excellent**
		Ability to adaptively manage system infrastructure	**Poor**
		Level of competency of system operators/ managers	**High**
		Presence of disaster preparedness and emergency management plans	**Somewhat**
		Frequency of data collection	**High**
		Quality of data	**Excellent**

System component	System subcomponent	Tier 2 resilience indicator	Benchmark resilience score (without resilience actions)
Biophysical	Supply	Degree of independence of different available water sources	Low
		Degree of diversity of water sources	High
		Degree of reliability of water quantity from different sources	High
		Degree of reliability of water quality from different sources	High
	Built and/or natural infrastructure	Suitability of the infrastructure design and placement	Good
		State of infrastructure to withstand shocks and stresses	Poor
		Level of infrastructure maintenance	Poor
		Ability of the constructed/natural ecosystems to provide goods and services	Good
		Ability of infrastructure to withstand shocks and stresses	Good
	Operations/system management	Access/availability to technology for the system to operate reliably and effectively	Good
	Technology	Level of effectiveness of infrastructure monitoring systems	High
	Biodiversity	Degree of environmental monitoring and evaluations	High

As resilience assessments are a new and evolving science, extensive libraries of such indicators are not developed yet. An illustrative list of potential Tier 1 and Tier 2 resilience indicators for BMPA applying the WRAF are presented in Appendix B.

SIP STEP 2.3: STRATEGY SELECTION

To determine resilience strategies and their effective combinations, the WG started with resilience indicators that were not performing to the required standards (e.g. Good and Poor resilience scores in Table 7), and carefully considered their resilience goals, system functions, resources, capacity and other relevant factors. The selected resilience strategies for each system, component, subcomponent and resilience indicators are presented in Table 8.

SIP STEP 2.4: DEVELOP RESILIENCE ACTIONS

Following the benchmark assessment using Tier 2 resilience indicators, the WG proposed several practical resilience actions (Table 8) to enhance system performance against these indicators. Based on the organization's goals, existing practices and available resources, the WG selected specific actions aligned with the resilience characteristic 'Robustness' as identified in the previous step.

TABLE 8. RESILIENCE ACTIONS SELECTED TO ENHANCE THE RESILIENCE CHARACTERISTIC 'ROBUSTNESS'

System component	System subcomponent	Tier 2 resilience indicator	Benchmark resilience score	Resilience strategy	Suggested resilience actions
Socio-economic	Access to funds	Economic ability to finance/ fund existing/planned operations and system maintenance	**Good**	Adaptation/ Transformation	• Prioritize budget for O&M • Develop financial models
		Economic ability to finance/ fund new or enhanced system infrastructure	**Good**	Adaptation/ Transformation	• Prioritize budget for additional/new infrastructures • Develop financial models
Institutional	Regulatory	Level of regulatory compliance	**High**	Persistence	• Compliance mechanism developed/ deployed • Continue training and workshop to enhance willingness and ability of basin managers and planning authorities to abide by the regulations
		Ability of regulatory, policy and legal frameworks to enable new operational and infrastructure solutions	**High**	Persistence	• Ongoing assessment of willingness and ability of BMPA to work within current regulatory structures to enable new approaches, e.g., NBS • Continue training and workshop to enhance these attributes
		Maturity of legal and policy frameworks	**High**	Persistence	• Ongoing assessments of existing regulations and their effectiveness to create gold standards • Develop new policies to address any regulatory gaps
		Practicality and applicability of legal and policy frameworks	**High**	Persistence	• Ongoing assessments of existing regulations and their effectiveness to create gold standards • Develop new policies to address any regulatory gaps

System component	System subcomponent	Tier 2 resilience indicator	Benchmark resilience score	Resilience strategy	Suggested resilience actions
Institutional	Governance	Degree that investment in infrastructure operations and maintenance is prioritized	**High**	Persistence	• Ongoing assessment of need for O&M • Continue budget prioritization for O&M
		Degree that investment in new infrastructure development is prioritized	**Low**	Adaptation/ Transformation	• Ongoing assessments of need for new/ different infrastructures • Long-term planning of potential infrastructure development opportunities (National Planning Authority) • Budget prioritization
		Degree of authority over water infrastructures and services	**Medium**	Persistence/ Adaptation	• Ongoing assessment of how current status is supporting or hindering process • Engage with relevant stakeholders to develop mitigation plans to remove such bottlenecks
	Operations/ system management	Capacity to operate available technology reliably and effectively	**Excellent**	Persistence	• Ongoing assessment of technological capabilities of relevant employees • Continue training and workshops to support use of current and emerging technologies
		Ability to adaptively manage system infrastructure	**Poor**	Persistence/ Adaptation	• Ongoing assessment of managerial capabilities in adaptive decision making • Training and workshops on adaptive management practices
		Level of competency of system operators/ managers	**High**	Persistence	• Ongoing assessment of technological capabilities of relevant employees • Continue training and workshops to support use of current and emerging technologies
		Presence of disaster preparedness and emergency management plans	**Somewhat**	Persistence/ Adaptation	• Ongoing assessment of existing plans for disaster preparedness and emergency management • Develop new practices to capture availability of emergency supplies, resources, and capabilities, • Develop and deploy relevant operational manuals and governing regulations
		Frequency of data collection	**High**	Persistence	• Continue current practices on data collection with respect to coverage and frequency
		Quality of data	**Excellent**	Persistence	• Continue current practices on data screening, processing, and recording

System component	System subcomponent	Tier 2 resilience indicator	Benchmark resilience score	Resilience strategy	Suggested resilience actions
Biophysical	Supply	Degree of independence of different available water sources	**Low**	Adaptation/ Transformation	• Consider inter-basin water transfer • Import water virtually in embedded in water intensive commodities
		Degree of diversity of water sources	**High**	Persistence	• Ongoing assessment of demand and supply
		Degree of reliability of water quantity from different sources	**High**	Persistence	• Ongoing assessment of demand and supply
		Degree of reliability of water quality from different sources	**High**	Persistence	• Ongoing assessment of demand and supply
	Built and/ or natural infrastructure	Suitability of infrastructure design and placement	**Good**	Persistence	• Ongoing assessment of suitability and placement of infrastructures for changing conditions • Engage with stakeholders to develop essential measures to supplement level of services
		State of infrastructure to withstand shocks and stresses	**Poor**	Adaptation/ transformation	• Ongoing assessment of level of maintenance of infrastructures • Develop or prioritize remedial measures by reinforcing the weaker components • Continue regular maintenance of the structure
		Level of infrastructure maintenance	**Poor**	Adaptation/ transformation	• Ongoing assessment of level of maintenance of infrastructures • Develop or prioritize remedial measures by reinforcing the weaker components • Continue regular maintenance of the structure
		Ability of constructed/ natural ecosystems to provide goods and services	**Good**	Persistence/ adaptation	• Regular assessment of functioning of constructed and naturally occurring habitats (e.g., wetlands and riparian and aquatic habitat) • Engage with stakeholders if supplementary measures can be taken to strengthen these systems
		Ability of infrastructure to withstand shocks and stresses	**Good**	Adaptation/ Transformation	• Ongoing assessment of infrastructure capacity to withstand designed and new stresses • Develop or prioritize remedial measures by reinforcing weaker components
	Operations/ system management	Access/availability to technology for the system to operate reliably and effectively	**Good**	Persistence/ adaptation	• Ongoing assessment of existing and emerging technology that is readily available • Develop plans and remedial measures to facilitate these operations
	Technology	Level of effectiveness of infrastructure monitoring systems	**High**	Persistence	• Continue adjusting and adapting new emerging monitoring practices and technological advancements • Develop/adapt current monitoring systems
	Biodiversity	Degree of environmental monitoring and evaluations	**High**	Persistence	• Continue monitoring and evaluation of environmental systems • Strengthen current mechanisms to track and protect aquatic flora and fauna

At the end of Step 2, the WG created a simple schematic that can facilitate future iterations of the WRAF (Table 9). It shows the interconnectedness of these steps and how each step informs the subsequent step.

