United Nations Educational, Scientific and Cultural Organization

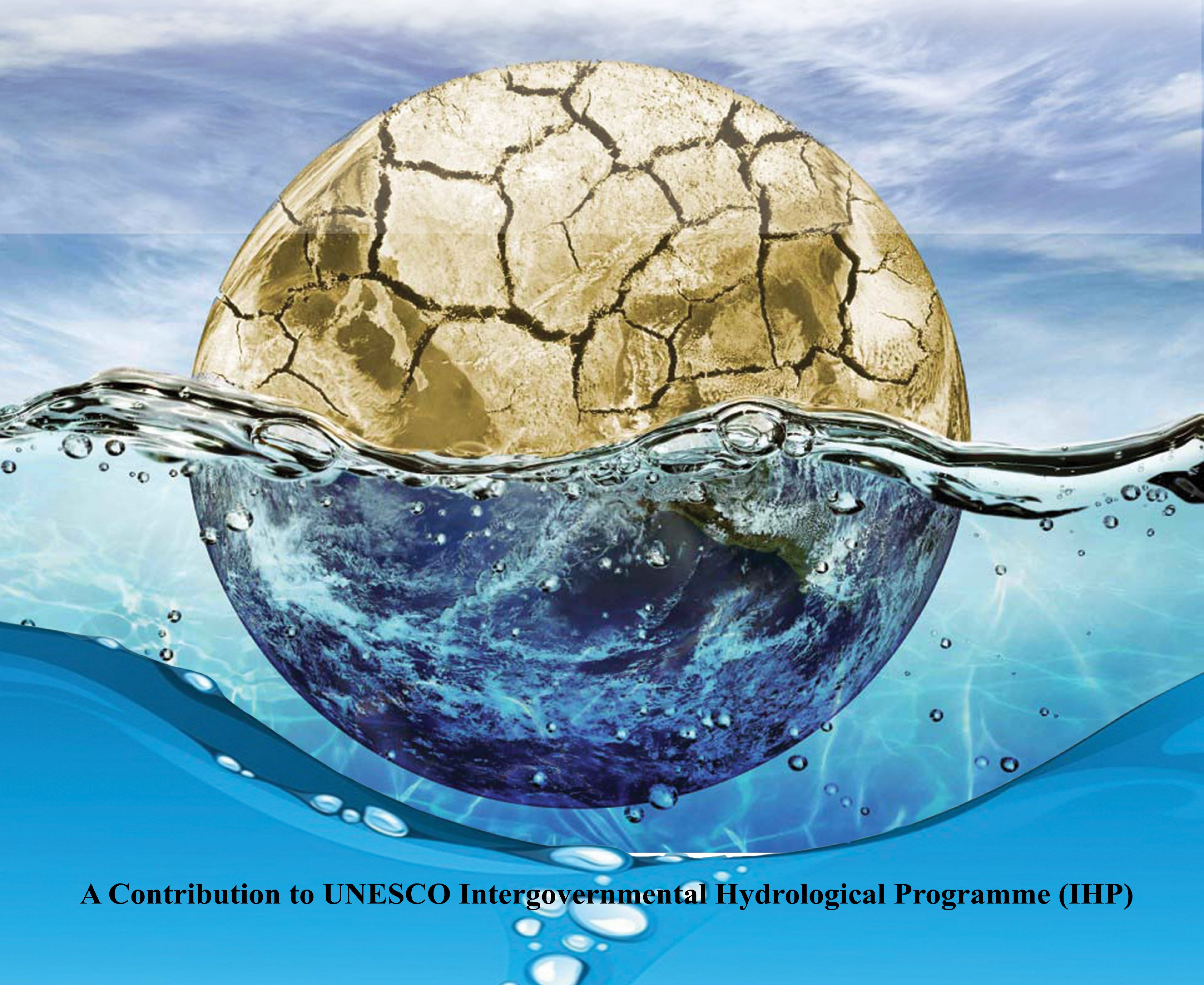
Regional Centre on Urban Water Management (under the auspices of UNESCO)

International Drought Initiative

Water Security in Human Settlements

Best Practices and Lessons Learned in Arid and Semi-Arid Areas

Regional Centre on Urban Water Management (RCUWM)



A Contribution to UNESCO Intergovernmental Hydrological Programme (IHP)

Water Security in Human Settlements

Best Practices and Lessons Learned in Arid and Semi-Arid Areas

Regional Centre on Urban Water Management (RCUWM)

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A Contribution to UNESCO Intergovernmental Hydrological Programme (IHP)

Regional Centre on Urban Water Management (RCUWM)-
Under the auspices of UNESCO, and
International Drought Initiative (IDI) Secretariat

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Foreword

Following the aridity index and its threshold values defined by UNEP, the combination of hyper-arid, arid, semi-arid and sub-humid lands cover 40% of the world's land area, and support two billion people, 90% of whom live in developing countries. According to the UNESCO World Water Development Report (2017) nearly a billion people do not have proper access to safe water and 2.5 billion to safe sanitation. It is worth to note, from those having services, more than 60% do not have a proper and reliable service (intermittent supply). Moreover, about 500 million people live in areas where water consumption exceeds the locally renewable water resources by a factor of 2.

This situation will most probably worsen with the impact of population growth, urbanization and climate change. In regions where water is already scarce, among those where the expected growth in needs of fresh water is the highest; and since the complexity would be added by high population density, these issues will become all the more acute in the urban context. There is a need to understand the importance of water scarcity adaptation to contribute to WATER SECURITY.

Throughout the arid and semi-arid regions worldwide, urban water utilities have defined and implemented solutions as a set of varied responses to the water scarcity challenges of today and of tomorrow. The content of this book is based on the combination of experts' knowledge and case studies from across the arid and semi-arid regions. This book highlights management practices, strategies, and efficient tools developed at urban water utilities specifically in arid and semi-arid regions. It also aims at gathering and at disseminating the recent state of the art and the most significant advances made in this field.

The following main issues were approved to be addressed in the chapters: Fit for purpose water usage and demand management, urban planning, operational efficiency, water quality issues, resilient water services, technological advances and smart water management. The target readers of this book are primarily water utilities and their mid-level managers. However, this book will also include water policy elements for high-level decision makers and managers.

Reza Ardakanian
Minister of Energy of I.R. Iran &
Chairman of RCUWM Governing Board

Foreword

Freshwater is a vital resource for humanity and is at the core of sustainable development. It is indispensable for and is being influenced by all social, economic and environmental activities.

UNESCO's Intergovernmental Hydrological Programme (IHP) defined in its strategy and eighth phase, IHP-VIII (2014-2021), Water Security as the capacity of a population to safeguard access to adequate quantities of water of acceptable quality for sustaining human and ecosystem health on a watershed basis, and to ensure efficient protection of life and property against water related hazards -- floods, landslides, land subsidence and droughts.

The importance of water has been increasingly recognized by decision and policy makers at all levels, elevating it as a Human Right (United Nations General Assembly on 28 July 2010) and ensuring its inclusion in the Agenda 2030 through the Sustainable Development Goal 6 (Ensure availability and sustainable management of water and sanitation for all), the Sendai Framework and the New Urban Agenda.

At the end of the Millennium Development Goals period (1990–2015), the proportion of the global population using safely managed drinking water, increased from 61% to 71%. An additional 19% of the global population used basic water services leaving 785 million people without access to it. Similarly, the global population using safely managed sanitation services increased from 28 per cent in 2000 to 43 per cent in 2015 and to 45 per cent in 2017. The proportion lacking even a basic sanitation service decreased from 44 to 27 per cent. Access to safe drinking water and sanitation is more than ever critical to contain the spread of the current COVID-19 Pandemic. Much remains to be done to reach the new, higher levels of safely managed water supply and sanitation services as defined under the SDGs.

Global challenges such as population growth, urbanization, degradation of water quality, increase in intensity of water related extremes due to global change, are threaten water security in many part of the world. This is more evident in arid and semi-arid regions characterized by low rainfall and increasing water demands which called for resilient solutions to address water scarcity.

In that regard, UNESCO in partnership with the Regional Centre on Urban Water Management developed a publication on "Water Security in Human Settlements: Best Practices and Lessons Learned in Arid and Semi-Arid Areas", which aims to provide water utility operators and decision makers knowledge on how to better to address global water challenges in human settlements located in arid regions.

The book provides information on how to quantify resilience and improve efficiency in managing droughts, use groundwater as a strategic resource, plan for resilient water services. It also offers lessons learned and best practices from arid and semi-arid regions across the world.

We might not be able to stop the effects of global change but we can help to manage them.

Audrey Azoulay
Director General
United Nations Educational, Scientific and Cultural Organization (UNESCO)

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A. Water Security Aspects

An Overview on Water Security in Arid and Semi-Arid Areas

By: Ali Chavoshian, Naser Dehghanian, Niloofar Sadeghi and Alireza Salamat,

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Introduction

Supply of freshwater will be a critical issue in the years to come, with the problems of growing population, climate change, increasing of urbanization and industrialization and grappling with poverty. Therefore, information, assessment and monitoring of water resources will be crucial. The consequences of the increasing global water scarcity will be largely felt in arid and semi-arid areas, in rapidly growing coastal regions and in the mega cities of the developing world. Water scientists predict that many of these cities already are, or will be, unable to provide safe, clean water and adequate sanitation facilities for their citizens – two fundamental requirements for human well-being and dignity.

Cities concentrate people in high-density settlements creating severe demand for services like water supply and sanitation. Hence, they are increasingly forced to transport water from longer distances, often beyond natural watersheds and even across national boundaries. In other cases, over-exploitation of groundwater has resulted in major environmental problems. Over the next years, population growth in developing world will occur mainly in urban areas, as rural populations decline. During 21st century, villages will cease to exist in many countries, and poverty will have been transferred to urban areas. Data from many developing country cities show that the substantial progress in improving water and sanitation in recent decades is now being reversed.

Urbanization and climate change lead to an increased need for studying water management on the urban scale. While in the 1950s only 30% of the world's inhabitants lived in cities, by 2007 this percentage had grown to over 50%. It is expected that by 2050, two-thirds of the world population will be urban dwellers (UN, 2014).

While global and regional climate change threatens water availability, increasing population and enhanced per capita water use with changing lifestyles are already putting stress on the existing water resources. Cities are also becoming increasingly at risk of water shortage as population and economic activities concentrate in cities. Urban areas also demand increasing amounts of water to support the intense pace of activities. The challenge is to make cities resilient to future urban growth and ecological degradation (Ray and Shaw, 2016).

In many cases, the fast rate of urbanization is exceeding the capacity of governments to respond, leading to a variety of water-related problems, such as inadequate water supply, lack of sanitation, failing stormwater management, and ecosystem degradation (Narain et al. 2013). At the same time, climate change is exerting increasing pressure on urban water systems by, for example, aggravating flood hazards due to rising sea levels and increasing the frequency of prolonged dry periods.

Water security is an emerging concept that adds value to the urban water management discourse (Bakker, 2012). In water management studies, the concept complements the dominant integrated water resources management (IWRM) paradigm. Related concepts are things like sustainable, resilient, adaptive, climate proof, and robust urban water management; although these terms have much in common, they emphasize different aspects of urban water management (van Ginkel et al. 2018). The term security implies certain thresholds beyond which a compromise is unacceptable (Bakker and Morinville, 2013).

The objective of this chapter is to describe the concept of urban water security in arid and semi-arid areas and provide some up-to-date information on new relevant technologies in such areas.

Arid and semi-arid areas

Water scarcity is certainly one of the many challenges in urban areas in arid and semi-arid areas of the world, particularly with the rising level of urbanization. The consequences of the increasing global water scarcity will largely be felt in the arid and semi-arid areas, in rapidly growing coastal regions and in the mega cities (populations of 10 million or more inhabitants) of the developing world. It is predicted that many of these cities already are, or will be, unable to provide safe, clean water and adequate sanitation facilities for their citizens – two fundamental requirements for human well-being and dignity.

As a consequence of the ever-growing global population, pressure on water resources is increasing continuously, especially in arid and semi-arid regions. In many cases, the presently applied management practices are non-sustainable and lead to serious water-related problems such as the depletion of aquifers, the accumulation of substances to harmful levels, to water conflicts or economically infeasible costs (Kinzelbach, et al. 2010).

Drylands have been defined by different measures such as the UN Environment Aridity Index (AI) – an annual rainfall and evapotranspiration ratio, and the Aridity Regime (AR) – a ratio between rainfall and evapotranspiration that also considers the duration of the dry period (UNESCO, 2010). According to UNESCO (2010), in the AR, a month is rated as dry if the P/ET (precipitation/evapotranspiration) ratio is less than 0.5 and a dry period duration is the number of months in the year that fulfills this condition. For instance, if the evapotranspiration ratio in a region stays below 0.5 for seven to eight months each year, it is classified as a semi-arid region (Table 1.1).

Table 1.1 Aridity indicators (UNESCO, 2010)

Aridity index	$Ia = P_a/ET_0$
Hyper-arid	<0.05
Arid	0.05 to 0.20
Semi-arid	0.20 to 0.5
Dry sub-humid	0.5 to 0.65
Humid sub-humid	0.65 to 1.0
Humid	>1

Aridity regime	Conditions
Xeric	12 dry months & Ia<0.05
Hyper-arid	11 – 12 dry months
Arid	9 – 10 dry months
Semi-arid	7 – 8 dry months
Sub-humid	5 – 6 dry months
Humid	3 – 4 dry months
Hyper-humid	1 – 3 dry months
Hydric	0 dry months & Pa (Annual precipitation) < 2500mm
Hyper-hydric	0 dry months & Pa > 2500mm

Aridity is defined as a lack of moisture which is essentially a climatic phenomenon based upon the average climatic conditions over a region (Agnew and Anderson, 1992). Arid regions have been identified by climatological mapping. Arid areas were defined as those in which the rainfall is not adequate for regular crop production; and semi-arid areas as those in which the rainfall is sufficient for short-season crops and where grass is an important element of the natural vegetation (Mays, 2014). Of the many classifications based on climate, Meigs (1953) developed a set of maps for UNESCO that received wide international acceptance and were recognized by the World Meteorological Organization (WMO) (Figure 1.1).

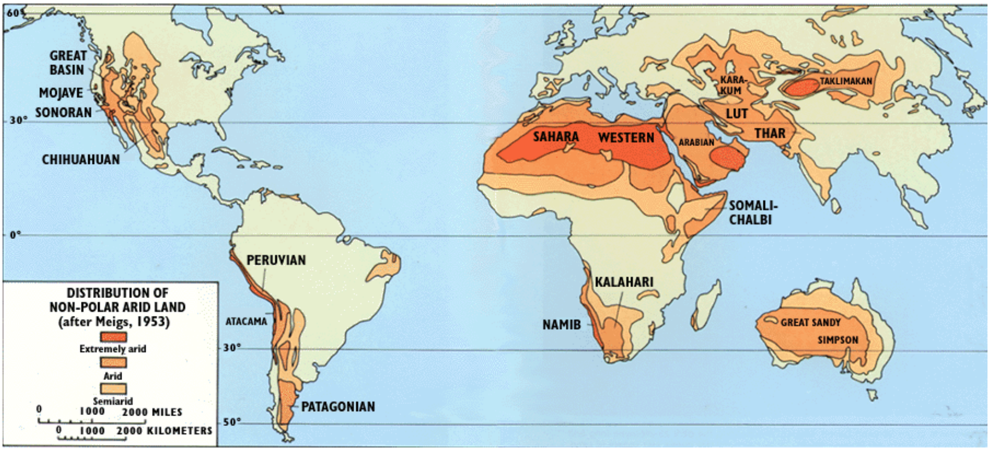

Figure 1.1 Distribution of non-polar arid land (after Meigs, 1953)

According to the climatic classification adopted by UNESCO in 1979, deserts can be classified as (1) semiarid (precipitation less than 500 mm); (2) arid (precipitation less than 250 mm); and (3) hyper-arid (precipitation less than 25 mm). Approximately 16% of the global arid zone is semiarid, 15% arid, and 4% hyper-arid (Tchakerian, 2015). More than one third of the earth's land surface (i.e. 49 million km^2) is arid or semi-arid, receiving less than 400 mm annual precipitation, supporting more than 1.2 billion people, or 20% of the world's population (Wickens, 1998).

Drylands refer to arid, semi-arid and dry sub-humid areas, and, in general, exclude deserts when referred to in the context of sustainable development. Drylands take up 41.3 percent of the Earth's surface. The total drylands population is of 2.1 billion; that is, one in three people live in drylands. The largest such areas are in Asia and Africa. By 2050, human populations in drylands are projected to increase by 40 to 50 percent (Aderita, 2019).

Water scarcity is certainly one of the major challenges in urban areas in arid and semi-arid regions of the world. Figure 1.2 shows regions with projected water scarcity around the world by 2025. Regions suffering from both physical and economic scarcity are also illustrated in Figure 1.2. Balancing water scarcity and population (human demand) is the major challenge in many arid and semi-arid regions of the world (Mays, 2014).

