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# The Infrastructure Imperative of Climate Change: Risk-Based Climate Adaptation of Infrastructure

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## 1. Introduction

Infrastructure provides a foundation for the quality of life civilization enjoys around the world. This includes not only the comforts of heat during the winter, reading lights at night, and convenient transportation options, but also items paramount to public health and safety such as water treated to standards suitable for human consumption, energy for critical operations, and transport to enable society's functioning on a daily basis.

Researchers, professionals, policy makers, technologists, planners and others are challenged regularly to create, maintain, and operate such infrastructure to improve quality of life, while balancing the Triple Bottom Line (environmental, societal, and financial factors). This is an amazing feat to strive for in itself, but now recognition of the greater potential impacts of climate change present additional components of uncertainty and risk that must be applied to this highly valuable and financially- and time-intensive infrastructure investment.

Water is a significant enabler of economic prosperity and well being. Water infrastructure is the medium that enables this. This infrastructure faces numerous threats and uncertainty from climate change, which directly leads to water change and subsequent needs to adapt this infrastructure in the face of a myriad of existing drivers, constraints, and expectations of water infrastructure. This chapter aims to tangibly frame the structure for adapting water infrastructure to climate change in the reader's mind.

This complex situation becomes additionally compounded by much of the infrastructure reaching the end of its useful life, which also provides an opportunity to renew it with much more planet-friendly approaches and designs. In many areas across the globe, megatrends add an additional layer of complex challenges and opportunities, as do applicable design standards. The impacts of these infrastructure complexities are already rippling through facets beyond utilities and governing districts that operate and maintain infrastructure to industry, banking, insurance, and policy.

The level of success that can be achieved in integrating and balancing these additional levels of complexity associated with or driven by climate change will ultimately influence the level of quality of life that can be reached or preserved for future generations and the impact on environmental assets that should not be squandered in a way that would negatively impact future generations. Several key concepts can help to optimize success, such as:

- Considering Potential Impacts of Climate Change on Infrastructure
  - Examples of Infrastructure Vulnerability and Consequences
  - Importance and Challenges of Mitigation in Infrastructure
  - Importance and Challenges of Adaptation in Infrastructure
- Infrastructure Asset Management Planning
  - Importance
  - Approach
  - Climate Adaptation - Incorporating Risk and Climate Change to Prioritize Renewal

This chapter aims to build and communicate the complex picture of the risks that climate change presents to infrastructure, largely focused on the context of water infrastructure as a specific case for analysis. It also examines how to pursue more sustainable and resilient ways in which to address these challenges. Included in this chapter is a solution framework for addressing the imperative need for adapting water infrastructure to climate change. This is accomplished through an investigation of how successful asset management is executed and the role it can play in adaptation. Also presented is how climate change adaptation planning can be rolled in to asset management to consider risks and appropriate strategies for moving forward.

A framework is needed to identify, assess, strategize, plan, and act on the risks that this infrastructure faces due to climate change. This chapter shows how climate adaptation planning and prioritization may be incorporated as a component of risk in what has been identified as a sound, successful, and actionable risk-based asset management program. The chapter aims to connect related best practices in infrastructure climate adaptation assessment, planning, and implementation in a robust, yet flexible manner for the long term.

## 2. Climate change and infrastructure

Key terms used in this chapter include “climate change”. For the purposes of this chapter, “climate change” is defined as “any significant change in measures of climate (such as temperature, precipitation, or wind) lasting for an extended period (decades or longer)” (EPA, 2011a). “Adaptation” in the context of climate change for the purposes of this chapter is the “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (Intergovernmental Panel on Climate Change [IPCC], 2007).

### 2.1 Climate change implications on infrastructure

Climate change can impact infrastructure in a variety of ways, and can present significant uncertainty and risk to natural resources and related infrastructure. The Intergovernmental Panel on Climate Change (IPCC) (Bates et al., 2008) notes that climate, freshwater, biophysical, and socio-economic systems are interconnected and interdependent. It also notes that water, its availability, and quantity will be the main climate change issues for societies and the environment.

Connor et al. (2009) agrees with this general philosophy. Specifically, Connor et al. (2009) calls out these major ties between climate change and the translation of the significance of its impacts on the key medium of water:

- “There is evidence that the global climate is changing. The main impacts of climate change on humans and the environment occur through water.
- Climate Change is a fundamental driver of changes in water resources and an additional stressor through its effects on other external drivers.

- Policies and practices for mitigating climate change or adapting to it can have impacts on water resources, and the way we manage water can affect climate.”

To emphasize the scale of the issue of climate change impacting water resources, often in a way that increases risk to society’s and natural resources’ well being note that Grey and Sadoff (2006) link water resources to being the foundation of economic well being. Below is a breakdown of all world-wide freshwater supply use purposes, as provided by the World Water Development Report (2006):

- 70% used for agriculture irrigation
- 22% used in manufacturing and energy applications
- 8% used for domestic applications such as consumption, sanitation, and recreation

In these applications, demand is expected to rise from 54% of available supply in 2001, to 70% in 2025 (90% if at developed country levels) (UN, 2006). The uses outlined above compete for this supply. This resource is additionally constrained by accessibility, quality, and the affects of climate change as outlined in this chapter and numerous other sources. This is especially problematic when 700M people already facing water scarcity and 900M lack access to safe drinking water. Climate change has the potential of magnifying this problematic situation and subsequently further undermining health and livelihoods (Water and Climate Coalition, 2011).

The magnitude of the water infrastructure needs in the face of climate change related to in costs (USD) is presented in Figures 2.1-1 and 2.1-2 (North America/US is outlined in subsequent tables of this chapter):

- Water adaptation to climate change, generally = US\$ 9-11B by 2030 (United Nations [UN], 2007), up to US\$ 20B in developing countries (Water and Climate Coalition, 2010B).
- Water adaptation to specific scenarios of climate change = US\$ 13.7B in drier scenarios, US\$ 19.2B in wetter ones for water supply and flood management (World Bank, 2008)
- Having the proportion of people without access to safe drinking water and sanitation (generally, without specific climate change adaptation considered) = US\$ 10B/year through 2015 (Toubkiss, 2006).

Total annual costs of adaptation for all sectors, by region, 2010–50 (\$ billions at 2005 prices, no discounting)							
Cost aggregation type	East Asia and Pacific	Europe and Central Asia	Latin America and Caribbean	Middle East and North Africa	South Asia	Sub-Saharan Africa	Total
National Centre for Atmospheric Research (NCAR), wettest scenario							
Gross sum	28.7	10.5	22.5	4.1	17.1	18.9	101.8
X-sum	25.0	9.4	21.5	3.0	12.6	18.1	89.6
Net sum	25.0	9.3	21.5	3.0	12.6	18.1	89.5
Commonwealth Scientific and Industrial Research Organization (CSIRO), driest scenario							
Gross sum	21.8	6.5	18.8	3.7	19.4	18.1	88.3
X-sum	19.6	5.6	16.9	3.0	15.6	16.9	77.6
Net sum	19.5	5.2	16.8	2.9	15.5	16.9	76.8
Note: The gross aggregation method sets negative costs in any sector in a country to zero before costs are aggregated for the country and for all developing countries. The X-sums net positive and negative items within countries but not across countries and include costs for a country in the aggregate as long as the net cost across sectors is positive for the country. The net aggregate measure nets negative costs within and across countries.							
Source: Economics of Adaptation to Climate Change study team.							

Fig. 2. 2-1. Annual adaptation costs (Source: World Bank, 2008).

With the resource put at risk (i.e., uncertain changes in water availability, quality, and timing), its infrastructure is also put at risk. Climate change impacts are expected to become increasingly severe, with the risk of more abrupt and large-scale changes at higher temperature (Stern, 2007). With high uncertainty and severe shifts, adaptation must enable infrastructure to be more dynamic and resilient, while playing within the bounds of much infrastructure being time and financially expensive, relatively static in many instances, and a direct enabler and potential risk (if neglected or inadequate) to the public's and environment's health and well-being. As noted from various sources, (Bates et al. 2008 and Water and Climate Coalition [Coalition], 2010b), climate change is ultimately water change. For these reasons, this chapter is largely focused on infrastructure that serves water needs and concerns as they relate to climate change for this infrastructure that serves societies public health and livelihood needs.

Bates et al. (2008) calls out the following evidence that freshwater sources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and natural ecosystems:

- “Observed warming over several decades has been linked to changes in the large-scale hydrological cycle.
- Climate model simulations for the 21st century are consistent in projecting precipitation increases in high latitudes (*very likely*) and parts of the tropics, and decreases in some subtropical and lower mid-latitude regions (*likely*).
- By the middle of the 21st century, annual average river runoff and water availability are projected to increase as a result of climate change at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics.
- Increased precipitation intensity and variability are projected to increase the risks of flooding and drought in many areas.
- Water supplies stored in glaciers and snow cover are projected to decline in the course of the century.
- Higher water temperatures and changes in extremes, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution.
- Globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits (*high confidence*).
- Changes in water quantity and quality due to climate change are expected to affect food availability, stability, access and utilisation.
- Climate change affects the function and operation of existing water infrastructure – including hydropower, structural flood defences, drainage and irrigation systems – as well as water management practices.
- Current water management practices may not be robust enough to cope with the impacts of climate change.
- Climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions.
- Adaptation options designed to ensure water supply during average and drought conditions require integrated demand-side as well as supply-side strategies.
- Mitigation measures can reduce the magnitude of impacts of global warming on water resources, in turn reducing adaptation needs.
- Water resources management clearly impacts on many other policy areas.



- Several gaps in knowledge exist in terms of observations and research needs related to climate change and water.”

