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Abstract

Water infrastructure investments are typically capital-intensive and long-lived, involving significant costs and benefits. Their performance over operational lifetimes is highly dependent on the vagaries of the hydrological cycle and subject to the risks and uncertainties associated with climate change. The challenge is to make the best use of scarce financial resources to deliver desired water services in the context of these complicating factors. Ideally, planning for water-related investments should be robust to known hazards and flexible to adapt to an uncertain future.

This paper presents a conceptual and analytical framework to sequence water-related investments along “Strategic Investment Pathways”. This approach considers a range of diverse investments over multiple scenarios and evaluates options relative to stakeholder-defined goals. It explicitly considers key dynamic processes, interdependencies and feedbacks within the water system. The aim is to inform investment decisions that contribute to water system resilience through effective and adaptive management over time.

Keywords: water security, water supply, sanitation, wastewater, flood protection, irrigation, infrastructure finance, investment

JEL Classification: H41, H54, L95, L98, Q25, Q53, Q54, Q58

Résumé

Les investissements dans les infrastructures de l'eau sont généralement des investissements à forte intensité de capital et de longue durée, impliquant des coûts et des bénéfices importants. Leur performance au cours de leur durée de vie opérationnelle dépend fortement des aléas du cycle hydrologique et est soumise aux risques et incertitudes liés au changement climatique. Le défi consiste à utiliser au mieux des ressources financières limitées pour fournir les services d'eau souhaités dans le contexte de ces facteurs de complication. Idéalement, la planification des investissements liés à l'eau devrait être robuste face aux risques connus et flexible pour s'adapter à un avenir incertain.

Ce document présente un cadre conceptuel et analytique permettant de séquencer les investissements liés à l'eau le long de "voies d'investissement stratégiques". Cette approche prend en compte une gamme d'investissements diversifiés sur plusieurs scénarios et évalue les options par rapport aux objectifs définis par les parties prenantes. Elle prend explicitement en compte les processus dynamiques clés, les interdépendances et les rétroactions au sein du système de l'eau. L'objectif est d'éclairer les décisions d'investissement qui contribuent à la résilience du système de l'eau par une gestion efficace et adaptative dans le temps.

Mots-clés : sécurité en eau, approvisionnement en eau, assainissement, eaux usées, protection contre les inondations, irrigation, financement des infrastructures, investissement

Classification JEL: H41, H54, L95, L98, Q25, Q53, Q54, Q58

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1

Strategic Investment Pathways: A Conceptual Framework

1.1. Introduction

Throughout human history, the transformation and management of freshwater ecosystems has enabled extraordinary gains in access to clean water and improved sanitation for households and communities, as well as in the reliable provision of water to agriculture and industry. Water system transformations have enabled societies and economies to flourish for thousands of years.

In addition to supporting virtually every aspect of the human endeavour, water influences the diversity and distribution of terrestrial ecosystems and biodiversity. In the context of climate change, water availability and variability will influence how the terrestrial biosphere adapts, driving shifts in the distribution of species and ecosystems (Poff, Tharme and Arthington, 2017[1]) (Rockström et al., 2014[2]).

Water management, policies and investment planning in the context of climate and societal change and of technological evolution must be both robust to known hazards and flexible and agile to adapt to futures that are unknown. Water systems must be resilient to changing futures, or risk becoming path dependent or “locked-in” to policies, infrastructure and development pathways that are difficult, expensive, or in some cases even impossible to reverse (Barnett et al., 2015[3]) (Markolf et al., 2018[4]).

Fortunately, our ability to assess and reduce threats to our water systems is rapidly improving. Tools for improved water policies, management, infrastructure design and environmental stewardship have been developed and are increasingly adopted as best practice. Advances in computing and modelling capabilities, design analytics and decision-making under deep uncertainty enable robust forecasting of water system stresses and likely impacts, and generate water system design and operation options that enable greater resilience to future challenges (Brown et al., 2020[5]) (Hallegatte et al., 2012[6]) (Haasnoot et al., 2013[7]) (Kwakkel, 2017[8]) (see also Box 1.1).

As we look towards a changing and uncertain future, incorporating resilience in water system planning, management and investment becomes increasingly important. By taking an inclusive and adaptive approach to water-related investments underpinning the development of resilient water systems, “Strategic Investment Pathways” represent a practical and flexible means to manage our complex, changing, and vital water systems.

The OECD defines a Strategic Investment Pathway (SIP) as a way to situate a pipeline of projects within a strategic planning framework, accounting for the spatial and temporal dimension of water resources and related infrastructure investments (Dominique, 2020[9]). This paper articulates an approach to designing and navigating Strategic Investment Pathways.

Water system planning and management is typically led by governmental management bodies such as local water management authorities. Financiers both public and private, including development finance institutions and donors, play an important role both in allocating funding towards specific water system projects and in supporting the strengthening of incentives, policies and the enabling environment under which investment occurs.

With these considerations in mind, this paper takes the perspective of a water system planner or investor (financier, policy-maker). Policy-makers overseeing water system management and public investment are a principal audience, as are financial institutions (development finance institutions, donors, public investment vehicles, private investors, and philanthropic funders).

Setting the conditions conducive for participation and investment in resilient water system management is not an easy task. Because water systems are vital to everyone, touch on complex ecosystems, and often require significant engineering and infrastructure for reliable service delivery, there are many perspectives, interests and even worldviews to be considered and included in their management.

To help planners, policy-makers and investors manage the complexity and uncertainty inherent in large, coupled and changing water systems, this paper describes a process of designing and adaptively implementing Strategic Investment Pathways (SIPs) for water system resilience. The SIPs approach aims to equip the process of identifying and sequencing investment projects to deliver resilient solutions, while enabling effective and adaptive management along the investment pathway and over time. Furthermore, as complex decisions must be made even when data are scarce, SIPs are a broadly applicable analytical framework that can be operationalised in a range of country socio-economic contexts (developed, emerging, and developing economies).

1.2. What is water system resilience?

Water systems may be defined by the services they provide and their attributes, including social, ecological, and technological aspects that are further discussed below. The natural biophysical unit of management for a water system is typically the basin or watershed, defined by the area over which precipitation falls and contributes to flow at the outlet. The basin delineates a distinct area and unit, within which physical and chemical processes influence water resources, notably: climatic variables, precipitation and surface runoff, water storage, evapotranspiration, spatial heterogeneity, connectivity, and the hydrologic flow regime (Baron et al., 2002[10]) (Grantham, Matthews and Bledsoe, 2019[11]) (Poff et al., 1997[12]).

Water systems are delineated by natural boundaries (e.g., basins) but are commonly linked to other water resources and reconfigured by connecting infrastructure to meet water service demands, resulting in a system boundary that may extend beyond natural bounds (e.g., interbasin transfers). Most freshwater ecosystems have been transformed to service human demands. At the turn of the last millennium, over half of large river systems had been dammed, with reservoirs intercepting more than 40% of global river discharge (Grill et al., 2019[13]) (Vörösmarty et al., 2021[14]).

Every water system must respond to a range of stressors, including routine and operational disruptions, socio-economic factors, climate and environmental shifts, and unexpected events. As climate change intensifies and uncertainty increases, the overarching goal in water system management must shift to designing and managing for resilience – the ability of a water system to maintain its function and expected services under stress and disruption.

Defining resilience

While many definitions of resilience exist, the SIPs approach draws on the concept of resilience as defined in (Boltz et al., 2019[15]) (Folke et al., 2010[16]) (Gunderson L.H., 2002[17]) (Holling, 1996[18]) (Walker et al., 2004[19]). Here, resilience is about more than rebounding or returning to a prior normal after disturbance. It is also the ability of a system to adapt and even to transform its configuration and operation in order to function under novel conditions, to establish a "new normal".

Advances in resilience science suggest a resilient system exhibits three key capabilities: persistence, adaptability, and transformability.

- *Persistence* refers to a system's ability to maintain coherent, "normal" functions under change without altering its design and operation.
- *Adaptability* refers to a system's ability to maintain coherent functions by modifying its design and operation to accommodate change.
- *Transformability* refers to a system's ability to modify its design and operation to establish a "new normal" function when pushed beyond a tipping point that precludes maintaining its prior state.

In other words, the resilience of a water system refers to its ability, by its design and operation, to sustain its functions and expected services under stresses and shocks. A resilient water system must be able to not only resist and rebound, but also to adapt and to transform in order to thrive under change. From a management perspective, building water system resilience is an optimal control problem -- the water system is dynamic and must be actively managed over time to continue to sustain its function.

For water systems, particularly at the basin scale, resilience is grounded in the ecology, climate, and hydrology of the natural system as well as the human alterations of that system, which enable it to function in a number of different potential stable states and deliver expected services (Boltz et al., 2019[15]) (Rockström et al., 2014[2]).

As they are human-managed natural systems, however, water system resilience requires not only the judicious management of freshwater ecosystems, and infrastructure, but also investment in strengthening the social dimensions of water management, use and equity. Social resilience, which is defined by the coping, adaptive, and transformative capacities of water-dependent systems and their users, underpins the resilience of managed water systems (e.g., (Keck and Sakdapolrak, 2013[20]) (Langridge, Christian-Smith and Lohse, 2006[21]).

1.2.1. Water system services

Water system resilience can be understood and measured relative to the system's function and performance under stresses and shocks. Function and performance are measured relative to the fulfilment of service provision expectations, which in turn, may be calculated from historic demand records across sectors (domestic, agricultural, energy, environment, etc.) and forecast demand models.

Public policies commonly set baseline expectations for water system performance in terms of supply requirements, quality standards, drainage and waste management requirements, as well as environmental imperatives such as maintaining instream environmental flows and preserving key species and habitats.

Beyond these policy baselines, stakeholders at the relevant spatial scale (e.g., basin, catchment, system) set specific objectives and expectations for water system function and service provision. Water system performance and resilience is then measured relative to the fulfilment of those objectives.

1.2.2. Water system attributes

Water systems can be designed and managed for resilience through adjustments and adaptations in their configuration and operation. For instance, natural and built infrastructure may be developed to augment water storage and bolster storm-water management, while sustaining environmental flows. Land use management across a watershed may preserve riparian habitat and water system connectivity, while limiting nutrient effluents and sediments. Strengthening governance and building knowledge and awareness enables greater cooperation and coherence in water management and disaster response across and within basins.

Water resilience diagnostics consider the interplay between the state of the water system, driven by its core attributes and revealed by its performance in service delivery, and the exogenous stressors that influence its function and resilience.

Water systems are social-ecological systems, or complex, integrated systems in which humans are part of nature (Folke, 2016[22]). Given the particular influence and agency of technology in water systems they may be usefully characterised as comprising three key dimensions: social, ecological and technological (cf., (Markolf et al., 2019[23]) (Boltz et al., 2019[15]).

Social attributes describe the relationship between stakeholders within a water system, and the institutions, incentives and structures that support and influence individual and collective actions. Social norms, behaviours, and values have long guided and governed the management of water systems. Key social attributes include:

- Enabling environment - the institutions, policies, regulations, and formal actions influencing water access and use;
- Social capital - relationships among water users, networks enhancing communication and cooperation, and trust and agency among individuals and collective actors; and
- Economics - the manner and extent to which water is valued for its multiple benefits – financial, social, ecological, spiritual, etc. -- and the incentives provided for water use and conservation (cf., (Garrick et al., 2017[24]) (Valuing Water Initiative, 2020[25]).

Ecological attributes influence water availability at the basin scale and are fundamental drivers of water system resilience. These attributes are essential to the function and resilience of a managed water system and the freshwater ecosystem that underpins it.

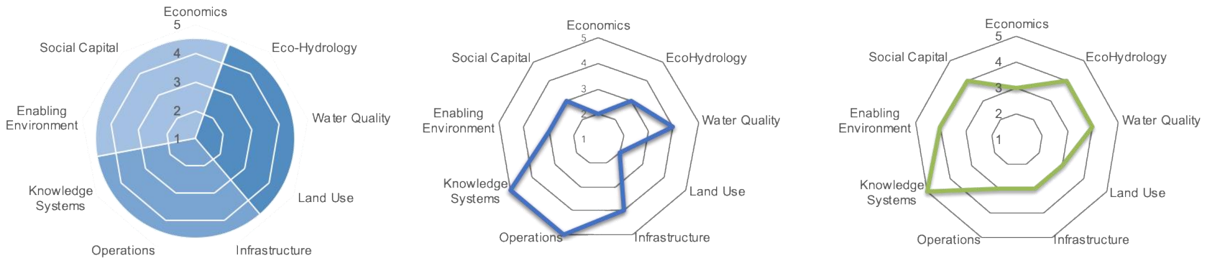
- Aquatic ecosystems provide valuable water services from water storage to storm-water regulation and wastewater depuration. Understanding key ecological conditions, such as stream flow, connectivity and water quality and impacts of the land-water nexus are key concerns.
- Recent advances in freshwater ecology suggest that three eco-hydrological dimensions are key to understanding and managing for resilience, as they underpin the capacity of freshwater ecosystems to respond to climate shifts and other stresses. These include, but are not limited to, hydrologic connectivity, temporal variability, and spatial heterogeneity (Grantham, Matthews and Bledsoe, 2019[11]).

Technological attributes include natural and built infrastructure, water system management and operation, and knowledge systems providing data and decision support. Water systems are managed and transformed to fulfil human demands for services. Technology is central to that endeavour.