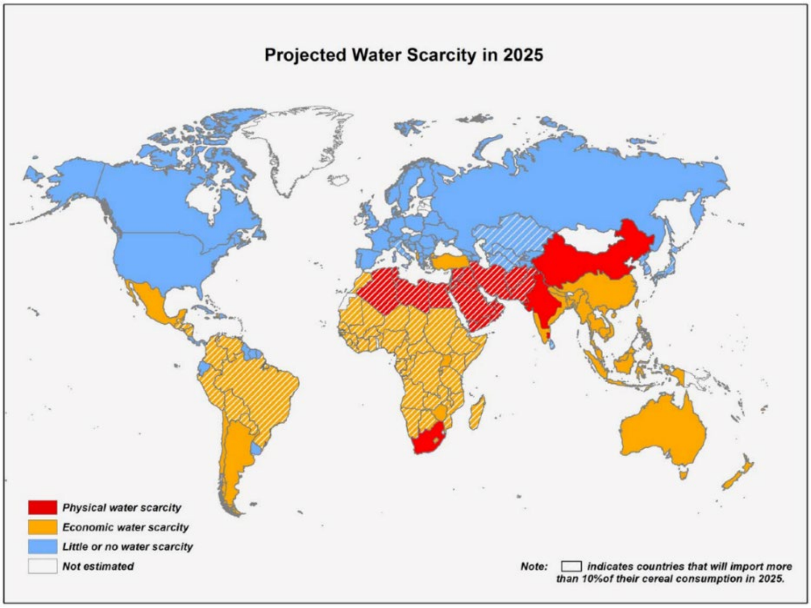

Figure 1.2 Projected physical and economic water scarcity by 2025 (Seckler, et al. 1998).
Note: countries marked with stripped yellow and red lines indicate those that although the respective countries show economic water scarcity, they will however have physical water scarcity by 2025 if no remedial solutions are taken now. The countries marked with stripped blue lines show countries that although they have little or no water scarcity, the trend is moving towards water scarcity by 2025

According to the Figure 1.2, the central and west Asia as well as North Africa regions are the driest water-scarce region in the world in 2025. Current predictions indicate that the global population will reach 9.3 billion by 2050 (UNDESA, 2015); much of this growth is expected to occur in sub-Saharan Africa and Asia, mostly in urban areas. These projections imply that regional water demand for agriculture, domestic and energy generation will increase. This also places emphasis on the region's economic development as it strives to provide a better life for its growing population—water and energy are key to economic development and the attainment of a better life (Mabhaudhi, 2016).

Some countries in the world today do not have sufficient water to meet future demand, which means extremely costly solutions to supplying water will need to be addressed. Such costly solutions often applied in arid climates include water desalination and the seeding of clouds with silver iodide to promote precipitation. The latter only works; however, if some cloud formation is present. Both methods are extremely expensive and make the reduction of lost water as a potential new source in these situations much more attractive. In addition, in arid and semi-arid regions, inter-basin water transfer plan has a long history as a means of addressing water scarcity in one region by transporting additional supplies from regions where water is relatively more abundant. Water quality related problems have also increased in the reservoirs of arid and semi-arid parts of the world due to deforestation, urban runoff and particularly the discharge of untreated sewage.

Water resources in arid and semi-arid areas are very scarce due to the low rainfall and high evaporation. This complicates the supply of water for domestic, industrial and agricultural uses. Water managers in arid areas must therefore have a very clear understanding of the constraints and opportunities of the available water resource base. This will facilitate the development of an appropriate institutional framework to address the challenge of water management. Another prerequisite is that proper policy, laws and regulations should be in place to guide the water manager (Heyns, 2009).

Some of the most important measures to practice water conservation in arid areas are the conjunctive use of surface and groundwater, the re-use of effluent, artificial aquifer recharge, and the utilization of sand storage dams to reduce evaporation. The recovery of the full supply cost of water from the consumers and the application of punitive water tariffs are also very successful in reducing water demand. The desalination of brackish water and seawater finds an application where such waters are available for treatment. The need for arid countries to gain access to perennial rivers that are, internationally shared water sources calls for cooperation with all the involved watercourse States to facilitate joint planning of water supply schemes (Heyns, 2009).

Arid and semi-arid regions are most vulnerable to climate change. Adaptive strategies to manage the climate change risk are necessary to be formulated for countries falling in this category. The measures will vary from one country to another. Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions. For each degree of global warming, approximately 7% of the global population is projected to be exposed to a decrease of renewable water resources of at least 20%. This will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security (Cisneros, et al. 2014). In addition, for many parts of the arid regions there is an expected precipitation decrease over the next century of 20% or more. Even if efforts to reduce greenhouse gas emissions are successful, it is no longer possible to avoid some degree of global warming and climate change. Accordingly, climate change impacts add to already difficult water management challenges in the arid and semi-arid regions (Arab Water Council, 2009).

There are several key policy challenges that have to be confronted for successfully adapting to climate change in respect to water. The first challenge concerns information and data collection and sharing. The current knowledge on the impact of climate change to water resource management requires systematic and well-planned improvement. With accurate scientific data, planning for adaptation, as well as advocacy among stakeholders, will be easier to achieve. On the other hand, the institutional capacity should be strong enough to undertake adaptive measures. In addition, one of the greatest policy challenges would be the financing of climate change adaptive measures. With imperfect information about the magnitude of climate change impact, the allocation of financial resource to construct expensive infrastructures will be a great challenge for developing countries. There is economic value to the information collected on climate change in relation to water. Hence, governments should be encouraged to commit to investments in this objective (Arab Water Council, 2009).

Urban water security

The world is becoming predominantly urban, dominated by human settlements and economic activities. According to the 2018 revision of World Urbanization Prospects, more than half of the global population -4.2 billion people - lives in urban areas, and this number is projected to grow by 68% to 2.5 billion people by 2050. Urbanization, urban water security, and economic growth move in tandem. However, for growth to be sustainable, the urban water security implications of rapid urbanization need to be at the center of the national and municipal development agenda (Aboelnga et al. 2019).

Urban populations demand high quantities of energy and raw material, water supply, removal of wastes, transportation, etc. Urbanization creates many challenges for the development and management of water supply systems and the management of water excess from storms and floodwaters. Many urban areas of the world have been experiencing water shortages, which are expected to explode this century unless serious measures are taken to reduce the scale of this problem (Mortada, 2005). Most developing countries have not acknowledged the extent of their water problems. This is evidenced by the absence of any long-term strategies for water management.

On the other hand, cities often rely heavily on infrastructure to improve water security through transfer, storage and treatment of water and wastewater, so a full picture of water security needs to take account of the impact of infrastructure. Moreover, cities often depend on other administrative jurisdictions for access to water resources and to discharge wastewater and their scale requires strong coordination mechanisms, bringing to the fore the importance of institutions of governance to manage these relationships (Jensen and Wu, 2018).

Urban areas face multiple challenges from climate change. Hence, urban water security is a major concern in the context of urbanization and climate change. While coastal cities are vulnerable to sea level rise and storm damage, flooding from more intense rains and higher peak river flows presents significant threats to cities inland. Failures of sewerage and storm water systems could lead to major disease outbreaks. Intergovernmental Panel on Climate Change (IPCC) reports state that higher water temperatures because of climate change, and an increase in droughts with lower stream flows, will adversely affect water quality due to pesticides, pathogens, sediments, dissolved organic carbon, and thermal pollution (Arab Water Council, 2009).

The concept of urban water security is a multi-faceted one and is interrelated with the broader frameworks and concepts of urban metabolism, ecological security, integrated urban water management (IUWM), the web of water–energy–food securities, risk management, resilient and adaptive water management, and water-sensitive cities. A clear understanding of the synergies and trade-offs between these frameworks will also provide more clarity on what urban water security means and will help with systematically operationalizing the concept of water security, including at the urban level (Aboelnga et al. 2019).

In its most comprehensive interpretation, the concept of urban water security addresses the fulfilment of all different 'water system services', considers overall welfare as well as social equity and environmental sustainability, and addresses both risks and uncertainties. There is an emphasis on supply security and access to safe water, prevention and assessment of contamination of water in distribution systems, the political perspective focusing on power structures, equity issues and conflicts over water, the governance perspective focusing on planning, institutional arrangements and division of responsibilities, the legal perspective focusing on water rights and ownership, and the economic perspective focusing on the efficiency of water resources use, the economics of water demand and supply, water pricing and market mechanisms, cost-benefit analysis of flood risk protection and water quality conservation, valuation of environmental services of water systems, and internalization of externalities (Figure 1.3) (Hoekstra et al. 2018).

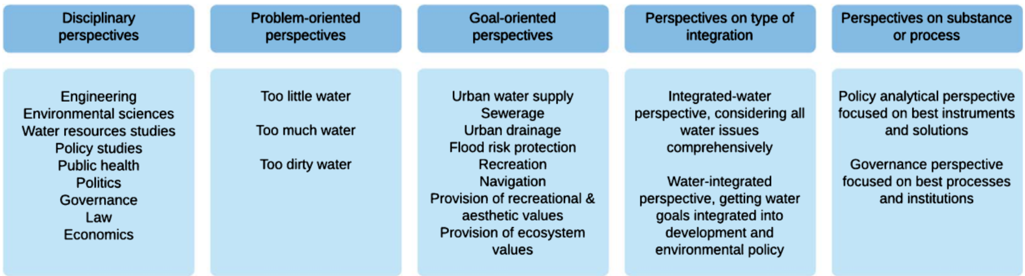

Figure 1.3 Multiple perspectives on urban water security (Hoekstra et al. 2018)

According to Figure 1.3 a true interdisciplinary approach should allow for a much wider array of perspectives, recognizing that water security is intricately linked to human development, governance in broader sense than 'water governance', food and energy security, social equity, and environmental sustainability (Hoekstra et al. 2018).

At present, there is no clearly defined and widely endorsed definition of urban water security. Urban water security is a complex and cross-cutting challenge that needs to be addressed holistically in order to achieve SDG 6. Aboelnga, et al. (2019) proposed working definition of urban water security is based on the United Nations (UN) SDG on water and sanitation and the human rights on water and sanitation. It captures issues of urban-level technical, environmental, and socio-economic indicators that emphasize credibility, legitimacy, and salience. The assessment framework depends on four main dimensions to achieve urban water security: Drinking water and human beings, ecosystem, climate change and water-related hazards, and socio-economic factors (DECS). The framework further enables the analysis of relationships and trade-off between urbanization and water security, as well as between DECS indicators.

However, urban water security is a complex concept, involving water availability, security of water supply, public health risks and water hazards. The disposal of inadequately treated or untreated wastewater into urban waters constitutes a serious risk to human health and represents a major problem across the world. The uncertainties and risks posed by climate change and climate variability with increasingly frequent and intense water-related hazards, and other global drivers such as population growth and urbanization are likely to have significant impacts on the availability and quality of water resources (Cisneros and Rose, 2009).

In this all-encompassing approach, urban water security may be seen more or less as equal to what others would call ‘urban water sustainability’ (when interpreted in its broadest sense as well). Therefore, it can happen that what the one calls a ‘sustainable cities water index’ may actually aim to capture the same as what others would call an urban water security index. A systems approach can be helpful to comprehend the complexity of the urban system, including its relation with its (global) environment, and better understand the dynamics of urban water security (Hoekstra et al. 2018).

Concern with water security is reinforced by the appreciation that the impacts of climate change on people will be felt first and most strongly though the water cycle (Stern, 2007). However, climate change associated with global warming is likely to have a major impact on the reliability and security of urban and rural water systems worldwide. Hence, water utilities should implement a range of adaptation strategies including large commitments to water efficiency for new consumers, water savings for existing consumers. Adaptation will also involve extensive development of new water sources. As many river and groundwater sources are already heavily allocated, there will also be extensive development of new water sources, including water reuse, desalination, and urban rainwater and stormwater harvesting, to restore and maintain the balance between supply and demand. Every water utility needs to overhaul its water supply strategy to be able to meet the future water needs of consumers (Cisneros and Rose, 2009).

Water supply and sanitation services are essential services for human welfare. So far, these services have not been organized and operated in an adequately planned and controlled mode of operation, even in many developed countries. Especially in urban areas, the systems are vulnerable to internal or external disturbance, which might cause severe health, environmental and economic challenges for communities. These kinds of disturbance can include, for example, technical and economic problems (internal) or changes in environment or policy (external). Climate change is one example in external disturbances affecting raw water resources and wastewater management (Laitinen, et al. 2020).

On the other hand, an adaptive approach to water management can address uncertainty due to climate change. Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible and low-regret solutions that are resilient to uncertainty. Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication (Cisneros, et al. 2014).

Urban water security is strongly related to resilience (Hoekstra et al. 2018). Water supply and sewer networks are technically and financially remarkable parts of sustainability and resilience in water services, however these are not the only aspects of water and sewer network management. In order to achieve Sustainable water demand management (SWDM), political, financial, technical and legal control and a variety of methods are needed. For example, 100% coverage of metering, pricing policy on water withdrawal, development of surface water sources and penalty or discount according to meeting the consumption goals (Laitinen, et al. 2020).

Below is a summary of the core elements necessary to achieving and maintaining urban water security, as found in a broad range of published definitions (UN Water, 2013):

- Access to safe and sufficient drinking water at an affordable cost in order to meet basic needs, which includes sanitation and hygiene, and the safeguarding of health and well-being;
- Protection of livelihoods, human rights, and cultural and recreational values;
- Water supplies for socio-economic development and activities (such as energy, transport, industry, tourism);
- Collection and treatment of used water to protect human life and the environment from pollution;
- The ability to cope with uncertainties and risks of water-related hazards, such as floods, droughts and pollution, among others; and,
- Good governance and accountability, and the due consideration of the interests of all stakeholders through: appropriate and effective legal regimes; transparent, participatory and accountable institutions; properly planned, operated and maintained infrastructure; and capacity development.

Water crisis indices

Perception of water crisis depends on the degree at which a system feels vulnerable. One way to measure the relative level of water crisis is to look at the indicators of water supply security. A weighted combination of reliability of supply and any reserve resources; vulnerability of the system to a high impact on the available safe water supply; and resiliency of the system to return to the satisfactory state of operation, shows the state of the systems' readiness to face a crisis.

A. Reliability

Regarding water supply system, reliability is the probability that no failure occurs within a fixed period of time. Based on this definition, reliability is the opposite of risk, in which the probability of system failure is expressed (Karamouz et al., 2003). Thus, reliability is conceptually related to the probability of system failure, and the rate, occurrence, and consequences of failure can be measured in several different but related ways, depending on the needs and relevance of the particular situation.

The stability and reliability of water distribution systems (WDS) is one of the important factors in ensuring public safety and the continuous operation of urban functions. Such functions include water supply, infrastructure construction and industrial development, etc. It is also the key field for infrastructure construction (Yazdani and Jeffrey, 2011).

The WDS is a large scale network system with complex topological structure. Its functions are designed to convey volumes of water to customers under adequate pressure. Nowadays, along with the increased population and population density, WDS is developing into wide-range supply which carries fluid under high or less pressure. A WDS can be represented as a spatially networks of multiple interconnected components. Pipes can be represented as links. Junctions, reservoirs and consumers can be represented as a collection of nodes. With the link-node representation of physical components in WDS, complex network analysis can be applied to evaluate the system reliability (Yazdani and Jeffrey, 2011).

The reliability is also defined as the probability that the WDS meet flow and pressure requirements under the possible mechanical failure scenarios (e.g., pipe breaks). Mathematically, the reliability can be expressed as the ratio of the available flow to the require demand (Shuang, et al. 2014).

Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions. This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change (Cisneros, et al. 2014).

B. Resiliency

Resilience has become a vital theme in the discussion concerning urban water services. Some special challenges are faced for urban water cycle due to disasters and climate change impacts. In order to prepare for recovering from these situations as soon as possible, and for providing uninterrupted water services, the water utility must become more resilient. Resilience in this context can be defined as both keeping up a good level of services, as well as rapid and fluent recovery from failures caused by natural disasters, unsound infrastructure or incorrect management (Laitinen, et al. 2020). In many countries, where water supply and sewer networks in cities are aging, resilience of urban water services is subject to risk of malfunction of deteriorated networks (Krueger et al. 2017).

Resilience in water services has no definite definitions in literature. The term has been increasingly used, especially during the last few years. United Nations International Strategy for Disaster Risk (UNISDR, 2009) defined the term resilience as follows: “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner”.

Resiliency describes how quickly a system recovers from failure once failure has occurred. In other words, resiliency is basically a measure of the duration of an unsatisfactory condition. It is perhaps the most important indicator of crisis recovery and how successful the management of disaster has been.

Although adequate water services resilience can be considered as sustainable, resilience is a wider concept than sustainability. Indeed, resilient water services and systems are the foundation of well-being, and resiliency is the key for sustainable water services (Howe, et al. 2011). In order to call water services resilient, all sections from policy and management to technical operation should be clear and coherent, and their operation in challenging situations also must be guaranteed. Sufficient technology and good water quality are not sufficient for achieving resilient water services, but also education and institutional management are essential issues (Laitinen, et al. 2020).

C. Risk management and vulnerability

Cities should be resilient to environmental conditions that affect water use, the stresses in the existing water supply infrastructure and to lifestyle changes. However, micro-level units in each city and the whole city in general differ considerably in terms of vulnerability and water stress. Hence, separate action plans may be formulated for cities to ensure sustainable water systems and resilient cities. An assessment and identification of the vulnerabilities and challenges in the existing urban water systems are a prerequisite to formulate water action plans in the urban areas (Ray and Shaw, 2019).

Vulnerability is a measure of extent of the differences between the threshold value and the unsatisfactory time series values. Clearly this is a probabilistic measure where some use expected values, some use maximum observed values, and others may assign a probability of exceedance to their vulnerability measures. Vulnerability analysis is a worthwhile tool in evaluating the entire event chain causing water crisis. Recovery analysis means a systematic investigation how a system returns to the state of normal operation (Karamouz et al., 2003)

The vulnerability of a system is a function of three elements including exposure (to disaster effects), sensitivity and adaptive capacity. Systems that are highly exposed, sensitive and less able to adapt are vulnerable (Figure 1.4). Therefore, adaptation strategies involve the identification of sectors/systems/regions vulnerable to change and an examination of the scope to increase the coping capacity of those systems - their resilience - which in turn will decrease that vulnerability (TOT, 2009).

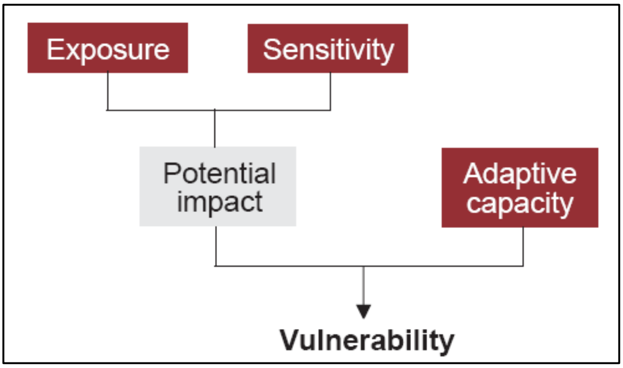

Figure 1.4 Vulnerability and its components (Australian Greenhouse Office, 2005)

This approach to vulnerability assessment is important because it highlights the key elements that combine to amplify (or alleviate) the costs and risks that disasters can impose on a system. Understanding these elements can help us identify the threat from disasters, and action in each of these areas can help us reduce or deal with that threat (TOT, 2009).