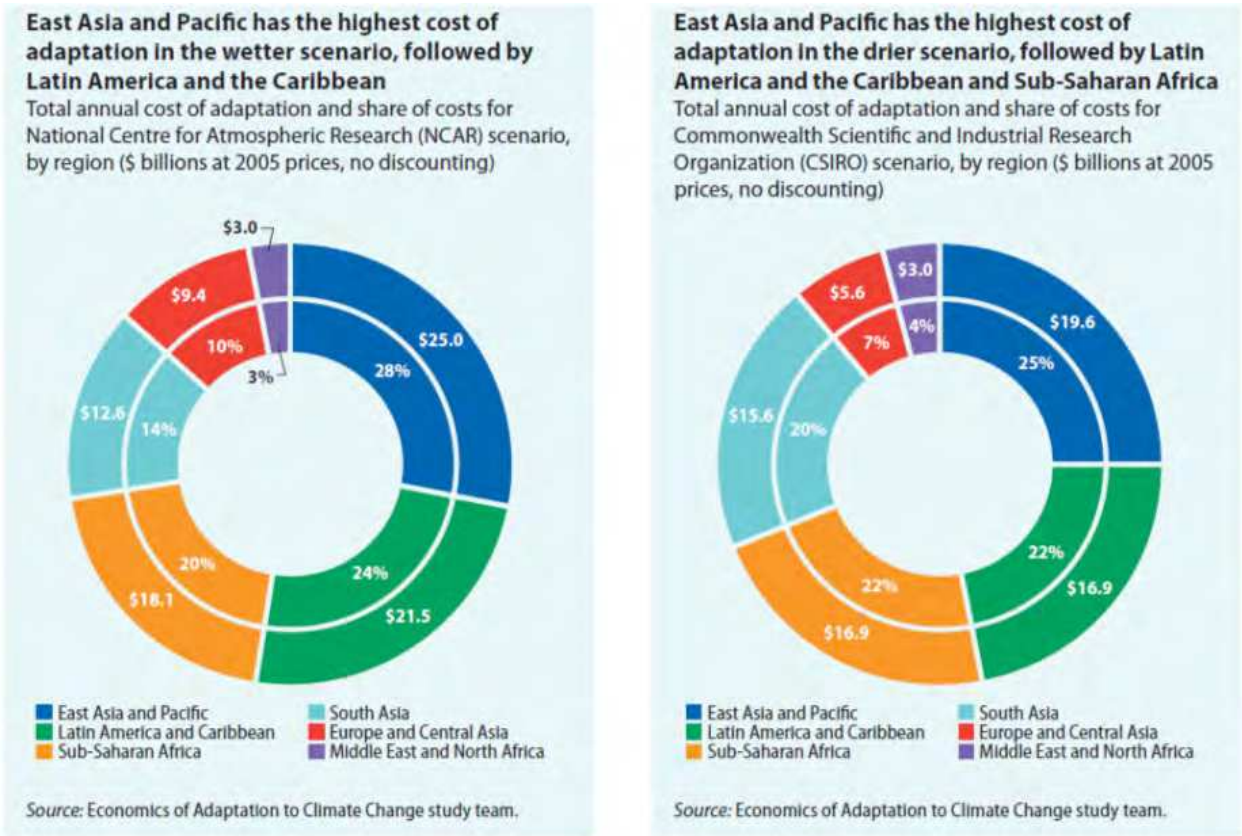


Fig. 2. 1-2. Total annual cost of adaptation and share of costs (Source: World Bank, 2008).

To further develop the profile of impacts and why to be concerned about climate change impacts on water, it is worth noting that with an intensifying water cycle, seasonal and annual water supply variations will determine the consequences of climate change in the form of droughts or floods. Billions of people will be exposed to either having more rainfall or less, which can lead to greater water availability (although not always quality or the ability to capture it) or scarcity, respectively (Stern, 2007). This can serve as the foundation for the conclusion that the impacts of climate change will be felt most strongly through the changes in water, its variability in availability, quantity, and subsequently quality to serve health and livelihood needs (Water and Climate Coalition, 2011).

An examination of potential climate change-induced water impacts on water infrastructure is worthwhile to better understand the criticality and magnitude of the issue of risk that water infrastructure (and subsequently quality supply faces). First, the simple issue of supply exists; that is, is enough water of a sufficient quality available to address the needs of the community and the environment that it serves. Availability relates to several important components; is the water supply consistent, sufficient in quality, protected from natural and humanistic disasters, economically viable to claim and transport, allocated appropriately among users, and part of a dynamic supply system that can adapt to changing needs, seasons, political drivers, etc.? If so, then is the necessary infrastructure in place to obtain the additional supply, and is that infrastructure managed in such away to maintain the investment in that infrastructure and the levels of service expected from the supply?

Next, is the quantity of the supply of water adequate and managed in a way to serve the needs of people without detracting from other natural resources? If more water is needed regularly or during particular seasons, is infrastructure in place to enable access to additional supplies? What about storing the supplies during high precipitation or runoff seasons – is infrastructure in place for this? Can additional benefits be achieved such as through claiming clean and substantive hydropower through streamflow or reservoir dams? Can runoff be captured and channeled by infrastructure to capture the necessary supply for community and environment uses and management in a way that protects, maintains, or enhances water quality to the levels necessary for society's use? These are all important issues and highlight how critical infrastructure is to providing water, as well as why it is important to protect, maintain, and adapt this infrastructure investment to changing conditions so that it can continue to serve society's water needs and provide for its well-being.

A few, more specific examples are worth considering to make the concepts of infrastructure criticality and vulnerability more tangible. As mentioned earlier, more severe water droughts and floods are expected. These directly impact the quantity and quality of water available for various forms of consumption. Depending on the particular local scenarios of climate change, runoff impacts, and various water infrastructure, the potential to overwhelm this critical infrastructure exists, subsequently jeopardizing critical water supplies, especially on an annual basis.

For instance, reservoirs and other types of infrastructure units are often used to store annual supplies of water captured during the high runoff season. If climate warms significantly in the area, increasing the ability of the atmosphere to contain moisture and subsequently leading to fewer but more severe precipitation events, rivers, canals, pipelines, reservoirs and other water infrastructure may not have sufficient capacity to capture the supply necessary for annual consumption; the water could simply top-out the infrastructure and flow downstream and the reservoir subsequently may not be able to meet demands over the course of the dry season when the reservoir has no replenishment refilling it.

A similar scenario could develop with increased temperatures and short winters in areas of glacial and snowpack water sources, frequently located in mountainous regions. With shorter winters and higher temperatures, the snowpack might not develop as greatly which would reduce the supply initially.

The same factors could lead the snowpack to melt more and melt sooner in the year, which could overwhelm water infrastructure in volume, leading to the demise of the supply's annual quantity due to the inability to store or convey the planned annual amounts allowing a portion of the supply to pass downstream, possibly resulting in flooding and subsequent risk to life. To provide an idea of the scale of this issue, more than one-sixth (1B people) of the world's population living in the impacted river basins could be affected (Stern, 2007 and UN, 2008). Additionally, the demise of the quality may be encountered as overall there could be less annual supply, and the earlier runoff may have encountered greater turbulence and pollutants from the watersheds, resulting in a higher concentration of quality degradents.

These issues associated with snowpack are specifically identified as a forecasted issue for the Indian sub-continent, over 250B people in China, and 10 of millions in the Andes. The issue can be exacerbated with long run dry season water disappearing permanently once the icepack has been completely terminated (Stern, 2007). If the snowpack would instead continue to melt more gradually as for which the canals and reservoirs were designed, a more consistent supply would be available through much more of the year. This would help to enable the infrastructure to more feasibly meet expected supply levels.

In some instances, these runoff supply issues may also be present in coastal areas. However, coastal areas are exposed to additional risks as well. For instance, more severe precipitation events could exceed soil and shallow aquifer abilities to retain runoff, if their available capacities are exceeded over the course of these events. The freshwater rainfall would just run out to sea and less would be stored and available in the dry season.

Another challenging risk is salt water intrusion into freshwater delta and wetland systems and aquifers. Rising sea levels bring rising pressures and elevations of sea water, which could potentially penetrate freshwater reserves lying geographically close to coastal waters, or those which lie at low elevations near coastal waters. This risk is further magnified if climate change in an increase of civilization's historic records of temperature has already caused delta and wetlands freshwater levels to drop through increased evaporation. The UN has identified that a high probability exists for rising sea levels to contaminate and subsequently reduce adequate freshwater supplies in Bangladesh, Egypt, and Thailand (UN, 2006). Bloetscher et al. (2010) includes a case focused on mitigating climate change impacts on coastal water supplies and infrastructure.

Additionally, with ice cap melting and subsequent sea level rise, stormwater infrastructure at low-lying, shallow elevations may not have the capacity to contain the rainfall events themselves, nor convey the rate of stormwater flow to outfalls, nor be physically capable of discharging if sea levels rise significantly enough to obstruct stormwater outfalls. As most stormwater pipe networks are not continuously pressurized, rising sea levels could complicate their ability to discharge, or worse, yet, result in backflow contamination or public health hazards and nuisances as stormwater backs up in combined sewer systems (those that convey both wastewater and stormwater flows) into neighborhoods, streets, households, and businesses. These scenarios or others could lead to the vulnerability of millions of people in low-lying coastal areas being at greater risk of flooding by storm surges over the course of the present century (Connor et al., 2009).

Another issue can arise when water supplies are over-allocated. For instance, it is common knowledge that the watershed and subsequent water supply to the Colorado River in the United States is overallocated. The allocation of the river's water supply was based on unusually wet years, as exemplified by tree ring data (Barnett and Pierce, 2009). Additionally, climate change is expected to compound the problem with warmer, shorter winters, and reducing snowpack and accelerating runoff, as shown in research on the river's Upper Basin by Hamlet et al. (2005) and Stewart et al. (2004). In general across the western part of the US, decline in snowpack has been commonly identified over the period of 1925-2000, especially near the middle of the century (Mote et al., 2005). This further decreases the projection of availability of the already over-allocated water supplies.

In all of the infrastructure vulnerability examples cited above, the common consequence of increased flooding with subsequent risk to public health and well-being, decreased supply and quantity, and subsequent rising costs for mitigation, adaptation, management, insurance, etc. are all inherent. AWWA (2005), EPA (2008c), and IPCC (2007) provide additional examples of climate change impacts on water and its infrastructure and subsequent implications.

## **2.2 Importance and challenges of adaptation and mitigation in infrastructure**

Water is critical for adaptation and mitigation of climate change, as climate change is to a great extent water change (Water and Climate Coalition, 2010a). As mentioned earlier, water has been identified as the primary medium through which society and the environment will be impacted by climate change (Bates et al., 2008). The drivers, constraints, stakeholders,



and various scenarios imposed on water resources are numerous. The *World Water Report 3* (UN, 2009) outlines these as decision-making criteria affecting water in Figure 2.2-1.