- Built and natural infrastructure sustain and enhance key water system capacities, such as storage, distribution, drainage, and waste management. Water system resilience will often require not only sufficient infrastructure capacity to accommodate forecast needs, but also surplus capacity and redundancies to sustain system function under protracted stresses and major disruptions.
- Effective management practices and system operation are also fundamental. Management capacity and complexity are key resilience concerns, as they inform response and recovery time from failures such as power loss and from unexpected failures such as extreme events.
- Resilience requires robust knowledge systems suited to capturing and incorporating updated data into decision-making – historic measures, forecast levels, risks and uncertainties are key inputs. Knowledge informs adaptive management and is fundamental to building water system resilience.

These key attributes of any water system represent “levers” whose management and modification can strengthen or weaken water system resilience. Assessing the state and vulnerability of those attributes can reveal resilience needs – i.e., which water system attributes merit strengthening to enhance resilience (Figure 1.1).

Figure 1.1. Social, ecological and technological attributes driving water resilience



a. Assessment of SET attributes influencing water resilience *(1=weak, 5 = strong)* Social, ecological and technological (SET) attributes influence water system performance and resilience. Hypothetical examples of water system SET conditions are portrayed in images b and c.

b. Hypothetical water system: A system weak in social attributes will commonly also exhibit a poor ecological state, including land uses detrimental to water functions, biodiversity loss, and disrupted ecohydrological processes. Where economic incentives and the enabling environment do not effectively deter detrimental water use, it is particularly difficult to change behavior to build water resilience.

c. Hypothetical water system: In water systems with a tradition of conservation, strong knowledge systems guiding water use and a favorable enabling environment and ecological assets provide a robust foundation for system resilience. Resilience may be strengthened with economic incentives for sound land and water use, by increasing operational capabilities, and enhancing natural and built infrastructure.

Source: Authors.

1.2.3. Water system stressors

Stressors refer to the shocks, stresses, and uncertainties to which the water system must respond. Incremental stresses from temperature and precipitation changes amplified by climate change are key environmental stressors. Socio-economic pressures may also stress water systems, including rapid and changing demand growth. Stressors also include shocks or disruptions – from 'routine' power failures, communications losses, and staff shortages to extreme and unexpected events, such as rapid-onset storms, flooding, earthquakes, fire, terrorism, and pandemics.

In water resilience planning efforts, the full range of stressors and their potential impacts should be clearly identified and articulated. Historic evidence relating water system performance to prior stressors provides a useful reference. Future environmental, climatic, and social stressors are likely to occur with greater frequency and magnitude, however, with the potential for heightened vulnerability to unexpected events or extremes.

Common stressors impacting water systems include the following:

- *Operational stressors* – Routine disruptions impacting water service provision include incidents such as power outages, communications breakdowns, staff loss, and mechanical failures, which water systems are commonly designed to accommodate with system back-ups or redundancies.
- *Socio-economic stressors* – Increases in water demand driven by economic and demographic growth, increased cooling demands from energy and industry, as well as heightened volatility in water use under changing temperatures and precipitation all have important implications for water system storage, provisioning, and regulation of services.
- *Climate and environmental stressors* – Changes in climate and environmental conditions have profound implications for water systems, which have been modified and managed relative to historic levels of water availability and variability.
- *Unexpected shocks* – Uncommon and unexpected events can have devastating impacts, which readily impair water system function. Water-system resilience design should, at a minimum, seek

to understand system requirements, options, and costs and to inform resilience investment decisions under uncertainty.

1.3. Water resilience approaches and tools

The impact of climate change on water systems will be perceived in changes to both water quality and quantity, as well as the ecosystem services supplied by the system. The next section details some of the ways that climate change is shaping water systems and describes traditional approaches that water systems have used to respond to these stressors, including robustness strategies and resilience-based approaches.

1.3.1. Climate change and uncertainty

Climate change presents profound challenges to the water services that sustain our economies and provide for the security of our communities and ecosystems. Climate change impacts will be most immediately and acutely expressed through water, notably through changes in water quantity (which also influences quality), in distribution relative to human needs, and in extreme events, such as flooding and droughts (Rockström et al., 2014[2]) (Sadoff and Muller, 2009[26]).

Under climate change, water availability and variability will define how the terrestrial biosphere adapts, driving shifts in the distribution and types of ecosystems and, thereby, directly affecting human interactions with prevailing environmental conditions (Boltz et al., 2019[15]) (Falkenmark, Wang-Erlandsson and Rockström, 2019[27]) (Poff, 2018[28]) (Rockström et al., 2014[2]).

For instance, changes in the distribution of invasive species may lead to the loss of endemic species providing food or recreational value (e.g., fish) and changes in precipitation may trigger a regime shift (e.g., from forest to savannah ecosystems), with a resulting change in the ecosystem goods and services provided to local communities. Changes in aquatic ecosystem structure and composition may result in shifts in the water storage, evapotranspiration and storm-water regulation functions historically provided by those ecosystems, upon which communities and societies have depended for generations.

> *"Water's central role in the biosphere has long implied that many of the most important human development challenges are related to water and to freshwater resilience" – Falkenmark, Wang-Erlandsson and Rockström (2019)*

Water systems are configured and managed to perform desired functions, to meet human service expectations, within the constraints of climatic and hydrological conditions. As these conditions are changing, water systems also must change to accommodate future magnitudes and frequencies of stresses and shocks, from extreme rainfall and flooding events, to drought and temperature extremes to broader societal disruptions from conflicts to pandemics.

Water management policies and investments in the context of a changing climate must be both robust to existing hazards and flexible and agile to adapt to potential future risks. Our water systems must be resilient to changing futures, or risk becoming path dependent or "locked-in" to development pathways that are difficult, expensive, and may be impossible to reverse.

1.3.2. Robustness and path dependency

Water infrastructure development and adaptation to extreme weather events have historically been guided by designs for robustness—the ability of the infrastructure to tolerate anticipated extremes, minimising disruptions through a risk-based approach emphasising control, armouring, and strengthening as opposed to enhancing flexibility and adaptability (Markolf et al., 2019[23]).

The effectiveness of robustness strategies is undermined by climate variability, unpredictability, and the magnitude of disruption caused by extreme weather events that are not anticipated during design. However, the enormous financial outlay and long time periods involved in water infrastructure development - which is commonly financed by loans repaid over decades - create an enormous reluctance to change in water-related investments.

Path dependency arises from political and social commitment to development trajectories that lock in specific responses, creating inflexibility and limiting future options to adapt to unforeseen changes (OECD, 2022[29]). Path dependency manifests as resistance to change, even when business as usual appears increasingly maladaptive (Barnett et al., 2015[3]).

Path dependency is created in successive policy steps: once a policy begins to follow a particular trajectory, the costs of change become increasingly high while other options become increasingly unlikely over time - systems "lock-in" (e.g., (Pierson, 2000[30])). Despite recognition that a project is flawed, convention and political expediency commonly result in decisions to build upon and reinforce existing projects rather than starting anew.

The path dependency common in large infrastructure development practices long dominant in the water sector is unsurprising (Ingram and Fraser, 2008[31]). As historic conditions of water availability, variability, and extremes can no longer serve as a reliable guide to future development, however, path dependency in water-related investment renders our societies and economies increasingly vulnerable.

1.3.3. A resilience-based approach

Water systems and the infrastructure and operational rules that undergird them have been designed using assumptions of climate stationarity and single "best guesses" of key assumptions such as water demand (Brown et al., 2020[5]). Recognising that our vital water systems are not suited for a changing climate, in recent years, scientists and policy-makers have mounted a growing effort to develop and adopt a resilience-based approach to water system planning and investment (Falkenmark, Wang-Erlandsson and Rockström, 2019[27]) (Rockström et al., 2014[2]).

Resilience approaches in/for the water sector aim not merely to strengthen defences and enable resistance to shocks and stresses, but to enhance the flexibility and adaptability of water systems. Incorporating resilience into water-related investments strengthens a water system's robustness to forecast events and residual risks, while enabling adaptation to incremental change and recovery from increasingly extreme events.

Under changing and uncertain futures, approaches to water infrastructure development and investment must consider the ability of water systems to adapt and transform to varying internal and external conditions, so as to build not only robustness, but resilience (Chester and Allenby, 2018[32]) (Markolf et al., 2018[4]). Building resilience reduces the risks of system failure over time, thereby reducing the likelihood of disruptions to economies, losses of lives, and livelihoods. Along with investment in risk reduction measures, resilience can minimise the costs of recovery when extreme events occur (OECD, 2022[29]).

The massive financial outlays and long-time-spans characteristic of most water system investments combined with our changing and increasingly uncertain climate futures makes a resilience-based approach to water system development and investment strategic, if not imperative. Strategic investment pathways are conceived in this light.

1.4. The Strategic Investment Pathways (SIPs) Approach

The Strategic Investment Pathways (SIPs) approach builds upon existing robustness, path dependency, and resilience-based strategies to inform project planning, prioritisation and sequencing to meet long-term resilience and performance objectives. This approach considers the multiple spatial scales and interdependencies and externalities between water system components, and integrates these considerations with systems thinking and strategic investment planning.

1.4.1. What are SIPs?

In the context of water systems, SIPs refer to planned and adaptively managed sequences of investments in water infrastructure, policies, and systems that aim to strengthen long-term water system resilience. SIPs should be designed to fully reflect the value of water to beneficiaries and to favour investments that maximise benefits for communities over the long-term (Dominique, 2020[9]).

The strategic sequencing of water system investments is undertaken with the aim of gaining efficiency and synergy by aligning multiple, complementary projects across social, ecological, and technological domains. Sequencing also considers the long temporal horizon for many water projects, and maintaining the option of making further investment as uncertainties evolve over time. The “option value” of investments made in the near term requires consideration of the possibilities that they enable in the future.

SIPs are not static plans, but are dynamic investment scenarios adjusted to changing opportunities, markets, and policy conditions. By their flexible, adaptive nature, SIPs improve the potential for strengthening water system resilience. SIPs are especially relevant for water investments due to the particular characteristics and challenges of water systems – their spatial scale and numerous interdependent users, their dependence on climate and landscape processes and their pervasive externalities.

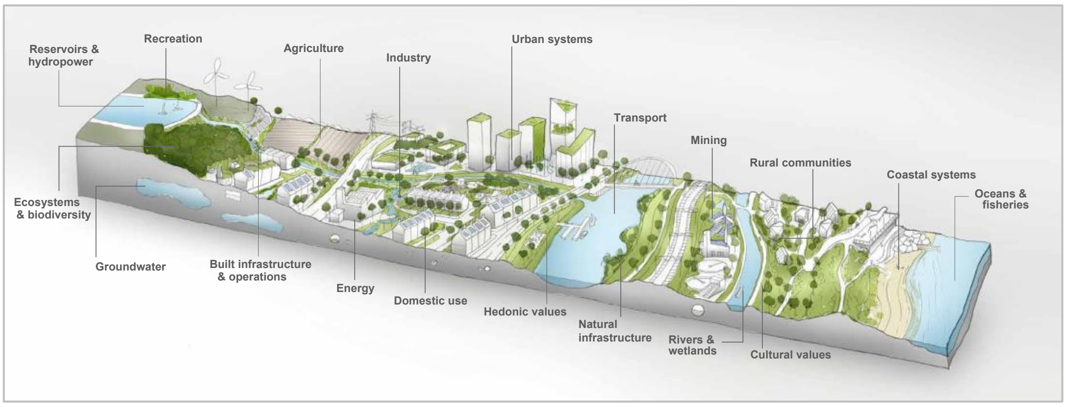
1.4.2. Spatial scale & interdependencies

Many water systems rely upon several basins and both surface and groundwater sources that are interlinked through the natural hydrological connections of streams, rivers and aquifers, as well as by built conveyance infrastructure. For instance, the water system serving Mexico City includes not only the Mexico City Aquifer but also the Lerma and Cutzamala Rivers to the west of the city (St. George Freeman et al., 2020[33]) (Tellman et al., 2018[34]).

Most basin-level water systems are sub-divided into managed systems serving distinct regions and stakeholders, all of whom are nonetheless dependent upon actions across the basin for their water security. Identifying the interdependencies across a water system, from its natural basin to sub-systems nested within and conveyances from other catchments, is important to understanding the implications of system change.

Delineation of the spatial scale and boundaries of a water system must include linked systems as well as built and natural storage, distribution, treatment and drainage infrastructure. Water systems may be delineated based upon biophysical attributes of the system, jurisdictional divisions in water management, and dependent sectors or user groups. The definition of a water system should fully incorporate physical connectivity and risks related to hydrology and infrastructure, as well as an understanding of the actors and institutions that may affect change within the system and their particular preferences (e.g., (St. George Freeman et al., 2020[33])). Defining boundaries to include key connections and interdependencies across the water system, and promote greater inclusivity in stakeholder engagement and equity efforts, is a key to building water resilience and security.

Figure 1.2. Basin and system of systems



Source: Adapted from (Arup, 2019[35]), https://www.arup.com/perspectives/publications/promotional-materials/section/design-with-water.

1.4.3. Externalities

Externalities refer to situations in which the effect of production or consumption of goods and services imposes costs or confers benefits on others. An externality is a negative or positive consequence, a cost or benefit of an action that is borne by a third party that is not reflected in the prices related to the production or consumption of those goods or services.

In a river system, upstream use may impose negative or positive externalities downstream. For example, building a dam in service of water supply objectives may also result in changes in habitat that results in a loss of aquatic biodiversity (negative externality) and in recreational activities being created (positive externality). Infrastructure development choices commonly have impacts across basins and user groups. Moreover, as the water cycle is a closed system in continual circulation, water use decisions commonly ripple across the water system. For example, groundwater abstraction and recharge may influence the state of surface water supplies.