There are many risks that may adversely affect the management of urban water systems. These risks can be caused by climatic variation (causing droughts or floods), mechanical failures, poor management, and health risks from pollution and water-borne diseases. The consequences of these risks can be considered in terms of financial, environmental, health, cultural and ethical impacts (to name a few), short-term, long-term and cumulative risks. Managing risk involves understanding the factors that contribute to that risk's causality (TOT, 2009).

By better understanding these risks and the factors that influence their magnitude, better decision-making processes can be implemented to create improved solutions for urban water disasters throughout a region. Excellent risk management planning does reduce risk, but rarely eliminates it. Thus appropriate contingency plans will need to be produced to effectively manage risk issues should they materialize. For example, is there adequate capability to monitor public health and respond to outbreaks of widespread diseases? (TOT, 2009).

D. Coverage and safety

Water supply coverage is the percentage of households with access to tap/ piped water supply. In addition, sewerage network coverage is of importance in accessing the sanitation as well as in ensuring access to sanitation and thus reducing public health risk. It is calculated as proportion of households with a sewerage system connection in percent (Jensen and Wu, 2018). In this regard, there are two important ratios calculated at country level by World Health Organization (WHO)[1] which are as follow:

- Proportion of population using improved drinking water sources
- Proportion of population using improved sanitation facilities

According to the WHO maps, the high water supply and sanitation coverage of Europe and North America seems to indicate that there are not pressing urban water problems in these regions. However, there are certainly difficulties linked to failing infrastructure. Some of the major problems are:

- Aging of the underground utilities, causing deterioration of water quality in distribution systems and leakage of wastewater from aged sewers causing adverse trends in the groundwater table;
- The insufficient capacity to cope with increased loads, causing frequent spills of combined sewer overflows, jeopardizing the quality of receiving water bodies;
- Flooding of settlements built-up in floodplains;
- Stormwater pollution (ignored in the past);
- Reluctance or slowness in gaining acceptance of innovative solutions based on source control (industrial and stormwater);
- Low priority or lack of care for urban streams and other urban water features; and
- Inappropriate institutional framework for efficient integrated urban water management.

Water safety and quality are fundamental to human development and well-being. Providing access to safe water is one of the most effective instruments in promoting health and reducing

1 https://www.who.int/gho/en/

poverty. Accordingly, the WHO Guidelines for drinking-water quality recommend water safety plans (WSPs) as the most effective means of consistently ensuring the safety and acceptability of a drinking-water supply. WSPs require a risk assessment including all steps in water supply from catchment to consumer, followed by implementation and monitoring of risk management control measures, with a focus on high priority risks. WSPs are adaptable to all types and sizes of water supply, and can be effectively applied in all socioeconomic settings. The water safety planning approach is increasingly being adopted globally as best practice for the provision of safe drinking-water (WHO, 2019).

Urban water security indices/ indicators

Among the broad definitions and assessment frameworks for water security, several well-established indicators have been applied at the city level to provide different perspectives on water security (Falkenmark, 1989). The most widely used indicators include:

- Stand-alone indexes, such as the water stress index and the water poverty index (Sullivan, 2002; Jensen and Wu, 2018). These are conceived to be applied at all levels, including at the city level, but they are not salient and narrow enough to capture the dynamics and multiple aspects of urban water security. In addition, the thresholds used are often arbitrary and not based on scientific principles (Aboelnga et al. 2019).
- Composite indicators, such as Asian Development Bank's urban water security index (Asian Development Bank, 2016), which forms part of its national water security rankings, using averages of all urban areas, and is thus likely to be used by decision-makers at the urban level. A city-specific water index can be developed and applied by including the city blueprint framework (CBF) to capture issues of urban water security, but it seeks specifically to measure the implementation of IWRM principles in different cities, and also to benchmark cities on their resilience at the social, economic, and environmental dimensions as 'water wise' or 'water sensitive' cities, as conceived in the IWRM perspective (World Economic Forum, 2019).

Some indicators are very widely used to benchmark the performance of public and privately owned water utilities as part of public management and regulatory processes (Berg and Marques, 2011). These indicators usually include measures of operating performance (i.e. coverage, service continuity, drinking water quality, leakage) and of financial performance (Danilenko et al., 2014). As water utilities are often city-level organizations, there may be considerable overlap between utility benchmarks and water security indicators. However, an important difference is the more comprehensive nature of water security indicators and their links to policy objectives, rather than managerial targets.

Asian Development Bank (2016) proposed the water security dimensions comprised of water security of household and urban areas, water security for economic development, urban water use, river health and resilience to disaster. The water security status is determined from five dimensions of water security index (WSI): WSI1 or basic water (renewable supply and sanitation), WSI2 or sufficient water (for water supply, consumption, use in agriculture), WSI3 or development water (irrigation water, industrial water use, water used in the energy sector and water for aquaculture), WSI4 or water disaster (floods and drought) and WSI5 or water for future (population growth, population growth in urban areas, water footprint). The index status thus analyzed was correlated with water productivity (US $ per cubic meter of water) with countries categorized into four groups in terms of per capita GDP. The indicators available from various sources were normalized and the index for each country is determined with ranking from average and standard deviation values. Based on the index, the distribution of water security status of 146 countries was calculated.

Jensen and Wu (2018) developed urban water security indicators (UWSI) based on the UN definition of water security (UN Water, 2013) and pilot them in two cities, Singapore and Hong Kong cited as being highly water insecure. They derived four perspectives from their working definition which specify different elements embedded in urban water security including resource availability, access, risk and capacity. These perspectives signal the direction of change required to improve water security. A more water-secure city can be achieved by increasing resource availability and access, minimizing water related risks, and enhancing management capacity.

Van Ginkel, et al. (2018) developed an urban water security dashboard of 56 indicators based on the pressure-state-impact-response (PSIR) framework. They applied the dashboard to ten cities to capture different characteristics of their water security and ranked the cities based on their overall water security index score. The highest level of water security was found in water-abundant and wealthy cities such as Amsterdam and Toronto, in which security is determined by the ability of the city to mitigate flood risks and the sustainability of hinterland dependencies for water supply. A desert city (such as Dubai) may reach a reasonable level of security but at the cost of energy consumption in desalinating sea water. However, before turning to unconventional sources and reducing water use, cities - especially those located in water-scarce environments - overexploit locally available resources. Megacities in emerging economies suffer from water insecurity even when located in favorable environments because their claim on the available resources is simply too large. The largest insecurities were found in cities in developing countries, for which all water system functions are inadequately fulfilled, even those that are not facing significant environmental pressures. The lowest security was found in developing cities (Nairobi, Lima, and Jakarta). The combination of large socioeconomic pressures (e.g., rapid population growth, slums, low GDP, polluting industries) and an inadequate response (weak institutions, and poor planning and operational management) leads to inappropriate fulfilment of all functions of the urban water system.

On the other hand, a wide variety of indicators are used for benchmarking water utilities. It is important that, in addition to indicators for the performance of the physical infrastructure, there are also indicators illustrating management and financial performance. These indicators point out that “There is a need to better understand the full potential of water-sensitive design, rainwater harvesting, recycling, reuse, pollution prevention and other innovative urban water approaches” (Hoekstra et al. 2018).

Ray and Shaw (2016) identified the parameters and indicators to assess water security in urban areas and resilience in the urban water system for sustainable development. Indicators have been used as a tool to describe the physical, socio-economic and institutional dimensions of urban water security. They summarize complicated measurements into simple ones easy to comprehend and highlight the main characteristics of the system. Apart from physical water scarcity, cities in Asia also suffer from water insecurity, often magnified by improper water management. Hence in the listing of indicators, greater emphasis has been given to institutional dimensions of urban water security. Ray and Shaw (2019) also prepared a listing of 50 indicators under the physical, socio-economic and institutional dimensions of urban water security based on the various water security indices and variables that are in use to identify water stress and potential threats to human and environmental water security in urban areas (Table 1.2).

Table 1.2 Indicators for urban water security (Ray and Shaw. 2019)

Dimension	Criteria	Parameters/indicators
Physical	Water quantity	Surface water reserve
		Groundwater reserve
		Source of freshwater supply to city
		Annual rainfall in mm
		Water availability per capita per year (>1700 m^3)
	Water quality	Total coliform and faecal coliform
		Total dissolved solids
		Hardness
		Contaminants like iron, fluoride and arsenic
		Industrial pollutants
	Provisioning	Total withdrawal for municipal supply in MGD
		Hours of supply
		% of area covered by municipal supply
		% of population covered by municipal supply
		%of population dependent on alternate water supply
Socio-economic	Affordability	%of households with individual tap connection
		% of metered connection
		% of population in slums
		Convenient source of water in slums
		Household expenditure on water services
	Livelihood	Population with access to safe water sources
		Daily per capita water supply
		Water vendors
		Manpower employed in the water sector
		Household expenditure on waterborne diseases
	Education and knowledge	% of population with knowledge on safe water
		% of students as dropouts to collect water
		% of population affected by waterborne diseases
		% of population using purification techniques
		Community-based capacity building
Institutional	Water management	Loss due to leakage
		Groundwater in city water supply in MGD
		Water treatment
		Wastewater treatment and reuse as % of total generated
		Booster pumping stations
	Disaster risk	Frequency of disasters like flood and drought
		% of population affected by floods and drought
		Fall in ground water level in meters
		Storm water drainage
		Sewage generated and capacity of sewage treatment plant
	Resilience	Cost recovery
		Rainwater harvesting
		Desalinization options and capacity
		Protection of natural water bodies
		Revamping the existing municipal water supply system
	Governance	Budget allocation for the water sector
		External Fund sourcing
		Private –public partnership
		Legislation related to water supply
		Water audit

Urban water security requirements and new technologies

Ensuring universal access to safe and affordable drinking water for all by 2030 requires investing in adequate infrastructure, providing sanitation facilities, and encouraging hygiene at every level. Protecting and restoring water-related ecosystems such as forests, mountains, wetlands and rivers is essential for water scarcity mitigation. More international cooperation is also needed to encourage water efficiency and support treatment technologies in developing countries[1].

The urban water system is considered as a single integrated whole. Urban water management is considered herein as consisting of two major entities, urban water supply and urban water excess management systems. Urban water supply systems include all the system components to provide drinking water and distribute it to users in addition to all the system components needed to collect and treat the wastewaters. Special emphasis is given to technologies, such as artificial recharge, water transfers, desalination, and harvesting of rainfall, which are typically not part of the conventional urban water supply systems, but are used in arid and semi-arid areas as viable sources of water supply. Water excess management systems include both the stormwater management system and the floodplain management system. In the big picture, integrated water management must include:

- The systematic consideration of the various dimensions of water: surface and groundwater, quality and quantity.
- The implication that while water is a system it is also a component which interacts with other systems.
- The interrelationships between water and social and economic development.

Water resources sustainability must be a major overall goal of water management. Many urban areas of the world, particularly in developing parts of the world, are unsustainable from the viewpoint of water (Mays, 2014).

Nature-based solutions

New solutions are required to managing water resources to offset the rising challenges to water security from population growth and climate change. Goal 6 of the 2030 Agenda for Sustainable Development recognizes the importance of ensuring the availability and sustainable management of water and sanitation. Nature-based solutions (NBS) are essential to meet this goal. Indeed, NBS are one of many important tools to shift to a more holistic approach to water management (WWAP/UN-Water, 2018).

The need to ensure that adequate volumes of water of suitable quality are made available to support and maintain healthy ecosystems has long been established. But, nature also plays a unique and fundamental role in regulating different features of the water cycle, in which it can act as a regulator, a cleaner and/or a supplier of water. As such, maintaining healthy ecosystems directly leads to improved water security for all (WWAP/UN-Water, 2018).

1 https://worldmapper.org/maps/housing-basicsanitation-2015/

There are several different types of NBS for water, ranging in scale from the micro/personal (e.g. a dry toilet) to landscape-level applications that include conservation agriculture. There are NBS that are appropriate for urban settings (e.g. green walls, roof gardens and vegetated infiltration or drainage basins) as well as for rural environments which often make up the majority of a river basin's area. In addition, the NBS idea is not necessarily to replace human-built ('grey') with green infrastructure, but to identify the most appropriate, cost-effective and sustainable balance between grey infrastructure and NBS considering multiple objectives and benefits. On the other hand, current obstacles, such as the lack of knowledge, capacity, data and information about NBS for water, can be effectively overcome (WWAP/UN-Water, 2018).

There are a number of mechanisms that can be used to accelerate the uptake of NBS for water. Payment for environmental services schemes and green bonds have been shown to generate interesting returns on investment while lowering the need (and costs) for larger, often more expensive infrastructure required for water resources management and the delivery of water supply and sanitation services (WWAP/UN-Water, 2018).

NBS for water are central to achieving the 2030 Agenda for Sustainable Development because they generate social, economic and environmental co-benefits, including in the fields of human health and livelihoods, food and energy security, sustainable economic growth, decent jobs, ecosystem rehabilitation and maintenance, and biodiversity. The substantial value of these co-benefits can tip investment decisions in favor of NBS. Moreover, implementation of NBS involves the participation of many different stakeholder groups, thus encouraging consensus-building and helping to raise awareness about what NBS can truly offer to improve water security (WWAP/UN-Water, 2018).

NBS are able to enhance overall water security by improving water availability and water quality while simultaneously reducing water-related risks and generating additional social, economic and environmental co-benefits. They allow for the identification of win-win outcomes across sectors. For example, watershed restoration and protection has become increasingly important in the context of meeting multiple challenges in sustaining water supplies to rapidly growing cities and reducing risks in them. Urban green infrastructure can yield positive results in terms of water availability, water quality and flood and drought reduction. In the context of water and sanitation, constructed wetlands for wastewater treatment can be a cost-effective NBS that provides effluent of adequate quality for several non-potable uses, including irrigation, as well as offering additional benefits, including energy production (WWAP/UN-Water, 2018).

NBS have also high potential to meet contemporary and future water resources management challenges, as reflected in the 2030 Agenda for Sustainable Development, the SDGs and their targets. Since water underpins most social and economic aspects of the SDGs, it is widely recognized as cross-cutting most of the SDGs and their targets. Therefore, the contributions of NBS to SDG 6 translate into further water-related benefits for other SDGs and their targets, alongside contributions from non-NBS interventions (WWAP/UN-Water, 2018).

Water Sensitive Urban Design

Water Sensitive Urban Design (WSUD) embraces a range of measures that are designed to avoid, or at least minimize, the environmental impacts of urbanization in terms of the demand for water and the potential pollution threat to natural water bodies (Melbourne Water, 2015). Moreover, WSUD is an approach to urban planning and design that integrates the management of the total water cycle into the urban development process. It includes (DPLG, 2009):

- Integrated management of groundwater, surface runoff (including stormwater), drinking water and wastewater to protect water related environmental, recreational and cultural values;
- Storage, treatment and beneficial use of runoff;
- Treatment and reuse of wastewater;
- Using vegetation for treatment purposes, water efficient landscaping and enhancing biodiversity; and
- Utilizing water saving measures within and outside domestic, commercial, industrial and institutional premises to minimize requirements for drinking and non-drinking water supplies.

Therefore, WSUD incorporates all water resources, including surface water, groundwater, urban and roof runoff and wastewater. WSUD recognizes all water streams in the total water cycle as valuable resources (DPLG, 2009):

- Rainwater (collected from the roof);
- Runoff (including stormwater, collected from all impervious surfaces);
- Potable mains water (drinking water);
- Groundwater;
- Greywater (from bathroom taps, showers and laundries); and
- Blackwater (from kitchen sinks and toilets).

By applying appropriate measures in the design and operation of development, it is possible to (DPLG, 2009):

- Maintain and restore the natural water balance;
- Reduce flood risk in urban areas;
- Reduce erosion of waterways, slopes and banks;
- Improve and protect water quality of surface and groundwater;
- Make more efficient use of water resources;
- Reduce the cost of providing and maintaining water infrastructure;
- Minimize demand on the reticulated water supply system;
- Protect and restore aquatic and riparian ecosystems and habitats;
- Protect the scenic, landscape and recreational values of streams;
- Minimize treated wastewater discharges to the natural environment;
- Integrate water into the landscape to enhance visual, social, cultural, biodiversity and ecological values; and
- Reduce greenhouse gas emissions by reducing water consumption, increasing rainwater harvesting and ‘natural’ treatment alternatives.

Table 1.3 contains a summary of the WSUD measures.