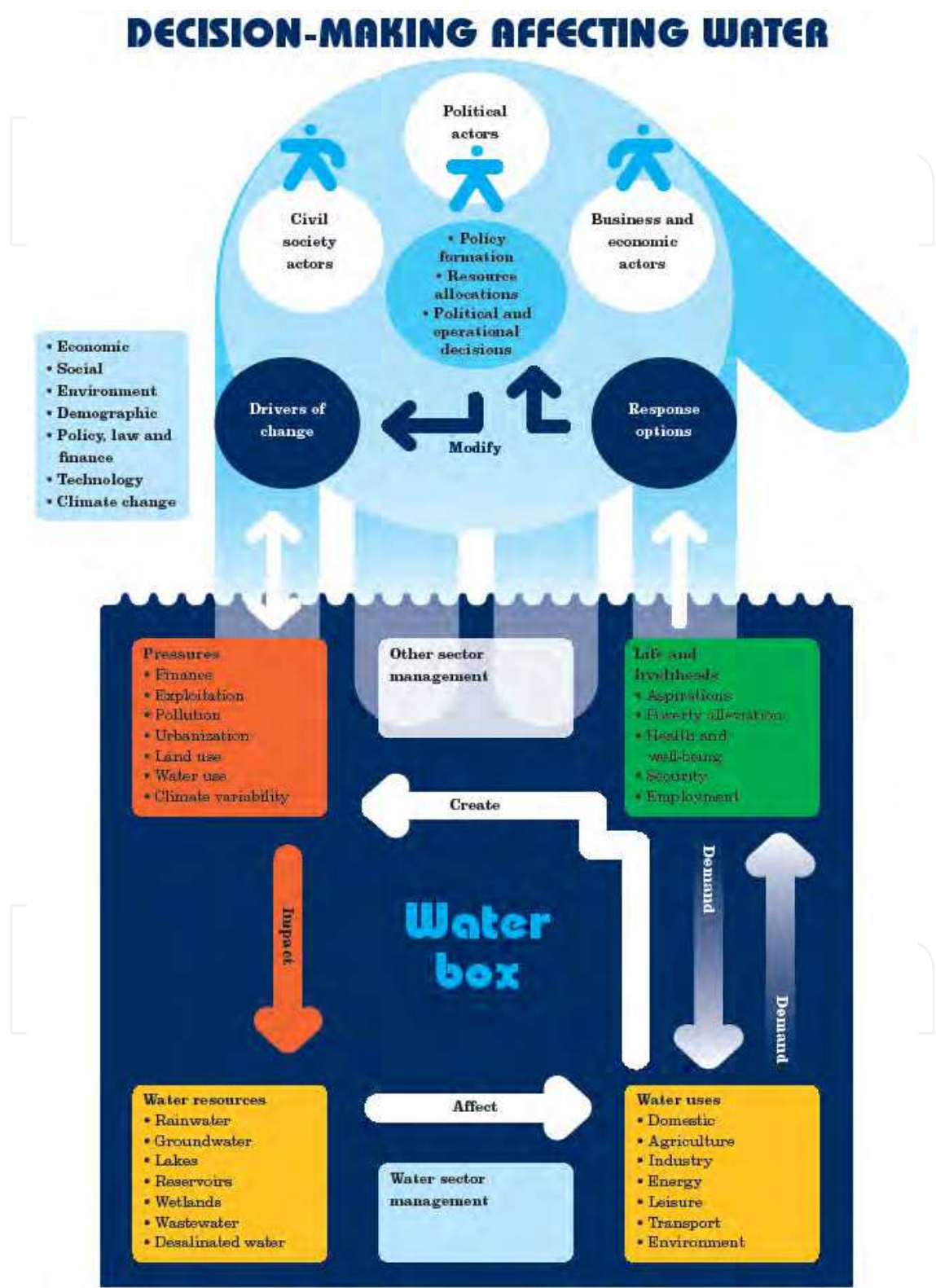


Fig. 2. 2-1. A Schematic of Water Resource Drivers, Constraints, and Issues (Source: UN, 2009)

Additionally, it provides a synopsis of challenges and stakeholders on the cover of the report, which help to provide additional context, as shown in Figure 2. 2-2.



Fig. 2. 2-2. A snapshot of water challenges and stakeholders (Source: UN, 2009).

At the United Nations Framework Convention on Climate Change's (UNFCCC) 16<sup>th</sup> Session of the Conference of the Parties (COP 16) in Cancun (UN, 2010), the Water and Climate Coalition (2010b) called out important fundamental concepts about water change due to climate change to be considered in further climate change examination (Water and Climate Coalition, 2010b). These are grouped in three categories: Climate Change Adaptation, Climate Change Mitigation and Water, Climate Change Finance and Water as interpreted below. These key philosophies are important to reflect upon in developing a deeper understanding of climate change adaptation and mitigation needed via water and its infrastructure.

#### Climate Change Adaptation and Water

- Climate change is water change.
- Resilience should be achieved through Integrated Water Resources Management (IWRM).
- National Adaptation Programmes of Action (NAPA) and IWRM should be integrated.
- Regional cooperation is necessary to respond to climate change impacts on transboundary waters.
- Adaptation that is eco-system based is necessary for the foundation of adaptation.
- Water supply and sanitation resilience must be strengthened in the face of climate change.
- Adaptive water management is important for life and livelihoods.
- Risk reduction strategies must be integrated with water resources management to address severe water events.

#### Climate Change Mitigation and Water

- The reciprocal relationship between climate change mitigation and water (and its eventual nexus with energy) must be recognized.

- The carbon (and energy) footprint of the water sector must be addressed, as it is a high contributor.
- Climate change mitigation should be integrated with water resources management to achieve “no regrets” scenarios.
- Avoid assumptions about future water availability, and fundamentally revisit plans.
- Energy efficiency must be enhanced in the water sector, and “smart” infrastructure can help to achieve this.
- Recognize the mitigation impacts of adaptation actions and vice versa in the water sector (i.e., scarcity drivers of desalination with large energy/carbon footprint).

#### Climate Change Finance and Water

- Economic resources need to be developed and grown for water adaptation infrastructure, especially in developing countries.
- Additional funding is needed to meet the United Nation’s Development Program’s Millennium Development Goal 7 of halving the proportion of people without access to safe drinking water and sanitation by 2015, as even just the costs of climate change (US\$ 10B/year through 2015) (Toubkiss, 2006) greatly exceed the sole costs of basic supply and sanitation at US\$ 9-11B by 2030 (UN, 2007) , or US\$ 13.7B in drier scenarios, \$19.2 in wetter ones for water supply and flood management (World Bank, 2008).

EPA (2008c) examines the water infrastructure adaptation to climate change in a similar light. In 2008, it developed the National Water Program Strategy on a response to climate change. This strategic response outlines the priorities of the EPA in terms of helping and enabling the U.S. to address climate change adaptation, mitigation, and finance (via research and other means) of water. This program is a supporting facilitator for water infrastructure adaptation that aligns well with the Coalition’s key philosophies.

The Water and Climate Coalition ([Coalition], 2010b) elaborates on its key philosophies. In its Water and Climate Change Roadmap for introducing a program on water and climate change under the UNFCCC, the Water and Climate Coalition (2010 a) distills these thoughts into generally recommended approaches. In its discussion, the Coalition explains that participatory water governance and function IWRM are essential for building social, economic, and ecological resilience to climate change (Water and Climate Coalition 2010a & 2010b). IWRM is important for recognizing, planning for, and actively balancing needs, allocations, and consumption, taking into account changing land use.

IWRM should be aligned with NAPAs and regional efforts to sustain freshwater supplies and ecosystems. As with many existing basic water management practices and plans, allocations should be optimized (i.e., efficient use), users should be prioritized based on need, and regular monitoring, evaluation, and adjustment should be made.

As mentioned in the Coalition’s (2010a) key concepts, regional cooperation and collaboration is necessary to manage and adapt in addressing climate change impacts on transboundary supplies in the face of various laws and conventions. Such supplies are most effectively managed at a basin level (Aspen Institute, 2009), which may include dynamic, hydraulically interconnected basins strategies to help to alleviate the impacts of water change caused by changing climate. Such infrastructure has been used to harden water resources against climate change, as well as to incorporate sustainability and other numerous key criteria into decision making (Conner et al., 2009).

The Coalition (2010b) also distills the key points of mitigation and water. Bates et al. (2008) importantly points out that water adaptation and mitigation to climate change have a

reciprocal relationship, in that the same efforts that are used to adapt water in the face of climate change, may be counter to mitigation of climate change, and vice versa. Options and benefits must be carefully considered and balanced in this context. Examples of this reciprocal relationship include:

- Desalination to adapt to water scarcity and cost, which subsequently creates the mitigation challenges of greater energy and carbon footprints, especially if undertaken by a large number of countries.
- Hydropower which aims to mitigate carbon footprints, while often relying on non-readily adaptable water resources in some ways, and environmental requirements and strategies.
- Biofuels which aim to mitigate carbon footprints, but do not always necessarily incorporate energy efficiency strategies, and which are frequently water intensive.
- In general, water purification and treatment facilities which are used to guard public and environmental health are enormously energy intensive and have high carbon footprints. In fact, water services (treatment, pumping, etc.) contribute about 4% of the global GHG emissions (Coalition, 2010a), which is on the same order of magnitude as air traffic. Additionally, they are often the largest energy consumers of municipalities and local governments (Coalition, 2010a), consuming 30-60% of a city's energy bill through 2006 (Energy Information Administration, 2007 and United States Environmental Protection Agency [EPA], 2008a), in the US equaling 3% of its national energy use among 60,000 water systems and 15,000 wastewater systems (Carlson et al, 2007). However, Carlson et al. (2007) and EPA (2008a) present some solutions to addressing high energy usage at treatment plants via benchmarking and energy reduction approaches and strategies. A breakdown of electricity use at treatment plants is provided in Fig. 2.2-3.

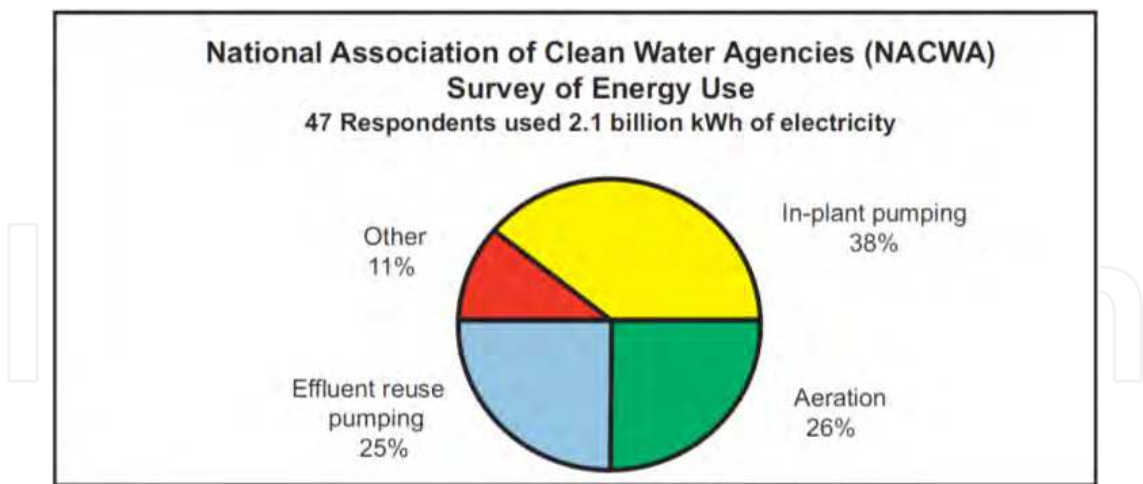


Fig. 2. 2-3. Breakdown of electricity use at treatment plants (Source: Jones, 2006).