TABLE 9. SCHEMATICS ON SELECTION OF RESILIENCE CHARACTERISTICS IN DEVELOPING RESILIENCE ACTIONS

2.1	**Resilience characteristics**	To address the challenge of increasing water availability during droughts, the WG prioritized "Robustness" as the main resilience characteristic to target first.	Ranking and selection of key resilience characteristics
2.2.1	**System components**	For example, under 'Scocio-economic', they selected 'Access to funds' system subcomponent ro address stresses such as 'declining O&M funds', 'declining investment in new infrastructures'.	Subcomponents identified based on how stresses and shocks impact the robustness of the system
2.2.2	**Resilience indicators**	First, the WG used Tier 1 resilience indicators to stress test (benchmarking), followed by selected set of Tier 2 indicators corresponding the system subcomponents selected in Step 2.2.1.	WG used the ReST to identify relevant indicators
2.3	**Resilience strategy**	The WG selected Persistence strategy where the resilience indicators scored excellent in benchmarking stage. They selected adaptation resilience strategy for the rest where the indicator perfomed poor or moderate at the best.	Persistence or adaptation strategies based on the results of the stress test
2.4	**Resilience actions**	The WG proposed several practical resilience actions aligned with the resilience characteristic "Robustness" as identified in the previous step.	Development and prioritization of the resilience actions

SIP STEP 3: TEST THE IMPACT OF RESILIENCE ACTIONS ON RESILIENCE CHARACTERISTICS

SIP STEP 3.1. BENCHMARKING STAGE

The WG conducted a benchmark resilience assessment to evaluate the system's 'Robustness'. This assessment was conducted immediately after identifying system subcomponents (Step 2.2.1) and resilience indicators (Step 2.2.2). The resilience scorecard from the assessment provided a clear overview of the selected system subcomponents' resilience strengths and weaknesses, enabling targeted resilience-building efforts (Step 2.3). The outcomes of this benchmarking resilience test can be noted in the 'without resilience actions' column in Table 10.

SIP STEP 3.2. VALIDATION STAGE

To thoroughly evaluate the effectiveness of the resilience actions, the WG conducted a comprehensive second stress test (validation stage). It meticulously analyzed the predicted impact of these actions on designated resilience indicators through rigorous modeling, quantification and qualification methodologies. This approach enabled the WG to assess the proposed interventions without substantial financial expenditure. A month after the initial benchmarking test, the WG convened a workshop to scrutinize the outcomes of its modeling and validation exercises. During this workshop, the WG presented the results of a second stress test to the workshop participants, where they engaged in a comprehensive discussion and unanimously agreed that the proposed resilience actions were remarkably effective in enhancing, developing and expanding system resilience across all indicators (e.g., Table 10, column 'with resilience actions'). These actions were deemed sufficient to achieve the desired level of robustness for the selected system components and subcomponents. The WG will prepare implementation plans, commence the implementation of these actions, maintain ongoing surveillance of the effectiveness of these actions and may revise or introduce additional resilience measures as deemed necessary.

The WG submitted its findings to the SC and the AWE for decisions regarding institutional and financial arrangements to implement these actions.

TABLE 10. RESILIENCE STRESS TEST AFTER TAKING RESILIENCE ACTIONS FOR RESILIENCE CHARACTERISTIC 'ROBUSTNESS'

System Component	System Subcomponent	Tier 2 Resilience Indicator	Resilience Score	
			Without Resilience Actions (Step 3.1)	With Resilience Actions (Step 3.2)
Socio-economic	Access to funds	Economic ability to finance/fund existing/planned operations and system maintenance	**Good**	**Excellent**
		Economic ability to finance/fund new or enhanced system infrastructure	**Good**	**Excellent**
Institutional	Regulatory	Level of regulatory compliance	**High**	**High**
		Ability of regulatory, policy and legal frameworks to enable new operational and infrastructure solutions	**High**	**High**
		Maturity of legal and policy frameworks	**High**	**High**
		Practicality and applicability of legal and policy frameworks	**High**	**High**
	Governance	Degree that investment in infrastructure operations and maintenance is prioritized	**High**	**High**
		Degree that investment in new infrastructure development is prioritized	**Low**	**Medium**
		Degree of authority over water infrastructures and services	**Medium**	**High**
	Operations/ system management	Capacity to operate available technology reliably and effectively	**Excellent**	**Excellent**
		Ability to adaptively manage system infrastructure	**Poor**	**Good**
		Level of competency of system operators/managers	**High**	**High**
		Presence of disaster preparedness and emergency management plans	**Somewhat**	**Yes**
		Frequency of data collection	**High**	**High**
		Quality of data	**Excellent**	**Excellent**

System Component	System Subcomponent	Tier 2 Resilience Indicator	Resilience Score	
			Without Resilience Actions (Step 3.1)	**With Resilience Actions (Step 3.2)**
Biophysical	Supply	Degree of independence of different available water sources	**Low**	**Medium**
		Degree of diversity of water sources	**High**	**High**
		Degree of reliability of water quantity from different sources	**High**	**High**
		Degree of reliability of water quality from different sources	**High**	**High**
	Built and/or natural infrastructure	Suitability of infrastructure design and placement	**Good**	**Good**
		State of infrastructure to withstand shocks and stresses	**Poor**	**Good**
		Level of infrastructure maintenance	**Poor**	**Good**
		Ability of constructed/natural ecosystems to provide goods and services	**Good**	**Excellent**
		Ability of infrastructure to withstand shocks and stresses	**Good**	**Excellent**
	Operations/ system management	Access/availability to technology for system to operate reliably and effectively	**Good**	**Excellent**
	Technology	Level of effectiveness of infrastructure monitoring systems	**High**	**High**
	Biodiversity	Degree of environmental monitoring and evaluations	**High**	**High**

SIP STEP 4: EVALUATE

As a final step, the WG met to evaluate the success of the WRAF process to date. The evaluation process consists of two phases: immediate and ongoing evaluation.

Immediate evaluation: The second stress test (validation stage) confirmed that the planned resilience actions would strengthen the individual resilience indicators, thereby enhancing the system's long-term robustness. However, five resilience indicators demonstrated moderate performance during the second stress test. Consequently, the WG reviewed the WRAF steps, focusing on additional effective resilience actions that could significantly positively impact these indicators.

Due to WRAF's modularity, the WG initially focused on the resilience characteristic 'Robustness', expanding the assessment scope as resources become available. Since plans to implement resilience actions were still being finalized, and the other resilience characteristics were not included in the initial assessment, the WG initiated a second round of the WRAF. This round will identify additional relevant resilience characteristics, indicators, strategies and actions to further strengthen long-term resilience. It also planned to reassess the relevance of the selected shared water challenges, system stresses and shocks as well as the drivers.

Ongoing evaluation: To address any potential changes in system subcomponents, shocks and stresses, resilience goals or internal factors that could necessitate another WRAF cycle, the WG drafted a long-term WRAF plan for the AWE's consideration. This plan recommends revisiting the full WRAF process regularly at five-year intervals, with a note that sudden context changes could trigger an earlier evaluation.

Conclusions

Climate change, population growth, environmental degradation and other drivers are causing unpredictable shifts in water availability, quality and accessibility, posing significant challenges for organizations, communities and the environment as well as impacting the interconnectedness of water systems globally. To address these challenges, basin managers and planning authorities must adopt resilience-focused strategies into their operations and long-term planning.

This guide details the implementation of the Water Resilience Assessment Framework (WRAF) for basin managers and planning authorities (BMPA), aiding practitioners with key steps and a hypothetical basin scenario for practical understanding. In an era of major climate uncertainty and anthropogenic impacts, the WRAF stands out with its nuanced approach to water resource management. By considering the unique characteristics of each basin, it fosters inclusive decision-making that prioritizes long-term environmental sustainability and aligns with the needs of communities and economies.

Unlike traditional static assessments, the WRAF approach considers the intricate interplay among socio-economic, institutional and biophysical factors, enabling a detailed understanding of water system vulnerabilities and capacities. The WRAF's adaptability allows for the tailoring of assessments to specific basin contexts, revealing the complexities of water systems and guiding BMPA towards a transformative journey to enhance water resilience. This versatility empowers BMPA to identify system vulnerabilities, develop targeted resilience strategies and chart a course towards achieving water security and sustainability. Ultimately, this will build long-term resilience across ecological, social and economic systems.

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Appendices

APPENDIX A: KEY CONTEXT IN OPERATIONALIZING WRAF AT THE BASIN LEVEL

Our ability to build water resilience at the system level requires not only the understanding of how water is embedded and distributed within it, but also the interlinkages beyond the hydrological boundaries. Basins are an important scale to assess and visualize water, but the water system can transcend basins, especially for water resources that have been 'hidden' in energy, transport, telecommunications or otherwise.

The operational and management dynamics of a basin differ significantly from those of corporations or utilities. The key aspects to be considered for the successful implementation of the WRAF at the basin level can be broadly grouped under three categories:

- Governance and management
- Planning horizon and direction
- Challenges and opportunities

GOVERNANCE AND MANAGEMENT

River basin governance has increasingly been focused on the management of surface and groundwater resources, mitigation of droughts and floods, fair and equitable allocations, wastewater management and apportioning environmental flows to maintain valuable ecosystem services (Garrick *et al.*, 2014; Tilleard and Ford, 2016). In some cases, shifts in basin management have changed from a top-down command and control model to a decentralized participatory model (Huitema and Meyerinck, 2014), recognizing that stakeholder engagement is paramount (Ansell and Gash, 2007) as are the legal frameworks that intersect the policy-practice interface (Bouckaert *et al.*, 2022).