Table 1.3 WSUD Measures: role, focus, , site conditions and benefits
(Council, 2005; Knox City Council, 2002)

Measure	Focus of WSUD measure: Water quality	Focus of WSUD measure: Water quantity	Potential benefits	Suitable site conditions	Unsuitable conditions
Demand reduction	Low	High	Reduction in mains water supply.	Residential, commercial and industrial sites.	Where water quality does not meet end use requirements
Rainwater tanks	Low	High	Storage for reuse. Sediment removal in tank. Frequent flood retardation.	Proximity to roof. Suitable site for gravity feed. Need to incorporate into urban design.	Non-roof runoff treatment. Where tank water is not used on a regular basis
Rain gardens	Medium	High	Volume retention. Water quality improvement.	Allotment scale	Reactive clay sites. Near infrastructure
Green roofs	Medium	Medium	Retention of water. Biodiversity.	Flat roofs, slopes up to 30 degrees	Roofs that are not structurally suitable
Infiltration systems	High	Medium	Volume retention. Water quality improvement.	Precinct scale	Non-infiltrative soils. High groundwater levels
Pervious pavements	High	Medium	Retention and detention of runoff.	Allotments, roads and car parks	Severe vehicle traffic movement and developing catchments with high sediment load
Urban water harvesting and reuse	Medium	High	Reduction in mains water supply.	Residential, commercial and industrial, generally more viable for precinct scale sites	Locations where demand is limited or adverse impacts to downstream users
Gross pollutant traps	High	Low	Reduces litter and debris. Can reduce sediment. Pretreatment for other measures.	Site and precinct scales	Sites larger than 100 ha. Natural channels. Low lying areas
Bioretention systems	High	Low	Fine and soluble pollutants removal. Streetscape amenity. Frequent flood retardation.	Flat terrain	Steep terrain. High groundwater table
Swales	Low	Low	Medium and fine particulate removal. Streetscape amenity. Passive irrigation.	Mild slopes (< 4%)	Steep slopes
Buffer strips	High	Low	Pre-treatment of runoff for sediment removal. Streetscape amenity.	Flat terrain	Steep terrain
Sedimentation basins	High	Medium	Coarse sediment capture. Temporary installation. Pretreatment for other measures.	Need available land area	Where visual amenity is desirable

Measure	Focus of WSUD measure		Potential benefits	Suitable site conditions	Unsuitable conditions
	Water quality	Water quantity			
Constructed wetlands	High	Medium	Community asset. Medium to fine particulate and some soluble pollutant removal. Flood retardation. Storage for reuse. Wildlife habitat.	Flat terrain. Need available land area	Steep terrain. High groundwater table
Wastewater management	Medium	High	Nutrient reduction to receiving environments. Fit for purpose substitution.	Where adequate treatment and risk management can be ensured	

Urban water management: institutional, legal and socio-economic perspectives

The subject of urban water is an obligatory theme in the agenda of all governments that have a commitment to promoting quality of life and public health. To achieve this goal requires promotion of the practice of integration for all main actors in the urban arena (Parkinson, et al. 2010).

Urban water management requires a process of articulation between different stakeholders who must act in an integrated way to harmonize the balance between the availability of water resources and the demand from domestic, commercial and industrial consumers. It focuses on the provision of adequate water quality conditions for the urban population and promotes sustainable use of water resources, taking into account all the corresponding social, economic and environmental interfaces within catchments (Parkinson, et al. 2010).

The development of policies for urban water management is important for the establishment of strategies to solve complex themes inherent to urban waters. Spatial questions aside, attention is required to address the complex set of socio-political issues related to urban conurbations and metropolitan regions (Parkinson, et al. 2010).

The main financial instruments that have a direct application on urban water management are the following (Parkinson, et al. 2010):

- Tax and credit-related incentives
- cost-recovery fees
- charging for use of the water, and
- Marketable licenses.

A summary of the problems and causes associated with the subject of urban waters is presented in the following table.

Table 1.4 Some key problematic issues in urban water management and their causes (Parkinson, et al. 2010)

Problems	Causes
Low priority attributed to the subject of water resources	Lack of political interest and competing sectors demanding use of limited financial resources
Poor coverage and access to infrastructure and services	Rapid urbanization, social exclusion, lack of institutional capacity to plan for infrastructure expansion, insufficient investment capacity in relation to demand
Poor operation and maintenance of existing infrastructure	Lack of effective cost-recovery mechanism and willingness to pay
Poor skills and technical capacity	Lack of training and poor salaries
Increasing environmental emergencies (particularly flooding)	Climate change, lack of monitoring, and poor system for flood preparedness
Contamination of water supply systems and bodies	Lack of good sanitation and effluent treatment
Increasing environmental emergencies with high incidence of urban inundations	Absence of a strategic approach, which would enable the system to, through a process of continuous evaluation, incorporate successful experiences and reorient efforts in a synergic way

The idea of a new approach to the management of urban waters has, as its starting point, the paradigm that water is a finite natural resource, with social and economic value. Adopting this approach helps to identify efforts that are necessary to reverse actions contributing to the lack of sustainability in the context of urban waters and their interface with public health, quality of life and environmental protection (Parkinson, et al. 2010).

One of the recommended actions to achieve this objective is the strengthening of inter-institutional relationships between countries, promoting the harmonization of legal frameworks, with special attention to the effective and efficient management process of urban waters towards achieving environmental sustainability. Common legal structures for defining general principles and guidelines can also be established for defining specific public policies related to urban waters, and to provide solutions to conflicts related to urban water management (Parkinson, et al. 2010).

This synergy of efforts and responsibilities assures a more favorable political– institutional environment for attracting public and private investments, international grants and loans, making credible the implementation of management policies for urban water. However, it is the combination of national contexts and the specifics of local environments that present significant challenges related to the development of integrated and strategic policies for managing urban waters (Parkinson, et al. 2010).

Many of these challenges are greater in unplanned areas where low-income populations have settled. Hence, the costs for implementing integrated solutions tend to be higher than in more consolidated urban areas. Overcoming this problem requires greater efforts between urban planners, engineers, social scientists and community facilitation specialists. It is essential that projects applicable to urban waters, such as the implementation of sewerage networks, water supply systems, collection and disposal of solid waste, drainage, and treatment units develop in a way that is compatible and integrated with other projects designed to engineer the environment and bring about improvements to other forms of urban infrastructure and services (Parkinson, et al. 2010).

This integration, from the perspective of public administrations, requires the structuring of policies and actions supported by proper institutional arrangements, which assure the allocation of responsibilities to the appropriate agencies involved. There is therefore a need for institutional training support to ensure sustainability of those policies and the corresponding actions. This also requires the participation of local stakeholders and communities (potential beneficiaries) in the planning and implementation of those strategies (Parkinson, et al. 2010).

At the regulatory level, the development of appropriate instruments such as levels of service standards, discharge permits and licenses to operate is required. However, in advance of this, there is a need for higher-level political acceptance and authorization for the need for institutional reform, which requires policy statements to support the reform process (Parkinson, et al. 2010).

The insertion of transparency is an important component of the reform process. This requires the engagement of key stakeholders from government, the private sector and civil society as part of the process of reversing established problems, and in the development of strategies to implement new plans. Engaging and enabling local stakeholders to become actors in the implementation process requires the integration of policies, plans, programmes and projects that contribute within a systematic approach to improvements to the local environment, and the instigation of better quality water and sanitation services. Water is an issue that can bring together stakeholders from different sectors to identify priorities of mutual benefit, connect policies, and develop the strategic and participatory planning tools to help negotiate and resolve conflicts (Parkinson, et al. 2010).

When considering the complexity of the subjects involved in the context of urban water management, and its relationship with social, economic and environmental components, it is mandatory to establish and structure information systems and a set of indicators to support the formulation, implementation and evaluation process of urban water policies. These systems should favor the integration of information from the various sectors related to the subject of urban water, understanding that the effectiveness and sustainability of management depends on the appropriate operation of the components. These include water supply and sewerage services, drainage and solid waste disposal systems, territorial planning, the water resource system and transport systems, amongst others. A suitable information system, with integrated indicators, favors understanding of the way in which the different components work and what potential risks they can pose to the management of urban waters (Parkinson, et al. 2010).

The analysis of policies for water resource management and their respective technical, economical, legal and institutional management instruments highlights the need for much greater efforts and resources to support intersectoral collaboration (Parkinson, et al. 2010).

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Water Scarcity Adaptation in Human Settlements

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Introduction

Technically, there is a sufficient amount of fresh water on a global scale, but the regions facing water scarcity have been growing significantly over time. Water use has been growing at more than twice the rate of world population growth in the last century (UN-Water, 2006) mostly due to changes in lifestyle, rapid urbanization, and inconsistency between the geographical distribution of population and renewable water resources. 3.6 billion people worldwide (nearly half the global population) are already living in potential water-scarce areas at least one month per year, and this could increase to 4.8–5.7 billion until 2050 (UNESCO, 2018). Consistent with the growing number of people and regions facing water scarcity, publications on water scarcity assessment have increased dramatically in the last two decades (Liu et al., 2017) and many indicators have been developed to assess the level of water stress and scarcity across the world.

Since water resources used for supplying urban water demands are shared with industrial and agricultural water users in many basins, this chapter presents water scarcity causes and indicators and adaptation interventions for all urban, industrial, and agricultural sectors. In many basins with shared water resources between water consuming sectors, water scarcity adaptation in for example agriculture or industrial sectors, can be much more effective on sustaining water resources needed for supplying urban water demands than adaptation interventions in the urban water systems.

Water Scarcity Definition

Water scarcity can be defined as the lack of adequate available water resources to meet the demands for water within a country, a basin, or in a region. In other words, water scarcity is an excess of water demand over available supply. Water scarcity can happen because of physical shortage, which defines a lack of water availability due to natural dry climate or impacts of climate change, or improper access to water. In other words, physical water scarcity defines a situation in which, there is not enough water to meet all water demands including domestic, industrial, agricultural, and environmental water needs. Physical water scarcity usually results in competition between water consuming sectors over getting formal water allocation licenses, groundwater resources depletion and overdraft, and environmental degradation.

Economic water scarcity is a result of inadequate or inefficient investment in infrastructure leading to inappropriate water distribution among users and sectors and less affectivity of investments in the water sector in poverty reduction. Inappropriate access to water can happen as a result of a failure in regular water supply due to lack of adequate infrastructure or mismanagement of water utilities and water management organizations. Water scarcity can also be a social construct and a result of water-intensive lifestyle and behaviors stemming from the illusion of affluence.

The World Water Development Report (UN-Water, 2006) defined water scarcity as:

"The point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully [...], and can occur at any level of supply or demand. Scarcity may be a social construct (a product of affluence, expectations and customary behavior) or the consequence of altered supply patterns stemming from climate change. Scarcity has various causes, most of which are capable of being remedied or alleviated."

Water Scarcity Causes

Causes of water scarcity can be classified to physical and anthropogenic. Physical causes of water scarcity can be further classified to:

- Natural dryness
- Climatic variability and change
- Little or no aquifer storage

Natural dryness when population exceeds the carrying capacity (explained in section 1.6) can cause water scarcity exacerbation. Lack of groundwater storage usually creates a high chance of vulnerability against seasonal and annual variability of surface runoffs due to natural climate variability and occurrence of dry (low precipitation) spells. Climate change as a result of greenhouse gas emissions has resulted in global warming and acceleration of the water cycle, which has led to alterations in geographical and temporal precipitation variations. In many arid and semi-arid regions such as those located in the Middle East and North African (MENA) region, climate change impacts can be characterized as less annual precipitation and more evapotranspiration losses.

Anthropogenic causes of water scarcity, as stated by Alcott (2010), can be classified to those related to population, affluence, technology. Alcott (2010) proposed Eq. (1) for assessing human impacts on the environment (anthropogenic impacts) (HI):

$$HI = f(P \times A \times T) \tag{1.1}$$

Where:

P: Population;

A: Affluence (a ratio) is consumption of resources, goods, or services per person;

T: Technology is a broad term showing how an economy produces goods and services and consumes resources under legal rules, institutional settings, governance mechanisms, and technologies available.

Adopting Eq. (1) to define influencing factors on water scarcity level in a society, Alcott (2010) classifies effective policies on reducing human impacts on the environment to two sets of left- and right-side policies. The so-called right-side policies are those influencing P, A, and T.

It is expected that by increase in population, water use and scarcity level increase. Affluence can represent the level of water consumption per person for domestic purposes and or volume of water used for producing various goods (agricultural, industrial, etc.) or services used by the people. Water-intensive life style can be an example of affluence. As nations develop and their economies grow, consumption of resources increases too. Changes in lifestyle are usually followed by increased per capita water use and popularity of water-intensive diets leading to further pressure on scarce water resources. Technology, in Eq. (1.1), can refer to various causes of water scarcity including the followings:

- Institutional and mismanagement causes:
  - Lack of suitable organizational settings
  - Lack of effective legislation
  - Lack of technical capacity and expertise
  - Short-sighted policies such as over-allocation of water
  - Corruption of water management organizations
- Socio-economic causes:
  - Improper land-use
  - Lack of investment in infrastructure development
  - Over-development of hydraulic infrastructures such as upstream diversions and multiple dams in a single river basin
- Political Causes
  - Food self-sufficiency policies due to political reasons such as limited international trading possibilities
  - Political popularity gained by water allocation or hydraulic infrastructure development
  - Lack of comprehensive agreements in trans-boundary river basins

Improper organizational settings and legislation can result in mismanagement of limited water resources and over allocation of these resources to users with less productivity. More advanced and flexible water allocation approaches such as water markets, which can improve water use efficiency over time need strong legislation and proper technical and law enforcement capacities. Over-allocation of water resources can create a constructed water scarcity. It can happen as a result of double-counting of groundwater and surface water rights. Over-allocation of groundwater resources occurs more frequently due to lack of licenses limiting extraction, granting too many permits and low. Corruption in the water sector affects the governance of water by altering the spatial and temporal distribution of access to water. It also affects how costs are distributed among individuals, society, and the environment (Stålgren, 2006).

Excessive expansion of irrigated agriculture is a typical example of improper land use. It usually happens where water is provided at a meager price or free or federal funds are allocated in favor of agriculture development. Agriculture sectors accounting for very high percentages of total water demands in many countries are responsible for ensuring certain levels of food security. Countries with limited possibility for food trade due to lack of financial sources or specific foreign policies seek food self-sufficiency leading to overexpansion of irrigated lands and low water productivity.

Lack of investment in infrastructure development in less developed or developing countries can also limit access to safe and clean water even in places with no physical water scarcity. In contrast with the basins lacking needed hydraulic infrastructure, over-development of hydraulic infrastructures can also be the leading cause of constructed water scarcity (Molle, 2008). In many river basins especially in developing countries, building large dams has increased the possibility of regulating surface runoffs to the extent that most annual runoffs in wet years can be allocated to water users. This situation usually leads to expansion of irrigated areas and other water-intensive economic activities to the extent that in dry years, water demands cannot be supplied, creating a general perception of water scarcity and generating calls for additional investments in water saving technologies. Wet years, instead, are seen as lost opportunities, when 'excess' water flows to the sea or out of the country. This situation often translates into new inter-basin water transfer or reservoir development. Molle (2008) found out that over-development of hydraulic infrastructure and growing constructed scarcity often results from an alliance of financial and political interests rather than from any legitimate 'need'. The pressure to 'save' any single drop of water from 'running to the sea' or 'flowing out of the country' is often politically very strong and leaves no chance for careful economic, environmental and social assessment of needs for further development.

Political reasons such as limited international trading possibilities or global food crises and jumps in food prices in the international markets (such as the case of 2007-08) have forced some countries to follow food self-sufficiency policies at least in specific periods. These policies can result in water scarcity especially in countries with arid and semi-arid climates. As water scarcity grows to more and more severe levels in unsustainable countries/regions, water gains more attraction as a commodity that brings political popularity. For instance, the administrative elite has rigged water management in various parts of Pakistan in favor of powerful landlords to patronize political allies and harass opposition parties (Mustafa 2002, Wegerich and Hussain 2016, Zulfiqar 2018). Gaining political popularity and power through attainment of water right permits or government funds for water transfer or large-scale hydraulic infrastructures in already fully developed basins have been sources of constructed water scarcity in many basins. Improper institutional settings have also created a suitable platform for such political corruption of water sectors in some countries (Madani et al. 2016).

Munia et al. (2018) reported that 386 million (14% of the total transboundary population) out of 1175 million people who live under water stress in transboundary river basins (42% of the total transboundary population) experience water scarcity because of water use by upstream population. "Hydro-political dependency" is an essential source of water scarcity in transboundary river basins.

Alcott (2010) defines left-side policies as those directly lowering impact with no reference to P,A or T. These policies address the following causes of water scarcity:

- Over-extraction of surface and groundwater resources
- Low water prices or free water

Over-extraction of water resources is very common in water scarce countries. Groundwater resources are among the most vulnerable when there is no cap on extraction of water resources. Water is a public good and is considered nonexclusive because people cannot be excluded from consuming it. Exclusions costs required to keep those not entitled from extracting water from a surface or groundwater body are usually very high; therefore, water resources are usually considered to be nonexclusive (Karamouz et al. 2003). The most common approach to limit water extraction is to design and implement a practical water pricing system. Further details on water tariffs and economic incentives for water scarcity adaptation are presented in this chapter.

Water Scarcity Indicators

Three major approaches have been used in the literature for assessing water scarcity. The first approach focuses on the state variables such as rainfall, population, land use, climate, etc. as physical causes of water scarcity. The indicators used for this type of assessment are driven by geospatial factors ignoring the role of human actions in intensifying or controlling water scarcity. Water Stress Index (WSI) explained later in this section is among these indicators.

The second approach for water scarcity assessment tries to combine socio-economic and physical/geospatial causes of water scarcity. Water Poverty Index (WPI) and Social Water Stress Index (SWSI) introduced later in this section are examples of the indices developed based on the second approach. The first and second approaches have been mostly used for comparing the general status of water scarcity in different countries, but they do not offer a roadmap to finding policy solutions at the local or regional scales (Srinivasan et al. 2012).

The third approach tries to identify the causes and consequences of water scarcity in case study basins. These studies are usually more detailed and differ in assessment methodologies and indices utilized and research questions. Because of these differences, it is generally difficult to compare their results to come up with a generalization (Srinivasan et al. 2012), but they can help to define policy solutions for damping water scarcity.

Table 2.1 shows a list of some of the frequently used indicators for quantifying physical water scarcity. WSI introduced by Falkenmark (1986) measures physical water scarcity as the per capita surface runoff generated in a country or in a basin. WSI, if estimated based on surface runoff, implicitly assumes changes in soil moisture and groundwater storage are negligible. It neglects inter-annual and spatial variabilities in surface runoffs, which can be very significant in many water-scarce regions and countries. It also considers a typical water consumption level of 100-600 people per flow unit based on the assessment carried out in some industrialized countries by Falkenmark (1986, 1989). This level of water consumption can vary significantly if the level of economic development changes. WSI has been used very often since it is very simple to estimate and it can be easily used for comparing regions/basins/countries. Even though surface runoffs were used in early applications of this indicator, later it has been used to quantify the level of water stress based on the per capita renewable water resources in some countries and by many researchers. Inverted WSI also shows a number of people that compete with each other in accessing a single flow unit of water and therefore represents "hydraulic density of population". Thresholds for classification of WSI and inverted WSI are shown in Table 2.2.