Note that all of these reciprocal relationship examples may often require a high capital investment, and may require additional significant investment to become more dynamic and subsequently resilient against climate change, or at least provide energy to these water investments.

Now that relationship of water change to climate change, infrastructure importance, and infrastructure vulnerability and footprints has been established, a suggested framework is



outlined in following sections to examine how to specifically go about assessing, planning, and implementing infrastructure adaptation.

### 3. Infrastructure asset management planning as a strategic solution

#### 3.1 Importance, benefits, and opportunities

With the case established for the significance of adapting water infrastructure to climate change, utilities, water managers, regulators, designers, operators, and other stakeholders need a practical method for addressing it. A structured approach for managing such infrastructure is known as asset management. Asset management may be the best framework on which to support and enable climate adaptation risk management for infrastructure in a realistic and capable fashion. Cromwell et al. (2010) also supports this notion.

Understanding some important definitions are important for context and greater comprehension. New Zealand Asset Management Support ([NAMS] 2011) defines infrastructure assets as, "...stationary systems (or networks) that serve defined communities where the system as a whole is intended to be maintained indefinitely to a specified level of service by the continuing replacement and refurbishment of its components." Assets also are defined as having a life of greater than one year (Urquhart et al., 2007).

In the context of discussion in this chapter, examples would include canals and pipelines, lakes and reservoirs, dams (may include hydropower), water purification facilities, water distribution networks, wastewater collection systems, wastewater treatment facilities, stormwater and other flood controls such as levees and combined sewer overflows, fisheries, and other such water infrastructure. NAMS (2011) also notes that the assets of infrastructure networks are interdependent, both within a particular asset network, as well as from one network to another (water supply and water purification), and across different types of infrastructure networks (i.e., water distribution and transportation).

Another important term is "asset management". Asset management may be defined as, "the combination of management, financial, economic, engineering, and other practices applied to assets with the objective of providing the required level of service to customers and the environment at acceptable levels of risk and in the most efficient manner" (Urquhart et al., 2007). NAMS (2011) notes that "customers" should include the consideration of both present and future customers. In the context of this chapter, the set of assets under consideration is the water one noted in the discussion of defining infrastructure assets

The key elements of infrastructure asset management are (NAMS, 2011):

- Utilizing a lifecycle approach
- Developing cost-effective management strategies for the long-term
- Providing a defined level of service and monitoring performance
- Understanding and meeting the impact of growth through demand management and infrastructure investment
- Managing risks associated with asset failures
- Sustainable use of physical resources
- Continuous improvement in asset management practices

Asset management is applied to (IPWEA, 2011):

- Determine how to meet the increasing demand for new and upgraded infrastructure
- Determine how to [choose] to prolong the life or renew existing infrastructure
- How to pay for these

Asset management is a core component of effective utility management. It helps to mitigate potential risks and is often targeted towards addressing a major concern, such as regulatory

compliance or critical asset failure (Baird, 2011). Such potential risk and failure could be associated with water change due to climate changes.

Other reasons for undertaking asset management efforts include aging infrastructure, more defensible budgets and utility rates in the face of limited funding, and workforce transitions (Parton et al., 2011), evidence of prudent leadership, transparency of sound financial management, protecting credit scores, gaining better interest rates for issuing debt, and helping to gain access to low-interest-rate loans and grants (Baird, 2011). These additional reasons tie directly into addressing climate change because they ultimately are important enablers for water infrastructure climate change adaptation. The benefits align well with the Aspen Institute's (2009) recommendations for making water systems more sustainable.

The underlying benefits of asset management help to enable several important components for the adaptation of water infrastructure for climate change. Parton et al. (2011) notes that underlying benefits of quality asset management include more transparent and defensible budgeting, more efficient and effective knowledge transfer, improved performance management and reporting, better communication with staff and stakeholders, as well as improved customer responsiveness and service.

Additionally, quality business enhancements associated with asset management in an organization can lead to better understanding and communication of near term and long term system risks and capital needs and better efficiency in business and data management (MWH, 2009). Through achieving these benefits associated with asset management, and incorporating climate change within the asset management process, utilities will be able to better adapt their water infrastructure to climate change, making it more sustainable over the long term to serving the water supply and quality needs of its customers.

Recalling the water infrastructure investment needs mentioned earlier and considering the tremendous undertaking of adapting water infrastructure to climate change, society must look for opportunities in these challenges. One such opportunity is with respect to infrastructure in the U.S. Although sophisticated, robust, well-designed and well-constructed, infrastructure in the U.S. is generally in poor condition, and much of it is generally near the end of its design life.

Of particular concern to the discussion of this chapter, water infrastructure in U.S. has received a grade of "D" or below in the American Society of Civil Engineers' Report Card on America's Infrastructure (ASCE, 2009), which translates to a condition rated as "poor", as noted in Table 3.1-1. Of the \$2.2T in estimated infrastructure needs in the U.S. (breakdown shown in Table 3.1-2), at least US\$ 367B is needed for water infrastructure over five years (ASCE, 2009). The U.S. is not alone; other modern, developed countries are experiencing a similar challenge, such as Australia (Institute of Public Works Engineering Australia [IPWEA], 2011).

Why are these ratings and costs important to take into consideration when examining approaches for adapting water infrastructure to climate change? These are important to consider because they present an opportunity; if this magnitude of infrastructure investment is needed, then this investment should be designed and managed in such a way that takes into account climate change and the ways in which water infrastructure can best be adapted within what is determined to be an acceptable level of risk.

Risk assessments, strategies and plans, and implementation and processes will need development and to be executed to successfully and sustainably enable this. The next sections delve into some of the approaches for delivering these in an effort to adapt water infrastructure to climate change. The first examines proven components of successful asset management. The second section, considers how to integrate climate adaptation planning for infrastructure into proven asset management approaches.

Infrastructure Category	Grade
Aviation	D
Bridges	C
Dams	D
Drinking Water	D-
Energy	D+
Hazardous Waste	D
Inland Waterways	D-
Levees	D-
Public Parks & Recreation	C-
Rail	C-
Roads	D-
Schools	D
Solid Waste	C+
Transit	D
Wastewater	D-
America's Infrastructure G.P.A.	D
Estimated 5-Year Investment Need	US\$ 2.2T
Note: Each category was evaluated on the basis of capacity, condition, funding, future need, operation and maintenance, public safety, and resilience	
A = Exceptional, B = Good, C = Mediocre, D = Poor, F = Failing	

Table 3. 1-1. 2009 Report Card for America’s Infrastructure (Adapted from: ASCE, 2009)

CATEGORY	5-YEAR NEED (BILLIONS)	ESTIMATED ACTUAL SPENDING *	AMERICAN RECOVERY AND REINVESTMENT ACT (P.L. III-005)	FIVE-YEAR INVESTMENT SHORTFALL
Aviation	87	45	1.3	(40.7)
Dams	12.5	5	0.05	(7.45)
Drinking Water and Wastewater	255	140	6.4	(108.6)
Energy	75	34.5	11	(29.5)
Hazardous Waste and Solid Waste	77	32.5	1.1	(43.4)
Inland Waterways	50	25	4.475	(20.5)
Levees	50	1.13	0	(1.13)
Public Parks and Recreation	85	36	0.835	(48.17)
Rail	63	42	9.3	(11.7)
Roads and Bridges Discretionary grants for surface transportation	930	351.5	27.5 1.5	(549.5)
Schools	160	125	0**	(35)
Transit	265	66.5	8.4	(190.1)
	2.122 trillion***	903 billion	71.76 billion	(1.176 trillion)
Total Need**** \$2.2 trillion				
* 5 year spending estimate based on the most recent available spending at all levels of government and not indexed for inflation				
** The American Recovery and Reinvestment Act included \$53.6 billion for a State Fiscal Stabilization Fund for education, as of press time, it was not known how much would be spent on school infrastructure.				
*** Not adjusted for inflation				
**** Assumes 3% annual inflation				

Table 3. 1-2. Estimated 5-year investment needs in the US in billions of dollars (USD) (Source: ASCE, 2009).

3.2 Approaches of asset management

Becoming familiar with a realistic, proven approach to managing such infrastructure is important to enable better understanding of how a framework for climate adaptation planning for water infrastructure may be structured, and the underlying foundation on which it must rely for many important components such as strategic direction, communication and buy-in, identified areas of improvement, useable data, and process implementation for execution and ongoing evaluation and revision. This section examines some key components for quality asset management.

Asset management planning can be envisioned in three major steps: service planning, asset management planning, and financial planning (Baird, 2011). Strategy must be developed based around business drivers, such as those mentioned earlier, and desired service levels of the assets, as well as an awareness of present strengths and weaknesses of the organization and its asset base. Service levels are “defined measures of performance or benefit as received by the community and environment. [They] usually relate to quality, quantity, reliability, responsiveness, environmental acceptability, and cost” (Urquhart et al., 2007). The State of Victoria Department of Treasury and Finance ([Victoria], 1995) diagrams the myriad of considerations in effective asset management. An agency’s asset management program should encompass all of the activities illustrated in Fig. 3.2-1.

To account for and coordinate the implementation of these many complex components in a comprehensive and cohesive manner across a utility, more robust asset management endeavors are implemented via a programmatic approach for an organization. A programmatic approach can also help to enable asset management to be managed as an ongoing effort, revisited and revised as necessary, and communicated across a utility on a regular basis. Managing assets in a programmatic manner can help to best realize the benefits of asset management. (Parton et al., 2011)



Fig. 3. 2-1. Components of an effective asset management plan (Source: Victoria 1995).



Major objectives of quality asset management problems are for their analysis to look into the future, rather than the past to determine budget needs, and to be proactive. Being proactive is important to optimize a utility's expenditure by determining the most appropriate time for refurbishment or replacement to maintain the levels of service at an acceptable level of risk and budget (Urquhart et al., 2007). These risk and budget components will need to evolve to take into consideration issues associated with changes in water due to climate change. Once the business drivers and service levels are defined for the asset set, then an assessment can be performed to identify the capabilities of the business processes of the organization and the capabilities of its assets. EPA (2008b) provides a general approach that is based on seeking the answers to "5 Core Questions of Asset Management Framework":

- What is the current state of my system's assets?
- What is my required sustainable level of service?
- Which assets are critical to sustained performance?
- What are my minimum life cycle costs?
- What is my best long-term funding strategy?