Within and across basins, water systems draw runoff from and provide water services to a variety of linked systems and land uses – from natural water catchment areas, riparian and aquatic ecosystems, to rain fed and irrigated agriculture, to industrial and urban water use, to the water sustaining ecosystems and biodiversity. Commonly, irrigated agriculture, industry, and urban demands are prioritised in water system planning, to the detriment of natural ecosystems and biodiversity. Consequently, over the past few decades, environmental flow requirements for threatened aquatic species that aim to meet basic ecological imperatives are increasingly being adopted in national to local water policies and regulatory actions (Poff, Tharme and Arthington, 2017[1]). Such measures aim to recognise and include ecological values in water system development decisions, integrating these otherwise neglected externalities in the evaluation of investment options and economic returns.

The inherent connectivity and interdependencies among water system elements (e.g., ecosystems and built infrastructure) and among water-dependent sectors (e.g., agriculture and energy) present a strong likelihood that externalities will result from management actions and investments. Identifying and assessing externalities related to water use decisions and investments, including trade-offs between sectors, is an important component of the water system evaluation process (Geressu et al., 2020[36]) (Hokstad, Utne and Vatn, 2012[37]).

1.4.4. Systems approach

A system is a group of distinct elements or components interacting to form and function as a complex whole. Water systems are coupled human-natural systems that include not only natural geophysical units guiding water storage flow and discharge but also built infrastructure and operating rules that influence their function.

A water system is the whole made from the connected hydrological, infrastructure, ecological, and human processes that involve water and freshwater ecosystems. It includes bio-geophysical processes, including the hydrologic cycle and ecosystem functioning, as well as human processes, including the construction, operation, and removal of infrastructure, and other human decisions and water uses (Brown et al., 2015[38]).

The interconnectedness of a water system to the broader social-ecological ecosystem in which it nests requires a systems approach to water management and investment. A systems approach is a means to understand, and benefit from, synergy and connection between the elements of the system through analytical methods that may be quantitative or qualitative. In systems analysis, the hallmark tools are simulation and optimisation modelling. Taking a systems approach to designing and navigating SIPs enables strategic sequencing and bundling of investments, as well as flexibility and adaptability in navigating development trajectories for long-term resilience. The systems approach to water resource management is an established standard of practice, one amenable to understanding and navigating change.

Water Resources Systems Analysis refers to the study of water resources systems using mathematical representations of the processes and interactions of a water system and its interdependent components to improve understanding or assist in decision-making (Loucks and van Beek, 2017[39]) (Loucks, Stedinger and Haith, 1981[40]). Systems analysis enables an evaluation of the likely results of alternative decisions related to water system configuration, management and investment across the water system and its numerous dependent sectors (Brown et al., 2015[38]). For instance, Water Resources Systems Analysis may focus on water utilised for domestic needs (Rosenberg et al., 2007[41]), water as an agricultural or industrial input (Rosegrant, Cai and Cline, 2002[42]), as a sustainer of ecosystems and species (Gao et al., 2009[42]), and as a hazard in extreme events such as flooding and drought.

1.4.5. Strategic Investment Planning with Water Resources Systems Analysis

Analytics for strategic water investment planning has been an active area of research and methodological development for over 70 years. In the United States, following decades of water infrastructure investment, studies revealed that too often, government-funded water infrastructure development projects failed to deliver expected benefits. Retrospective analysis of investments found that the projects delivered much lower economic rates of return than estimated during project design, and resulted in unanticipated environment or social costs (Reuss, 2003[43]).

This reckoning led to the development of a new project assessment framework, summarised in Design of Water Resource Systems (Maas et al., 1962[44]). This approach introduced the concept of multi-criteria analysis for water investment, explicitly incorporating environmental and social with prevailing economic objectives for water system service provision. This work also pioneered the use of optimisation models for multi-project river basin planning, methods that were subsequently applied to river basins throughout the U.S. Guiding strategic investment decisions with an optimisation analysis revealing system design options that achieve economic, environmental and social goals has been long-established.

Methods building upon this history but suited to current, intertwined water and climate challenges are urgently needed. Fortunately, methodological advances in water system design under uncertainty, coupled with the emergence of advanced computer analytics and tools have reduced many of the practical barriers to analysing, understanding and managing for water system resilience.

The effects of climate change and climate uncertainty has been a recent focus of methodological development in water planning and decision models. Because of the climate influence and long-lived nature of water projects, methods for addressing and evaluating climate uncertainty in infrastructure design have been pioneered through water applications. A number of methods introduced in Box 1.1 have been applied to or developed for water investments and represent leading methods for planning adaptations to climate change. Each of these tools are compatible with the SIPs approach and evaluation strategies, though none encompass the full SIPs process, from stakeholder engagement and goal-setting to analytics, SIP design, and SIP navigation, presented here.

The synergies and benefits possible through strategic planning are significant in water investments and for this reason, interest in river basin planning continues to advance, as do methods. Although the results of model-based analysis are not always the most influential factor in the selection and execution of water investments, they are usually a contribution to the decision-making process. Single financial performance metrics and political considerations are often more influential. Recent large-scale examples of model-based analyses include investments options for the Nile River (Jeuland and Whittington, 2014[45]), the Mekong (Wild et al., 2018[46]), and the Indus (Yu et al., 2013[47]). These studies illustrate the potential for synergies across a cohort of investments and methods for incorporating multiple futures and evaluation across multiple objectives for water system investments at river basin scale.

Strategic planning that utilises a systems perspective can also open up the potential to exploit interdependencies among related investments, for example, where certain investments can unlock opportunities for others. For instance, the implicit benefits to water utilities or corporations deriving from avoided costs resulting from improved watershed management may be leveraged to stimulate investment in watershed conservation and sustainable land use. Such an approach underpinned the articulation of strategic investment pathways for the Zambezi Basin (Dominique, 2020[9]).

By utilising a long-term perspective that evaluates and adjusts investments based on changing future conditions, the SIPs approach offers important value to water system planners and investors relative to traditional methods. Traditionally, water investment projects are identified to address immediate demands and service gaps. Moreover, candidate investments are typically evaluated in terms of their performance relative to the historical climate and hydrological record and relative to static assumptions for other uncertain factors such as demand.

Consideration of how the investments may interact with changing future conditions, needs and potential investments is not part of the calculus; rather the analysis focuses solely on the next project. Given the irreducible uncertainty of the future that pervades water-related investment and the potential value of sequencing and integrating investments along a strategic pathway, our conventional investment approaches are likely to underperform in estimating system options, performance and returns relative to the SIPs approach.

Strategic Environmental Assessment (SEA) and Environmental Impact Assessment (EIA) approaches, are complementary but distinct to SIPs. SEA includes a range of “analytical and participatory approaches that aim to integrate environmental considerations into policies, plans, and programmes and evaluate the inter linkages with economic and social considerations” (OECD, n.d.[49]). SEAs and EIAs produce important information and parameters to guide optimal choices and investment decisions revealed through the SIPs analytical approach (Chapter 2 of this Working Paper).

Box 1.1. Water resilience evaluation approaches and tools

Water Planning Engagement Approaches

River Basin Report Card compares ecological, social, and economic information against predefined goals or objectives, synthesising large, and often complex, information into simple scores to provide performance-driven numeric grades that reflect the status of a river basin (Costanzo et al., 2017[48]).

Water Governance Indicator Framework considers water governance indicators and direct interview data to inform multi-stakeholder water system assessment and planning for improved water governance. It is applicable across governance scales and water services (OECD, 2018[49]).

Water Supply and Sanitation Utilities Resilience Roadmap supports utilities to incorporate resilience in their choices through a three-step process of – 'knowing the system, identifying vulnerabilities, choosing actions'. The roadmap is adapted from the Decision Tree Framework (described below) to address the needs of WSS utilities (Bonzanigo et al., 2018[50]).

City Water Resilience Approach is a five-step process and toolkit guiding stakeholder engagement, governance diagnosis, city water system assessment, action planning, and adaptive management of urban water systems, nested within the river and groundwater basins that serve them (Arup, 2019[35]).

Design Analytics & Decision Support Tools

The Decision Tree Framework incorporates climate change and uncertainty into decision-making, through discovery of climate changes likely to affect the water system and their probabilities of occurrence, in order to identify system design options robust to plausible futures (Hallegatte et al., 2012[6]) (Ray and Brown, 2015[51]).

Eco-Engineering Decision Scaling quantitatively explores trade-offs in stakeholder-defined engineering and ecological performance metrics across a range of possible management actions under unknown future hydrological and climate states (Poff et al., 2016[52]).

Robust Decision Making is a decision analysis methodology that focuses on identifying and addressing the failure scenarios for different decision alternatives. It uses sensitivity analysis and "scenario discovery" for this purpose. It is specifically designed to address situations of deep uncertainty, where decision makers do not have or cannot agree on a single set of probability distributions to characterise uncertain variables (Kwakkel, 2017[8]).

Dynamic Adaptive Pathways and Policies couples 'adaptive policy making' - a planning process with different types of actions and signposts to monitor adaptation needs - with 'adaptation pathways', an approach to exploring adaptive actions relative to scenarios of change (Haasnoot et al., 2013[7]).

Hydro-economic Modelling Tools

Hydro-economic models are computational software programs that are designed for modelling water resource systems. They link geophysical processes to socio-economic processes and constraints, such as infrastructure operations, water withdrawals and return flows, and water allocation policies.

Examples include: *ECHO* (Wada et al., 2015[53]) (Kahil et al., 2016[54]), *WEAP* (Raskina et al., 2009[55]) (Yates et al., 2009[56]), and *RiverWare* (Zagona et al., 2001[57]). See also (Harou et al., 2009[58]) for a conceptual review of approaches.

1.5. What principles should guide strategic investment pathways?

At a conceptual level, there are five key principles that should guide SIPs: Stakeholder engagement, Understanding enabling environments, Going beyond bankable projects, Understanding and managing uncertainty, and Adaptive management.

1.5.1. Ensuring stakeholder engagement

Building water system resilience derives from an interplay among stakeholders, communities, and decision makers across the water system at basin or multi-basin scale. Developing a shared understanding of the entire system, including resilience objectives, options, and trade-offs among all stakeholders is fundamental to effective, collective action to build resilience and water security.

A participatory planning process aims for full inclusion and representation of different stakeholder and sectoral values for water resources and, accordingly, different goals for water system management. With large variations in social and economic agency, effective inclusion that reflects this diversity can be difficult to achieve. For instance, rural communities may be disenfranchised, both economically and physically, through a lack of access to quality infrastructure, social, natural, and political resources. Communities of colour and those with religious, cultural, or language differences are also commonly marginalised. Gender equity is also an important concern given traditional marginalisation of women and gender-nonconforming persons.

Policymakers and planners must strive for broad inclusion, diversity and equity in water system planning and investment decisions. The extensive literature on participatory planning (e.g., (Gilman, 2016[59]) (von Korff et al., 2012[60])) suggests the following general principles:

- Include vulnerable and traditionally excluded groups.
- Address gender equity.
- Identify and foster the common ground, where possible, at the outset.
- Support the disenfranchised voices where and when needed.
- Conduct the process over time, with patience, and in several meetings.
- Understand and accommodate limitations to participation.
- Cover all issues of interest, understanding disparate values.
- Set realistic goals and include a degree of flexibility in goals and metrics.
- Identify and include systems of mutual accountability.

System dynamics tools, particularly those that utilise visuals like stock and flow icons, can help stakeholders engage with and understand water systems.

1.5.2. Understanding enabling environments

In the context of water system investment, an “enabling environment” comprises the institutions, policies and economic conditions (fiscal and monetary) that a nation or jurisdiction (e.g., state, municipality) establishes to enhance investment performance and security. This includes sector-specific policies, regulations, and institutional arrangements as well as those relating to the financial sector and capital markets (OECD, 2022[29]). The enabling environment considerably influences investment risk, return and viability. For a socially optimal outcome, the enabling environment should provide for the most efficient use of investments to achieve goals of economic growth, social welfare, and nature conservation.

Water-related infrastructure investments should be made in strategic combination with investments in strengthening the enabling environment. Complementary investments in such “soft measures” provide the conditions under which larger capital-intensive investments may best perform, enhancing their likelihood of delivering reliable services over their operational lifetimes (Dominique, 2020[9]).

Robust public policy and institutional frameworks are essential to mitigating the risks of water sector investment and, indeed, for the water sector to function effectively overall (OECD, 2019[61]). The common pool and rival nature of water resources, the public goods aims of water policies, and challenges of internalising the full value of water in investment decisions require that policies mitigate potential market failures.

Understanding how a given enabling environment affects potential investments informs the design and implementation of strategic investment pathways. For instance, fiscal policies may provide incentives for investment in infrastructure or in water use technologies that encourage and leverage private finance. Sound policies and institutional arrangements reduce the risk of investment in water systems for public and private actors alike; their absence has the inverse effect of hindering investment. The effect of the enabling environment may be simulated in the systems analysis tools used for investment evaluation or in some cases be used informally to assess expected investment performance.

Even conditions not “internal” to the water system but exogenous can enable or constrain investment, particularly political instability, conditions of governance, fiscal policies and incentives and creditworthiness. Issues such as corruption, bureaucracy, or poor educational infrastructure may increase risk or the costs of doing business and negatively affect investment incentives.