Another index for quantifying physical water scarcity was introduced by Raskin et al. (1996) as the freshwater Withdrawal to Availability (WTA) ratio. As shown in Table 2.1, WTA is equal to the ratio of water withdrawals for municipal (M), industrial (I), and agricultural (A) purposes to the long-term average annual runoffs. Table 2.3 shows the thresholds for water stress levels quantified by WTA. Even though WTA is a more accurate index of water stress than WSI since it accounts for water consumed by sectors, but it still has its own drawbacks of not differentiating between consumptive and non-consumptive water uses and neglecting groundwater and soil moisture variations.

The following indicators, which are very similar to WTA were also used by UN-Water and FAO to assess progress on achieving SDGs and MDGs:

Table 2.1 Physical water scarcity indices

Index name/ Reference	Definition/pros/cons	Formula
Water Stress Index (WSI) (Falkenmark 1986, 1989)	WSI, also known as Falkenmark indicator or the Water Crowding Index, measures the fraction of total annual runoff (MARR) available for human use. This definition, implicitly assumes changes in soil moisture storage and groundwater storage are negligible. It neglects inter-annual variabilities in surface runoffs, which can be very significant in many water-scarce regions. It does not also take into account water stresses caused by growing water demands associated with economic development. This index is very easy to estimate and can be used effectively for comparing water stress levels of various countries and regions.	$\mathrm{WSI} = \frac{\mathrm{Population}}{\mathrm{MARR}}$
Withdrawal-to-availability ratio (WTA) (Raskin et al. 1996)	WTA is equal to the ratio of total annual withdrawals of municipal (M), industrial (I), and agricultural (A) sectors to annual (renewable) resources estimated based on long-term average annual runoffs. WTA similar to WSI neglects soil moisture and groundwater storage variations and inter-annual variabilities of surface runoffs. It does not differentiate between consumptive and non-consumptive water uses, and there are difficulties related to return flows and reuse of water by various users/sectors when estimating this index.	$\mathrm{WTA} = \frac{\mathrm{M} + \mathrm{I} + \mathrm{A}}{\mathrm{MARR}}$
MDG water indicator	This indicator is equal to the ratio between total water withdrawal by M, A, and I sectors over Total Renewable Freshwater Resources (TRWR). It is hard to be quantified because of the lack of reliable data of water used by various sectors and possibility of double accounting of reused return flows.	$\text{MDG Water Indicator} = \frac{\mathrm{M} + \mathrm{I} + \mathrm{A}}{\mathrm{TRWR}}$
SDG indicator 6.4.2	This indicator quantifies water stress percentage as the ratio between Total Freshwater Withdrawn (TFWW) by all major sectors and Total Renewable Freshwater Resources (TRWR), after taking into account Environmental Flow Requirements (EFR). This indicator is hard to be quantified because of the lack of reliable data of water used by various sectors and possibility of double accounting of reused return flows.	$\text{Water Stress (\%)} = \frac{\mathrm{TFWW}}{\mathrm{TRWR} - \mathrm{EFR}} \times 100$

Table 2.2 Water Stress Index (WSI) thresholds

Water stress category	WSI threshold (m3capita−1 year−1)	Inverted WSI* (people/106 m3 flow)
No stress	>1700	<600
Water scarcity	1700-1000	600-1000
Water stress	1000-500	1000-2000
Absolute water stress	<500	>2000

* Inverted WSA estimated considering a typical water-consumption level of 600 people/106 m3 in some industrialized countries (equal to 1667 m3 capita−1 year−1) based on the study carried out by Falkenmark (1989) (Damkjaer and Taylor, 2017).

Table 2.3 Withdrawal-to-availability ratio (WTA) thresholds

Water stress category	WTA threshold
Low water stress	<0.2
Medium water stress	0.2-0.4
Severe water stress	>0.4

- The Millennium Development Goals (MDG) water indicator (FAO-AQUASTAT, 2012): It measures the level of human pressure on water resources based on the ratio between total water withdrawal by M, A, and I sectors over total renewable water resources.

SDG indicator 6.4.2 (FAO, 2018): It quantifies water stress percentage as the ratio between Total Freshwater Withdrawn (TFWW) by all major sectors and Total Renewable Freshwater Resources (TRWR) minus the Environmental Flow Requirements (EFR).

These indicators entail the same difficulties in estimating WTA such as double accounting of reused return flows and lack of time series of water used by various sectors. All of the aforementioned indices only account for physical water scarcity while as mentioned before, water scarcity is a multi-dimensional phenomenon highly influenced by economic status and institutional capacities available in a country. In the past two decades, several indicators have been introduced by which non-physical aspects of water scarcity have also been taken into account. Some of these indicators are listed in Table 2.4. WPI introduced by Sullivan (2002) proposes a relationship between the water availability, its accessibility, and the level of community welfare by five components:

1. available water resources,
2. access to water,
3. capacity for water management,
4. water uses for domestic, industrial and agricultural purposes and
5. Environmental protection.

Table 2.4 Socio-economic and physical water scarcity indices

Index name/ Reference	Definition/pros/cons	Formula
Water Poverty Index (WPI) (Sullivan, 2002)	WPI employs a multi-dimensional approach to represent the capacity for maintenance of ecosystems. It is formed by five components: (i=1) available water resources; (i=2) access to water; (i=3) capacity for water management; (i=4) water uses for domestic, industrial and agricultural purposes and (i=5) environmental protection. Since the weights in estimating WPI are usually selected based on expert judgment and there are not standard equations for estimating five components of the index, WPI values are not usually useful for comparative studies. Lack of data in many regions makes estimating WPI very difficult.	$\mathrm{WPI} = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i}$
Social Water Stress Index (SWSI) (Ohlsson, 2000)	SWSI integrates the adaptive capacity of a society to consider how economic, technological, or other means affect the overall freshwater availability status of a region. It is a function of wealth, education opportunities and political participation as represented by the UNDP Human Development Index (HDI) and the Falkenmark Indicator. There have been arguments that HDI does not represent the adaptive capacity of nations against water scarcity since there are high correlations between HDI components and simple economic indicators.	$\mathrm{SWSI} = \frac{\text{Inverted WSI}}{\text{HDI}} \times \frac{1}{\text{Scalar}}$ (Scalar = 2) (Ohlsson, 2000)

Table 2.5 Social Water Stress Index (SWSI) thresholds (Ohlsson, 2000)

SWSI intervals	Inverted WSI/SWSI Score	Degree of Stress
0-5	>1700	Relatively sufficient
6-10	1700-1000	Water stress
11-20	1000-500	Water scarcity
20+	<500	Absolute water scarcity

Before estimating WPI, the five components are standardized to fall in the range of 0–100. While WPI is a comprehensive index, lack of data for some of the components is the main obstacle against its application. SWSI proposed by Ohlsson (2000) tries to explicitly address ‘adaptive capacity’ in coping with water scarcity. Distributional equity, political participation, and access to education are taken into account in the estimation of SWSI by using the Human UNDP Development Index (HDI). HDI incorporates non-physical factors such as life expectancy, adult literacy, and per capita GDP in assessing the adaptive capacity of a country for coping with water scarcity. Table 2.5 shows the Social Water Stress Index (SWSI) thresholds as suggested by Ohlsson (2000).

In the case-study oriented approaches for assessing levels, causes, and trends of variations of water scarcity, more detailed variables for defining the type and quantifying the level of water of scarcity can be used. As an example, Srinivasan et al. (2012) compared 22 different case studies using the following indicator variables:

1. Persistent lack of access to minimum quantity of water for drinking and hygiene needs for much of the population
2. Persistent lack of access to minimum quantity of water to satisfy subsistence livelihood needs for much of the population, resulting in extreme poverty
3. Highly unequal distribution of access to water: some have plentiful water supply while others have none
4. Temporary lack of access to minimum quantity of water for drinking and hygiene needs
5. Temporary lack of water for livelihood needs, resulting in sudden but temporary declines in income and wellbeing
6. Persistent and adequate supply of high-quality potable water for most of the population
7. Persistent and adequate supply of water for agricultural water demands
8. Long-term decline in quantity of water stock available to future generations (groundwater levels or lake area)
9. Aquatic ecosystem decline
10. Long-term trend of decline in quality of water stock available for future generations (large-scale groundwater or surface water contamination)
11. Long-term recovery of previously depleted water stock
12. Aquatic ecosystem recovery

Urban water scarcity indicators

Water scarcity indicators such as WPI, SWSI, and WSI are less useful for measuring water scarcity in the urban context. Water scarcity in urban areas has to be assessed by taking into account multiple influencing factors such as various sources of water, water supply and treatment and wastewater collection and treatment infrastructure and organizational settings of water and wastewater utilities and urban water governance system as a whole (Jensen and Wu, 2018). To design a holistic and integrated framework for urban water scarcity assessment, first, "urban water security" has to be defined. Jensen and Wu (2018) proposed the following definition of urban water security based on the UN definition of water security (UN Water, 2013):

> "The capacity of a city to safeguard sustainable access to adequate quantities of acceptable quality water to sustain livelihoods, human wellbeing, and socio-economic development for its inhabitants and to ensure reasonable protection against water-borne pollution and water-related damage, and to establish and preserve healthy ecosystems in the city and its catchment".

In order to take into account these multiple aspects in water security assessment in urban areas, methodologies such as Driving Force-Pressure-State-Impact-Response (DPSIR), System Dynamics Modelling (SDM), and Process Analysis Method (PAM) have been used by various researchers so far. The results of these approaches are usually in the form of a set of multiple indicators each addressing certain influencing factor. Some of the recently developed frameworks/indicators for assessing urban water security based on DPSIR (or PSIR), SDM, and PAM approaches are as follows:

- Water Provision Resilience Index (Milman and Short, 2008)
- Sustainability Index for Integrated Urban Water Management (Carden and Armitage, 2013)
- City Blueprint (Van Leeuwen et al., 2012; Koop and Van Leeuwen, 2015)
- Sustainable City Water Index (Arcadis, 2016)
- Urban Water Security Indicators (Jensen and Wu, 2018)
- Urban Water Security Dashboard (Van Ginkel et al. 2018)

Water Provision Resilience, proposed by Milman and Short (2008), provides a measure of the ability of an urban water provider to maintain or improve the percent of population with access to safe water into the future. This indicator uses six color codings, each representing a measure of the ability of the water system to maintain or improve the current percent of the population with access to safe water in key areas of the water provision sector: <u>supply</u>, <u>infrastructure</u>, <u>service provision</u>, <u>finances</u>, <u>water quality</u>, and <u>governance</u>.

The Sustainability Index for Integrated Urban Water Management proposed by Carden and Armitage (2013) include 16 indicators and 35 variables in four main <u>social</u>, <u>economic</u>, <u>environmental</u>, and <u>institutional</u> components. The indicators/variables used in this index require both qualitative and quantitative data over widely differing ranges. Therefore, standardization on a categorical scale has been necessary in estimation of this index.

The City Blueprint developed by Van Leeuwen et al. (2012) is a framework comprising of 24 indicators for assessing sustainability of urban water management systems. It can be used to assess and compare the status of Integrated Urban Water Management (IUWM) in various cities. Later, Koop and Van Leeuwen, (2015) proposed an updated version of City Blueprint, by differentiating between trends and pressures (on which urban IWRM has a negligible influence) and IUWM performances. The modified version of the City Blueprint focused on aspects of urban water security, which are further controllable by water utilities.

The *Sustainable City Water Index* was developed by Arcadis (2016) as a tool to help inform future improvement and long-term water sustainability. The index distinguishes three main categories: <u>resiliency</u> (water stress, green space, water-related disaster risk, flood risk, water balance, and water reserves), <u>efficiency</u> (leakage, water charges, service continuity, wastewater reuse, metered water, drinking water, and sanitation) and <u>quality</u> (drinking water, sanitation, treated wastewater, water-related disease, water pollution, and threatened freshwater species).

Urban Water Security Indicators proposed by Jensen and Wu (2018) based on PAM, are classified in the four following categories:

- Resource availability: availability of water resources (either surface or groundwater or other sources of urban water such as desalination, rainwater harvesting, etc.), taking into account diversity, quality and renewability of the resources.
- Access: the extent of access to water for human use, including both domestic and industrial water uses, taking into account water treatment capacity, coverage and affordability.
- Risk: the extent of water related risks such as flood and health related risks.
- Capacity: institutional capacity to manage water supply and water demand, and water-related disasters.

Urban Water Security Dashboard, proposed by Van Ginkel et al. (2018), uses 56 indicators covering all relevant aspects of the PSIR framework for urban water security assessment. The dashboard groups indicators (tier 1) into categories (tier 2). Further aggregation results in quantification of pressure, state, impact, and response in the PSIR framework (tier 3), which eventually combine into the Water Security Index Score (tier 4).

The concept of water saving

A system that is suffering from water scarcity is one that is unable to provide enough water to meet the demands in the right location and time. One logical way to address this challenge is to save water for decreasing the gap between supply and demand. Reducing consumptive and non-consumptive water uses can both be effective in reducing this gap but on very different scales. To analyze the effectivity of water saving interventions, one must pay attention to the definitions and differences between consumptive and non-consumptive water uses and water withdrawals (adapted from Karamouz et al. 2003):

- Water withdrawal is the water removed from the ground or delivered from a surface water source for offstream uses.
- Consumptive water use is the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment and is no longer available for use. A significant change in water quality in a way that water will no longer be usable by other water users even if water is not removed from the sources can be classified as consumptive water use as well. Consumptive water uses can further be classified to the following two components (FAO 2017):
    - Beneficial Consumption such as crop transpiration, evaporation from cooling towers, etc.
    - Non-beneficial Consumption such as evaporation from free water surfaces and wet soil, transpiration by weeds, etc.
- Non-consumptive water uses remain in liquid status after use. Instream water uses (hydropower generation, navigation, fisheries, etc.), which does not significantly change the quality or quantity of withdrawn water, while almost all of it remains in the system or returns to it are examples of non-consumptive water uses. Non-consumptive water uses can be further classified to the following two components (FAO, 2017).
    - Recoverable flows (returning to a river or aquifer for potential reuse)

- o Non-recoverable flows (flowing to the sea or significantly polluted water bodies or other economically unviable sinks)

The term "significant change" in the definitions above might be defined differently according to the standards or regulations used in various countries (FAO, 2010). Figure 2.1 shows the schematic of a river basin in which two dams regulate water for irrigation and urban water supply. There is an interaction between surface and groundwater resources by which groundwater recharges surface water resources. Return flows from FARM 1 and CITY recharge groundwater and return flows from FARM 2 recharge surface runoffs, which eventually drains to the lake. Consider the case of deficit in supplying environmental flow recharging the lake resulting in lake drying up. An intervention of irrigation efficiency improvement in FARM 1 & 2 if maintaining the level of crop production, reduces the water withdrawal from the river but also reduces the return flows to the system and thus basin-wide, does not help in the lake restoration. The same argument can be made for an intervention of water loss reduction from the water distribution network in the CITY as the losses recharge groundwater and surface water resources in the basin. The local effects of these interventions are however different. For example, water loss reduction in CITY and fewer water withdrawals for FARM 1 result in less pressure on DAM 1 for supplying water for urban and agricultural purposes but do not necessarily have a significant impact on water balance in DAM 2.

Now consider a different status for the aquifer shown in Figure 2.1, which is recharged by the wastewater from the city and return flows from FARM 1. If not properly treated, the recharging flows contribute to water quality degradation of the aquifer. If significantly polluted, the water leakage from the urban water distribution network is considered lost from the system (same as evaporated water) and therefore, any intervention related to water loss reduction from the urban water distribution network is considered effective on reducing consumptive losses (2030 WRG, 2013). When assessing the impacts of interventions on water saving in a basin, the following indicators can be assessed locally, while an integrated assessment in the whole basin is also necessary (adapted from 2030 WRG, 2013):

- *Water withdrawals from surface and groundwater resources*: The level of positive impact is equal to the reduction in the volume of water withdrawn from a source.
- *Recharge of groundwater resources*: The level of positive impact is equal to the excess recharge of the groundwater source. It should be noted that same amount of storage in surface water bodies involves much higher evaporation losses, which should be considered when assessing the impacts of an intervention.
- *Consumptive water uses*: The level of positive impact of consumptive water use reduction has to be measured carefully since most interventions for reducing consumptive uses reduce return flows as well (such as replacing surface irrigation with hi-tech irrigation in agriculture sector in absence of close monitoring and control of water abstracts (FAO, 2017)). Cases of increase in production (either agricultural or industrial) usually result in further consumptive uses unless carefully gathered evidence indicate a specific reason to the contrary. Overall, the level of positive impact can be measured as the reduction of non-beneficial consumptive uses for producing the same product. If the product itself is changed, the beneficial consumptive uses may also change (such as

changing the crop mix in agricultural lands), and thus the level of positive impact can be measured as the reduction in beneficial and non-beneficial consumptive uses.

- *Variations in water quality*: Positive impact of an intervention can be measured as improvement in quality of water in a system or increase in volume of water saved from entering to significantly polluted water bodies.
- *Water productivity*: The level of positive impact can be quantified as the amount of increase in the economic value of production per unit of beneficial consumptive water use
- *Net basin impact*: The level of positive impact can be measured as the reduction of water evapotranspiration from a basin plus improvement in the water quality and reduction of water flow to the sea or significantly polluted surface or groundwater bodies.