The flow chart in Figure 3. 2-2 shows the relationships and dependencies between each one of these core asset management questions (EPA ,2008b).

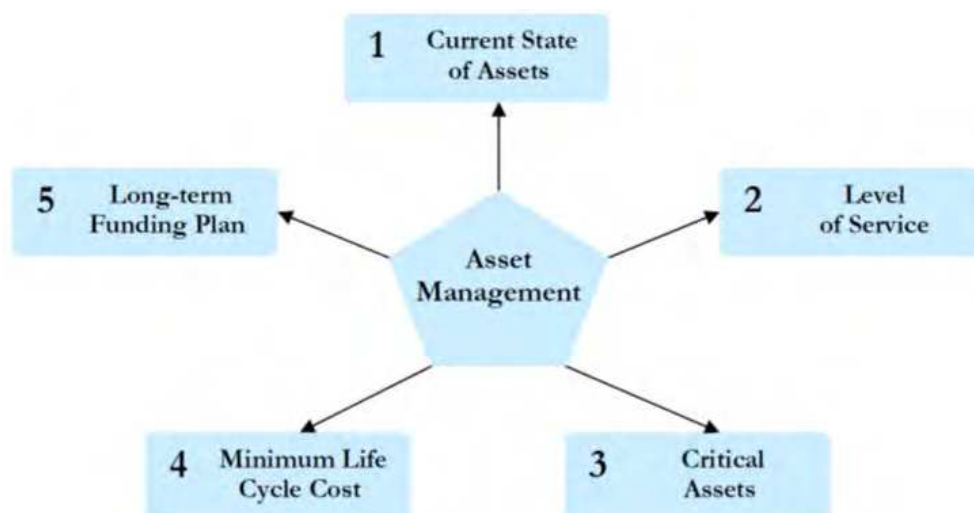


Fig. 3. 2-2. Relationships and dependencies among the core framework questions (Source: EPA, 2008b).

Asset management can evolve to more sophisticated analysis (Urquhart et al., 2007):

- Condition-based
- Performance-based
- Service-based (service-driven)
- Risk-based

Risk assessment is defined as "the process of identifying sources of hazards, estimating risk, and evaluating the results" (American Bureau of Shipping [ABS], 2003). Note that "risk-based" asset management is regarded as the highest level of sophistication. This is important, as "risk" is defined as accounting for both condition- and criticality-based failure of assets (Association of Local Government Engineering New Zealand, Inc. [INGENIUM], 2006). The condition analysis takes into account the likelihood that an asset would fail, based on the health, applied type of use, time in use, and typically-accepted life expectancy

of that asset. These components can help to construct the declining functionality of an asset, as represented by the following curve in Figure 3.2-3 representing an asset’s probability of failure (“P-F”) over its lifespan:

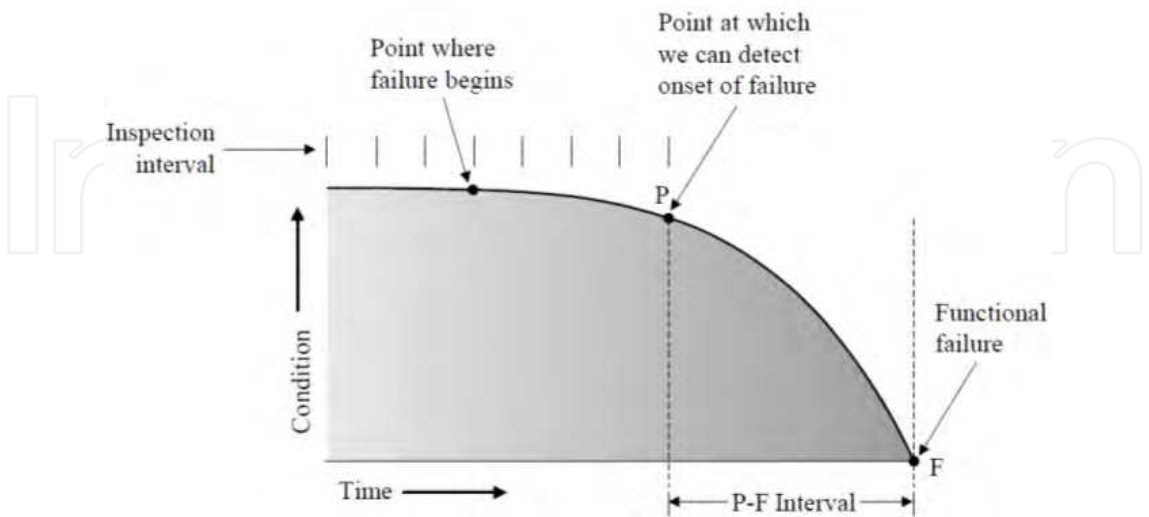


Fig. 3. 2-3. Asset condition deterioration curve (Source: ABS, 2004).

The criticality analysis considers how crucial the asset is to meeting the business drivers and levels of service, as well as enabling its system and its components to also meet these. For instance, if the asset fails, what is the consequence to service, public safety and health, and how would it impact the rest of the system, integrated water resources infrastructure, or the environment if it were to fail? Combining these condition and criticality components helps to define risk for assets and numeric scales may be utilized to quantify this risk (ABS, 2003, INGENIUM, 2006, Urquhart, 2007). Risk can be expressed quantitatively as a measure of loss per unit time or presented qualitatively (ABS, 2003), as shown in Figure 3.2-4.

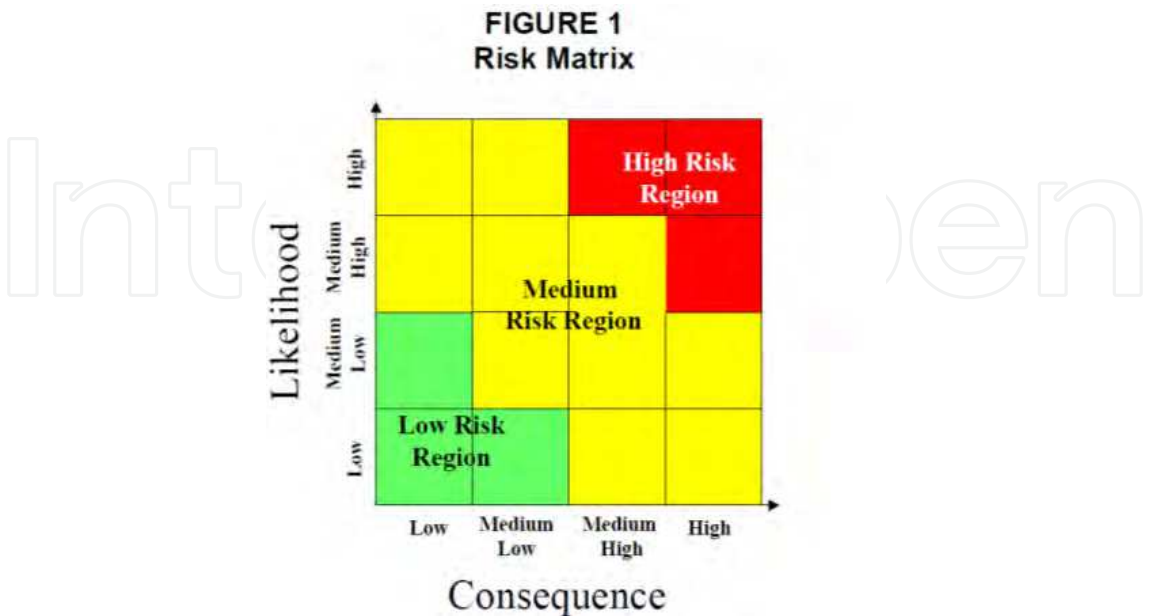


Fig. 3. 2-4. Components of risk which can be evaluated as a function of time (Source: ABS, 2003).

Risk is the product of condition deterioration and criticality (ABS, 2003, INGENIUM, 2006, Urquhart, 2007). This is expressed in Equation 3.2-1 as likelihood and criticality.

$$\text{Risk} = \text{Likelihood} \times \text{Criticality} \quad 3.2-1$$

This product may be further evaluated based on detectability. “Detectability” indicates how easy or difficult the identification of a symptom of failure is, preferably before it occurs or before a process enabled by the asset is affected. Sydney Water Corporation (SWC) has applied detectability in its asset management practices (Urquhart et al., 2007). Incorporating climate change via water change impacts on infrastructure should be a component included in this risk analysis. This is addressed later in this chapter.

Asset data and asset systems have an important role in asset management, and when climate adaptation is overlain upon it. Data must be accurate and complete. Data systems must be useable, consistent, and up-to-date, and usually include computer maintenance management systems (CMMS) and geographical information management systems (GIS) in conjunction with an asset database at a minimum. Sound business processes must also be refined, integrated, and communicated across utilities striving for successful asset management programs. Life cycle management planning is important to maintain the value of the infrastructure asset investment and to sustainably operate it in a manner that meets service level expectations within the constraints of business drivers.

Additional approaches, details, and cases of asset management best practices are included within, ASCE (2008), Bloetscher et al. (2011), INGENIUM (2006), Urquhart et al. (2007), and other sources.

### 3.3 Climate adaptation planning to incorporate risk and climate change to prioritize renewal

As noted earlier, the Water and Climate Coalition (2010b) stated that one of the key philosophies related to climate change adaptation and water is that “risk reduction strategies must be integrated with water resources management to address severe water events”. Now that an understanding of how successful asset management of water infrastructure is conducted has been achieved, this section examines how to fold-in climate adaptation planning on such an asset management platform to enable water infrastructure to be adapted to climate change. As Cromwell et al. (2010a) notes, asset management may be the best approach to climate adaptation risk management.

As mentioned earlier, climate vulnerability ratings of water infrastructure should be assigned during the risk analysis step of asset management. A framework is needed to facilitate the roll-in of climate change risk into this risk analysis.