The enabling environment in many nations may be sufficiently robust to allow a planner to delve straight into designing and coordinating specific projects. In places where the enabling environment is not suitable, however, the most strategic initial investments may be those creating the very enabling conditions in which water system investment can succeed. SIPs include these “soft” investments to strengthen the enabling environment, which must also adapt and transform to changing conditions, risks, and values.

Enabling environments change over time, which may then affect the ranking and sequencing of investments needed for resilient water systems. The long temporal horizons of water system investment are somewhat unique. SIPs are designed to enable adaptation to changes in the enabling environment over time, through decision rules and systematic reviews, to determine optimal investment choices for water resilience.

1.5.3. Going beyond bankable projects

A key concept in the design and implementation of SIPs is one of evolving investment horizons and objectives beyond considering discounted financial returns and “bankable” projects. A bankable project is one where risks are allocated in a sufficiently optimal way to allow for it to be financed on market-based terms (Money, forthcoming).

In the case of water systems many of the benefits are social, cultural or environmental in nature and even non-market valuation methods may fail to generate the financial incentives to motivate investments. Add this to the complex nature of water infrastructure with high initial investments and long pay-off periods, and bankability becomes restricted to a few types of projects or components of the system.

Bankable projects are often evaluated at the early stage of the water system investment process and commonly focus on system efficiency gains. Notably, water infrastructure projects commonly suffer from poor project pre-feasibility and design and weak pipeline identification, limiting even bankable project investment (Cardascia, 2019[62]).

While financiers have traditionally prioritised investment in the pipeline of bankable projects offering acceptable financial risk and return, governments and development funders should consider more comprehensive SIPs that are not limited to financial considerations but also contribute to equity and/or ecosystem outcomes while achieving water security and resilience over the long term. A long-term strategic investment approach that moves beyond financial considerations can ensure that water system assets deliver anticipated benefits over their operational lifetime and help to secure a stable flow of investment opportunities and returns for investors (OECD, 2022[29]).

1.5.4. Understanding and managing uncertainty

As with any system, there is considerable uncertainty in any water system, found in both the physical and the socio-economic components of the system. Uncertainty complicates decision-making but is intrinsic to complex systems, particularly under changing environmental and societal conditions.

Managing a water system means aligning system components and operations to deliver services under both constant and changing conditions, including stresses and shocks. The goal is to build a robust system that can weather the spectrum of risks from seasonal variability in rainfall to extreme events. Whereas previously the historical record served as the basis to estimate the probability of such risks and, thereby, to reduce uncertainty in decision-making; there is now increasing uncertainty relative to the magnitude and impacts of climate and planetary change. Stresses and shocks impacting water systems are becoming less predictable in both frequency and strength. Deep uncertainty in the nature, frequency, and magnitude of water system stressors creates unknowns that cannot now be easily described probabilistically.

Deep uncertainty is the condition under which there are limits to predictability or a lack of understanding and agreement on how a system works and thus on the likelihood of possible future trajectories. This is a devilish planning challenge because the most common approaches to dealing with the uncertainty of the future depend on well-characterised uncertainty. Such approaches include the maximum likelihood method (plan for the most likely future) and the maximum expected value method (select the plan that has the highest mean net benefit). When uncertainty is poorly understood and characterised, using these approaches can expose plans to much more risk than is realised or intended.

The Decision Making Under Deep Uncertainty literature brings these problems to light and suggests solutions. The essence of these methods is the use of sensitivity analysis to directly identify and describe investment risks, without regard to their probability. The vulnerability, and inversely, the robustness of investments are used as additional metrics for evaluation, alongside traditional measures, such as Net Present Value. (Marchau et al., 2019[63]) provides a recent review of methods. Decision Making Under Deep Uncertainty approaches are consistent with the concept of resilience, which incorporates the aspect of managing variability and changing futures as they evolve. In these ways, these methods provide a means of characterising and managing the implications of uncertainty, in lieu of the ability to reduce it.

1.5.5. Adaptive management - incorporating flexibility

Over time, as conditions change, assumptions made during the planning process will be revealed to be accurate or will otherwise lead to a re-evaluation of system needs and investment choices. This means that the value of a given investment choice will change over time and, therefore, optimal decisions related to water system management and to the sequencing of future investments will change, requiring dynamic, adaptive management of both past and potential new projects.

Water-related investments options include both flexible and inflexible projects. Large financial outlays for built infrastructure projects lasting decades are generally inflexible, however, the portfolio and pipeline of investments within the lifespan of infrastructure investments may be flexibly deployed, as enabling conditions, risks and return profiles evolve. By identifying the relative flexibility of investment options, it is possible to rank projects and minimise the uncertainty that delaying or advancing investments can generate. If new information is expected to occur at a future time, investment uncertainty declines.

By ranking and selecting the first investment and then re-ranking the remaining investment options, the planner can maximise the benefits of new information. By developing an understanding of which variables most affect investment calculations and which are most likely to change over time, one may increase attention to those specific components and capture the benefits of flexible project sequencing.

The planner must therefore seek to continually inform and evaluate success or failure within the system and the impact and process of the investment portfolio. Adaptive policies and investment strategies aim to address this issue by flexibly adapting the water system as new information becomes available (Pahl-Wostl et al., 2013[64]). Several approaches have demonstrated the value of using indicators of change to inform water resource planning and operation, including applications to water systems in Kenya (Fletcher, Lickley and Strzepek, 2019[65]), the UK (Murgatroyd and Hall, 2021[66]), and the US (Herman and Giuliani, 2018[67]) (Trindade, Reed and Characklis, 2019[68]).

Developing ‘signposts’ or indicators of the need for system adaptation is also a sound practice that complements decision analysis within SIPs. The Dynamic Adaptive Policy Pathways approach (Haasnoot et al., 2013[7]) describes an analytical approach to exploring and sequencing actions that can be based on uncertain future events. While uncertainty will continue over time, the active and direct management of it will increase the likelihood of project and investment success.

2

Strategic Investment Pathways: An Analytical Approach

2.1. Introduction

Water-related infrastructure investments are costly, long-lived, and typically involve external costs and benefits. They are often highly dependent on the vagaries of the hydrological cycle and subject to the risks and uncertainties associated with climate change. Typical water investments include water supply, sanitation and wastewater treatment, storm water drainage, hydropower, irrigation and management of water-related risks (such as floods and droughts). The challenge for the water investment planner is to make the best use of scarce financial resources to deliver the desired water related services in consideration of these complicating factors.

It has long been the desire of planning experts to identify and implement an "optimal" set of investments rather than selecting a single optimal investment (cf., (Burges, 1980[69]) (Maas et al., 1962[44]) (Major and Lenton, 1979[70]) (Thomas, 1965[71])). The logic is that considering multiple water projects simultaneously creates the opportunities for improved overall investment performance because of synergies between projects. In practice, planning processes are rarely sufficiently rational, structured, and continuous to allow for the adaptive management of an "optimal" plan over many years. As a result, the concept of optimal river basin planning largely receded until recent surfacing in the EU Water Directives for River Basin Management Plans.

The alternative approach, currently dominant in water investment planning, is a single project method, that optimises for a single economic performance objective, evaluated under a singular assumption of future conditions. The current gaps are identified, the candidate investments that address the gaps are evaluated, and the optimal investment is selected based on the highest net economic returns, cost-benefit, or bankability. Candidate investment options are evaluated over a single, "most likely" or best guess future for ease of analysis. Importantly, long-lived and capital-intensive water investments are especially sensitive to faulty assumptions related to changing future conditions, water system interdependencies and externalities.

The common practice of evaluating investments over a single future and in terms of a single metric is likely to lead to "fragile" investments, or investments that underperform when assumptions do not hold. Without a strategic approach grounded in robust analytics, investments may suffer increased operational costs, premature obsolescence, and/or the need for costly retrofitting due to impacts not anticipated. Furthermore, the social and environmental costs of the investments may outweigh whatever service benefits are provided. Finally, current practices that focus on single futures and projects may result in unrealised synergies and foregone benefits that can be realised using a SIP approach.

The design of SIPs encompasses an evaluation of multiple investments considered jointly over multiple futures across the full spectrum of future uncertainties and relative to the multiple objectives articulated by the diverse community of water stakeholders. SIPs design seeks to define the scope of analysis in terms of broader system boundaries (basin or multi-basin) with purposeful consideration of how key dynamic processes and feedbacks within the system are represented. In this way, the likely functioning of the system relative to a variety of stressors and impact magnitudes can be reflected in the analysis. Finally, the analytic framework is based on methods drawn from the field of Decision Making Under Deep Uncertainty, which uses formal analysis of uncertainty and performance evaluation over numerous scenarios to design investments that are robust and are resilient to the surprises of the future. This systematic SIPs approach enables more strategic investment planning that accounts for water system complexities and potential investment synergies across a wide range of future possibilities.

The SIPs process is a pragmatic, systems approach to investment planning that is informed by the potential benefits of optimised investment portfolios but remains compatible with the reality of political, discontinuous planning processes that are true almost everywhere. SIPs build upon a resilience design systems analysis described analytically in (Brown et al., 2020[5]), based on the systems analysis tools of simulation and optimisation modelling and trade-off analysis. Here this “Resilience by Design" approach is expanded upon, and translated into an implementable process – a series of analytical steps for SIPs design and navigation.

In this process, strategic investment pathways are created incrementally, using a “feedforward” approach. This approach is adopted because it is consistent with conventional planning processes used in water investment planning. That is, planning processes typically select the next immediate investment, rather than selecting and implementing an entire investment pathway. Nonetheless, there is benefit in generating a pipeline of vetted investment options and in building an understanding of how they may perform under future conditions and work towards a more resilient system.

When selecting investments, there is both need and benefit to evaluating the implications of an immediate choice relative to the future choices -- that is: How does investing in this project in the present affect future investments? And how may future investments affect the currently considered project? The methodology described below addresses these questions in the formation of strategic investment pathways.

The SIPs analytical framework follows five general steps (Figure 2.1), equipping users to:

- **set the stage for analysis** by understanding the water system and set goals for its management;
- **evaluate options and stress test** their ability to achieve water system resilience;
- **design SIPs** that are optimal, adaptive pathways for strategic investment to achieve those goals;
- **mobilise investment** across the value chain, including through blended finance of public, private, and philanthropic funding;
- **navigate resilient SIPs** through monitoring, forecasting, and adaptive management relative to system changes and key thresholds.

Figure 2.1. The Strategic Investment Pathway process in five steps

Source: Authors.

2.2. Step 1. Setting the Stage for Analysis

2.2.1. Define the system of interest

The initial step for water investment planning is to define the water system of interest. Defining the system of interest guides the articulation of goals for the water system and enables the identification of key system drivers, interdependencies, and externalities. Given that all water-dependent sectors and users are influenced by development and management of the water system, addressing only a subset of these interests in planning efforts can result in system-wide vulnerabilities.

As discussed in Chapter 1, water systems typically comprise ecological components such as watersheds and aquifers that are the sources of water, technological aspects, such as built infrastructure, and social dimensions such as institutions and human capital. In water investment planning, there may be a tendency to focus on the technological aspects, the built components of a water system, at the expense of ecological and social components. This is a mistake, as all components and their relationships influence the functioning and performance of the water system as a whole. Careful study of the system and discussion with expert stakeholders representing multiple viewpoints of the system is the best way to see the whole.

By defining the water system of interest, the analyst sets the stage for what is included in the analysis. Water system components that affect or are affected by the investment are the starting point. The dependent or beneficiary communities and ecosystems are then identified and the water services expected for these beneficiaries are articulated in the form of objectives or performance metrics, measuring services provided or other outputs (Box 2.1).

Defining the system also includes identifying factors not included in the analysis or addressed with assumptions. Factors influencing water systems that are beyond the control of the investment are commonly set as assumptions. For example, rainfall is often a key factor in the design of an investment but is not directly influenced by a typical water investment. Instead, the attributes of rainfall are assumed, and multiple assumptions, in the form of scenarios, may be used to address inherent uncertainties.

2.2.2. Set spatial boundaries

In defining the water system, the goal is to account for both the dynamic internal components of the system, which are the components that comprise the system’s response to investment, as well as the external stressors that may influence the success of the investment. By setting the system boundary, the line is drawn between the internal components, which are represented dynamically in a model, and the external stressors, which are addressed with assumptions and scenarios.

Spatial boundaries follow the definition of the system boundary and as a result may not be geographically continuous. Water systems are transformed freshwater ecosystems, comprising both natural components and built infrastructure. The spatial boundaries for comprehensive water system planning encompass all connected basins, as well as built and natural storage, distribution, treatment and drainage infrastructure.

Subunits of the comprehensive water system may be considered discretely (e.g., tributary, reservoir, irrigation network, urban water system), but as these subunits are nested within the broader system, their fundamental dependency must be considered in analysis and investment planning.

In some water systems, important components are geographically separated, with management implications in both source and service areas. For example, many large cities draw water from distant river basins, thus water security and resilience are driven by actions in both rural source areas and cities, and across the integrated water system.

Setting spatial boundaries also enables the identification of key dependent communities and stakeholders. Understanding the interests of and impacts to all stakeholders is fundamental to sound decision-making for water system stewardship.

2.2.3. Engage stakeholders

Water investments commonly affect a multitude of varied communities, both human and natural. All water-dependent communities have an interest in the plans that are made and the right to equitable access and inclusion in decision processes. Successful water planning efforts engage dependent stakeholders to benefit from their knowledge and to build their partnership in pursuing shared water security goals. Sound, equitable stakeholder engagement improves the chances for a successful project but reduce the likelihood of unintended consequences and unwanted surprises, and increase the likelihood of public support for the project.