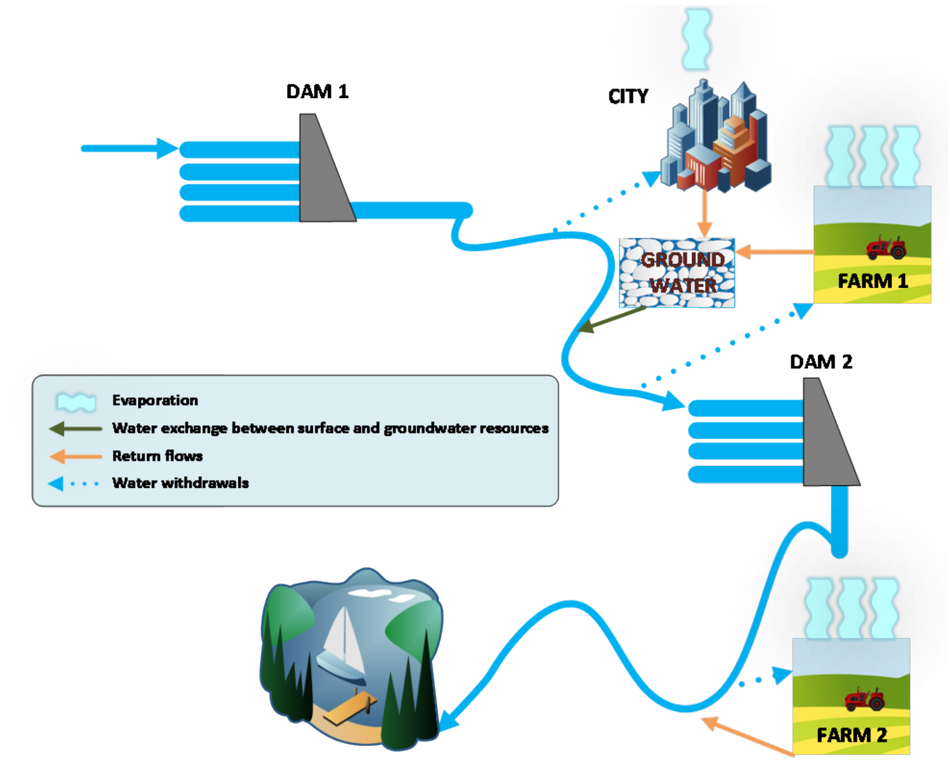

Figure 2.1 Schematic of surface and groundwater resources, withdrawals, and return flows in a river basin

Water resources overshoot and oscillation

The carrying capacity of a biological species in an environment is the maximum population size of the species that the environment can sustain indefinitely, given all the resources available in the environment. Ecological overshoot refers to the phenomenon by which the population of a species temporarily exceeds the carrying capacity of its environment. When overshoot occurs, the species in question degrades the quality of its habitat, reducing carrying capacity and thus the ability of the environment to support a smaller population in the future. This is a how nature controls the growth of species with reference to resource availability (Meadows et al. 2004). Large exceedance from the carrying capacity of ecological systems may lead to a terminal overshoot and collapse. Collapse may also happen as an oscillating overshoot cycle around the carrying capacity (Mirchi et al. 2014).

Water is an important resource in nature. Water resources carrying capacity can help policy makers to understand how the socio-economic systems are supported and restrained by the water resources system characteristics. Figure 2.2 shows overshoot and collapse behaviors in relation to the level of water consumption. Figure 2.2.a shows variations of water use due to natural fluctuations of water availability in a basin/country with stable economic and water use status. As dry periods happen naturally or severity of droughts increases as a consequence of climate change, water use may go beyond water resources carrying capacity, which can result in degradation of carrying capacity. Water resources carrying capacity of various nations/basins may be very different. Adaptive capacity of communities against water scarcity is the main factor that can assist in avoiding carrying capacity degradation. Figure 2.2.b shows an unsustainable situation of extensive growth of water scarcity as a result of for example: over development of hydraulic infrastructure, population growth, or declining supply due to climate change or groundwater depletion. Figure 2.2.b shows a large perturbation from carrying capacity, which resulted in overshoot and collapse and significant loss of carrying capacity. After collapse, due to decrease in carrying capacity, significant reduction of water use should happen to keep the water resources system sustainable.

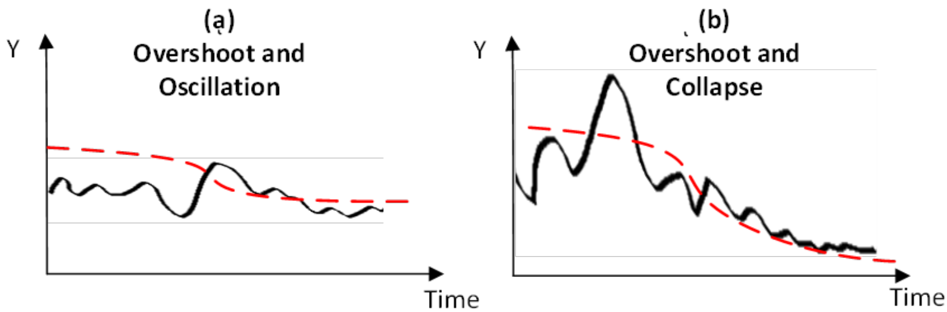

Figure 2.2 Water resources overshoot in a basin/country

(Y=Volumetric water use (black line), the dashed red line shows carrying capacity of water resources)

Interventions for Water Scarcity Adaptation

Various success stories of water scarcity adaptation across industrial, agricultural, and municipal sectors have been reported in the literature. A list of major classification of these interventions is presented in Table 2.6. Further details of interventions in each class are provided in this section; however, it should be emphasized that this list is not complete and there might be other successful interventions, which are not reported here. Further details on some of these interventions are presented in the next sections of this chapter.

Table 2.6 Interventions for water scarcity adaptation
(A: Agriculture, I: Industrial, M: Municipal)

Intervention	Sectors
Water accounting and auditing	A, I, M
Climate-smart agriculture and reduction of food losses and waste	A, M
Reduction of per capita water demand and change of life style	A, M, I
Virtual water trading	A, I
Non-revenue water reduction	M
Reduction of evaporation and evapotranspiration losses	A, I
Water reuse	A, M, I
Municipal water use reduction	M
Public awareness raising and stakeholder engagement	A, I, M
Enhancing water supply from alternative water sources	A, I, M
Water quality trading programs	I, M
Water tariffs and economic incentives	A, I, M
Water markets and water banks	A, I
Water governance reforms	A, I, M
Capacity building	A, I, M

Water accounting and auditing

Strategies for addressing water scarcity must be designed based on a thorough understanding of temporal and spatial characteristics of various supply and consumption elements of water balance. As it was shown earlier in Figure 2.1, water scarcity adaptation interventions can be ineffective without detailed analysis of basin-wide water exchanges and flows. Water accounting and auditing not only help in quantifying water balance elements but also can go beyond a simple accounting of volumes and flows by addressing issues related to water governance and pressures imposed by economic sectors on water resources (FAO, 2017).

No adaptation policy can be designed effectively if not based on a thorough understanding of the hydrologic cycle and the inter-relationships between the water cycle and economic drivers and pressures. FAO defines water accounting and water auditing as:

> ″Water accounting is the systematic quantitative assessment of the status and trends in water supply, demand, distribution, accessibility and use in specified domains, producing information that informs water science, management, and governance to support sustainable development outcomes for society and the environment (FAO, 2012, 2016)”.

> ″Water auditing builds on water accounting to advise water governance. It sits between water accounting and water governance. By examining trends in water supply, demand and productivity, water auditing examines features of water governance such as institutions, public and private expenditure, laws and the wider political economy of water in specified domains (FAO, 2016)”.

Water accounting and auditing can help in water scarcity adaptation planning by the following means:

- By obeying the conservation of mass law, water accounting helps in distinguishing between water withdrawals and consumptive and non-consumptive water uses (FAO and WWC, 2018). Therefore, it helps in avoiding common mistakes leading to over-allocation of available water such as double counting of water exchanges between surface and groundwater. Other examples of common wrong engineering assumptions, which can be verified by water accounting are shown in Table 2.7.
- By projecting trends in supply and demands (as shown in Figure 2.1), it can assist in sustainable development planning.
- It can help decision-makers to avoid human induced water scarcity due to for example over-allocation of water, improper land-use, inadequate or over-investment in development of hydraulic infrastructure, and unachievable levels of food self-sufficiency.
- It can also help in examining the adequacy of institutional and legal capacities for addressing water scarcity issues.
- It can increase preparedness for extreme events (droughts and floods) by monitoring the status of infrastructure and water reserves. It also provides a reliable basis for early warning.

Table 2.7 Common wrong engineering assumptions avoidable by water accounting (Adapted from FAO and WWC, 2018)

Plausible wrong assumption	Why the Assumption is wrong?	Assumption is correct if:
Pressured irrigation reduces consumptive water use and saves water	In the absence of metering and monitoring of water withdrawals, farmers usually extend their cropping using the water saved. Therefore, the return flows of lands irrigated by surface irrigation do not return to water resources systems of basins and are consumed by the extended cropping leading to an increase in consumptive water use.	The assumption is correct only if water withdrawals are metered and monitored and water withdrawal permits are reduced according to the estimated reduction of water demands according to the selected type of modern irrigation technique.
Dams can reduce the level of water scarcity	In dry climates, water losses through evaporation from the lake behind dams can be significant. Increasing water supply through regulation of streamflows by dams provides possibility for over development of irrigated agriculture to a level that its water needs cannot be supplied in dry or even normal years. Over-reliance on reservoirs especially if not correctly sized and operated can increases vulnerability and higher potential damage caused by droughts and even floods. Reduction of frequency of flooding downstream of dams can increase social vulnerability to floods (Di Baldassarre et al. 2018).	If correctly sized and operated, dams can reduce water scarcity in dry seasons only if increase in downstream consumptive water uses over the supply capacity of the basin in dry years does not happen.
Rainwater harvesting creates additional water	Rainwater harvesting can increase seepage to groundwater. Water captured by rainwater harvesting interventions can also be utilized directly for consumptive uses. But water captured in upstream parts of a basin can deplete water from downstream uses.	Rainwater harvesting in islands for example, where water if not captured usually drains to the sea or where it drains to the very polluted water bodies can create additional water.
Forests act as water towers and increase streamflows	The forest ecosystem is a major user of water. Tree canopies reduce groundwater recharge and streamflows, through interception of precipitation and evapotranspiration. Forests use more water than most other land uses such as agriculture. Therefore, there is no question that forest removal increases downstream water yields. Studies suggest that in arid or semi-arid regions, forests are not the best land cover to increase downstream water yield (Calder et al. 2007).	It is theoretically possible that in basins with degraded agricultural, the extra infiltration associated with afforested land might outweigh the extra evaporation loss from forests, resulting in increased rather than reduced dry-season flows – but this has rarely been observed (Calder et al. 2007).

Climate-smart agriculture

Climate-smart agriculture aims at sustainably increasing productivity while decreasing vulnerability of agriculture producers to climate variations and change. It also aims at reducing greenhouse gas emissions and therefore helps in mitigating climate change. Climate-smart irrigation is an essential component of climate smart agriculture. Climate-smart agriculture practices can include but not limited to the followings:

- Switching to heat, wind, saline water, and flood and drought tolerant varieties

- Shade and green houses
- Mulching
- Rainwater harvesting
- Smart and hi-tech irrigation
- Diversifying crops
- Intercropping
- Underground farming
- Improved storage and processing and reduction of agricultural product losses

Smart irrigation is a critical element of precision agriculture. It helps farmers to avoid non-beneficial consumptive water use and increase productivity by keeping the soil moisture at the proper level at all stages of plant growth. In smart irrigation systems, soil moisture and temperature sensors placed in the field send real-time data to a microcontroller. If the field data falls out of the predefined moisture and temperature range, microcontroller starts water pumps for further irrigation. Hi-tech irrigation methods such as Micro-Irrigation (MI) is an essential element of modern agriculture. Hi-tech irrigation techniques such surface and sub-surface drip irrigation, bubbler and jet/mist/spray systems improve water delivery to farms and provide following benefits:

- Reduced water pumping costs,
- Reduced utilization of fertilizers and pesticides and thus less environmental pollution,
- Fewer labor costs

Reviewing the case studies of real-world applications of hi-tech irrigation techniques by FAO (2017) has shown that in the absence of metering of water withdrawals and controls on water allocations, hi-tech irrigation usually leads to expansion of agriculture and increase in consumptive water uses. Therefore, establishment of water accounting systems that quantify all types of consumptive and non-consumptive water uses and water withdrawals, as well as water licenses that limit the water withdrawals to a sustainable level, are pre-requisites to success in water saving by these technologies.

Improved storage and processing and reduction of agricultural product losses is an important intervention for reducing water demands of agricultural sector. While more than 40% of the food losses and waste in developing countries occur at post-harvest and processing levels, the same share of food losses in industrialized countries occur at retail and consumer levels (FAO, 2011). The blue water footprint (i.e. the consumption of surface and groundwater resources) of food wastage is about 250 km3 (FAO, 2013). Therefore, reduction of food loss and wastage has significant impact on water resources used for food production and it can be considered as an important element of water scarcity adaptation national plans. Main causes of food waste in low income countries are the followings:

- Lack of managerial capacities
- Lack of technical capacities and infrastructure needed for efficient harvesting, transportation, and storage of food products
- Lack of packaging and marketing systems

The strategies to address wasted food fall into the following categories (FAO, 2011; Commonwealth of Australia, 2017):

- Prevention/source reduction:
  - Addressing data and knowledge gaps about food waste and its causes and economic and environmental impacts.
  - Enhancement of communication and cooperation between farmers to reduce the risks of over production specific products.
  - Organizing small farmers and diversifying and upscaling their production and marketing skills.
  - Sales closer to consumers, which reduces the need for transportation, cooling and storage facilities and reduces rejected crops due to sub-standard appearance or size.
  - Investment in storage infrastructure and transportation by governments or private sectors
  - Improving knowledge and capacity of food chain operators to apply safe food handling practices
  - Developing markets for 'sub-standard' products, which are safe with good nutrition value
  - Creating enabling environment for developing business linkages between processors and farmers
  - Marketing cooperatives and improved market facilities
  - Public awareness about current state of food waste and its consequences
- Rescuing wasted food and using them to feed hungry people:
  - Establishment of food rescue organization
  - Repurposing aesthetically imperfect food for human use (e.g. packaged carrot sticks)
  - Repurposing without processing for animal feed
- Reprocesses:
  - Conversion to pharmaceutical and nutraceuticals
  - Conversion to cosmetic products
- Recycling/energy recovery solutions such as:
  - Composting and anaerobic digestion
  - Worm farms
  - Soil conditioners
  - Biotechnology solutions for animal feed

Reduction of per-capita water demand and change of life style

The share of urban population of the world has increased from 33.6% in 1960 to 54.8% in 2017. While a constant rate of increase in the share of urban population has been observed since 60s, it is expected that because of combination of the gradual shift in residence of the human population from rural to urban areas and the world's population growth, another 2.5 billion people add up to the urban population of the world by 2050 (UN, 2018). Based on the study carried out by McDonald et al. (2014) on 264 large cities, large cities obtain around 78% of their water from surface sources, most of which from far distances through inter-basin water transfer systems. McDonald et al. (2014) found that cumulatively, 184 billion m3 of water is transferred around 27000 km annually to supply urban water needs of the selected large cities and the cumulative area of basins supplying urban water demands are 41% of the global land surface. Despite this huge global investment in urban water supply infrastructure, people living in one out of four cities studied by McDonald et al. (2014), remain affected by water scarcity issues.

There has been a long history of human settlement near freshwater surface and groundwater systems but so many dense conurbations and megacities with over 10 million people are results of globalization trends and recent engineering advancements. Carefully engineered pipelines, canals, and distribution networks in most developed basins have practically supplied unlimited water to water users in cities causing life styles to be shaped by abundant water not limited water. Water-intensive lifestyles, especially in urban areas and megacities, has significantly escalated water scarcity.

Water needs of large urban areas are supplied through large scale water transfer systems that convey water from the neighboring basins putting extra pressure on their ecological reserves and agricultural activities. Prioritizing urban water demands over water needs of the neighboring basins escalate rural-urban migration, which again intensifies urban water needs. Even though in most countries, total urban water demands are much lower than the average volume of water consumed by agricultural and industrial sectors but inconsistent lifestyles and spatial population distribution with available water resources, have made large cities hot spots for all kinds of water quality and water scarcity related challenges.

As an example of how life style can intensify water scarcity, growing meat consumption leads to an increased demand of land and water. One calorie derived from beef consumption requires about 87 times more land and 36 times more water than a calorie derived from wheat consumption (Lehmann and Rajan, 2015). Therefore, meat-based food diets contribute not only to loss of biodiversity due to deforestation, but also intensifies fresh water scarcity. Rizvi et al. (2018) found out that global adherence to the dietary guidelines put forth by the United States Department of Agriculture (USDA) (The Dietary Guidelines for Americans, 2010) would require 109 hectares of additional land—roughly the size of Canada–under current agricultural practices.

Efforts of societies to modify their diets and - lifestyles to reduce their environmental footprint can be essential elements of the water scarcity adaptation policies. Example of such efforts are as follows:

- Replacing old toilets with water saving low flush toilets
- Promoting “xeriscape” or water saving landscaping especially for dry conditions
- Promoting organic food markets, which reduce water and soil pollution by chemical products used in conventional farming
- Modifying diets to use less animal products
- Promoting installation of faucet aerators
- Promoting use of recycled materials with high virtual water such as recycled paper products
- Food loss reduction at consumer level

Virtual water trade

For many countries located in arid and semi-arid areas with limited renewable water resources and limited capability in providing self-sufficiency in food production, importing virtual water through importing agricultural products with high water demand is already a reality (FAO, 2008). The volume of water associated with global food trade more than doubled in 22 years from 1986 to 2007, which shows that many countries decided to import certain food products instead of producing them (Dalin et al., 2012). Globally, virtual water transfers associated with food trade has saved around 6% of the water used in agriculture, which is a significant contribution. As an example, China's food imports contributed to around 36% of the global water savings associated with international food trade (Dalin et al., 2012). Therefore, strategic decisions of water scarce countries to import products with high virtual water content instead of producing them inside their country can be incorporated into water scarcity adaptation plans. These products can range from various crops and food items to various industrial commodities.