- **Stakeholder engagement:** Basins are used and managed by a variety of stakeholders. When engaging with stakeholders, decision-making is guided by the immediate interest of the relevant stakeholders and existing rules and regulations to govern the basin. Stakeholders could include national planning authorities, basin managers, agricultural bodies and individual farmers, regional agencies, environmental and social groups, utilities and local authorities, industrial bodies and interested and affected parties including Indigenous Peoples and local communities (Brill *et al.*, 2022). Engaging these stakeholders in decision-making is critical as a successful river basin management plan must also balance multiple goals and objectives, such as providing water for human use, protecting ecosystems and biodiversity and reducing flood and drought risk (Molle, 2009). The needs and views of these stakeholders may be complementary in many regards, but in some cases may be competing or even conflicting. Conflicting goals can make it difficult to reach consensus on governance and management actions.

  It is critical that stakeholder engagement be prioritized by BMPA to ensure that decision-making in water systems is inclusive and that water resources are allocated in a just and equitable manner. Resilience- building requires collaboration across levels of Government, jurisdictional boundaries, and different economic sectors such as water supply, energy, food, industries, manufacturing etc. The ideas, beliefs or practices shared by a group of people play a vital role in developing, prioritizing and operationalizing resilience strategies. For example, in systems where equitability and inclusivity have historically been ignored, new resilience strategies should focus on redress or reconciliation. Effective stakeholder engagement requires a high level of political will (across multiple tiers of Government), a dedicated budget, open lines of communication and transparency in their decision-making.

- **Legal frameworks and rules and regulations:** Many countries have complex legal frameworks for water management. These rules and regulations are often guided by national or international framework directives the country has adopted or adapted. These will directly guide and influence BMPA in their governance and management activities. National planning authorities, regional agencies and even local utilities and municipalities will be directed by national regulations (e.g., water act), state-wide laws and even local by-laws respectively. These key legal frameworks are the foundation to the governance and management activities and will inform the direction taken in deciding on appropriate resilience actions and strategies taken in a basin.

  The governing rules and regulations in a basin follow the local context, stakeholders' interest and other guiding principles on issues, such as:

  - Human right to water
  - Environmental flow requirements,
  - Various local, regional, national and international planning objectives, and
  - Mandates, directives, treaties and agreements.

  Additionally, as basins often span across national borders, representatives from several countries may have to cooperate for the management of the basin (transboundary basins). Transboundary basin authorities and multiple national departments of agencies may have to consider how surface and groundwater systems are appropriately and equitably managed and governed. These agreements will influence decision-making at even the local level, and the needs of individuals and organizations on this scale should be considered.

PLANNING HORIZONS

BMPA are facing and anticipating many types of changes in water systems, which affect critical system processes with respect to both temporal and spatial scales. The types and longevity of those changes in a particular system guide the preparation for continuity, gradual shifts or abrupt transitions, which in turn informs the selection and implementation of appropriate strategies and actions in the system. BMPA can look to different temporal and spatial planning horizons to better understand how resilience strategies and actions can be developed.

- **Temporal planning horizon:** Planning for resilience typically requires working with long-term temporal scales. This allows planners and managers to consider the basin's future needs by assessing potential problems and opportunities and thus develop management strategies that are designed to address those issues over time. However, working with long-term temporal scales can reduce the business case for resilience objectives – a lack of immediate results and/or return on investment may be harder to justify or fund, thus decreasing political willingness for such investments. Additionally, physical infrastructure can often lock the system into rigid regimes, which may be difficult to retrofit, and carry high maintenance costs. These investments are often a political or engineering preference. Due to the scale of interventions in some cases, the retrofitting of mega-structures is often financially difficult to justify in the short-term.

- **Spatial planning horizon:** Basins often cross political boundaries, making effective spatial planning a crucial piece of implementing resilience strategies. Jurisdictional boundaries can have a significant impact on decision-making in basin management, and it can be difficult to coordinate management among different jurisdictions. When different levels of Government/organizations have varying responsibilities and authority over segmented parts of the river basin, it can create challenges for coordinating efforts and making decisions that are in the best interest of the entire basin. Additionally, jurisdiction boundaries can also lead to competing interests among different organizations and agencies, which can make it difficult to reach agreements on shared management strategies. Furthermore, jurisdiction boundaries can also limit the ability of organizations and agencies to share information and coordinate management activities across the boundary, which can lead to a lack of understanding of the overall conditions of the basin and hence poor management decisions.

CHALLENGES AND OPPORTUNITIES

Although operationalizing the WRAF at the basin level can be challenging, it can provide opportunities to enhance the resilience of the overall system. The key challenges faced by BMPA in implementing the WRAF are issues-related and include, but are not limited to, the following:

- **Meeting conflicting priorities**: Balancing the competing demands for water resources is not an easy task and requires a holistic approach that takes economic, societal and environmental impacts into consideration. For example, conflicting priorities between environmental flows and development objectives can be a significant challenge in river basin management. Operationalizing WRAF at the basin level can help decision-makers make informed trade-offs between environmental and development objectives.
- **Data and information availability:** Basin management often relies on data and information about water resources, but in many cases, this data is not available or not of high quality. Lack of accurate and up-to-date information can have a significant impact on basin management by limiting the ability of managers to address problems in a timely manner and make informed decisions. A well-designed data and information collection system is important for guiding resilience strategies, especially during times when the system's conditions are in flux.
- **Understanding of natural system dynamics:** Natural systems are often not linear. As changes occur in one component of a system, the cascading impacts to other components can be complex, and these interdependencies are not always established. Due to the lack of understanding on how a system works, we often do not have a firm grasp on how our actions and activities impact physical, chemical and biological processes and how these processes result in the ecosystem goods and services (Brill *et al.*, 2023).
- **Level of existing knowledge, tools and practices:** A key element for implementing the WRAF framework is a thorough understanding of current practices and tools used in basin management. This knowledge helps ensure well-informed decisions based on sound science and established best practices. For a comprehensive list of existing knowledge, data sources, initiatives, tools and practices in resilience science, please see the WRAF.

- **Level of maturity of the management and governance systems**: The effectiveness of selected resilience strategies, resilience actions and their implementation are highly context specific and depend on the level of maturity of the system. A relatively mature system would have better structures in place for effective water management, which includes clear laws, regulations and policies, adequate funding, resources and institutions and strong partnerships and collaboration among stakeholders. In contrast, an immature system may have weak laws and regulations, lack of funding and resources, poor data collection and monitoring and weak or non-existent institutions and organizations.
- **Strength of institutional capacity**: Limited institutional capacity can have a significant impact on basin management by limiting the ability of organizations and agencies to effectively plan, implement and enforce policies and regulations related to the river basin. When institutions lack the necessary resources, such as personnel, funding and infrastructure, they may not be able to effectively gather and analyze data, design and implement management strategies or enforce regulations. Additionally, limited institutional capacity can hinder cooperation and coordination among different organizations and agencies responsible for managing the river basin. Without effective communication and coordination, these institutions may have conflicting goals and strategies, which can lead to conflicting policies and regulations and, ultimately, ineffective management of the basin resources.
- **Financial capacity and challenges:** Funding the implementation of resilience actions at the basin level can be a significant challenge due to high costs, limited funding sources, levels of uncertainty, political factors and limited public awareness. These challenges can make it difficult for organizations and agencies to effectively plan and implement effective resilience strategies.