Participatory planning and decision-making processes, such as those referenced in Box 1.1, enable the identification and negotiation of water system interests and demands from a wide range of stakeholders. Inclusive and equitable planning processes are essential to effective actions increasing water system resilience and water security. Ensuring that all interests and impacts are included in the water system analytics and planning and understanding and addressing externalities that may lead to suboptimal social and economic outcomes are key not only to correcting inequities, but to building social resilience and strengthening the general resilience of the social-ecological water system.

2.2.4. Set goals for water system management

Having delineated the spatial scale of analysis and the systems of interest, decision-makers must set goals for water system management and service provision. Water systems provide a myriad of valued benefits from the provision of drinking water to the preservation of recreational and cultural services (Garrick et al., 2017[24]) (Kenter, 2016[72]).

Common water system management goals include the reliable provision of water supply and treatment, storm water management and wastewater regulation. Increasingly, broader social and environmental aims are also recognised in planning and policy-making. Box 2.1 suggests a common typology of water system services relevant to goal-setting efforts.

Achieving such objectives at minimum cost is another goal, one that underpins economic assumptions of efficiency in the supply of desired services. Cost considerations must not only address operational and infrastructure expenses, but also the social and environmental costs pervasive in water investments.

While goals for water system management may seem unchanging; in fact, societal values and expectations for water systems evolve considerably over time. One example is the changing expectations for Great Lakes management, from an initial focus on navigation, to an emphasis on hydropower to finally prioritising recreation and ecosystem preservation over the course of the last century (Clites and Quinn, 2003[73]). By monitoring stakeholder satisfaction with water system performance, changing preferences and goals for the water system can be identified and accounted for in adjustments to the SIPs trajectory.

Box 2.1. Water system services

- Bulk water supply: The production of water for various end-users, including drinking water supply. Bulk water supply may be produced from the abstraction of surface or groundwater or through non-conventional sources, such as desalination or wastewater reuse.
- Water supply services: The production and distribution of high quality water at standards required for consumption, such as drinking.
- Wastewater treatment: The safe collection and treatment of sewage and wastewater.
- Irrigation: The distribution and application of water to land in support of agricultural production.
- Water resources management: Conservation and rehabilitation of inland surface waters, ground water and coastal waters; prevention of water contamination.
- Storm water management: Providing drainage and discharge from storm water and flooding.
- Flood protection: Interventions intended to mitigate the risk of and to manage flooding caused by coastal storms and precipitation events.
- Fisheries and biodiversity conservation: Meeting the environmental flow and habitat conservation requirements for aquatic species and managed fisheries.
- Transport: Supporting shipping and distribution, public and private transportation.
- Recreational services: Providing for human recreational uses: boating, swimming, fishing, etc.
- Cultural services: Maintaining natural and managed water landscapes, sacred sites and species, aesthetic and spiritual values.

Source: Adapted from (Dominique and Bartz-Zuccala, 2018[74]).

2.2.5. Define metrics of water system performance

Setting goals for the water system is, in effect, the translation of stakeholder values for water services to specific expectations for their provision. Metrics take that process a step further to quantification. Performance metrics are quantitative measures corresponding to goals and service expectations of the water system, and may be expressed in financial, hydrological, or other measures (e.g., population levels for a particular species).

Performance metrics serve as the basis by which project development and management options are identified, monitored and adaptively managed. Metrics of water system service provision also serve as the basis for understanding and measuring water system resilience, defined as its ability to sustain the provision of desired services at expected levels under stresses and shocks.

Typical water utility metrics include volume and rate of water supply, water quality measures, number of people served, and the economic rate of return for water use in different sectors. Metrics commonly also address risk reduction and management objectives, such as those related to reduced exposure to flood and droughts. Additional metrics that may more comprehensively capture environmental and social benefits are warranted to better reflect desired societal outcomes. For instance, metrics related to social equity, environmental flows and ecosystem conservation are important in planning for water system performance and resilience.

2.2.6. Address conflicting goals and trade-offs

Changes in water system performance, service provision, as well as the multiple values and well-being resulting from different management alternatives may be compared according to metrics specified for each goal. Translating the full diversity of water values into a single metric cannot effectively convey the impact of different choices. Understanding trade-offs in their own relevant terms (e.g., economic rate of return, distributional equity, species conserved) more transparently and meaningfully reflects the impact of different choices (e.g., (Hellegers and Davidson, 2021[75]).

Through multi-objective analysis, investments can be identified that offer a means of meeting seemingly opposed goals. Trade-offs between objectives can revealed in the analysis, informing stakeholder negotiations and investment choices. As meeting all expectations is generally unattainable, stakeholders must understand, negotiate and agree to system options representing a balance of economic, social, and environmental outcomes now and in the future.

2.2.7. Gather data and develop models

A large and ever-growing wealth of modelling tools are used in water investment planning (Box 1.1). In general categories, these tools address stakeholder engagement, decision analytics and evaluation, and simulation or optimisation in water resource system models. The latter are essential for SIPs analyses. Water resource system models are a mathematical representation of the water system that are executed on digital computers, and typically include water sources (wells, rivers), water infrastructure (reservoirs, levees, distribution networks, treatment plants), water service beneficiaries (populations, water-dependent ecological communities) and often economic valuation of outcomes.

Water resource system models, also referred to as human-hydrologic or hydro-economic models are designed specifically for modelling water systems. Such models often include simplified hydrologic modelling tools and directly model infrastructure operations, water allocation policies, and water demand and use. They include network models that track the flow of water between points in river basins, through canal systems and account for extractions and return flows.

Notably, water systems, in reality, are not bound by a single set of governing principles (e.g., Bernoulli fluid dynamics) while models typically are bound. Rarely does a single model include all of these features, and instead a number of models are used.

Water Resources Systems Analysis is the application of simulation modelling, optimisation and typically trade-off analysis in cases of multiple objectives. These tools are quite general and can be implemented generally, but specific water resources modelling tools, also often called Hydro-economic models, have been developed. There are computational software programs that are designed for modelling water resource systems. Unlike typical hydrologic models, which are constrained by a single set of governing equations (e.g., geophysical principles of hydrodynamics and thermodynamics), hydro-economic models link the geophysical processes to socio-economic processes and constraints, such as human demand for water, infrastructure operations, water withdrawals and return flows, and water allocation policies.

Examples include: *WEAP* (Raskina et al., 2009[55]) (Yates et al., 2009[56]), and *RiverWare* (Zagona et al., 2001[57]). See also (Harou et al., 2009[58]) for a conceptual review of approaches. While not specific to water systems, system dynamics models are also commonly used, e.g., Stella (Coyle, 1977[76]).

Two important considerations in model selection for use in SIPs development are computational requirements and predictive uncertainty:

- **Computational requirements** refer to the amount of computing power that is needed to execute the model or models. This is an important consideration because the number of scenarios that need to be simulated is typically very large. Models that require long run times (the amount of time required to complete a single scenario) are problematic for scenario analysis.

- **Predictive uncertainty** refers to the range of possible differences between the model result and what will happen in reality. It is important to characterise the range of uncertainty in models, in order to appropriately interpret the differences in the estimated benefits of different projects. If a model has high predictive uncertainty, differences in projects' performance that are small relative to the range of uncertainty are unlikely to be meaningful. Small differences may be ignored and the projects considered essentially equal on that metric. This avoids the mistake of "false precision."

In terms of data requirements, the design of SIPs does not require any additional data beyond that required for any major water investment design and decision process. Current best practice methods for diligence on a water investment requires the estimation of costs, benefits and potential third party effects (externalities). These estimations require historical hydrologic and climate data, in addition to the engineering data necessary for particular aspects of a design (for example, water quality data, population data, geotechnical data for foundations, water demand data). Hydrologic and climate data are often available from open access global datasets. These data are greatly improved by verification and correction with locally available data. Typically, the most difficult data to attain is data needed for a specific engineering design that is related to a specific location or water system component.

In addition to the typical data needed for any major water investment, the SIPs approach may benefit from projecting future scenarios for key uncertain variables, including climate variables. The use of climate change projections from General Circulation Models (or Global Climate Models) is not strictly necessary, although they can provide useful context for creating climate scenarios. Open access data sources that provide global climate change projections can meet this need, such as the World Bank Climate Change Knowledge Portal[1]. Approaches to developing climate and non-climate scenarios are further described in The Decision Tree Framework (Ray and Brown, 2015[51]).

The technical capacity requirements for implementing this approach are consistent with the requirements needed to conduct required analyses for major water investments under standard best practice methods. This framework is simply a use of those methods in a new manner. This guidance documents provides the instructions for doing so.

2.3. Step 2. Option Evaluation and Stress Testing

This section describes the process of evaluating alternative investment. The particular innovation of the SIPs option evaluation approach is that it accounts for deep uncertainty, including unknowns related to climate and societal change, as well as the effect of sequencing investments for each option. Options are evaluated in terms of their individual performance, using stress testing to assess their performance comprehensively, over a wide range of possible futures.

2.3.1. Option evaluation

Option evaluation consists of assessing each water system design option in terms of its ability to contribute to meeting the goals established in Step 1. Model representations of each option are used to evaluate performance relative to stakeholder expectations and resilience goals. Performance is compared to a baseline or control scenario in order to assess the advantage of each option relative to no action, and in comparison to each of the other options. Multiple objectives are considered in trade-off analysis, informing water investment decisions. Current methods are reviewed in (Loucks and van Beek, 2017[39]).

In model representations of the water system, the assumption of stationarity - that the water system remains in a steady-state in key aspects such as precipitation, temperature, and hydrology, retaining a constant variance over time. For long-lived water investments, however; future conditions over which the performance of each option is evaluated are uncertain and nonstationary. In addition to the key aspects above, other influential variables that are nonstationary and increasingly uncertain include demand and willingness to pay for water service provision. Given future change and uncertainty, the use of a single future for project evaluation would be an important project design flaw. Water investment planning is more robust when evaluation is conducted over many possible futures, as the SIPs approach proposes.

2.3.2. Stress test investments

Addressing uncertainties in investment assessment involves evaluating each investment option under different possible realisations of those uncertainties; i.e., evaluating the investment over different values of the unknown and uncertain variables. Probabilistic methods, including the use of expected values integrated over probability distributions, offer an approach to addressing these uncertainties.

Probabilistic methods are effective when the uncertain variables can be well described by a single probability distribution. Experience suggests that this is rarely the case in water investment planning, however. For this reason, the SIPs approach focuses on understanding project performance over a wide range of possible futures, without regard to relative probability. This comprehensive performance evaluation is called a “stress test”.

The stress test is used to evaluate performance over many plausible future scenarios, creating a rigorous understanding of the project’s strengths, weaknesses, and vulnerabilities. Results of a stress test are reported along relevant performance metrics, which serve as the basis for project evaluation and trade-off analysis. Performance metrics also serve as planning indicators, informing measures of robustness, vulnerability scenarios, and project “sunset” or expiration date (“tipping point”) for SIPs design.

Stress testing consists of using the modelling system to simulate the performance of each investment option under each plausible future scenarios. When many uncertainties exist, a very large number of scenarios must be generated, as each combination of scenarios for each uncertainty is evaluated. Tools and methodologies for designing and executing stress tests as part of water system design analytics have advanced considerably with growing computational capacity (See (Kwakkel, 2017[8]) (Ray et al., 2018[77]) (Steinschneider and Brown, 2013[78]) (Taner, Ray and Brown, 2019[79])).

2.3.3. Quantify performance

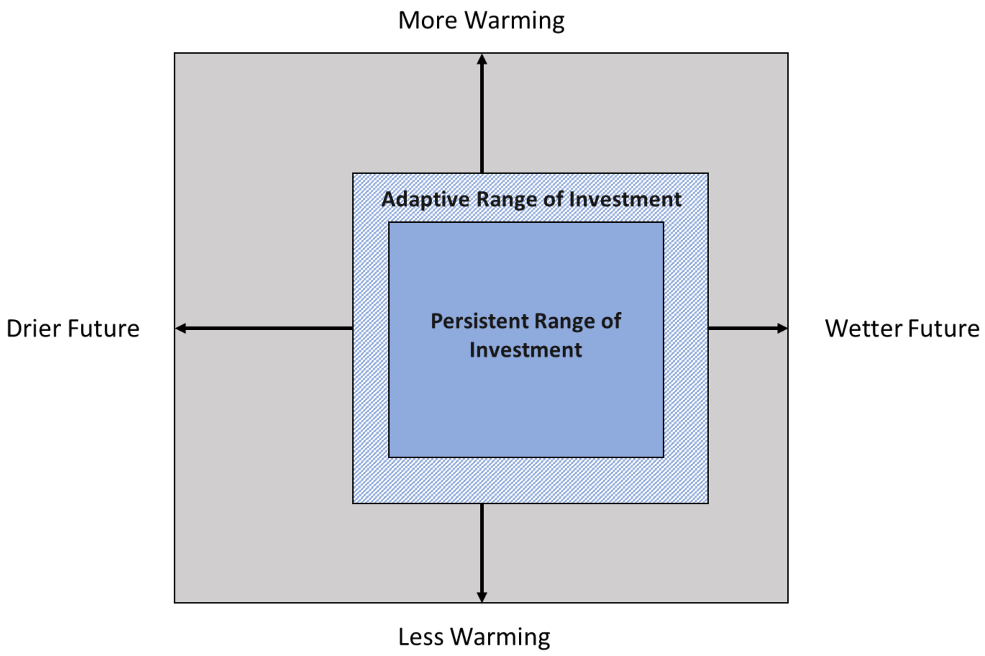
Conventional planning processes report metrics for a single expected future, or for the mean (arithmetic average) of a range of futures. Properly addressing uncertainty in SIPs design requires additional information about project performance; however, including results of the stress tests. While not exhaustive, the following planning indicators are key measures:

- *Mean Expected Performance* – The best single estimate of the project performance for each performance metric. The starting point for results evaluation.
- *Persistence* – This refers to a system’s ability to maintain coherent, “normal” function without changes to design and operation. It can be quantified as the range of uncertain futures over which a project can provide acceptable performance. This corresponds to robustness metrics recently described in the scientific literature (Herman et al., 2015[80]) (Moody and Brown, 2013[81]).
- *Adaptability* – This represents the ability of a system to adapt to changing conditions by modifying its configuration and operation. While infrastructure is often considered rigid, operational aspects of some infrastructure can provide the ability to adapt to changing conditions. For example, dams and reservoirs are structurally rigid and difficult to modify in terms of design. However, the operating rules of reservoirs are highly flexible and may be changed to prioritise new objectives or to accommodate changes in hydrologic regimes including changes to the volume and timing of runoff. Moreover, investments in natural and built water system components may increase adaptability by strengthening redundancy, connectivity and self-regulatory capabilities. It is thus useful to understand the additional range over which a project may sustain its through flexibility in operations and strengthening key components for greater resilience.