Non-revenue water reduction Non revenue water (NRW)

NRW is the difference between volume of water that has been produced and billed authorized consumption. NRW can be divided into the following categories:

- Physical losses through leaks
- Apparent losses (e.g. water theft or metering inaccuracies)
- Unbilled authorized consumption

As explained earlier, water needs of many large urban areas are supplied by spending significant economic and energy resources and through large scale water transfer systems that convey water from the neighboring basins putting extra pressure on their ecological reserves and agricultural activities. Losses of water before it reaches to the consumer is equivalent to not only the loss of water but also loss of money spent on production and distribution of water and energy and other resources used for production of water. Therefore, for water stressed basins with high NRW levels, NRW reduction is usually an element of water scarcity adaptation plans. Interventions for NRW reduction include (Karamouz et al., 2003):

- Municipal leakage detection and control
- Full and accurate metering policy
- Removal of unmetered water supplies
- Pressure management in water distribution networks
- Flow monitoring

As an example, municipal leakage detection and repair, modified tariffs and economic incentives, pressure management and water metering were used in Sao Paulo, Brazil, to reduce NRW and municipal water consumption during 2014 record drought. Total cost of this program was about $165 million and total annual water savings has been about 600 million m3. In the United Kingdom, a 5-year program was implemented between 2010-2015 to reduce supply-demand gap by installing 500,000 intelligent meters and leak reduction. The program costed around $192 million and resulted in 16.5% reduction in water demand (2030 WRG, 2013).

Reduction of evaporation and evapotranspiration water losses

Shifting to higher value crops in irrigation and limiting evapotranspiration are among important interventions for water scarcity adaptation specially in basins with high share of water consumption by agriculture sector. Reducing water losses from evaporation and excessive transpiration can be achieved through interventions such as the followings:

- *Mulching*: One of the most effective solutions to high evaporation losses of soil water is covering soil surface. Grasses, shrubs, weeds, litter, husks and other organic waste materials can be used for mulching.
- *Weed control*: Transpiration losses may be the result of weeds. Weed control can assist in reduction of non-beneficial water consumption in agricultural lands.
- *Wind breaks*: Excessive crop transpiration in hot windy conditions can be controlled by planting single, double or triple rows of trees or tall grass species oriented at right angles to the direction of the prevailing winds during the growing season.
- *No tillage*: Converting to no-tillage reduces irrigation water needs due to soil water evaporation reduction and preservation of soil moisture.
- *Maintaining crop residues on the soil surface*: The evaporation rate from bare soil after initial wetting is greater than from soil under residues.
- *Drought-tolerant varieties*: Better yields can be obtained from drought tolerant varieties under drought conditions.
- *Supplemental irrigation*: In rainfed agriculture in water scare regions, supplemental irrigation can significantly improve water productivity.
- *New cropping patterns*: For producing more food with less water and improving water productivity, low value crops with high water demand can be replaced with water stress resilient high value crops.
- *Land leveling*: Modern irrigation techniques can help farmers to recover costs of crop production, where water is scarce and expensive. In cases of cheap or free water for agriculture, farmers can benefit from land leveling for improving efficiency of surface irrigation.
- *Planting date*: Improved productivity in relation to temperature, rainfall, and available water for irrigation can be achieved through change in planting dates according to climate change impacts on local meteorological conditions.

Industrial processes might have large demands for water but in most cases, a high percentage of withdrawn water returns to water resources systems or sewage systems with an altered quality. The quality of the returned flows to the environment varies significantly depending on the type of the industry and the production process (Pereira et al., 2002). In the less developed countries, agricultural water demands are often much higher than industrial water needs. In further developed countries, industrial water needs can significantly exceed municipal water demands and sometimes they are in competition with domestic water uses and very often are supplied by the municipal water distribution networks. The following interventions can be used for industrial water use and pollution reduction (Pereira et al., 2002; 2030 WRG, 2013):

- Regular audits for detecting water leakages and energy losses and repair
- Accurate monitoring of water uses in various processes
- Engagement of staff in water saving programs and awareness raising
- Wastewater recycling for use in cooling systems or production processes
- Water pollution prevention measures
- Rainwater harvesting
- Implementation of low flow plumbing fixtures
- Recovery of backwash water in the water treatment works
- Dry cooling systems and substitution of water-cooled heat transfer pumps
- Replacement of water use processes by mechanical ones
- Adjustment of water quality to process requirements
- Outdoor water use management by high-tech irrigation methods or using plants less sensitive to water stress
- Separating heavily polluted from less polluted effluents
- Economic incentives

Economic incentives can also be effectively used for controlling water consumption and pollution in water-intensive and water-polluting industries such as steel and petrochemicals and textiles. Water tariffs, effluent charges, and tax concessions for the use of water-saving and wastewater treatment equipment can encourage industries to invest in water-saving and recycling technologies and to reuse treated wastewater (Karmouz et al. 2003).

Several industrial water-saving success stories have been published in the past, which can be used as a guide for industrial development. As an example, the results of the study carried out by Alkaya et al. (2015) shows that implementation of 19 carefully selected water saving interventions in 7 industrial plants in Turkey (sea food, soft drink, metal processing, chemical, textile, and surface coating/painting companies) has not only resulted in considerable water savings but also consumption of energy and chemicals was also reduced. The payback period of interventions reported by Alkaya et al. (2015) range from 1.5 to 27.8 months.

Water reuse

While most of treated wastewater (effluent) returns to surface and groundwater resources, some countries have taken further steps to treat wastewater to the levels of purification needed for reusing it in agriculture, industries, or even as a source of potable drinking water. Globally, more than 80% of all wastewater is discharged into the world's waterways creating various health and environmental risks (IWA, 2018). Sato et al. (2013) addressed the challenge of lack of availability of wastewater generation, treatment, and use data in 181 countries. They found out that only 55 countries have data available on all three aspects of wastewater generation, treatment, and use. Based on the data assessed by Sato et al. (2013), the high-income countries on average treat 70% of the generated wastewater, followed by upper-middle-income countries (38%), lower-middle-income countries (28%), and low-income countries (8%). Major applications of treated wastewater include the followings:

- Direct potable use
- Indirect potable use through groundwater recharge or mixing with surface water
- Direct and indirect use for irrigation of agricultural lands and green landscapes in urban and rural areas
- Industrial use
- Non-potable urban uses
- Recreation/environmental uses

Each of these applications usually face constraints. Even though treated wastewater is a reliable source, which exists in close proximity to the demand, direct potable uses usually face public perception issues. Despite all the recent wastewater treatment technological advancements, people around the world are still skeptical that direct potable use of treated wastewater is a viable option. Therefore, indirect potable use has become a more publicly accepted option. In indirect potable use, a lake, river, or an aquifer is used as an environmental buffer, before the water is treated again at a drinking water treatment plant.

Singapore is among the pioneer countries in indirect potable water use. Industrial water and NEWater are two forms of water reuse in Singapore. Industrial water, first introduced in 1966, is a lower grade of reclaimed water utilized for non-potable water uses in industries. In 2003, high-grade reclaimed water, known as NEWater was introduced. NEWater is treated wastewater, which is produced through 3-step purification processes involving ultrafiltration/microfiltration, reverse osmosis and ultraviolet disinfection. For indirect potable use, NEWater is injected into reservoirs to mix with rainwater before being treated again for potable use. It is expected that NEWater meet up to 55% of total Singapore water demands by 2060 (Tan, 2018).

Municipal water use reduction

The primary measures of municipal water use reduction can be classified as (Karamouz et al. 2003; 2030 WRG, 2013):

1. Water loss reduction:
    - Water metering
    - Leakage detection and reduction
    - In-house retrofitting
    - Reduction of illegal connections
    - Pressure management in the water distribution network
    - Establishment of distribution zones within the network
2. Education and training:
    - Public awareness
    - In-school education
    - Training and education programs for the staff in water related agencies
3. Economic incentives and tariff structure
4. Institutional measurements and effective legislation:

- Regulations for water demand management
- Regulations on resale of water

5. Wastewater reuse
6. Non-potable distribution network
    - Use of seawater for toilet flushing and evaporative cooling for the cities located near coastlines
    - Use of recycled greywater or rainwater for various non-potable domestic and service water uses
7. Urban stormwater harvesting
8. Establishment of certification programs or new standards and regulations for water efficient homes
9. Restrictions on grassed landscape and outdoor water use and promotion of xeriscaping

Even though technical solutions for municipal water use reduction has been available for several years, but experiences from various countries are consistent in showing importance of awareness raising and utilization of economic incentives in ensuring success of technical solutions.

Public awareness raising and stakeholder engagement

Water scarcity affects all societies and economic activities. Even those living in water-abundant regions/countries, are dependent on partial food supply from countries facing severe water stresses. Water scarcity adaptation needs actions in various levels:

- At international level not only enhanced collaboration in dealing with shared water resources between neighboring countries is necessary but also strengthening of international markets for virtual water trade, which eventually lead to global water saving is needed.
- At national level, policies related to water scarcity adaptation and water allocation to competing users need cross sectoral coordination among governmental and non-governmental agencies and organizations and private sector.
- At local level, better water resources management and water conservation practices leading to improved water productivity are needed.

Achieving the ultimate goal of water scarcity adaptation requires an integrated plan for all of the levels and enhanced stakeholder involvement is also essential. Water scarcity adaptation planning is an opportunity for bringing governments, NGOs, businesses, universities and research institutes together to change attitudes toward water. First step in achieving this goal is awareness raising about water scarcity and its consequences. Multi-level awareness raising consistent with aforementioned levels of action is necessary:

At international level, high level global advocacy efforts are needed to bring more awareness at political level. There is still a low perception of importance of water scarcity issues by many governments that has led to vanished or highly polluted wetlands and aquifers. Political commitment is a necessity for water scarcity adaptation specially at national level since cross sectoral coordination is needed. Water scarcity adaptation solutions need to be adapted to local contexts and for that to happen engagement of local communities are essential. Various countries have developed scientific and technical interventions supported by policies to cope with water scarcity. There is a need for raising awareness about results of these efforts with all stakeholders and general public (UN-Water, 2007).

Enhancing Water Supply from Alternative Water Sources

In arid and semi-arid regions with limited surface and groundwater availability, water supply enhancement is one of the important adaptation response options for coping with water scarcity and impacts of climate change. Enhancement of water supply for water users can be done at different scales depending on the quality and quantity of the water needed. The following interventions can be used for water supply augmentation for industrial (I), agricultural (A), and municipal (M) water uses:

- Adding regulating capacity by for example building small or large dams (I, A, M)
- Water desalination (M, I)
- Rainwater harvesting (I, A, M)
- Artificial groundwater recharge (I, A, M)

Water Quality Trading (WQT) Programs

Water pollution control is among main pillars of any water scarcity adaptation policy. Water pollution monitoring and control in most cases is more expensive than water loss monitoring and reduction. Therefore, in contrast to water loss reduction, further attention to economic incentives for water pollution control has been paid by researchers and policy makers in the past. It took more than a decade after John Dales (1968) first proposed using water quality markets until experimental water-quality-trading (WQT) mechanisms was established in the United States in the 1980s. United States Environmental Protection Agency (EPA) introduced total maximum daily load (TMDL) levels for pollutants and started financial and technical support for WQT during 1990s and 2000s.

WQT programs provide the possibility for a polluting source to meet its regulatory obligations by purchasing pollution reductions achieved by another source instead of lowering its own pollution. The main purpose of the water quality trading programs is to reduce the costs of water quality improvements. While WQT provide environmental and financial benefits, it also provides a platform for communication among point and nonpoint pollution sources, regulatory agencies, the public and other stakeholders to promote solutions for water quality improvements with less costs (Corrales et al. 2013). The followings are examples of existing trading programs (Greenhalgh and Selman, 2012):

- AUSTRALIA
    - Hunter River Salinity Trading Scheme, New South Wales, Australia
    - Murray-Darling Basin Salinity Credits Scheme, Australia
    - South Creek Bubble Licensing Scheme, New South Wales, Australia
- CANADA
    - South Nation Total Phosphorus Management Program, Ontario, Canada
- NEW ZEALAND
    - Lake Taupo Nitrogen Trading Program, New Zealand
- USA

- Bear Creek Trading Program, Colorado
- Chatfield Water Quality Trading Program, Colorado
- Cherry Creek Basin Water Quality Authority Trading Program, Colorado
- Clean Water Services Permit, Tualatin River, Oregon
- Delaware Inland Bays, Delaware
- Dillon Reservoir Pollutant Trading Program, Colorado
- Fall Lake, North Carolina
- Grassland Area Farmers Tradable Loads Program, California
- Great Miami River Water Quality Credit Trading Program, Ohio
- Jordan Lake, North Carolina
- Las Vegas Wash, Nevada
- Long Island Sound Nitrogen Credit Exchange Program, Connecticut
- Lower St Johns River Water Quality Credit Trading Program, Florida
  Maryland Nutrient Trading Program, Maryland
- Minnesota River Basin Trading Program, Minnesota.
- Neuse River Basin Nutrient Sensitive Waters Management Strategy, North Carolina
- Ohio River Basin Trading Program, Ohio
- Pennsylvania Nutrient Credit Trading Program, Pennsylvania
- Rahr Malting Company Permit, Minnesota
- Red Cedar River Water Quality Trading Program, Wisconsin
- Sole-source Pennsylvania Nutrient Credit Trading Program, Pennsylvania
- Sole-source Williamette Partnership (Lower Columbia), Oregon
- Sole-source Williamette Partnership (Williamette), Oregon
- Southern Minnesota Beet Sugar Cooperative Permit, Minnesota
- Sugar Creek, Ohio.
- Taos Ski Valley, New Mexico
- Tar-Pamlico Nutrient Reduction Trading Program, North Carolina
- Virginia Water Quality Trading Program, Virginia

Most WQT programs have been more successful in controlling point-sources while nonpoint-sources such as agricultural pollution loads are less costly to control. New Zealand is the most successful country in regulating agricultural nonpoint sources. Lessons learned from the Lake Taupo Nitrogen Trading Program in New Zealand can be used by other countries in which high portion of nutrient non-point loads are coming from agricultural lands.

Water tariffs and economic incentives

In many river basins especially, those located in arid and semi-arid areas, water use has by now reached or exceeded its limits. Reviewing literature shows that water is often allocated to economically inefficient uses (usually agricultural) and that reallocation to more efficient water users with higher added value (usually urban) can reduce water stresses and conflicts associated with water scarcity (Molle and Berkoff, 2009). Rebalancing of sectoral water allocation specially were shared water resources are utilized by multiple sectors needs a mix of political, administrative, and market mechanisms, among which water tariffs and economic incentives play an important role.

Tariffs for water used for irrigation can have a significant impact on water shortage reduction since agriculture sector is the major water user in most basins and in many cases uses the same source of water, which supply urban water needs. There are many examples of irrigation water tariffs that do not encourage water users to save water. Irrigation water tariff schemes are usually defined in one of the following formats (⬆: encourage water saving; ⬇: does not encourage water saving) (Giannopoulou et al. 2017, FAO, 2004):

- No fee for surface or groundwater or both (⬇).
- Fixed rate per cropping season (⬇).
- Based on hours of pumping (⬆).
- Volumetric charges of the water consumed (it can also be multi-rate where pricing differs according to the amount of water consumed) (⬆).
- Crop production (⬇).
- The water-production relation, thus water pricing is connected to the production, irrigation method, climate, etc. (⬆)
- The irrigated area (⬇) (it can also be connected with the type of cultivation, the irrigation method, etc. ⬆).
- Two-part tariffs, in which the users are charged a fixed annual amount (to provide for maintenance costs of infrastructure managed by the chronically under-funded sector) plus a constant marginal price per unit (⬆).
- Betterment levy, where water pricing is based on the irrigated area taking into account the increase in land value due to the irrigation (⬇).
- Market based water pricing (⬆).

In some areas in South Africa, farmers pay for water according to their irrigated land (2030 WRG, 2013) or in Iran, groundwater is provided for irrigation, free of charge. Farmers pay for surface water according to the price of their products assuming a fixed rate of production per hectare of land. These are examples of water schemes that do not encourage water users to save water. Using water tariffs sensitive to the amount of water consumed is among effective interventions for water saving.

In urban areas, water and sanitation tariffs play an important role in water scarcity adaptation. If water tariffs are not set high enough to ensure cost recovery, replacement of assets in the drinking water systems may not be enough to reduce leakage and funds available for wastewater treatment and recycling may not be sufficient to control environmental pollution (European Commission, 2012).

The amount of water bill that customers pay for water and wastewater services act as a price signal that may encourage the customers to decrease consumption. In some countries, the share of water bills in the total household cost or income is very low, which makes the water consumers insensitive to water consumption or conservation level. It should be noted that when water costs make water unaffordable, it can cause health issues and may initiate political and social conflicts. The United Nations, in recognition of access to water and sanitation as a human right, recommends that expenditure on household water bills should not exceed 3% of household income (UNDP, 2006). As Priestley and Rutherford (2016) reported the UK National Audit Office (NAO) found that in 2013, water bills represented

2.3% of the average household expenditure in the UK. This ranged from 5.3% for the 10% of households with the lowest incomes, to 1.1% for the 10% of households with the highest income. Affordability of drinking water for the poorest group of people living in 27 EU member counties was assessed by Gutorova et al. (2018). They found out that share of water bills in the income for the people with the first quintile of income distribution range from 0.28% in Malta to 10.96% in Bulgaria. Uruguay, Poland, Jamaica, El Salvador, Burkina Faso, and Argentina are among the countries in which poor segments of the population pay more than 10% of their income for water bills (Hutton, 2012).

In addition to the total amount of a water bill, the tariff structure of the bills is also important. In brief, water and wastewater tariffs are usually in one of the following forms or combination of them (↑: encourage water conservation; ↓: does not encourage water conservation) (Figure 2.3):

- *Fixed charge*: the water bill is independent of the volume of water consumed (metering is not needed) (↓).
- *Uniform volumetric tariff*: The water bill is proportional to water consumption. All units of water consumption are priced the same (metering is needed) (↑).
- *Increasing block tariff*: This tariff is a step-wise volumetric charge. With this tariff the unit charge is constant over a specific range of water use block) and then increases as the consumption increases (metering is needed) (↑).
- *Decreasing block tariff*: The rate per unit of water is high for the initial block of consumption and decreases as the volume of consumption increases (metering is needed) (↓).
- *Two parts tariffs*: have a fixed charge component (usually based on the fixed costs of production) plus a variable charge depending on the volume of water consumed (e.g., increasing block or uniform tariff) (metering is needed) (↑).