APPENDIX B: WATER RESILIENCE INDICATORS FOR BMPA

ILLUSTRATIVE LIST OF TIER 1 RESILIENCE INDICATORS

Resilience Characteristic	Tier 1 Resilience Indicator	Measure	Score Range	Notes
Robustness	Percentage of time that the basin provides the required volume of water to meet environmental flow requirements and to meet the needs of all water users in the system	Low Medium High	Low (<70%) Medium (70-79%) High (>80%)	Does the system provide enough water to support environmental flows and the needs of different water users? How often do users need to reduce water use based on water levels, flow rates or other environmental factors?
	Percentage of time that the basin maintains required water quality levels to meet environmental flow requirements and to meet the needs of all water users in the system	Low Medium High	Low (<70%) Medium (70-79%) High (>80%)	Does the system provide enough water of sufficient quality to meet the environmental requirements and the needs of different users? These quality requirements/standards will be developed, monitored and enforced by local or national Government bodies, including environment agencies, water and sanitation departments or even the legislature.
Redundancy	Percentage of time the backup, supplementary and/or alternative replacement components of the system can support key functions	Low Medium High	Low (<2%) Medium (2-5%) High (>5%)	The higher the percentage of time the system components could rely on backup elements, the more effective the redundancy in the system.
	Capacity of the backup, supplementary and/or alternative components to meet critical functions	Low Medium High	Low (<5%) Medium (5 - 25%) High (>25%)	The higher the capacity in the backup system, the greater the redundancy of a system.
Flexibility	Ability of the system sub-components to be adapted or shifted to meet critical functions	Low Medium High	Qualitative assessment/ value judgment	The flexibility of the system can be measured using multiple variables. The system manager could consider the following elements: • The system can rely on different alternate options to function when normal operations are insufficient. For example, under drought conditions the surface water sources may dry up and the water can still be secured from the groundwater or wastewater treatment facilities etc. • Additionally, being able to move financial and human resources around to meet current needs shows a flexible and dynamic system. • The ability to alter policies, legislation and budgets dynamically shows a flexible system that can quickly adapt to shocks and stresses etc.
Integration	Degree that sub-components within the system are linked and coordinated	None Minimal Sufficient	Qualitative assessment/ value judgment	Ideally, at least part of the system is or can be quantitatively modeled and tested, such as for a stress test.
Inclusiveness	Level of inclusion of diverse stakeholders in decision making of the system	Low Medium High	Qualitative assessment/ value judgment	If the engagement processes in making key decisions are inclusive (i.e., all stakeholder groups considered), and if the perspectives of all the stakeholders are adopted (as appropriate), this would result in a higher level of inclusiveness. This does not apply to all decisions, such as real time/near term operational decision making.
Justice and Equity	Degree of provision of fair and equitable water-related services for all users in the system	Low Medium High	Qualitative assessment/ value judgment	If most of the available water-related services in the system are fairly distributed to all stakeholders, this has a higher degree of Justice and Equity. This includes access to water of suitable quality as well as enough to meet demand.

ILLUSTRATIVE LIST OF TIER 2 RESILIENCE INDICATORS

RESILIENCE CHARACTERISTIC: ROBUSTNESS

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Socio-economic	Access to funds	Economic ability to finance/fund existing/planned operations and system maintenance	Poor Good Excellent	Poor (<70%) Good (70-95%) Excellent (>95%)	Mobilization and expenditure of the O&M budget are effective and efficient - for both planned and unplanned expenditure under shifting climatic and other conditions (e.g., demographic change, economic change, etc.)	Organization	• Internal assessments • Budget processes and reviews • Funding/financing applications American Society of Civil Engineers (2016), World Bank (2018)
	Access to funds	Economic ability to finance/ fund new or enhanced system infrastructure	Poor Good Excellent	Poor (<70%) Good (70-95%) Excellent (>95%)	Mobilization and expenditure of the capital budget are effective and efficient - for both planned and unplanned expenditure under shifting climatic and other conditions (e.g., demographic change, economic change, etc.)	Organization	• Internal assessments • Budget processes and reviews • Funding/financing applications American Society of Civil Engineers (2016), World Bank (2018)
Institutional	Regulatory	Level of regulatory compliance	Low Medium High	Qualitative assessment/value judgment	The willingness and ability of BMPA to abide by laws, by-laws, policies, etc. Compliance can be attained via incentives, fines, guidance, behavior and mindset changes. Basin managers and planning authorities that follow/ abide by rules and regulations create a more reliable and effective system.	Organization	• Compliance audits • Internal and external assessments OECD (2012), Udell (2014)
	Regulatory	Ability of regulatory, policy and legal frameworks to enable new operational and infrastructure solutions	Low Medium High	Qualitative assessment/value judgment	Intended to capture the ability of organizations to work within current regulatory structures to enable new approaches, e.g., NBS, to be implemented.	Organization and System	• Internal assessments • Regulation/policy reviews • Budget processes and reviews Brandle *et al.* (2018), Mahoney and Locke (2019), Victor *et al.* (2020)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Regulatory	Maturity of the legal and policy frameworks	Low Medium High	Qualitative assessment/value judgment	This indicator assesses the extent to which a water system's legal and policy frameworks are well-developed, comprehensive and effectively implemented to support the system's overall effectiveness and reliability. The more mature these regulations and policy frameworks are, the more proactively BMPA can plan for future scenarios, invest in necessary infrastructure and ensure the long-term well-being of the basin and its inhabitants.	Organization and System	• Regulation/policy reviews • Maturity model Smith and Doe (2023), Ramanathan *et al.* (2020)
	Regulatory	Practicality and applicability of the legal and policy frameworks	Low Medium High	Qualitative assessment/value judgment	Having a comprehensive national framework that deals with reliability and effectiveness is essential. At the same time we need appropriate local-level laws/by-laws to be more specific in the local context.	Organization and System	• Regulation/policy reviews • Maturity model Smith and Doe (2023), Ramanathan *et al.* (2020)
	Governance	Degree that investment in new infrastructure development is prioritized	Low Medium High	Qualitative assessment/value judgment	Level of priority in allocating sufficient capital budget to ensure reliability and effectiveness. The higher the degree of prioritizing capital investment, the greater the potential for building robustness in the system.	Organization and System	• Budget processes and reviews • Internal and external assessments Flyvbjerg *et al.* (2003), Flyvbjerg (2017)
	Governance	Degree that investment in infrastructure operations and maintenance is prioritized	Low Medium High	Qualitative assessment/value judgment	Levels of priority in allocating sufficient operations and maintenance budget to ensure reliability and effectiveness of existing infrastructure. The higher the degree of prioritization, the greater the potential for building robustness in the system.	Organization and System	• Internal and external assessments • Budget processes and reviews • Regulation/policy reviews • Surveys/ questionnaires National Research Council (2013), American Society of Civil Engineers (2017)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Governance	Degree of authority over water infrastructures and services	Low Medium High	Qualitative assessment/value judgment	BMPA have the authority/mandate to develop appropriate resources and infrastructure, demand management mechanisms, impose restrictions, etc. Those with a high degree of authority can effectively execute necessary functions to ensure the delivery of goods and services. On the other hand, limited authority can hinder a system's ability to adapt to changing conditions or respond to emergencies, potentially compromising service delivery.	Organization and System	• Internal assessments • Internal and external surveys/ questionnaires • Regulatory reviews Ostrom (2009), Pahl-Wray *et al.* (2018)
	Operations/ system management	Level of competency of system operators/ managers	Low Medium High	Qualitative assessment/value judgment	Effective water-related goods and services delivery hinges on the ability of system managers to operate and execute essential functions. Are employees sufficiently trained to implement and operate available technology? Effective technology operation is crucial for organizations to achieve their goals and optimize operational efficiency.	Site and Organization	• Performance-based assessments • Knowledge-based assessments • Behavior-based assessments • Feedback surveys and reviews Brown and Devereux (2008), Kraiger (2013), Barrows (1999), Bruke and Rau (2017), Olivera and Martins (2011)
	Operations/ system management	Capacity to operate the available technology reliably and effectively	Poor Good Excellent	Qualitative assessment/value judgment	This indicator assesses whether the organization has sufficient employee resources with the necessary skills and expertise to implement, operate and maintain available technology effectively.	Site and Organization	• Internal surveys/ questionnaires • Interviews • Assess technology utilization rate and technology-related incident rate Jones and Miller (2022), Johnson *et al.* (2023)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Operations/ system management	Ability to adaptively manage system infrastructure	Poor Good Excellent	Qualitative assessment/value judgment	This is intended to capture how well the infrastructure can be operated in an adaptive manner to manage climatic changes or additional demands or challenges in the system.	Site and Organization	• Assessments focused on evaluating managerial capabilities and decision-making processes • Internal surveys and interviews Schwartz & Ingram (2019), Lindley *et al.* (2011)
	Operations/ system management	Presence of disaster preparedness and emergency management plans	No Somewhat Yes	Qualitative assessment/value judgment	BMPA should create documented plans specifically tailored to their unique risks and potential hazards. These plans should outline emergency supplies, response protocols, operational procedures, basin-specific considerations and collaboration strategies with key stakeholders. Comprehensive plans empower BMPA to effectively minimize disaster impact, safeguard water resources and ensure uninterrupted delivery of clean water during water-related emergencies.	Site, Organization and System	• Document reviews/internal assessments • Expert interviews Simulation exercises Dunn, *et al.* (2016), Stewart and Melchers (2020), Pahl-Wostl and Knieper (2013)
	Operations/ system management	Frequency of data collection	Low Medium High	Qualitative assessment/value judgment	How regularly an organization collects data on water quality, quantity, access, biodiversity, etc. will inform how well the system dynamics can be understood. If, for example, data is only collected once a month, then this could skew how data is interpreted. A higher frequency of data collection enables more accurate baselining, average value estimation and trend analysis, leading to more informed decision-making.	Site, Organization and System	• Internal assessments • Data collection policies and schedules WHO (2003)
	Operations/ system management	Quality of data	Poor Good Excellent	Qualitative assessment/value judgment	Trustworthy data fuels impactful decisions. Quality assurance is maintained by checking the data collection practices. This means collecting enough relevant data, regularly calibrating equipment and employing effective qualitative measures.	Site, Organization and System	• Internal assessment • Data collection policies and schedules • Data quality assessment tools