Cromwell et al. (2010a) presents an approach for evaluating the vulnerability of water infrastructure. Additional studies also provide further specifics that complement this approach well. The approach is based on the typical risk management paradigm:

- Risk identification – what constitutes a risk
- Risk assessment – defining what risks exist, and to what degree information and data competencies are important
- Risk management – deciding what to do about the risks at hand to achieve “low regrets” situations and implement a strategy forward for adaptation

The challenge of identifying climate change risks on infrastructure is broken into pieces, or “deconstructed”, for individual analysis and possible action. Deconstruction is initiated with

the use of cause-effect climate change impact tree diagrams to provide a framework for understanding the full scope of the challenges at hand and to organize relative information. The tree diagrams represent four major “chains” of causation expected from the global warming scenario, including:

- Sea level rise
- Warmer and shorter winters
- Warmer and drier summers
- More intense rainfall events

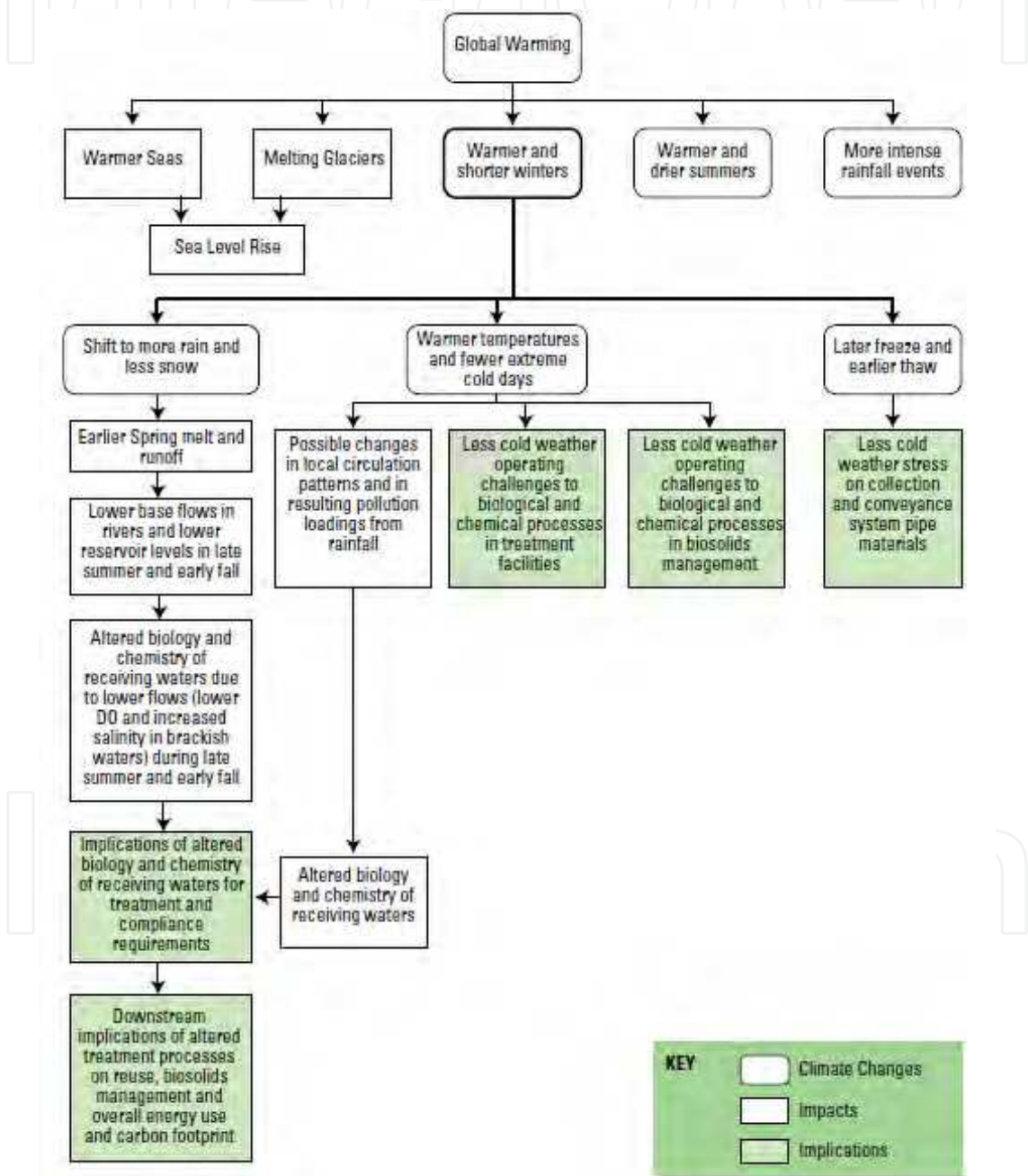


Fig. 3. 3-1. An example of cause-effect tree diagrams for use in climate change risk evaluation: “Impacts and implications of warmer and shorter winters for wastewater agencies” (Source: Cromwell et al., 2010a).



An example of the cause-effect tree diagrams is shown in Figure 3.3-1. A similar platform could be considered for additional scenarios of climate change. Tracing through the cause-effect logic of the trees shows how climate changes produced by the global warming scenario may result in impacts on hydrologic and environmental processes that may have implications for water infrastructure (Cromwell et al, 2010b).

Next, an assessment of the magnitude and timing of the various potential climate change impacts and subsequent implications should be performed to use in a risk assessment of the water infrastructure (includes both human-made infrastructure and natural assets such as lakes and streams, etc.). The IWRM (Integrated Water Resource Management) can help in this analysis.

As noted earlier, the Water and Climate Coalition (2010b) called out IWRM as a key philosophy of climate changed adaptation and water. Others agree as well (Bogardi et al., 1994, Kindler, 2000, Miller et al., 2005). IWRM can be the most effective method for assessing adaptation options for water infrastructure and their implications in the context of an evolving regulatory environment that inherently presents competing demands (Miller et al., 2005).

IWRM is defined as a systematic approach to planning and management that considers a range of supply-side and demand-side processes and actions, incorporates stakeholder participation in decision processes, and continually monitors and reviews water resource situations. It must simultaneously address the biophysical system and the socio-economic management system that both influence water management. The associated analysis relies on hydrologic models for physical processes and must account for the operation of hydraulic structures (i.e., dams and diversions) and institutional factors that govern the allocation of water between competing demands. (Miller et al., 2005).

In the face of the high amount of uncertainty presented by climate change on water infrastructure planning, important in the analysis of climate change implications on infrastructure is what is known as the “top-down” and “bottom-up” approaches (Miller et al., 2005), as summarized in Figure 3.3-2.

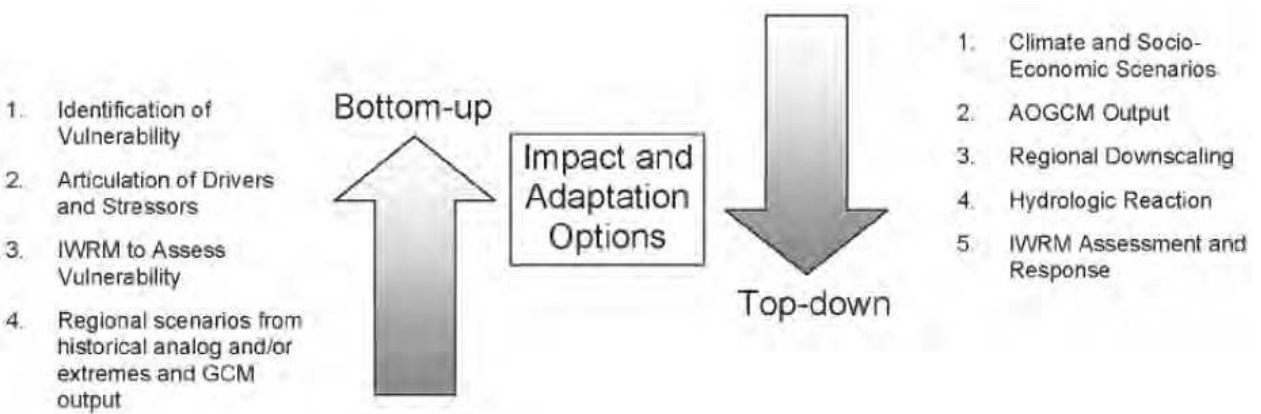


Fig. 3. 3-2. Bottom-up and top-down approaches to climate change assessment (Source: Miller et al., 2005).

The bottom-up approach relies on water system managers’ knowledge of their operations to assess the wide array of practical consequences of climate change, especially over the course of years or a couple of decades, that cannot be predicted by climate models. The typical climate models have analyses based on larger geographical and time horizons. The staff

knowledge of water management organizations is used to consider the performance characteristics and tolerances of its water systems in extreme operating conditions. (Cromwell et al., 2010a).

This leads back into the specific methodology proposed by Cromwell et al. (2010a) for determining climate change risk to which water infrastructure is exposed, which also aligns well with the decision-making approach recommendations for water utilities in the U.S. as presented in Means et al. (2010). Once defined through the course of the rest of this approach, the risk component could then later be integrated into the risk analysis and subsequent planning components of a successful asset management program. The first fundamental question of assessing the risk of climate change on a water asset is now presented (Cromwell et al. (2010a): *“What threshold level of change in the combination of climatic hydrologic and environmental parameters would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations?”* This question should be answered by the water management staff based on their expertise of each of their particular assets in the analysis at risk in the face of climate change.

Once the potential risks to assets have been defined in terms of a critical threshold, Cromwell et al. (2010a) presents the second guiding question: *“What is the likelihood of seeing a threshold level of change in the combination of climatic, hydrologic, and environmental parameters that would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations within capital planning or other meaningful time horizons?”* The answer to this second question will need to consider climate change science to determine what climate changes and subsequent impacts and implications could exceed the thresholds defined in the first question, including the likelihood (remember the defining equation of risk) of occurrence and timing. Much of the best science, if it is even known for the particular issue, often encompasses such a high uncertainty, that the best scientific answers may be presented in the form of ranges. (Cromwell et al., 2010a)

With this high degree of uncertainty present, Cromwell et al. (2010a) emphasizes not to freeze planning decisions to await more refined scientific information, which will take much time to develop. This point is where the top-down approach depicted in Figure 3.3-2 comes into consideration. The top-down approach involves refining predictions of climate change, downscaling of climate models to apply them to local geographies and streamflow situations, and eventual IWRM planning (Miller et al., 2005). Some of this downscaling of models to local streamflows has progressed, including developing a transferable model of the process to expand applications (Bloetscher et al., 2010, Colorado Water Conservation Board [CWCB], 2011, King County, 2007, and Means et al., 2010).

To address the high uncertainty associated with the timing and possible magnitude thresholds of climate impacts, Cromwell et al. (2010a) proposes a third questions to guide the analysis: *“What is the overall adaptation strategy that leads to more sustainable infrastructure over the course of this century – the sustainable path?”* This question can be broken down into two considerations for analysis: *“How can the consequences of an anticipated threshold level of impact be avoided or mitigated through adaptive responses?”*, and, *“How are short term adaptation options different from longer term choices, and what is the strategic path that leads from one to the other?”* Cromwell et al. (2010a) presents this third set of questions to help formulate adaptation decisions by distinguishing between the short term and long term responses to a climate change threat to give the progression of the decisions some traction. With the high degree of uncertainty inherent in such decisions, and pursuing low-

or no-regret actions to adapt infrastructure to climate change, the key is to keep the selected strategies flexible. To keep them flexible, such decisions are often targeted with incremental, short-term solution. Very important, these incremental steps should keep options for the longer term open without restricting the ability to adapt the infrastructure in a way to respond to new revelations and changing conditions among climate, water, targeted service levels, and the regulatory environment. (Cromwell et al., 2010a).