- *Transformation* – When conditions change to a degree that a project will no longer provide acceptable performance after accounting for the additional range of adaptability, transformation is required. For example, if a project's adjusted design costs exceed thresholds, it may be necessary to consider abandoning or changing project functions. In traditional investment analysis, this is the expected lifetime of a project - typically 30-50 years for infrastructure. However, project lifetimes are shorter in reality and should be reconsidered in SIPs navigation, if future conditions vary from the expected conditions used in design. The need for transformation of a project is expressed as its Sunset: the conditions under which the project is no longer able to deliver a satisfactory level of service. The Sunset accounts for a given project's vulnerability to change, and relates that vulnerability to the expected time at which such change would occur.

Figure 2.2. The range of climate change over which an investment is persistent and adaptive

Beyond this range of climate change, the project will not be able to deliver the desired services and transformation to a new investment is needed. This transformation is guided by the SIPs.



Source: Authors.

2.3.4. *Ex-post scenario analysis: vulnerability and robustness*

The result of the stress test is a database of system response to all combinations of the uncertainties, which represent plausible futures. Distilling this output into plain, tractable insights to guide SIPs planning is not an easy task. A useful analytical approach to meet this need is the creation of *ex-post* scenarios, also known as Scenario Discovery. The Scenario Discovery method establishes a threshold for a key performance metric to divide the possible futures into two groupings: those where the performance metric threshold is satisfied (acceptable performance) and those where it is not (unacceptable performance). Cluster analysis is used to determine the values of the uncertain variables. A growing literature on the development of tools and methods for ex-post scenario analysis provides further insight (e.g., (Bryant and Lempert, 2010[82]) (Culley et al., 2021[83]).

Scenario Discovery, through ex-post scenario analysis, reveals the vulnerabilities of individual projects and pathways, and in doing so, reveals their relative persistence, adaptability and transformation. These key planning indicators then inform the SIPs Futures Map described below, and serve variables for water system performance monitoring to inform management and investments to build resilience.

2.3.5. "Optimal", "non-dominated", and "best" investments

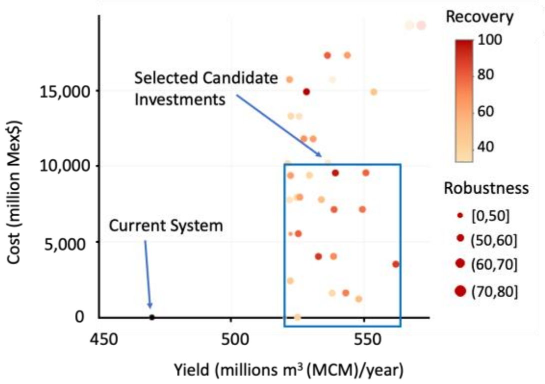
Decision analysis generally, and the specific application described herein, use data and analysis to identify the options that are expected to perform the best relative to key water system performance metrics. In multi-objective analysis, however, there is rarely a single dominant solution. Instead, there is a set of "non-dominated" solutions, which cannot be improved upon without degrading performance in another objective. In other words, there will be no easily identified "optimal" investment. Instead, a set of non-dominated investments will emerge as the set of candidate investments.

In decision analysis, a "dominated" investment is one that is surpassed by another investment in every objective, as measured by the performance metrics. "Non-dominated" means that for a given investment no other investment offers better performance on each of the objectives than that investment, although they may offer better performance on one or more objectives. This is also referred to the set of Pareto optimal solutions. Figure 2.4. provides an example of a non-dominated set of hydropower investments from a case study in Nepal.

The final selection of a "best" investment is a selection from among the non-dominated solutions. In this manner, a selection is made from among the best possible solutions that only differ in their relative performance on specific, individual objectives (Figure 2.3). To select between non-dominated investment options, each option's trade-offs between water system goals and performance metrics are compared and the preferred option is selected. In other words, the selection of a best investment from the set of non-dominated solutions (pareto optimal) is ultimately a choice of preference between different objectives.

Figure 2.3. Options for water infrastructure investments in Mexico City

Multi-dimensional plot of the set of possible water investments, in terms of water yield (x-axis), cost (y-axis), recovery from outage (colour) and persistence (robustness to climate change; circle size). Note that the robustness measure is very similar for most candidates (similar size). The blue box encloses the set of "best investments" selected in the planning process, which undergo pathways analysis.



Source: Authors.
Note: MCM refers to Million Cubic Meters

2.3.6. Resolving trade-offs

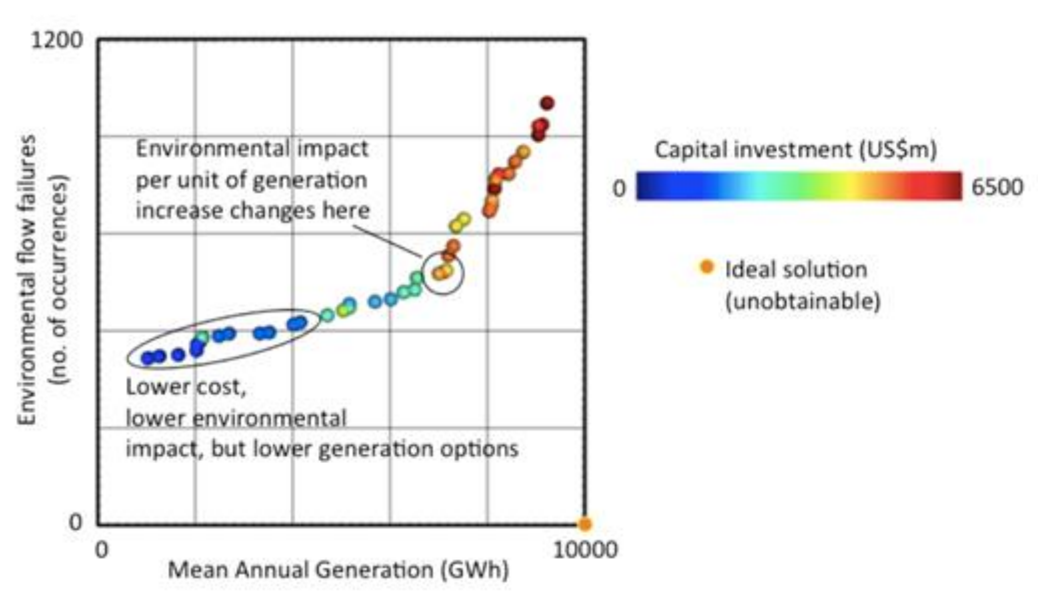
The process for selecting a single or small set of “best” investments will benefit from an understanding of the trade-offs between the options in terms of their performance across different objectives. In other words, how much does better performance in one objective “cost” in terms of decreased performance in another objective? Trade-offs occur both in terms of performance differences across objectives as well as the potential trade-offs between the present and future. Time-related trade-offs may be addressed through sensitivity analysis on any discount rates utilised or through explicit representation of future and present performance.

Trade-off analysis can be facilitated with visualisations of performance, displaying key metrics in multiple dimensions. A number of software packages can support the design and production of such informative visualisations (e.g., (Kwakkel, 2017[8])). Box 2.2 illustrates the use of a multi-dimensional plot to inform trade-off analysis among multiple objectives and water system investment options.

Box 2.2. Investment options for the Koshi River basin, Nepal

The World Bank sought to develop a strategic investment strategy for hydropower development in the Koshi Basin that was robust to climate change. As detailed in (Ray et al., 2018[77]), a climate stress test approach was developed to assess individual hydropower projects relative to a numerous key performance objectives. The hydropower projects were then evaluated as strategic investment portfolios. The figure below shows the resulting trade-off plot per investment options. Each circle represents a portfolio of hydropower investments. The y-axis is the number of violations of environmental flow targets (environmental objective), x-axis is the mean annual hydropower generation (finance objective) and colour indicates the capital investment required (cost). The plot portrays the trade-offs between environmental and financial objectives for the Koshi water system.

Figure 2.4. Trade-off analysis for investment options in the Koshi River basin, Nepal



Source: Adapted from (Bonzanigo et al., 2018[50]).

2.4. Step 3. Designing Strategic Investment Pathways

In Step 2 of the SIPs approach, the most promising investments were identified in terms of their individual performance using stress testing. However, an investment made on the basis of individual project evaluation neglects the potential synergies gained by developing multiple projects together. It also overlooks the potential advantages of making smaller individual investments near-term, while preserving the option of making further investment as uncertainties resolve with time.

The "option value" of investments made in the near term requires consideration of the possibilities that they enable in the future. For this reason, the pathways that projects enable, and those that they preclude, should be included in option analysis. In Step 3, these results are used to design Strategic Investment Pathways.

2.4.1. Prioritisation and sequencing of projects

Optimisation and stress testing are used to evaluate the full investment pathway for the purpose of selecting the best next investments. This is pragmatic and rational, as the future is uncertain and even the most rigorous stress test will undoubtedly exclude key uncertainties that would likely change the ranking of investments and could not have reasonably been foreseen (e.g., a global pandemic).

The process consists of evaluating each project individually first, and then evaluating the most promising projects in terms of (a) their influence on future investments and (b) conversely, the influence of future investments on those projects. By doing so, the approach addresses the concern that an investment pathway may overly influence and constrain near-term decisions and immediate investment needs.

The process uses repeated applications of stress testing to assess the projects individually and as pathways. As a result, the best immediate investment can be identified in a way that also incorporates the potential of the investment pathway that such a project initiates (and those that it foregoes).

The process described here draws on sequential decision analytic approaches (Barto et al., 1989[84]). Such approaches seek to optimise the net present value of each investment sequence given well-defined probability distributions of uncertain variables and a specified discount rate.

The pragmatic nature of the process described here reflects the gap between the decision-making process in reality and optimal analytical methods. In particular, the selection of projects requires analysis of trade-offs between the present and the future and between objectives and performance metrics reflecting differing interests, objectives, and politics, under conditions of climatic and social change that are commonly unpredictable. The process presented here is designed to best use the available information as a guide through the real world of decision making under uncertainty, rather than to provide the optimal analytical solution. The prioritisation and sequencing process for SIPs is implemented as follows:

Select initial investment candidates

Select the set of best performing investments - generally described as the non-dominated set of investments - using the performance metrics. Investments can be selected quantitatively, based on ranking of the performance metrics and trade-off analysis, qualitatively, using the performance metrics as guidance, or by a combination of both approaches. This initial, top-down selection to identify the most promising individual investments aims also to identify the projects that serve as the first step in a SIP.

Create candidate investment pathways

For each of the potential initial investments, create portfolios by iterating through all possible combinations of investments with that initial investment in place. Collectively, the portfolios represent all the possible investment pathways for each of the initial investments.

Each of these portfolios represents a potential SIP. At this point of the analysis, the specific timing and sequencing of investments are not identified, as the results are only used for assessment of the initial investment from the pathway perspective of possible follow-on investments.

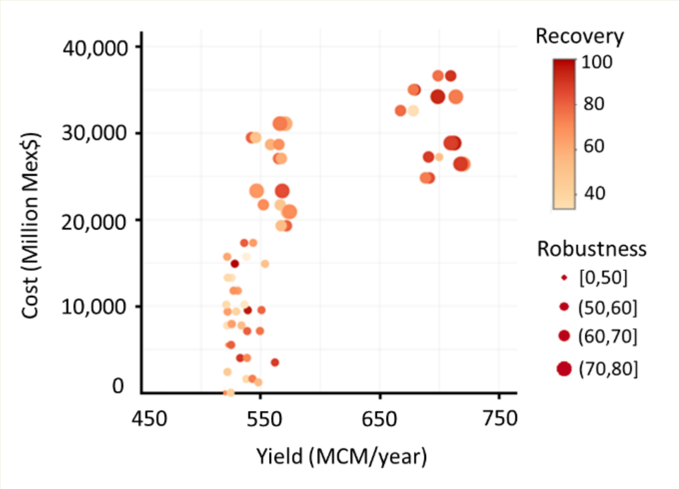
Stress test candidate investment pathways

Stress-test each of the portfolios using the same methods used to evaluate the individual investments. This analysis creates a second key piece of information for evaluating investments - the portfolio performance for each of the initial investments. Having evaluated the most promising investments, in terms of their individual performance, this step complements the analysis with an evaluation of their portfolio performance. Box 2.3 and Figure 2.5 display the results of a stress test for options considered in an expansion of the water supply of Mexico City, Mexico.