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Biophysical	Supply	Degree of independence of different available water sources	Low Medium High	Qualitative assessment/value judgment	One critical way to measure independence is by how correlated supply sources are. For example, if a utility decides to partner with another jurisdiction to tap into its supplies, but if that new supply has similar timing of flow regimes, weather patterns and supply accumulation then the sources may be highly correlated. Given that set of circumstances, one could argue that the sources are not independent, at least as it relates to supply availability.	Site and Organization	• Desktop studies on dependence correlations • Assessing existing diversification strategies Ahmad *et al.* (2014) Salas *et al.* (2013) Xu *et al.* (2018)
	Supply	Degree of diversity of water sources	Low Medium High	Low (1-2 sources) Medium (3-4 sources) High (>4 sources)	Variability in sources (10% of supplies secured from desalination, 30% from groundwater and 60% from surface water). This indicator is to be read in conjunction with the indicator on supply reliability (one below).	Site and Organization	• Desktop studies on dependence correlations • Assessing existing diversification strategies Ahmad *et al.* (2014) Salas *et al.* (2013) Xu *et al.* (2018)
	Supply	Degree of reliability of water quantity from different sources	Low Medium High	Low (<80%) Medium (80-99%) High (>99%)	The degree of reliability should be measured under different scenarios. For example, under normal conditions, there could be 99% certainty to get water from dams, 50% certainty to get water from groundwater, 99% certainty to get water from desalination, etc. Under extreme conditions, this level of certainty could change. The degree of reliability should be measured under different scenarios. This can inform long-term planning about the need to adjust the overall supply mix.	Site and Organization	• Desktop studies on reliability of different water sources Vogel *et al.* (2016)
	Supply	Degree of reliability of water quality from different sources	Low Medium High	Low (<80%) Medium (80-99%) High (>99%)	The degree of reliability with respect to the quality of water could change under different conditions. For example, under normal conditions, a utility receives high-quality water from dams and medium- to low-quality water from other sources. Under extreme conditions, this degree of reliability in water quality could change. The degree of reliability should be measured under different scenarios. This can inform long-term planning about the need to adjust the overall supply mix.	Site and Organization	• Desktop studies on reliability of different sources Characklis & Wiesner (2017)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Biophysical	Built and/ or natural infrastructure	Suitability of the infrastructure design and placement	Poor Good Excellent	Qualitative assessment/value judgment	This indicator evaluates how well the infrastructure fits its location and purpose. For example, a dam may be a stranded asset if it is built in an area with low water availability or high environmental risks.	Site and System	• Water Infrastructure Sustainability Assessment Tool (WISAT) • Sustainable Asset Valuation tool Gumbo and van der Zaag (2018), IISD (2023)
	Built and/ or natural infrastructure	State of infrastructure to withstand shocks and stresses	Poor Good Excellent	Qualitative assessment/value judgment	Evaluates factors such as structural integrity and ability to adapt to changing environmental conditions. For example, it examines whether desalination plants can handle increased salinity caused by sea level rise or if the pump power supply can withstand sudden surges in power supplies.	Site and System	• Structural assessments • Stress testing • Maintenance records assessment
	Built and/ or natural infrastructure	Level of infrastructure maintenance	Poor Good Excellent	Qualitative assessment/value judgment	The level of infrastructure maintenance measures the effort put into maintaining the infrastructure to an appropriate standard. It reflects the structural integrity and stability of infrastructure in the face of extreme events and ongoing stresses, reflecting its ability to withstand extreme events as well as ongoing stresses and wear and tear.	Site and System	Physical inspections • Performance data analysis • Maintenance records assessment • Expert judgment Maier and Martinez-Paz (2016), Griffith and Iyer (2005)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Biophysical	Built and/ or natural infrastructure	Ability of the constructed/ natural ecosystems to provide goods and services	Poor Good Excellent	Poor (<20%) Good (20-50%) Excellent (>50%)	Constructed and naturally occurring habitats (e.g., wetlands and riparian and aquatic habitat) can store, treat and release water. These goods and services are dependent on the size, location and condition of the habitat. For example, the larger the size, the greater the ability to hold and filter water; upstream habitat location can provide additional benefits to downstream locations; the more intact the wetland system, the greater the ability to function optimally.	Site and System	• Aquatic macrophyte surveys • Hydrological monitoring • Soil and sediment analysis • Wetland condition assessment Prendergast and Mitsch (2012), Wetzel (2001), Kadlec and Knight (1996)
	Built and/ or natural infrastructure	Ability of infrastructure to withstand shocks and stresses	Poor Good Excellent	Qualitative assessment/value judgment	It reflects the degree of robustness of the infrastructure to cope with shocks and stresses and maintain structural integrity. For example, desalination plants located in coastal areas are susceptible to damage from rising sea levels and tidal surges. These infrastructures are exposed to shocks and stresses such as flooding, intrusion of saline water or erosion and structural damage, etc. The higher the ability of the desal plants to cope with these threats, the more robust is this infrastructure and ultimately the system.	Site	• Desktop studies under different load simulations • Historic data assessment of similar water infrastructure failure Bruneau *et al.* (2003) O'Brien *et al.*. (2014) van der Hoeven *et al.* (2014)
	Operations/system management	Access/availability to technology for the system to operate reliably and effectively	Poor Good Excellent	Qualitative assessment/value judgment	This indicator first checks whether appropriate technology is immediately deployable. For example, in a desalination-based system, this includes effective, locally obtainable pumping, filtration and distribution systems to meet the demand.	Site and System	• Surveys/interviews • Analyze performance indicators • Internal assessments • Documentation reviews Al-Kadi and Hassan (2019), Kulkarni and Bhalerao (2018)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Biophysical	Technology	Level of effectiveness of infrastructure monitoring systems	Low Medium High	Qualitative assessment/value judgment	An effective monitoring system seamlessly integrates various infrastructure operation processes and monitoring components. It helps proactively identify and anticipate potential synergies, conflicts and bottlenecks.	Site and System	• Assessment of internal system performance metrics, • Simulation models • Expert interviews Al-Kadi and Hassan (2019), Kulkarni and Bhalerao (2018)
	Biodiversity	Degree of environmental monitoring and evaluations	Low Medium High	Qualitative assessment/value judgment	This indicator seeks to determine whether regular monitoring and evaluation of environmental systems are conducted, and whether mechanisms exist to track and protect aquatic flora and fauna.	Site and System	• Biodiversity and habitat surveys/ assessments • Simulation models • Expert interviews Baker *et al.* (2018), Jones *et al.* (2019)