In Figure 3. 3-3, Cromwell et al. (2010a) depicts the framework of its components of the above overall suggested approach of this section in Figure 3.3-3. Its structure reveals how each of the climate change impacts identified in the cause-effect trees can be distilled into possible adaptation strategies via the methodology described above to keep water infrastructure on the “sustainable path”(Aspen Institute, 2009) in the face of climate change. The impacts can be grouped into “threat bundles” to be evaluated as a package to asses which specific influences are likely to be the most critical to a water manager’s assets to consider adaptation options in a composite approach, rather than piecemeal (Cromwell et al. 2010b). These likelihoods, consequences, risks, and possible solutions can then be overlain with the same components in the asset management planning mentioned earlier to roll-up into overall strategies, budgets, communications, and organizational business for the water utility.

At the high level, Cromwell et al.’s structure may be massaged at this point into further detail and analysis to consider life safety, cost/benefits, and initial categories of action, including “must do”, “investigate further”, etc. as shown in Figure 3. 3-4. Other criteria that can be incorporated at this point include commitment, regulations, readiness, catalysis, sustainability, complimenting opportunities, and other important considerations (DeGeorge et al., 2008).

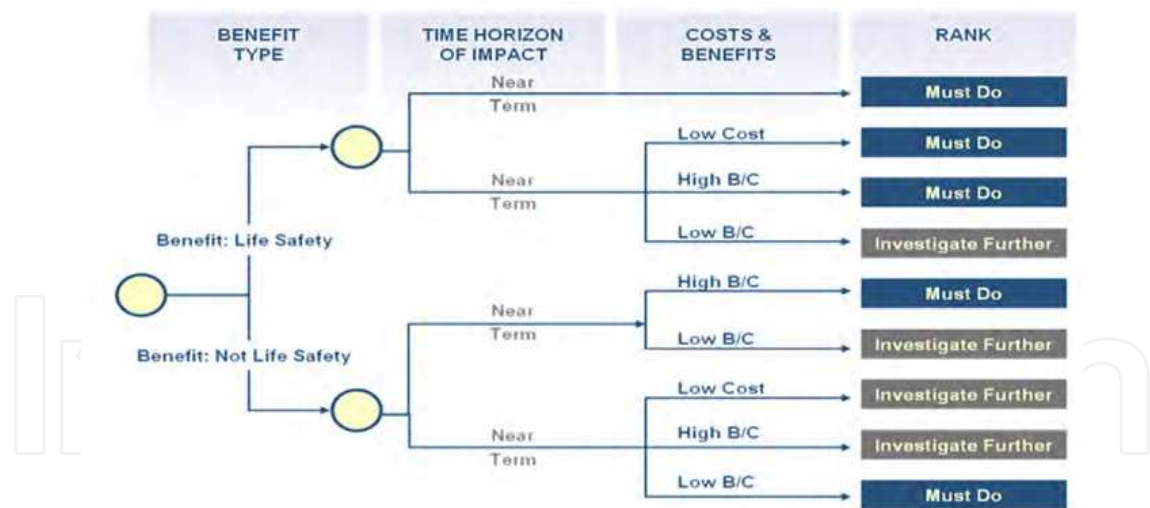


Fig. 3. 3-4. Additional structural details for identifying and prioritizing adaptation (DeGeorge et al., 2008).

As criteria and solutions continue to build in complexity, formal, proven decision making approaches and tools may be necessary to aid in analysis, prioritization, feasibility, transparency, communication, reconciliation, opportunity identification and efficient and effective comparisons and breakdown analyses. An outline of how to apply such decision making is presented in Conner et al. (2009). Additionally, the criteria and solutions enable important sustainability considerations such as:

- Gray vs. green infrastructure
- Low Impact Development (LID)
- Sustainability visions and plans
- Life Cycle Analysis (LCA)

Opportunity identification could include such strategies as (Conner et al., 2009):

- Energy recovery
- Enhanced water quality
- Supply optimization (i.e. water rights) and reuse
- Shared infrastructure/finance
- Conservation
- Environmental impact mitigation

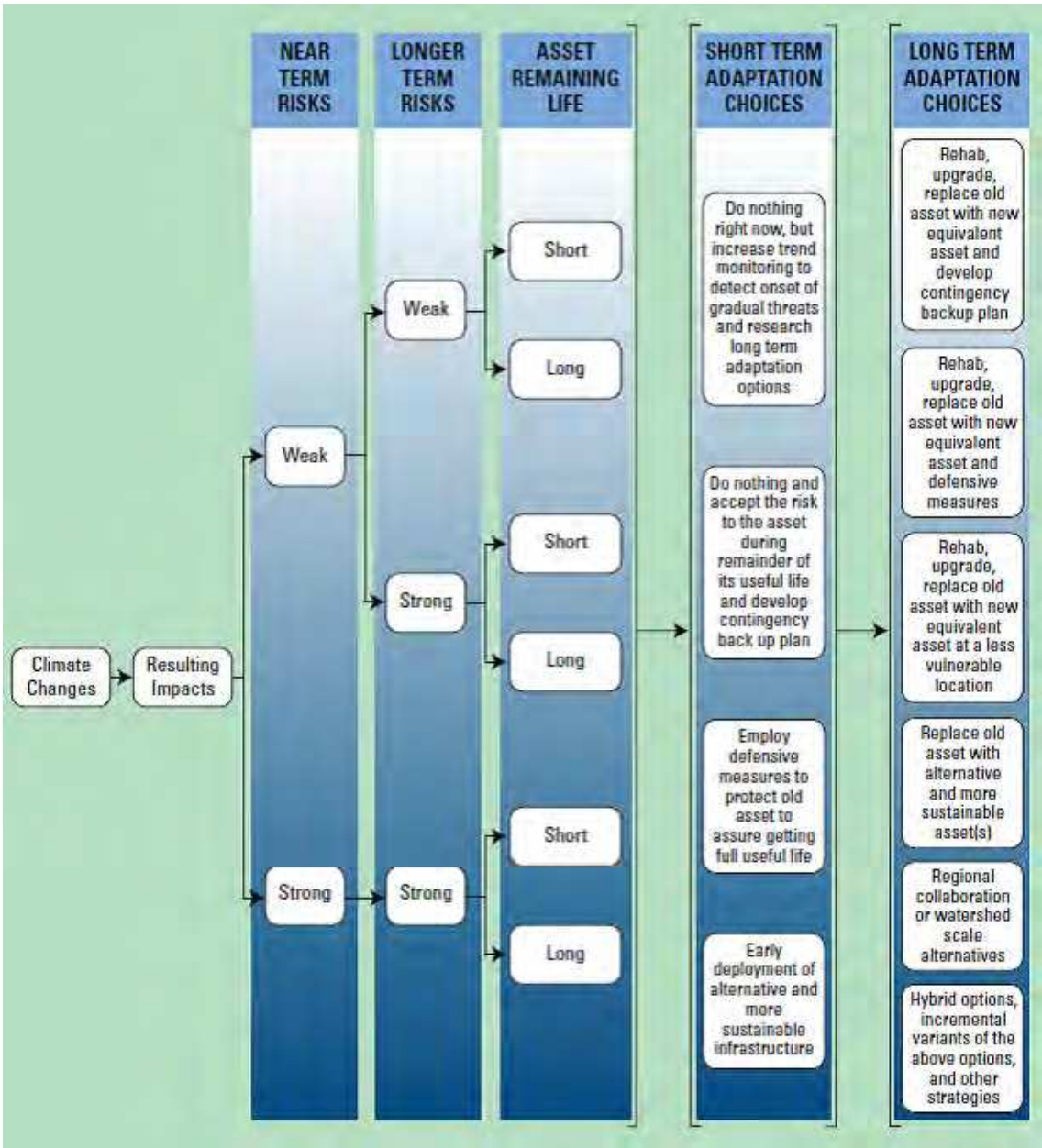


Fig. 3. 3-3. Finding the sustainable path in adaptation planning (Cromwell et al., 2010).



While continuing to tie together suggested methodologies for adapting infrastructure in a cohesive manner in this chapter, Bloetscher et al. (2010) presents another subsequent step. Bloetscher et al. (2010) assesses vulnerable infrastructure for climate change impacts and presents specific strategies that could address the effects of climate change on that infrastructure. Once the adaptation options have been determined, Bloetscher et al. (2010) develops very specific strategies for addressing climate change impacts on the community on which their case focuses.

The community examined in the case is Pompano Beach, Florida, a coastal city which could encounter various effects of climate change on their water assets. The implications examined include those arising from the impacts of sea rise and more intense rainfall events, such as sea level rise, salt water intrusion, hydrodynamic barrier challenges, and programs involving new wells, reclaimed water, and aquifer recharge. The conclusions of the case align well with Cromwell et al. (2010), Water and Climate Coalition (2010b), and others that regional solutions will be needed and long-term water management should consist of vulnerability analysis, short- and long-term applicability of current practices. Additionally, a toolbox of technical and management solutions and a planning framework for increasing resilience and sustainability using adaptive management to deal with uncertainties was found to be necessary. Table 3.3-1 shows the specific implementation program of adaptation alternatives and supporting analysis that is considered when evaluating solutions and choosing the path forward for the community's water infrastructure and vulnerabilities.

Bloetscher et al.'s (2010) implementation program of adaptation alternatives provides an example of how to structure the consideration, analysis, and action related to specific climate change implications on local water infrastructure. The researchers examined very specific strategies, barriers, costs, and strategy changes. These could be generally included in the "hybrid" classification of scenarios as mentioned as an adaptation alternative in Cromwell et al., (2010) for evaluating implications and action necessary for sea level rise.

Bloetscher et al. (2010) also provided a toolbox of general recommendations, largely in a coastal context, for protecting various water resources from climate change effects, as shown in Table 3.3-2.

Impact criteria and ratings can be defined, and weighting assigned to show the correlation the severity of climate change impacts and the importance of needed adaptation activities for infrastructure. This may be accomplished in a manner similar to the method presented by EPA (Johnston, 2010) for identifying the vulnerability of EPA Region 8 areas to climate change impacts. These impact rankings will help to create a ranking that can be used to prioritize adaptation activities.

For instance, a ranking of "1" would be the most severe or most threatening climate change impact to infrastructure. This would be the highest priority vulnerability to address, and its adaptation solution the highest priority adaptation activity to pursue. In many cases, this ranking would be determined as the climate change risk ranking of the product of likelihood and consequence. This can be rolled into the asset management risk scoring as an additional weight on the overall risk score.