Box 2.3. Stress testing water supply investment options in Mexico City

Mexico City depends on the overexploitation of groundwater for its primary water supply. Government entities and stakeholders at various levels are seeking ways to reduce the stress on the aquifer through alternative water supply sources. The Cutzamala System in the State of Mexico supplies approximately 20% of the City's water and there was interest in investing to increase the supply from this system. A number of possible investments were identified including combinations of investments. Each investment was assessed according to traditional objectives of the stakeholders, which included the yield, or amount of additional water that would be produced and the cost, as well as new objectives that assessed the resilience of the investments. Resilience metrics were defined as Recovery, the probability of returning to full service after a failure and Robustness, the fraction of future scenarios over which the investment provided satisfactory service. The figure below illustrates each of the possible investments in terms of these four performance metrics: yield (x-axis), cost (y-axis), recovery (circle colour) and robustness (circle size).

Figure 2.5. Investment options for water infrastructure serving Mexico City relative to key performance metrics



Source: Authors.
Note: MCM refers to Million Cubic Meters

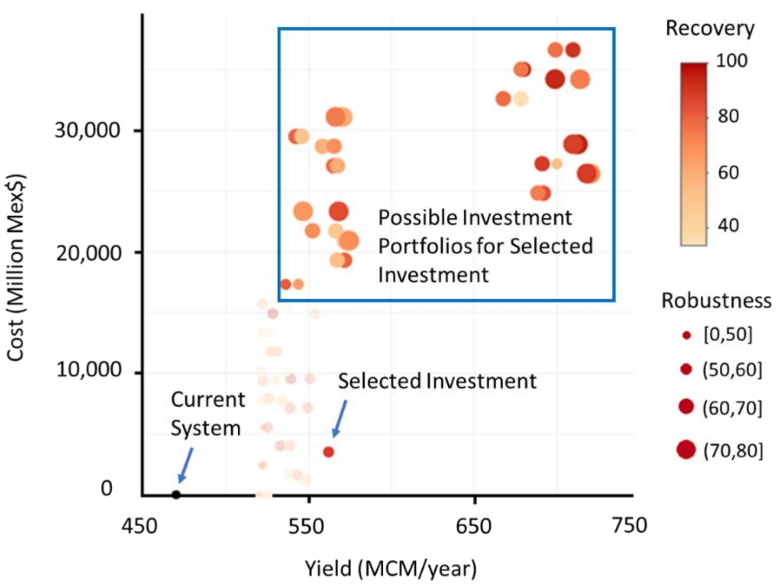
Select initial investment

Using both the results for individual project performance and for portfolio performance, the next step is to select the best initial investment. Best investments are those that are non-dominated in terms of their individual performance and their portfolio performance. "Non-dominated" means that they are Pareto optimal, i.e., no investments perform better across one objective and at least as well as these on all other objectives. The "best" investment is ultimately determined by investors and other decision-makers based on their assessment of options and determination of relative preference between trade-offs.

Choices among alternative water system options and investment pathways is not determined strictly by the results of this analysis, but rather is informed by the analysis. Such choices are commonly the result of political, multi-stakeholder processes and investment deliberations.

If investment capacity exists to make multiple investments, this process can be repeated for the next stage of investment and continued over time as conditions and preferences may change. That is, with the optimal set of initial investments fixed, select the set of best next investments using individual and pathway scores by repeating the process.

Figure 2.6. The selected investment and the investment portfolios that include this investment, which are the basis for sequencing in SIPs



Source: Authors.
Note: MCM refers to Million Cubic Meters

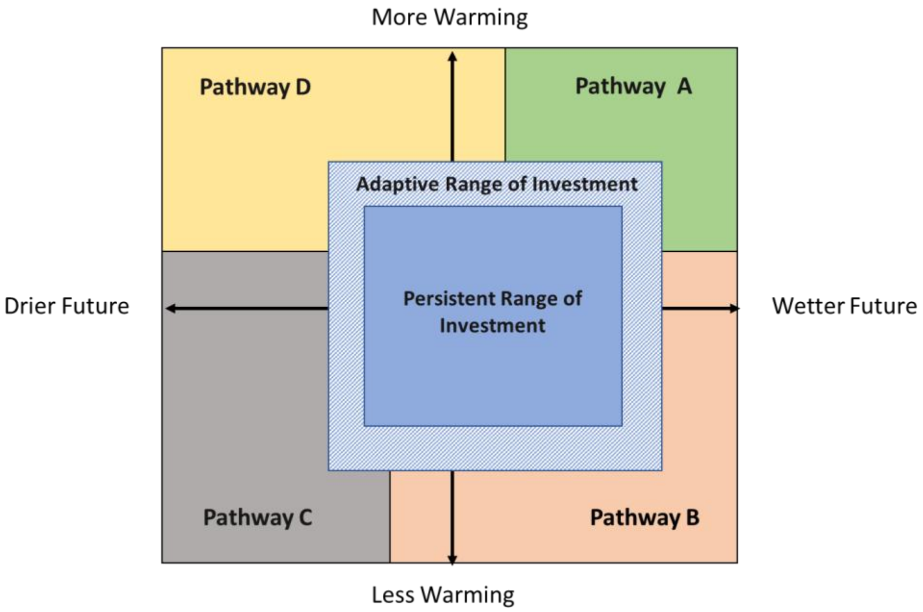
Create a "Futures Map" of strategic investment pathways

With the selection for initial investment completed, the final part of the process is to develop an understanding of the best follow-on investments and their sequencing under alternative futures. The understanding is created by using ex-post scenario analysis on each of the candidate pathways made possible by the initial investment. The analysis is used to identify vulnerabilities and the futures under which a pathway would not provide satisfactory performance (Figure 2.6).

A "Futures Map" is a navigational decision-support tool that specifies under which conditions a particular pathway should be undertaken (Figure 2.7). Futures are defined in terms of specific water system variables and threshold measures of these variables that constitute investment vulnerabilities. Stress testing of candidate investments, described above, provides the necessary data for Futures Mapping.

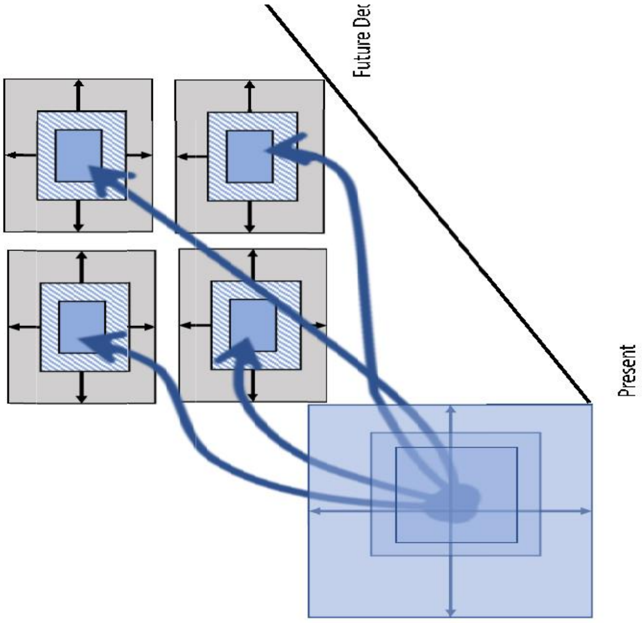
As each new investment is made and as external conditions change, new pathways are made possible and some original pathways are precluded. Figure 2.7 provides an illustration of how Futures Maps may develop over time, adapting to changing futures conditions.

Figure 2.7. Futures Map for a selected investment in terms of its persistence (blue), adaptability (blue hash), and strategic investment pathways in terms of future climates



Source: Authors.

Figure 2.8 An illustration of tracking trajectories over time and developing new Futures Maps depending on the future that is realised



Source: Authors.

The Futures Map serves as a basis for developing a monitoring and forecasting plan that provides the information required to turn the Futures Map into a SIPs navigation strategy, as described in Step 5; but prior to that step, financing sources and options merit consideration.

2.5. Step 4. Mobilising investment in SIPs

To this point, the SIPs process has focused on evaluating and selecting specific investments based on their expected performance and potential contribution to meeting water system goals. However, additional considerations are necessary if the investment pathway is also to be strategic from a financing perspective, in order to reduce risk and inefficiencies in the investment pathway.

Water-related investments can be unattractive to commercial investment because they are often capital intensive and long-lasting, with relatively low risk-adjusted returns. Widespread undervaluing of water and its many benefits by both public and private actors significantly constrains financing opportunities. Numerous bottlenecks that hinder the mobilisation of the full range of sources of financing to build water security and resilience. Key bottlenecks include weak enabling environments, insufficiently robust strategic planning and prioritisation, a lack of attractive risk-return profiles for specific projects, and the local, small-scale nature of many investments (OECD, 2022[29]).

Moreover and critically, water-related investments typically lack distinct revenue streams and assets that can be used as collateral, given that they commonly address one component of the larger water system and its provision of valued services, and consequently, they lack specific ring-fenced revenue sources (Baker, 2022[85]).

Furthermore, water systems provide a mix of public and private benefits across a range of beneficiaries and time scales. While these traits can complicate investment mobilisation; they can also open opportunities to mobilise capital (public and commercial) from multiple sources (e.g., public budgets, payments from users, development finance, commercial banks, corporate and philanthropic funders, etc.).

The SIPs approach aims to address these important constraints and capture key opportunities to mobilise investment through its comprehensive systems approach, its sequencing and bundling investments, and its attention building the enabling environment to mitigate risk and enhance the provision of water system benefits to all stakeholders both near- and long-term.

The next section summarises a process to identify potential sources of financing and relevant financing models that can support the development of SIPs, to ensure that well-designed investment pathways can mobilise finance at scale.

2.5.1. Diagnose the enabling environment for investment

It is widely recognised that water-related investments need robust public policies, regulations and institutional frameworks to function effectively, given the common pool nature of water resources and the public good dimensions of selected water policies and services (OECD, 2019[61]) (See also Chapter 1). Such frameworks also have a profound influence on the water sector's attractiveness to investors and its ability to recover costs and secure sustainable financing (OECD, 2022[29]).

A strong enabling environment for water-related investment can be broadly characterised as a set of policies, regulations and institutional arrangements that facilitate investment in activities contributing to water security. This includes sector-specific conditions (for agriculture, industry, public utilities) as well as those relating to the regulation of the financial sector and capital markets. Well-designed policies and institutions are important for not only attracting investors, but also for ensuring that individual investments deliver their intended benefits and contribute to the sustainable financing and provision of water services (OECD, 2022[29]). The enabling environment influences the extent to which financing for SIPs can be mobilised, as well as the performance of SIPs over time.

A diagnostic tool to assess the strengths and weaknesses of the enabling environment to attract commercial capital is currently under development. The tool is comprised of a scorecard with indicators grouped in three categories: liquidity, bankability and capacity. (Money, forthcoming[86]).

- *Liquidity* refers to the availability of capital in the amount, denomination, duration and cost that is necessary for the viability of blended finance;
- *Bankability* refers to the availability of projects that could be financed on market terms, and considers inter alia creditworthiness, performance, resilience, sustainability and growth prospects;
- *Capacity* refers to the institutional, regulatory, policy, market and human capacity requirements for projects with a commercial finance element.

The diagnostic tool can reveal the extent to which it may be possible to mobilise commercial financing, as well as highlighting how the enabling environment may be further strengthened.

2.5.2. Map benefits, beneficiaries & potential revenue streams

Benefits from SIPs investments accrue to distinct sets of beneficiaries. At an aggregate level, investments in water security should seek to maximise social welfare. But determining how such investments should be financed and how benefits can be used as a basis for cost recovery requires an understanding of what *types* of benefits an investment generates and *who* benefits from them. This can help to distinguish between investments that generate public goods - where the benefits accrue to society broadly, such as water resources management and ecosystem preservation - and investments that generate private goods and services - such as water supply and sanitation services that directly benefit households and firms who enjoy the service. Some water-related investments, most notably those supporting multi-purpose infrastructure development, provide both public and private goods (OECD, 2017[87]). The more varied and far-reaching the benefits from investments in water security are, the more difficult they are to quantify and value in economic terms.

The benefits of water security investments that deliver private goods and services are more easily monetised to generate a revenue stream that form a basis for cost recovery. Thus, they can potentially draw on a wider range of financing modalities, from both governments and commercial sources.

Financing options for public goods and services are more limited. Major projects of water infrastructure with long-term strategic benefits, including multi- purpose infrastructure, normally require a contribution from public finance, with possible participation by private investors and commercial lenders (Winpenny, 2015[88]).

The User (or Beneficiary) Pays Principle calls upon the user of a natural resource or the beneficiary of a service to bear the cost. It accounts for the opportunity cost of using public funds to enable the provision of private goods that users can afford. Water users are not the only beneficiaries of investments in water security. For instance, improved flood protection or the extension of urban water infrastructure can benefit property developers, who could extract the economic rent of the rise in property values as a result of these investments.