RESILIENCE CHARACTERISTIC: REDUNDANCY

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Socio-economic	Access to funds	Percentage of contingency financial reserves to operate and maintain the system	Low Medium High	Low (<2%) Medium (2-5%) High (>5%)	This indicator measures whether there is sufficient budget ring-fenced specifically for operations and maintenance during emergency situations, e.g., rainy day funds, (e.g., parametric insurance) or not. The score ranges are only representative; they would need to be tailored to individual utility circumstances.	Organization	• Internal assessments • Budget processes and reviews • Funding/financing applications American Society of Civil Engineers (2016), ADB (2018), World Bank (2018)
Institutional	Governance	Level of reserve capacity to govern water systems	None Insufficient Sufficient	Qualitative assessment/value judgment	This indicator assesses the preparedness of water systems to handle emergencies by evaluating the alternative governance options available. For example, if a regional water department is not able to perform its mandate, then there are other institutional actors who could step in to perform these roles and responsibilities.	Organization	• Organizational survey and analyses • Skills assessment • Resource assessment
	Operations/ ystem management	Level of reserve capacity to manage water systems	None Insufficient Sufficient	Qualitative assessment/value judgment	Number of staff able to fulfill their roles in the organization. If the system engineer goes for an unexpected absence, are there enough existing personnel to handle the roles and responsibilities to meet the shortfall?	Site and Organization	• Organizational survey and analysis • Skills assessment • Resource assessment
	Operations/ system management	Presence of contingency plans for disaster preparedness and emergency management	No Somewhat Yes	Qualitative assessment/value judgment	Contingency plans for disaster preparedness and emergency management exist in the form of emergency provisions in operational manuals and governing regulations, which allow for flexibility in responding to disasters without requiring cumbersome approval processes.	Site, Organization and System	• Document review • Plan evaluation • Expert consultation Smith *et al.* (2022)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Biophysical	Built and/ or natural infrastructure	Level of reserve capacity built into the biophysical components	None Insufficient Sufficient	Qualitative assessment/value judgment	This indicator measures the buffer built into key natural and built infrastructure to withstand shocks and stresses in the system. It focuses on excess capacity, like a dam designed to hold more water than currently needed, enabling essential functions to continue even during emergencies.	Site and System	• Internal data collection, document review and analyzing records • Calculate capacity and demand ratio, analytically or qualitatively using models, etc. Gibert *et al.* (2020)
	Built and/ or natural infrastructure	Degree of reliability of the backup infrastructures	Low Medium High	Low (<80%) Medium (80-99%) High (>99%)	This indicator assesses the ability of backup infrastructure and components to resist shocks and stresses. It evaluates whether regular maintenance and operation ensure the backup system's readiness when needed.	Site and System	• Infrastructure Inventory • Capacity Assessment • Performance Evaluation • Integration Analysis Ahmad and Sarma (2015)
	Built and/ or natural infrastructure	Factor of safety in physical infrastructure design	Low Medium High	Low (<20%) Medium (20-50%) High (>50%)	This indicator assesses the margin of safety built into existing infrastructure designs. A factor of safety (FS) of 1 implies the design just meets calculated load demands, while an FS of 2 indicates it can withstand double the anticipated load. The question is: what is the current safety margin before infrastructure performance deteriorates? For example, a flood embankment designed for a 1250-year flood event exhibits greater redundancy compared with one designed for a 500-year event. The chosen return period influences the level of built-in safety and redundancy.	Site and System	• Document review • Structural analysis • Risk assessment • Performance monitoring ASCE (2017), WRF (2016)

RESILIENCE CHARACTERISTIC: FLEXIBILITY

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Socio-economic	Demand management	Willingness to invest in and adopt demand management and efficiency measures	Poor Good Excellent	Qualitative assessment/ value judgment	BMPA can exercise more flexibility in demand management during crises, using tools such as taxes, fees, regulations and reduced access. This indicator assesses the extent to which water management entities are prepared to implement such measures.	Organization and System	• Internal surveys • Economic models Chen and Koomey (2015)
	Access to funds	Level of flexibility in reallocating budget	Low Medium High	Qualitative assessment/ value judgment	This indicator measures the ability of BMPA to dynamically shift funds among different budgets or units within the organization. For example, can BMPA shift maintenance funds to operations during a crisis, or vice versa, such as to purchase additional supplies or to cover unexpected costs.	Organization	• Review financial records • Budget analysis • Managerial interviews and surveys to gather quantitative data on their perceptions of budget flexibility. Brown and Lee (2021)
Institutional	Operations/ system management	Degree of dynamic decision-making in planning and operations	Poor Good Excellent	Qualitative assessment/ value judgment	This indicator measures the flexibility in the internal decision-making processes to plan and operate in tandem with regulatory flexibility. For example, although the regulatory framework may allow a higher degree of flexibility, can a decision be easily made to flip between different sources - such as from surface water to groundwater or dams to desalination? Can the operations manager flip easily from one source to another or does a decision need to be escalated upwards that would delay decision-making and the ability to switch between sources?	Site and System	• Internal decision-making process analysis • Scenario simulation • Surveys among operations personnel to gauge their perceived ability to make dynamic decisions and identify potential barriers Ganjeti and Bhat (2020)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Operations/ system management	Degree of dynamic decision-making in investment	Poor Good Excellent	Qualitative assessment/ value judgment	This indicator measures the decision-makers' ability to invest in different infrastructure options in response to changing needs and conditions. For example, can budget managers invest in: • Headwaters protection measures, such as reforestation and wetland restoration, improve water quality and reduce sedimentation. • Flood-control infrastructure, such as dams and levees • Water storage infrastructure, such as reservoirs and groundwater recharge systems, to increase water availability during dry periods. • Inter-basin water transfer systems to move water from areas of surplus to areas of deficit.	Organization and System	• Review of financial records/financial assessments • Review of key investment decisions • Simulation model to quantify the degree of dynamic decision-making Loucks *et al*.. (2018), Li *et al*. (2019)
	Operations/ system management	Degree of dynamic decision-making in maintenance	Poor Good Excellent	Qualitative assessment/ value judgment	This indicator measures the flexibility of maintenance managers to make timely and informed decisions without the need for extensive escalation. For example, can maintenance managers: • Decide to repair a flood embankment under a certain budget threshold without approval from the director of the unit? • Reroute traffic around a road closure caused by a fallen tree without waiting for approval from the city engineer? • Dispatch a maintenance crew to a critical infrastructure that is experiencing a higher flood level and associated threats in barrage operations, even if the crew is already scheduled to work on another project?	Site, Organization and System	• Review of decision-making criteria for maintenance managers • Interview/surveys of maintenance managers on decision making records Sharma and Deshmukh (2015), Goulter and Coombes (2011)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Operations/ system management	Level of flexibility in demand management	Low Medium High	Qualitative assessment/ value judgment	Under demand-management options basin managers or authorities can prioritize supplies to some sectors or locations over others. Options may include: - Pressuring management to reduce supply throughout the system or parts of it. - Diverting water to priority locations or to those most in need of water during times of shock and stress If significant changes can be made, the flexibility is higher.	Site	• Review of internal documents • Simulation optimization approaches • Flexibility assessment frameworks Aldaya *et al.*. (2017) Cominola *et al.* (2018)
	Regulatory	Ability of the regulatory, policy and legal frameworks to be adjusted or updated	Low Medium High	Qualitative assessment/ value judgment	This indicator measures the ability of regulatory agencies to adapt and update their frameworks to enable new approaches and to allow for more flexible and dynamic decision-making in water management. For example, basin managers may need to be able to adjust water allocation permits in response to drought conditions, or planning authorities may need to be able to approve new types of development that incorporate green infrastructure.	Organiza-tion and System	• Review of records on adherence to existing regulatory frameworks and policy • Analyze the frequency of framework updates and the impacts on decision making • Internal surveys/ interviews Gupta *et al.* (2015), Warner *et al.* (2012)
Biophysical	Technology	Ability to secure, treat and distribute supplies from different sources	Poor Good Excellent	Qualitative assessment/ value judgment	This indicator evaluates a basin manager/ authority's technological ability to secure water from diverse sources, adapt treatment methods (e.g., desalination) and efficiently distribute water. For example, advanced, on-demand treatment technologies like desalination offer advantages over constant-operation methods like boreholes, as they provide greater flexibility and potentially reduce costs.	Site	• Review of internal documents • Internal surveys

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Biophysical	Supply	Ability to switch between different components of the systems	Poor Good Excellent	Qualitative assessment/ value judgment	This indicator evaluates the system's ability to isolate, segment or temporarily sever different parts. Different parts of a system could be isolated, segmented or severed (temporarily) so that failures in one part of a system are not transmitted across the rest of the system. Similarly, supplies or services can be augmented by connecting other components in the system. This indicator is closely connected with 'Interconnectedness' of 'Built and/or natural infrastructure'.	Site, Organization and System	• Review of internal documents • Internal surveys
	Supply	Ability to switch between different types/sources	Poor Good Excellent	Qualitative assessment/ value judgment	This indicator measures the basin manager's ability to utilize different water sources strategically. During periods of abundant supply, they may rely primarily on readily available sources like surface water. However, when facing scarcity, an effective basin manager can readily switch to alternative sources such as groundwater or even external supplies, ensuring water security.	Site	• Review of internal documents • Internal surveys