Considering non-climatic drivers applicable to each of the applicable climate impacts and adaptation activities of concern is also important. Non-climatic drivers are, "external dynamics that have the potential to exacerbate climate change impacts". In this sense,

Trigger*	Implementation Strategy	Barriers to Implementation	Cost	Point When Action May Need to be Abandoned
Immediate 0–0.5-ft SLR by 2030	Install stormwater pumping stations in low-lying areas to reduce stormwater flooding (requires study to identify appropriate areas, sites, and priority)	NPDES permits, cost, land acquisition	\$1.5 million–\$5 million each, number unclear without more study	When full area served is inundated (> 3–5 ft SLR)
	Water conservation	Budget, staff time, cost, political will	\$30 million/year thereafter	NA
	Armoring the sewer system (G7 program)	Budget, recurring expense	\$12.5 million start, plus annual cost allocation	When area served is inundated
0.5–1-ft SLR 2031–50	Additional reclaimed water production	Budget, lack of application sites in the city; long term frustrates SLR protection efforts	> \$25 million, depending on permit requirements	Before 3-ft SLR makes soil saturation a problem
	Aquifer recharge/salinity barriers	Regulations for indirect potable reuse, public perception	Up to \$200 million depending on permit requirements	Before 3-ft SLR makes soil saturation a problem
1–2-ft SLR 2043–78	Desalination	Cost, but plant and deep well are already in place	\$45 million–\$50 million to convert, and wells (\$750,000/mgd)	NA
	Control flooding west of the coastal ridge	Cost, discharge location for water	\$1.5 million–\$5 million each, number unclear without more study; at least a dozen would be needed (\$25 million)	When full area served is inundated
	Central sewer installation in OTDS areas	Cost, assessments against property owners	\$10,000 per household	When full area served is inundated
	Closing of private wells	Private property rights	Cost unknown	NA
	Relocate well fields westward/horizontal wells	Cost, concern over saltwater intrusion east and west, inundation of well fields, permitting by SFWMD	\$20 million, assuming locations can be permitted in Biscayne Aquifer	When well is inundated
	Salinity/lock structures	SFWMD, western residents, private property rights arguments	Up to \$10 million, may require ancillary stormwater pumping stations at \$2 million–5 million each	NA
	Regional desalination/aquifer recharge/Everglades	Perception, nutrients, cost	\$200 million	NA: solution to slow sea encroachment
	Aquifer storage and recovery with reclaimed water	Regulations for indirect potable reuse, public perception, assumes desalination in place	Wells are \$30 million, unknown treatment requirements	NA
3–4-ft SLR 2085–2100	Massive groundwater dewatering, send to Everglades	Regulations for redirection of stormwater that likely has high phosphorous levels, public perception, cost	Billions (\$)	NA: solution to slow sea encroachment
Beyond 4-ft SLR after 2100	Large areas of the city must be abandoned	Public perception: worst-case scenario, likely more than 100 years out	Billions (\$)	NA

NA—not available; NPDES—National Pollution Discharge Elimination System; OTDS—onsite treatment and disposal system; SFWMD—South Florida Water Management District; SLR—sea level rise

\*Projected time frames are approximate.

Table 3. 3-1. Implementation program of adaptation alternatives (Source: Bloetscher et al., 2010)

Water Resource Issue	Tool
Water Conservation	Reduce requirements for additional treatment capacity and for development of alternative water supplies
Protect Existing Water Sources Against Saltwater Intrusion	Create hydrodynamic barriers: aquifer injection/infiltration trenches to counteract saltwater intrusion using treated wastewater
	Drill horizontal wells
	Build salinity structures and locks to control advance of saltwater intrusion
	Relocate well fields when saltwater intrusion or other threats render operations impractical
Develop Alternative Water Resources	Desalinate brackish waters
	Acquire regional alternative water supplies
	Capture and store stormwater in reservoirs and impoundments
Wastewater Reclamation & Reuse	Irrigate to conserve water and recharge the aquifer
	Apply to industrial uses and cooling water
	Implement indirect aquifer recharge for potable water
Stormwater management	Re-engineer canal systems, control structures, and pumping strategies

Table 3. 3-2. Tools for protecting water resources from climate change (Adapted from: Bloetscher et al., 2010).

climate change activities should be developed and implemented using a holistic approach, rather than considered in isolation. Non-climatic drivers include:

- Land use change
- Population change
- Failing infrastructure
- Increased demand
- Demographic shifts (rural to urban migrations)
- CO2 effects on vegetation (Johnston, 2010)

As mentioned earlier, infrastructure asset systems can be inter-related and should be coordinated. The climate change risks and adaptation approaches should be considered in conjunction with climate water change risk as well, perhaps considering the risk and adaptation findings of approaches for other infrastructure systems.

One such approach is for transportation. The U.S. Federal Highway Administration has identified a useful approach for evaluating the vulnerability of the national highways to climate change, largely subsequent water change and risks (ICF, 2009). Such analysis and possible integration of climate change assessments on other such infrastructure will ultimately be useful in a more complete, efficient, and likely effective adaptation of infrastructure to climate change. Well-designed asset management approaches can help to coordinate and execute the coordinated climate adaptation of multiple infrastructure systems.

#### 4. Adapting infrastructure intelligently, sustainably

As may be concluded from the discussion within this chapter, a variety of considerations, drivers, constraints, stakeholders, and other issues will be considered in actionable adaptation decisions, strategies, and actions. Ideally, and hopefully with purposeful intent, the infrastructure adaptations should be made in as resilient, dynamic, intelligent, and sustainable manners as possible:

- **Resilient** in the sense that the water infrastructure is modified, protected, or managed in a way that helps to serve its business drivers and levels of service commitments, while protecting and serving the health and welfare of society and the environment. Emergency management plans and contingency plans should be in place.
- **Dynamic** as being enabled to adapt to changing climate, and subsequently, water conditions to the extent possible, and, otherwise, strategically managed in a regular, ongoing manner to incorporate new knowledge, new risks, and new actions.
- **Intelligent** as in short-term steps are taken in the best interest of critical present vulnerabilities and in the best interest of the long term by not limiting the paths ahead that can be taken. Also, the management of the infrastructure includes new technologies and approaches to operating, maintaining, managing, and sustaining the infrastructure. Tools include strategic metrics and key performance indicators, real time monitoring technology, reporting performance dashboards, and other “smart” technology. The organization(s) managing the infrastructure must also have a solid foundation to enable this intelligence including a well-defined strategic direction, communication, and alignment; strong organizational capabilities and processes; and quality, applicable, accessible and well-managed data. This also includes regional collaboration and knowledge sharing.
- **Sustainable** in the sense of balancing the triple bottom line across the interests of society, the environment, and financial enablers and feasibilities. This includes sustainable infrastructure design, life cycle assessment, life cycle management planning to maintain asset value while operating it to meet service levels, mitigating negative impacts of the infrastructure on society, natural resources and surroundings, and closing the loop of resource use to reduce waste streams and unneeded resource consumption (Conner et al., 2009).

As mentioned earlier, much of the infrastructure in developed countries has reached the end of its designed life. The time has come to significantly refurbish, or often, replace this infrastructure (ASCE, 2009). This presents an enormous opportunity to green significant amounts of infrastructure that will serve society for decades to come, often 50 years or more. Examples of some general green infrastructure opportunities and strategies are included from Conner et al. (2009) in the previous section of this chapter. Additional approaches may be found at the Institute for Sustainable Infrastructure ([ISI], 2011) and WERF (2011).

Standards provide a framework for greening infrastructure in a sustainable manner. For instance, ASCE, the American Council of Engineering Companies (ACEC), and the American Public Works Association launched a new standards organization and rating system for sustainable infrastructure (ASCE, 2011). ISI's (2011) rating system for sustainable infrastructure aims to be:

- Performance-based (outcomes) rather than prescriptive
- Scalable for size and complexity of projects
- Adaptable for specific needs and circumstances
- Conducive to self-assessment, as well as independent verification
- Voluntary



The demand for water resources will also have to be managed. Two main channels exist to accomplish this (Miller et al., 2005):

- Improve water efficiency – for instance, through price incentives, water transfers, technology improvements, regulations, and reduction of system water loss.
- Effective reallocation of saved water – this could often require regional collaboration and infrastructure and management mechanisms in place for the future.

## 5. Conclusions and recommendations

As discussed in this chapter, water is a significant enabler of economic prosperity and well-being. Water infrastructure is the medium that enables this. This infrastructure faces numerous threats and uncertainty from climate change, which directly leads to water change and subsequent needs to adapt this infrastructure in the face of a myriad of existing drivers, constraints, and expectations of water infrastructure.

A framework is needed to identify, assess, strategize, plan, and act on the risks that this infrastructure faces due to climate change. This chapter has shown how climate adaptation planning and prioritization may be incorporated as a component of risk in what has been identified as a sound, successful, and actionable risk-based asset management program. The chapter has aimed to connect the dots among related best practices in infrastructure climate adaptation assessment, planning, and implementation in a robust, yet flexible manner for the long term.

Additional efforts and knowledge need to be pursued to better define specific climate change impacts on local water and its infrastructure to reduce the level of uncertainty. This information should be shared and leveraged in a collaborative manner through Integrated Water Resources Management, and on a watershed, rather than political, basis when considering water supplies.

Also, ripple effects will be felt throughout associated sectors that are important to infrastructure. These include the banking, insurance, business policy (i.e., U.S. Securities and Exchange climate change disclosure risk requirements, corporate social responsibility, etc.), and industrial sectors.

Very importantly, to successfully enable and implement this adaptation, organizations that manage water and its infrastructure must develop the readiness to address climate change vulnerability and provide strategy for ongoing monitoring with needed adjustments. The organization must develop both the capacity and the capability to adapt its infrastructure, for which sound leadership, knowledge management and transfer, tools, internal and external communication, and possible change management will be needed.

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## **Climate Change - Research and Technology for Adaptation and Mitigation**

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This book provides an interdisciplinary view of how to prepare the ecological and socio-economic systems to the reality of climate change. Scientifically sound tools are needed to predict its effects on regional, rather than global, scales, as it is the level at which socio-economic plans are designed and natural ecosystem reacts. The first section of this book describes a series of methods and models to downscale the global predictions of climate change, estimate its effects on biophysical systems and monitor the changes as they occur. To reduce the magnitude of these changes, new ways of economic activity must be implemented. The second section of this book explores different options to reduce greenhouse emissions from activities such as forestry, industry and urban development. However, it is becoming increasingly clear that climate change can be minimized, but not avoided, and therefore the socio-economic systems around the world will have to adapt to the new conditions to reduce the adverse impacts to the minimum. The last section of this book explores some options for adaptation.

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