Furthermore, identifying the drivers of water-related risks (e.g., industries that pollute water or urban development that increases flood risk) can help to identify who (if anyone) is accountable for additional water-related risks and how they may contribute needed investment to manage them. For instance, the Polluter Pays Principle calls upon polluters to bear the cost of measures to reduce pollution, determined according to the extent of damage done to society or relative to a set level of pollution, commonly codified in regulatory standards (OECD, 2017[87]).

Policy instruments, such as property or pollution taxes, can be used to implement the above-mentioned Principles in order to internalise such positive and negative externalities. Pollution taxes, for example, can thus be a source of tax revenue to finance water-related investments and simultaneously provide an incentive to reduce pollution.

In addition to pollution taxes, there are a diversity of instruments available to policy makers to recover the costs of investment in water security and provide a revenue stream for investors. These include tariffs for water and sanitation services, abstraction charges, taxes on impervious surfaces that contribute to storm water run-off, taxes on urban development in floodplains and value-capture mechanisms. Payments for Ecosystem Services agreements can also be employed to compensate improved resource management that provides water security benefits.

Value-capture mechanisms can be used to extract a portion of the economic rent arising from the growth in property values associated with (and partly generated by) the expansion of public services, including investments in water security. Examples of such mechanisms include property taxes, betterment levies and capital gains taxes.

When designing policy instruments, it is important to consider equity issues, in particular affordability, especially when water bills are disproportionate with stakeholders' capacity to pay (OECD, 2017[87]).

2.5.3. Tailor financing approach to distinct conditions

In service of SIPs, combing finance from various sources enables alignment with the risk and return profiles of a diversity of investors. Deploying public, development finance and philanthropic capital to reduce investment risk or to enhance returns (for example via blended finance), can attract and leverage commercial capital in certain contexts. Risk mitigation and enhanced returns can inform the prioritisation and sequencing of investments.

The role of time in water system investment adds complexity to the finance approach, as it does in any financing calculation. As mentioned, investment portfolios in water systems often comprise long-term investments with low risk-adjusted returns and long payback periods. Long tenor finance on affordable terms is often unavailable in many countries. Further, risks and associated expected financial returns may change over time, according to the phase of the project cycle. Risks may be lowered when a project is maturing and/or when effectively blending with public support instruments.

Furthermore, different types of financiers and financial instruments can replace or add to instruments deployed in earlier phases of water system development (Gietema, 2022[89]). In cases where financing is combined from different sources, the fact that each financier may have significantly different discount rates, means that accounting for the timing and sequencing of investments within a SIP requires incorporating the lifespan of the investment, the discount rates of a variety of actors, and how these can best be balanced to maximise investment interest and system efficiency.

2.5.4. Design an appropriate financing vehicle

The structuring of financing vehicles for water-related investment should account for and resolve key issues identified in the SIPs design process, such as the need for long tenors, small ticket sizes, limited creditworthiness, perceived high risks, and lack of clearly defined revenue streams. Financing approaches should be tailored to specific contexts and to specific types of water-related investments. If private investors are involved, they will require appropriate investment vehicles that satisfy fiduciary requirements and provide investment opportunities at scale (OECD, 2022[29]). This sub-section describes some of the financing approaches that may be considered.

Use-of-proceeds bonds

Bonds are a fixed income financial instrument to raise capital from investors through the debt capital market. The bond issuer raises a fixed amount of capital from investors, which is paid back after a specific time period with an agreed amount of interest. Bond finance can facilitate the flow of capital for water-related investments with clearly defined revenue streams and a creditworthy issuer (e.g., a government, utilities, corporation, municipality, etc.). Bonds with long tenors, typical of the water sector, can attract institutional investors such as pension funds. Investors increasingly show interest in use-of-proceeds bonds, whose proceeds are earmarked for particular projects and purposes and which need to meet specified standards, concerning for instance social responsibility or sustainable development (OECD, 2022[29]). Additionally, there are growing examples of “green”, “blue” and “sustainable” bonds issued for the purpose of mobilising investment towards environmental and social goals, in balance with the economic returns from water-related investment.

Credit enhancement, including guarantees

Credit enhancement improves the credit profile of structured financial products or transactions. It can be employed to enable existing revenue streams to be used as collateral (OECD, 2019[61]). Traditional loan securitisation and political risk insurance are other instruments deploying public finance to improve the risk-return profile of water-related projects and, thereby, unlocking additional sources of finance (Goksu et al., 2017[90]).

Public guarantees are an effective tool to reduce credit risk for commercial investors against non-payment. Public funds can be used strategically to mitigate for financial risks, resulting in a lower cost of capital. Structured funds, for example, allow donor governments to use concessional finance in a first loss position to provide a risk cushion for commercial investors. Guarantees can also be applied for political, regulatory, contractual or currency risks (OECD, 2019[61]) (World Bank and UNICEF, 2017[91]).

The use of guarantees should be carefully assessed in order to ensure that governments and donors do not take on excessive risk in terms of contingent liabilities. Guarantees should also be designed to avoid crowding out private finance. While designing guarantee schemes, donors should pay particular attention to ensuring their financial sustainability. Guarantees should ideally be time-bound, with credible expectations that they will be phased out over time (Garbacz, Vilalta and Moller, 2021[92]).

Special purpose vehicles

Small-scale projects might face difficulties raising debt financing. A special purpose vehicle (SPV) can be created to enable the aggregation of small-scale needs of a number of actors, to making it viable be put on the market. A familiar structure to commercial investors, a SPV is a distinct enterprise with its own balance sheet that acts as a holding company for the securitisation of debt, assuring repayment for investors. (OECD, 2019[61]).

SPVs must be tailored to local conditions and project specificities. In many cities or regions, a public development bank can assist in fitting the vehicle to local needs. SPVs can also service special investment fund, established trusted partner organisations, such as non-profits and civil society organisations. When accepted by all stakeholders, SPVs can build trust in project implementation both in the short and the long term (OECD, 2022[29]).

SPVs are also commonly used for large scale multi-purpose water infrastructure (MPWI) projects, owned by a consortium of project sponsors. These companies have limited recourse to their owners' infrastructure assets, and hence depend on the quality and cash flow from that asset, which is generated through tariffs and power purchase agreements. An example are Uganda's pre-agreed tariffs for transport, electricity and water services with the Kalangala Infrastructure Services SPV, a MPWI project to develop transport, water piping, and wastewater plant infrastructure (OECD, 2019[61]).

Revolving funds

Revolving funds are a strategic use of public funds to attract commercial finance for water-related projects. The Clean Water and the Drinking Water State Revolving Funds (SRF) in the US are a model for mobilising water infrastructure financing through public loans that strategically leverage non-public sources of finance. The U.S. Environmental Protection Agency capitalises the SRFs with annual grants, in partnership with U.S. State governments, who provide a 20% match. States are responsible for the operation of their SRF programs, which function like environmental infrastructure banks offering concessional financing. SRFs support water infrastructure investment through loans at below-market interest rates, with periods of up to 30 years. SRFs can also provide refinancing, guarantees or purchase of local debt and bond insurance. As money is paid back, the State makes new loans to other eligible high priority water projects. Repayments and interest earnings are recycled back into the programme, financing future projects (Gebhardt, Zeigler and Mourant, 2022[93]) (US EPA, 2021[94]). Similar approaches have been used in the Philippines and Cabo Verde, among others.

Water Funds

Water Funds are collective investment vehicles that pool together grant funding from donors, local communities and commercial actors within the spatial area and basin to finance investments in water security through nature-based solutions. The approach has been piloted throughout Latin America by the Inter-American Development Bank, FEMSA Foundation, the Global Environment Facility, the International Climate Initiative, and The Nature Conservancy (Latin American Water Funds Partnership, 2020[95]).

Water funds offer no direct financial return on investment; instead, the profitability of the capital provision arises from the positive impacts on local actors reliant on water resources (Latin American Water Funds Partnership, 2020[95]) (Trémolet et al., 2019[96]). Water Funds are an effective tool to tackle governance failures in multi-stakeholder settings and can mobilise multiple types of funding sources. Yet, development finance remains essential to support the setup of these complex structures that bring together the needs of the various commercial actors as well as the different sources and expectations regarding returns (Trémolet et al., 2019[96]).

2.6. Step 5. Navigating Strategic Investment Pathways

The development of SIPs and Futures Maps in Step 3 are the key, "final products" of the SIPs design process, but they are not the conclusion of the SIPs process overall. Future investment management and adaptation are central to navigating an uncertain future. Essential to the SIPs approach is the planning and sequencing of follow-on investments that are responsive to changing conditions, and account for changing risks and opportunities.

This ability to adaptively navigate and respond to changing external conditions can only be effective, if an organisation fulfils the responsibility of monitoring the water system and key external factors, and informing and undertaking adaptive management of the SIP. The Futures Map provides a robust analytical basis to inform SIPs design and navigation, but institutional support is needed to ultimately reap the efficiency, synergy and resilience rewards of SIPs.

2.6.1. Managing the Process/Decision-Making

Managing the investment plan over time is necessary to realise the rewards of SIPs. Yet, experience shows that, in practice, adaptive management often fails to be sustained. The reasons cited are a lack of a clear institutional home and lack of funding for adaptive management actions. In short, the questions: "Who is responsible?" and "Who pays for it?" are too often left unanswered.

Examples from the United States illustrate how Adaptive Management practice can be successfully implemented and may serve as a model for SIPs navigation: Chesapeake Bay restoration (Boesch, 2006[97]) (LoSchiavo et al., 2013[98]), and the Great Lakes Adaptive Management committee (Brown et al., 2011[99]). In each of these cases:

- a plan for adaptively managing the (restoration) project was created during the planning process;
- a single lead agency was designated as the responsible party;
- a multi-agency committee held decision-making authority;
- the lead agency was funded to execute their adaptive management role;
- monitoring was conducted by existing agencies and leveraged existing monitoring networks;
- novel monitoring strategies were also employed.

In sum, a purposeful effort was made to plan for and execute informed, adaptive management of the projects, enabling greater flexibility and alignment of strategic investments over time.

2.6.2. Tracking Variables and Signposts

The Futures Map is developed relative to key external variables that when realised over time suggest alternative choices and pathways. For water investments, key variables include local annual mean temperature and precipitation, water demand, water sources and storage capacity, and the status of key ecosystems and species populations.

When these variables trend towards conditions that threaten system performance, additional system investments and development choices present themselves. Here too, SIPs should be evaluated and adapted to revealed water system resilience needs.

The levels of the variables at which these actions are indicated are the Signposts. The Signposts indicate that the system is currently outside its range of persistence, external conditions are unfavourable for the current system and action is warranted. Variables and signposts are derived from the Futures Map. A monitoring and forecasting plan is developed to provide the information that empowers the Futures Map for the decision-making process.

Adaptation measures may be sufficient to ensure water system performance and resilience, for instance, operational changes and strengthening system redundancies. In instances of extreme change or disruption, transformation may be required, meaning that investments are necessary to shift system performance to accommodate new norms for these key variables. In cases of transformation, a new branch of the SIP is also embarked upon.

2.6.3. Monitoring and Forecasting

The Futures Map provides the variables to be monitored and the Signposts or levels at which those variables indicate change is needed. Establishing effective monitoring systems to track and share information on those key variables may require additional investment. In many cases the necessary data exist and what is required is the structuring of information flow from the monitoring systems to the agency or body responsible for SIPs decision-making.

Monitoring is essential for navigating the Futures Map and can be enhanced through forecasting key variables. For the purposes of planning, the relevant timescales for such forecasts are likely annual or interannual, that is, the year ahead to several years ahead. This tends to be a challenging timeframe for making skilful forecasts for many variables, however.

This is especially true of quantities that exhibit a high degree of variability, which makes detection of long-term trends more difficult. For example, in locations where the interannual variability of precipitation is very high, detection of a trend toward a wetter or dryer climate is challenging. A succession of dry years may be attributable to a permanent climate change or simply a transient expression of natural climate variability.

Growing computational capacities as well as the increase in water planning capabilities in many places provide the skills needed to interpret and even conduct monitoring and forecasting. These needs must not be overlooked in building the necessary conditions and enabling environment for SIPs.

3 Conclusion

Water investment planning approaches and analytical methods have a well-established history of development and application. Moreover, there are numerous software tools available to enable the required analyses, including identifying trade-offs between multiple objectives, and, more recent advances to address climate change and deep uncertainty. These approaches have not been employed to inform strategic and flexible investments to enhance the resilience of water systems. Thus, the efficiency and impact gains of sequencing, bundling and leveraging co-investments through systematic Strategic Investment Pathways (SIPs) planning remain unrealised.

The SIPs approach attempts to harness advances in system-scale modelling and analytics to guide investments that enhance efficiency and co-benefits, while enabling adaptive management of investments in water systems under change. The scope of analysis follows broad, basin or multi-basin water system boundaries with explicit consideration of key dynamic processes, interdependencies and feedbacks within the water system. The approach is rooted in water resources systems analysis to handle the distinct spatial nature of water and potential for generating externalities. It also incorporates recent developments in Decision Making Under Deep Uncertainty and Adaptive Management.

The result is a framework for developing Strategic Investment Pathways (SIPs) for resilient water systems, detailing a pipeline of projects while incorporating the anticipation and flexibility needed for long term planning. SIPs consider multiple and diverse investments over multiple futures that represent the spectrum of future uncertainties, evaluating investment options relative to stakeholder-defined goals. The results serve as the basis for guiding and mobilising needed water investment.

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Note

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