RESILIENCE CHARACTERISTIC: INTEGRATION

System component	System subcomponent	Tier 2 Resilience Indicator	Measure	Score range	Notes	Assessment level	Examples and Methods
Institutional	Governance	Level of integration in water governance mechanisms	Low Medium High	Qualitative assessment/ value judgment	This indicator measures how integrated decision-making and water management options are across different components of the water system. It assesses whether there are governance mechanisms that can coordinate multiple water management options, such as inter-basin water transfers, virtual water imports and exports, groundwater recharge and catchment restoration.	Organization and System	• Policy reviews and analyses • Internal surveys/ interviews UNESCO (2006)
	Regulatory	Presence of policies and mechanisms for the integration of green and hybrid gray-green infrastructure in basin management	No Somewhat Yes	Qualitative assessment/ value judgment	This indicator measures the extent to which basin management institutions have policies, rules/regulations and mechanisms in place to support the use of green and hybrid infrastructure alongside traditional gray infrastructure. For example, a basin management institution could have a policy that requires all new water infrastructure projects to incorporate green infrastructure elements, such as rainwater harvesting or stormwater infiltration.	Organization and System	• Policy reviews and analyses • Internal surveys/ interviews Ghazouani and Zwarteveen (2014), Warner and Zeitoun (2014)
	Governance	Inter-connectedness of water-infrastructure planning, operations and management	Low Medium High	Qualitative assessment/ value judgment	This indicator measures the integration of plans, policies and management options promoting infrastructural connectivity. For example: Plans: Develop interconnectivity plans for major dams and reservoirs. Policies: Require new water infrastructure projects to be designed with interconnectivity in mind. Finance: Provide financial and other incentives for water utilities to interconnect their infrastructure.	Organization	• Internal interviews • Internal assessments • Analyze performance indicators Ayyoob (2011)

System component	System subcomponent	Tier 2 Resilience Indicator	Measure	Score range	Notes	Assessment level	Examples and Methods
Institutional	Governance	Level of integration in basin planning across agencies	Low Medium High	Qualitative assessment/ value judgment	This indicator measures the extent to which basin planning and governance is fragmented and uncoordinated among different agencies. For example, do agencies share data and information effectively? Do they collaborate on developing and implementing basin plans? Are there clear mechanisms for resolving conflicts between agencies?	System	• Internal and external interviews • Internal and external Assessments • Policy reviews and analyses UNESCO (2006)
	Regulatory	Level of integration in water-related policy and regulations	Low Medium High	Qualitative assessment/ value judgment	A resilient water system necessitates legal instruments, including policies and regulations, that function in a mutually supportive and reinforcing manner. A resilient water system relies on legal mechanisms that complement and support each other, rather than conflicting or creating gaps. This means evaluating whether the various regulations work together to achieve common goals and avoid unintended consequences. For example, agricultural regulations might encourage water conservation practices that align with the goals of the National Water Act, while disaster risk reduction measures might consider the water needs of different sectors outlined in the Act.	Organization and System	• Policy reviews and analyses • Internal surveys/ interviews Ghazouani and Zwarteveen (2014), Warner and Zeitoun (2014)
Biophysical	Built and/ or natural infrastructure	Inter-connectedness of water infrastructure	Low Medium High	Low (<50%) Medium (50-80%) High (>80%)	Interconnecting different water infrastructures, like irrigation and drinking supply, can boost resilience. Similarly, green and gray infrastructure's synergy enhances sustainability and efficiency. Stormwater management, for instance, can recharge aquifers and provide non-potable water. High connectivity does not equal rigidity; well-designed systems remain adaptable.	Site, Organization and System	• Internal interviews • Internal assessments • Analyze performance indicators Ayyoob (2011)

RESILIENCE CHARACTERISTIC: INCLUSIVENESS

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Socio-economic	Access to funds	Economic ability to fund stakeholder participation in system planning	Poor Good Excellent	Qualitative assessment/ value judgment	This indicator checks if there is dedicated funding for ongoing and unexpected stakeholder engagement. These budgets could cover the operational expenses of stakeholder engagement processes by BMPA as well as a ring-fenced fund to allow stakeholders to travel to these engagements or to hold such engagements where stakeholders are not burdened by travel costs. This indicator should be assessed in conjunction with the indicators' 'Ability of stakeholders to participate in decision-making processes' and 'Presence of processes to overcome barriers to participation' under 'Governance'	Site and Organization	• Internal assessments • Budget processes and reviews • Funding/financing applications ADB (2018), American Society of Civil Engineers (2016), World Bank (2018).
	Knowledge systems	Level of integration of local and Indigenous knowledge into decision-making processes	Low Medium High	Qualitative assessment/ value judgment	Recognizing the value of local and Indigenous knowledge in building system resilience would ensure a more inclusive process. This will generate feelings of ownership by local stakeholders.	Site and Organization	Internal assessments
Institutional	Affordability	Economic ability of stakeholders to afford services from the system	Low Medium High	Qualitative assessment/ value judgment	This indicator asks if the system helps people from all backgrounds afford water services. How can stakeholders from all socioeconomic backgrounds afford water services? Are there water management plans that include strategies for improving affordability? Is there support available for community-led water management practices? Is there financial assistance for low-income households to help them pay for these services?	System	• Census • Household surveys • Service utilization analysis • Financial assistance programs Brown and Wolfram (2017)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Governance	Ability of stakeholders to participate in decision-making processes	Low Medium High	Qualitative assessment/ value judgment	There are many factors that can influence the stakeholder's ability or capacity to participate in a decision-making process. These include time of day (e.g. they may not be able to find time to attend the process due to their home and work commitments), transportation availability, access to services and information, and priorities (e.g. home and work priorities may take precedence). The engagement/inclusion process must consider these factors. This indicator should be assessed in conjunction with the indicators 'Economic ability to sufficiently fund regular stakeholder participation in system planning' & 'Presence of processes to overcome barriers to participation' under 'Governance'.	Site and Organization	• Household surveys/interviews • Internal policy reviews • Engagement assessments Zhang and Wang (2017)
Institutional	Governance	Presence of processes to overcome barriers to participation	No Somewhat Yes	Qualitative assessment/ value judgment	Stakeholders may face several barriers to participating in decision-making processes, including time constraints, transportation availability, access to services and information and competing priorities. Engagement processes should be designed to overcome these barriers and ensure that all stakeholders have an opportunity to participate.	Organization and System	• Household surveys/interviews • Internal policy reviews • Engagement assessments Zhang and Wang (2017)
	Governance	Level of diversity of stakeholders included in decision-making	Low Medium High	Qualitative assessment/ value judgment	Effective decision-making requires input from a diverse range of stakeholders, including representatives from different sectors, demographics and interest groups. A diversity of perspectives can help to ensure that decisions are informed by a wide range of perspectives and worldviews and that they reflect the needs of all stakeholders.	Organization and System	• Stakeholder mapping • Household surveys/interviews • Internal policy reviews • Engagement assessments Oliveira and Lacerda (2018)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Governance	Level of trust, engagement and cooperation between stakeholders	Low Medium High	Qualitative assessment/ value judgment	Transparent and accountable decision-making builds trust between stakeholders and planners. Breaches in decisions, implementation failures and broken promises erode trust. Engaging and collaborating with stakeholders throughout all stages of decision-making and implementation is critical. Is the utility utilizing its stakeholder engagement processes to develop service-level agreements with its stakeholders? Is it utilizing this opportunity to explain how climate change may affect service level delivery and the funding that may be needed to maintain those levels?	Organization and System	• Household surveys/interviews • Engagement assessments Ring (1996) Arnstein and Sherry (2006)
	Governance	Level of accountability in implementation	Low Medium High	Qualitative assessment/ value judgment	The level of accountability for system operations is ensured through mechanisms that hold the system responsible for its performance. For instance, when a dam fails, established rules and regulations require the operators/managers to take corrective actions. These actions could involve providing alternative water sources, implementing a feedback loop for improvement, such as overhauling the management structure, or actively consulting stakeholders about the situation. This ensures that the system is held responsible for its actions and takes necessary steps to address any failures or shortcomings.	Organization and System	• Internal interviews/surveys • Internal assessments • Review of project and program documentation • Analyze performance indicators Ostrom (1996)

RESILIENCE CHARACTERISTIC: JUSTICE AND EQUITY

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Socio-economic	Access to services	Percentage of people from marginalized communities with access to safe and secure water supply	Low Medium High	Low (<50%) Medium (50-90%) High (>90%)	This indicator focuses on equitable access to safe water within marginalized communities. It tackles questions such as: do all marginalized, vulnerable or frontline communities have adequate access to water of a suitable quantity and quality, regardless of their socioeconomic status? Do all the users in the system have access to taps in their homes, or do they need to go and use shared facilities, if these exist?	System	• Census • Household surveys • Mapping of water infrastructure • Financial assistance programs Adler and Kirsch (2014) Barlow *et al.* (2019)
	Access to services	Percentage of people from marginalized communities with access to safe and reliable sanitation and hygiene services	Low Medium High	Low (<50%) Medium (50-90%) High (>90%)	This indicator measures the extent to which all people have access to safe and reliable sanitation facilities, regardless of their socio-economic status or location. Safe and reliable sanitation facilities are those that safely dispose of human waste and protect people from exposure to harmful contaminants.	System	• Census • Household surveys • Financial assistance programs Adler and Kirsch (2014) Barlow *et al.* (2019)
	Access to services	Percentage of people from marginalized communities with access to water resources for cultural, recreational, spiritual/religious and other purposes	Low Medium High	Low (<50%) Medium (50-90%) High (>90%)	This indicator measures how well all people can enjoy the benefits of water-related assets, such as recreation, relaxation, religious and spiritual practices and cultural enrichment, regardless of their socio-economic status or location. Water-related assets include things like rivers, lakes, beaches and water parks.	System	• Census • Household surveys • Financial assistance programs Adler and Kirsch (2014) Barlow *et al.* (2019)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Socio-economic	Access to services	Percentage of people from marginalized communities with flood-protection services	Low Medium High	Low (<50%) Medium (50-90%) High (>90%)	This indicator measures the extent to which all people have adequate flood-protection measures (availability and quality of protection), regardless of their socio-economic status or location. Flood protection measures include things like levees, seawalls and flood insurance. Are there adequate support systems in place before, during and after flooding events?	System	• Census • Household surveys • Analysis of flood risk maps • Financial assistance programs Aitsiselmi *et al.* (2015)
Institutional	Affordability	Ability of the people from marginalized communities to pay for services	Low Medium High	Qualitative assessment/ value judgment	This indicator measures the ability of the systems to support low-income customers by making water services affordable through appropriate financial mechanisms (e.g. free water allocations, subsidized or low rates/fees, etc.).	Organization and System	• Household surveys • Review of Government budgets and financial records • Policy reviews • Analysis of water utility tariffs and subsidies • Assessment of microcredit and revolving loan programs • Internal surveys/ interviews Hutton *et al.* (2012)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Regulatory	Presence of policies and regulations to address historic and current inequities	No Somewhat Yes	Qualitative assessment/ value judgment	This indicator assesses the organization's commitment to addressing historical and ongoing inequities, particularly regarding service access for disadvantaged populations. It evaluates the existence and adequacy of concrete plans and active practices aimed at remedying these disparities.	Organization and System	• Review of legal and regulatory frameworks • Policy reviews and analyses • Assessment of monitoring and evaluation mechanisms • Internal surveys/ interviews Ghazouani and Zwarteveen (2014), Warner and Zeitoun (2014), Ayres and Braithwaite (1992)
	Regulatory	Presence of just and equitable water allocation rules and practices	No Somewhat Yes	Qualitative assessment/ value judgment	Water allocation regulations should ensure equitable distribution during varying water availability. While minimal restrictions may suffice in times of abundance, flat percentage reductions during scarcity can disadvantage certain sectors and communities. Therefore, regulations should mandate tailored percentage reductions based on legislated allocations and specific user/sector needs. This should consider both environmental flow requirements and local wastewater limitations for a holistic approach. The indicators tackle issues such as: are there plans, strategies and/ or mechanisms in place to enable equitable allocation of water during different water availability?	Organization and System	• Document reviews • Policy reviews and analyses • Internal surveys/ interviews Ghazouani and Zwarteveen (2014), Warner and Zeitoun (2014)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Regulatory	Presence of environmental rules and regulations	No Somewhat Yes	Qualitative assessment/ value judgment	This indicator assesses the adequacy of national, federal and local legislation and rules for allocating goods and services under diverse circumstances. For instance, water restrictions during periods of abundance should be less stringent than during droughts. However, simply implementing a flat percentage reduction during scarcity may disadvantage essential users and sectors. Therefore, regulations could mandate flexible allocation mechanisms based on specific needs, considering environmental flow requirements, natural systems and wastewater discharge limitations within the local context.	Organization and System	• Document reviews • Policy reviews and analyses • Internal surveys/ interviews Ghazouani and Zwarteveen (2014), Warner and Zeitoun (2014)
	Regulatory	Presence of policies and regulations to address compliance measures	No Somewhat Yes	Qualitative assessment/ value judgment	While the indicator itself does not directly measure justice and equity, it can offer indirect insights when considered within a broader context: - If fines are the primary tool, they can disproportionately burden low-income households, potentially exacerbating existing inequities in water access and affordability. - Are the compliance measures clearly communicated and enforced consistently across all demographics?	Organization and System	• Document reviews • Policy reviews and analyses • Internal surveys/ interviews
	Regulatory	Degree of regulatory compliance	Low Medium High	Qualitative assessment/ value judgment	This indicator tracks how well everyone follows the rules on water use, pollution, development and other environmental impacts. It is not enough to just have laws in place; everyone – households, businesses and communities – need to comply for a just and equitable use of resources.	Site, Organization and System	Compliance audits Internal and external assessments OECD (2012), Udell (2014)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Governance	Level of transparency in sharing information about water-related policies and practices	Low Medium High	Qualitative assessment/ value judgment	This indicator gauges openness in sharing water policies and practices, reflecting an organization's accountability and commitment to productive stakeholder engagement. Sharing clear information on water plans within the basin management organization fosters a just and equitable river basin, as it empowers stakeholders and enables informed decision-making for all.	Site, Organization and System	• Internal interviews/ surveys • Internal assessments • Analysis of freedom of information (FOI) requests • Analyze performance indicators World Bank (2016)
	Governance	Level of effectiveness of water-related policies and practices	Low Medium High	Qualitative assessment/ value judgment	This indicator looks at how fairly water policies treat all groups, considering both social and environmental aspects, while addressing past inequalities. Effective policies ensure water justice: ensuring everyone has access to clean water, protecting the environment and righting historical wrongs.	Organization and System	• Document reviews • Policy reviews and analyses • Internal surveys/ interviews Ghazouani and Zwarteveen (2014), Warner and Zeitoun (2014)
	Governance	Percentage of organizational leadership from diverse groups	Low Medium High	Low (<50%) Medium (50-90%) High (>90%)	This indicator tracks how well the organization reflects the community it serves. When a river basin organization's leaders reflect on the community it serves, with different ethnicities, genders and backgrounds represented, it fosters a fairer, more just system. This diverse perspective ensures everyone has a voice in decision-making, leading to solutions that benefit the entire community.	Organization and System	• Internal surveys/ interviews • Internal policy reviews • Review of organizational charts and personnel data • Analysis of diversity reports and surveys Dasgupta and Wah (2018)

System Component	System Subcomponent	Tier 2 Resilience Indicator	Measure	Score Range	Notes	Assessment Level	Examples and Methods
Institutional	Governance	Level of fairness in workplace governance	Low Medium High	Qualitative assessment/ value judgment	This indicator assesses how fairly the river basin organization governs its workforce. Fairness means everyone, regardless of background or identity, has an equal chance to contribute to decisions and leadership. It fosters a just and equitable system where everyone feels valued and heard, leading to a more engaged and effective workforce.	Organization	• Internal surveys/ interviews • Review of workplace policies and procedures • Analysis of employee surveys and feedback Cropanzano *et al.* (2007)
	Governance	Level of transparency in fairness practices in the workplace	Low Medium High	Qualitative assessment/ value judgment	This indicator assesses how openly a river basin organization communicates its fairness practices. Does it publicly share clear information about these practices and how they are applied? And if fairness lapses occur, are documented examples readily available? When everyone has easy access to this information, it fosters trust and helps ensure a just and equitable system for all.	Organization	• Internal surveys/ interviews • Review of workplace policies and procedures Bernstein (2012)
Biophysical	Biodiversity	Effectiveness of basin infrastructure in maintaining or protecting biodiversity and ecosystem	Low Medium High	Qualitative assessment/ value judgment	This indicator assesses how well basin infrastructure projects minimize harm to biodiversity and ecosystems while ensuring everyone benefits equitably. Just and equitable infrastructure means balancing development needs with nature conservation and sharing the costs and rewards fairly among all communities involved.	Site, Organization and System	• Biodiversity and habitat surveys/ assessments • Simulation models • Expert interviews Baker *et al.* (2018), Frappart, *et al.* (2019)

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The CEO Water Mandate's six core elements:

DIRECT OPERATIONS
Mandate endorsers measure and reduce their water use and wastewater discharge and develop strategies for eliminating their impacts on communities and ecosystems.

SUPPLY CHAIN AND WATERSHED MANAGEMENT
Mandate endorsers seek avenues through which to encourage improved water management among their suppliers and public water managers alike.

COLLECTIVE ACTION
Mandate endorsers look to participate in collective efforts with civil society, intergovernmental organizations, affected communities, and other businesses to advance water sustainability.

PUBLIC POLICY
Mandate endorsers seek ways to facilitate the development and implementation of sustainable, equitable, and coherent water policy and regulatory frameworks.

COMMUNITY ENGAGEMENT
Mandate endorsers seek ways to improve community water efficiency, protect watersheds, and increase access to water services as a way of promoting sustainable water management and reducing risks.

TRANSPARENCY
Mandate endorsers are committed to transparency and disclosure in order to hold themselves accountable and meet the expectations of their stakeholders.