All tariff structures, which encourage water conservation, require metering. Therefore, metering and reducing non-revenue water in urban water systems have to be considered as a pre-requisite to improving tariff structures as an intervention for water scarcity adaptation.

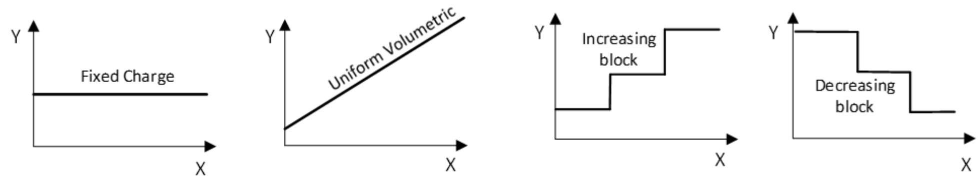

Figure 2.3 Urban water tariff structures (X: Volume of water consumed, Y: Price)

Modifying tariff structures has been among water scarcity adaptation policies in several cases including water demand management scheme of Drakenstein, South Africa, Regional water conservation programs in Seattle and Nevada, USA, Water demand management strategy in Singapore, and Emergency water demand management in Beaufort West, South Africa. Increased tariffs have also been used in Singapore as a source of funding for wastewater reclamation and reuse network development (2030 WRG, 2013).

Water markets and water banks

Water markets provide a suitable platform for buying and selling water rights (water access entitlements). The transfer of rights in the water market can be either permanent or temporary, depending on the legal status of the water rights, which can significantly differ in various countries. While informal water trading exists in most countries, formal water trading schemes have been implemented in limited number of countries such as Australia, USA, Iran, South Africa, Spain and Chile mostly in local scale.

The re-allocation of water resources among competing uses can be one of the interventions for water scarcity adaptation. It can be used for reallocation of water among users in a single sector (e.g. farmers in an agricultural district) or across various municipal, industrial or agricultural sectors. It is expected that by water trading in a water market, improved water productivity can be achieved since producers with higher efficiencies of water use, are able to pay higher prices closer to marginal values of water in the trading sectors.

Water markets can differ according to the following characteristics (Montilla-López et al. 2016):

- Formal or informal status of water entitlement exchanges
- Rights or entitlements being traded including permanent, temporary or spot markets
- Parties involved (seller/buyer direct exchange or agents or agencies facilitating the trade)

Water banks are specific type of a water market in which an administrative agency (public or private) acts as an intermediary in the trading of rights. Water banks have been used in various states in the United States and some other countries including Spain, Australia and Chile (Montilla-López et al. 2016). Advantages and disadvantages of water markets and water banks as interventions for water scarcity adaptation based on the international experiences reported in the literature are listed in Table 2.8.

Table 2.8 Advantages and disadvantages of water markets and water banks as interventions for water scarcity adaptation

<table>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Improved productivity</td><td>Negative environmental externalities (mainly through alteration of environmental flows)</td></tr>
<tr><td>Raised income of buyers and sellers</td><td>Negative social and political externalities due to loss of jobs in less productive activities</td></tr>
<tr><td>Rationalizing constructing new water supply infrastructure</td><td>Higher water pollution due to changes in water use</td></tr>
<tr><td>Transparency of water right exchanges</td><td rowspan="5">Increase of overall basin evapotranspiration because of higher water use efficiency and activation of water rights that are not being used (sleeper rights)</td></tr>
<tr><td>Promotion of private investment</td></tr>
<tr><td>Promotion of technical advancement</td></tr>
<tr><td>Promotion of public participation and reduction of state intervention</td></tr>
<tr><td>Reduced costs of government interventions for water resources management</td></tr>
</table>

The main disadvantage of water markets and water banks is that they could generate negative environmental externalities by lowering the reliability of providing environmental flows. Disadvantages listed in this table can be avoided by certain administrative interventions. For example, in some water markets, some organizations even 'compete' for buying the rights to ensure certain levels of environmental flows (FAO, 2008). As stated earlier, when transferring water rights in a market, it is important to differentiate between water 'evapotranspirated by crops' (in case of irrigation) and the amount 'used'. In order to reduce negative environmental externalities of water banks and water markets, fraction of water use corresponding to return flows should not be transferred (Montilla-López, et al. 2016).

An example of application of water banks for agricultural water demand management has been experienced in the Orange-Senqu Basin, shared by Lesotho, South Africa, Botswana and Namibia. A virtual water bank was established to encourage farmers to sell unused water allocations, while legal and institutional reform was also carried out to create a platform for stakeholder consultation and participation (2030 WRG, 2013).

Examples of water markets can be found in many countries including western USA and Murray-Darling Basin in Australia. In the Murry-Darling Basin, the volume of water traded exceeds 20% of surface water extractions and the total water market turnover in water rights exceeds US$2 billion per year. In the western USA, Arizona, Colorado, California, Nevada and Texas, between 5 to 15% of total state freshwater diversions have been annually traded with over US$4.3 billion spent or committed by urban buyers.

Some of the necessary conditions for large water markets such as those active in Murry-Darling Basin in Australia or those active in western USA include (Grafton et al. 2012):

- Decoupling of the use of water from land rights
- Legal and financial enable environment for water trading
- Infrastructures for water storage and conveyance between upstream and downstream users

Smaller water markets, which have been active in several basins around the world for many years without almost any government intervention may not need any of the aforementioned pre-requisites.

Water governance reforms

OECD (Organization for Economic Corporation and Development) defined water governance as "the set of rules, practices, and processes through which decisions for the management of water resources and services are taken and implemented, and decision-makers are held accountable" (OECD, 2011). Adapting water governance to the environmental changes due to population growth, climate change, urbanization, growing water demands and widespread water and soil pollution is key to successful water scarcity adaptation. Even though, technical solutions play an important role in water scarcity adaptation but their effectiveness is highly dependent on the enabling environment provided by the water governance system in place. Water governance adaptation to water scarcity has been behind the requirements in many countries and therefore, they remain inefficient in solving water scarcity issues. Water governance reforms for coping with water scarcity should address the following important issues:

- Providing a suitable platform for stakeholder engagement and participatory water management
- Enhanced transparency
- Sound and clear financing schemes
- Coherency across sectors
- Capacity building, human resources development, and organizational development
- Enhanced monitoring and evaluation
- Shift from crisis management to long-term planning
- Enhanced water and environment legislation

Capacity building

Building adaptive capacity is fundamental to water scarcity adaptation for most nations especially in the developing world. Eakin and Lemos (2006) summarized the determinants of adaptive capacity as shown in Table 2.9.

Table 2.9 Determinants of adaptive capacity (Eakin and Lemos, 2006)

Determinant	Encompasses
Human capital	Knowledge (scientific, "local", technical, political), education levels, health, individual risk perception, labor
Information and Technology	Communication networks, freedom of expression, technology transfer and data exchange, innovation capacity, early warning systems, technological relevance
Material resources and infrastructure	Transport, water infrastructure, buildings, sanitation, energy supply and management, environmental quality
Organization and social capital	State-civil society relations, local coping networks, social mobilization, density of institutional relationships
Political capital	Modes of governance, leadership legitimacy, participation, decentralization, decision and management capacity, sovereignty
Wealth and financial capital	Income and wealth distribution, economic marginalization, accessibility and availability of financial instruments (insurance, credit), fiscal incentives for risk management
Institutions and entitlements	Informal and formal rules for resource conservation, risk management, regional planning, participation, information dissemination, technological innovation, property rights and risk sharing mechanisms

Based on the determinants listed in this table, capacity building efforts become more effective in water scarcity adaptation if they enhance the following capacities:

- Human resources capacity development with specific attention to T-shaped human resources capable of facilitating cross-sectoral analysis and policy development and implantation (T-shaped individuals have deep knowledge and skills in a particular area of specialization along with ability to make communicate with other disciplines)
- Enhanced monitoring capacities and data banks related to water availability and use, socio-economic and political factors influencing water systems and livelihoods dependent on water
- Technological capacities for water scarcity adaptation in municipal, industrial, and agricultural sectors
- Infrastructure needed for water supply and pollution prevention, water resources management and flood and drought warning

- Capacities needed for stakeholder involvement and participatory water resources management
- Institutional capacities needed to ensure efficient water governance for water scarcity adaptation

Concluding remarks

As population increases overtime, water demands grow over the sustainable withdrawal level (Figure 2.4). First set of responses to the growing water demands are usually focused on water supply enhancement by interventions such as dam construction, water transfer, and desalination.

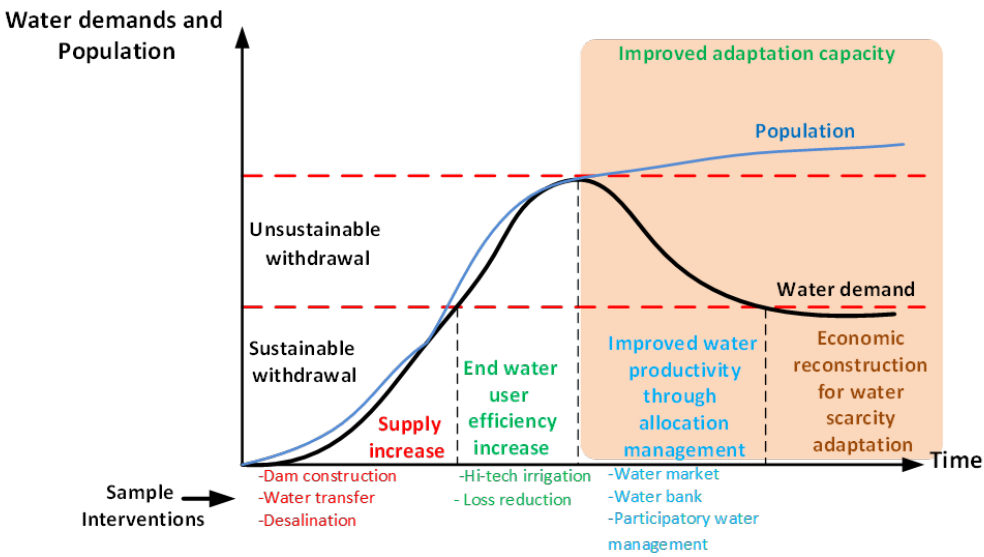

Figure 2.4 Water use trends vs water scarcity adaptation interventions

As water demands increase over the sustainable level of supply and possibilities for further water supply enhancement become more difficult due to less physical or financial opportunities, water management efforts usually further focus on improvement of end water user efficiency. Interventions for reduction of water losses such as hi-tech irrigation lie in this category. Improved water scarcity adaptation capacity however requires significant capacity building, awareness raising, and water governance reforms that provide an enabling environment for improved water productivity through interventions such as establishment of water markets/banks and participatory water management. This process can eventually lead to economic reconstruction for water scarcity adaptation.

Cities as products of complex interactions between sociopolitical, cultural, institutional, and technical networks, are a major element in the process of economic reconstruction for water scarcity adaptation. Taking into account all these networks, management of urban water systems has been transformed significantly in the past decades. Reviewing these transformations shows how the future perspectives might look like for many less developed urban water systems. Based on the historical analysis of the Australia's urban water management practices over the last 200 years carried out by Brown et al. (2009), six subsequent stages were recognized (Figure 2.4):

- *Water supply city*: Focus of urban water management system is on ensuring high reliability in supplying water demands with a safe and high-quality water
- *Sewered city*: In these cities, urban water managers focus on wastewater collection and treatment as well as supply systems. This added focus is usually a response to epidemic outbreak of diseases or degradation of quality of reception environment.
- *Drained city*: Focus is added on urban drainage systems in response to the increasing damage from stormwater due to multiple drivers such as development of areas vulnerable to flooding, intensification of floods and sea level rise due to climate change, etc.
- *Waterways city*: Further focus on the cleanliness of water bodies and wastewater treatment is added in response to increasing water pollution.
- *Water cycle city*: In these cities, further attention is given to water demand management and closing water and substance cycles in response to water supply constraints and assimilation of pollution.
- *Water sensitive city*: In these cities, further attention is given to adaptive management of water and wastewater systems. In these cities, multi-functional infrastructure and urban design are used to increase the capacity needed for climate change and water scarcity adaptation.

Various water scarcity adaptation interventions explained in this chapter, can be used to transform cities through these six stages. Figure 2.5 shows how water scarcity adaptation can be enhanced through each of these stages.

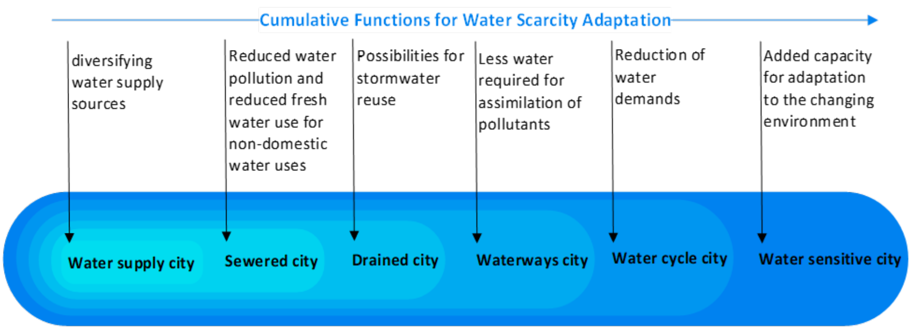

Figure 2.5 Enhancement of water scarcity adaptation in through urban water management transitions framework (based on Brown et al., 2009; Hoekstra et al. 2018).

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Planning for Resilient Water Services in Arid & Semi-arid Regions

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Introduction

The supply and demand for water in arid and semi-arid regions provide major challenges for urban water service providers and planners. Firstly, there is often significant water scarcity, driven by low rainfall. Where groundwater resources exist, they are often constrained, subject to depletion, or to saline intrusion in coastal regions. Secondly, demand for water is typically elevated compared to more temperate zones, due to the irrigation and cooling demand. Thirdly, there is often a higher peak demand, on a seasonal and even daily basis, due to the strong influence of climate on these two demand categories. Fourthly, there are often different sectors competing for the same constrained water source, such as nearby agriculture, industry or mining. Finally, there is an increased likelihood of extreme climate events that constrain the resource even more.

In arid regions therefore, there is an even greater need for best practice urban planning in the interests of water management, and the use of best practice water planning. This chapter describes what such best practice planning and management might involve, and uses several case studies undertaken by the authors in arid regions in central Australia and in the Middle East and North Africa (MENA) region to demonstrate its application.

Best practice planning

In the context of urban water use, and improving the resilience of urban water services, there are multiple layers of planning across a range of stakeholder groups.

A. Water resource planning

Water resource planning is primarily carried out by state, provincial or national governments. The planners in each specific context need to recognize the constraints on the sustainable yield of the catchments and groundwater sources, as well as climate variability, long term climate change and the needs of the environment. In addition, the needs of traditional owners, riparian users, other recreational and productive users must also be considered. Often the boundaries of jurisdictions for catchments do not neatly coincide with institutional boundaries and may even cross international borders. This means that a greater emphasis on establishing systems of engagement, including community engagement, is important to reduce conflict and ensure the best outcome for all stakeholders, especially those with less power, including the environment.

B. Water utility planning

Utility planning includes planning for utilities and urban water use, as well as planning by utilities and water agencies, both of which have a very important role to play. Best practice utility planning includes ensuring that the supply-demand balance in a particular region, refer to Figure 3.1, is maintained at the lowest cost to consumers, while recognizing the limits imposed by the ecosystem in providing sufficient water of suitable quality.

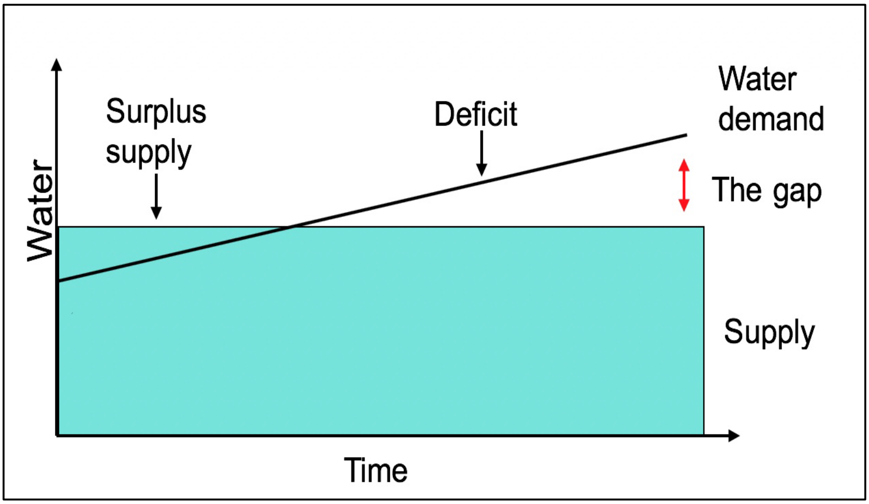

Figure 3.1 Supply-demand balance

Best practice water utility planning also requires integrating long term planning, including the best estimates of the impact of climate change, and short-term planning to enable adaptive and flexible responses to unforeseen or rapid changes, including extreme drought or disaster. Both government regulators and utilities themselves have a key role to play in ensuring best practice utility planning. This includes a requirement for utilities to undertake integrated resource planning (Turner et al. 2010), as shown in Figure 3.2, which importantly requires:

- Careful planning and bringing together of stakeholders;
- Detailed and context specific water demand forecasting;
- economic assessment of supply options (i.e. new sources, dams, groundwater sources, desalination) and demand options (i.e. improved water efficiency/demand management, reduced system losses and small-scale source substitution) on an equal basis; and
- Ongoing monitoring and evaluation after implementation of supply and/or demand responses.

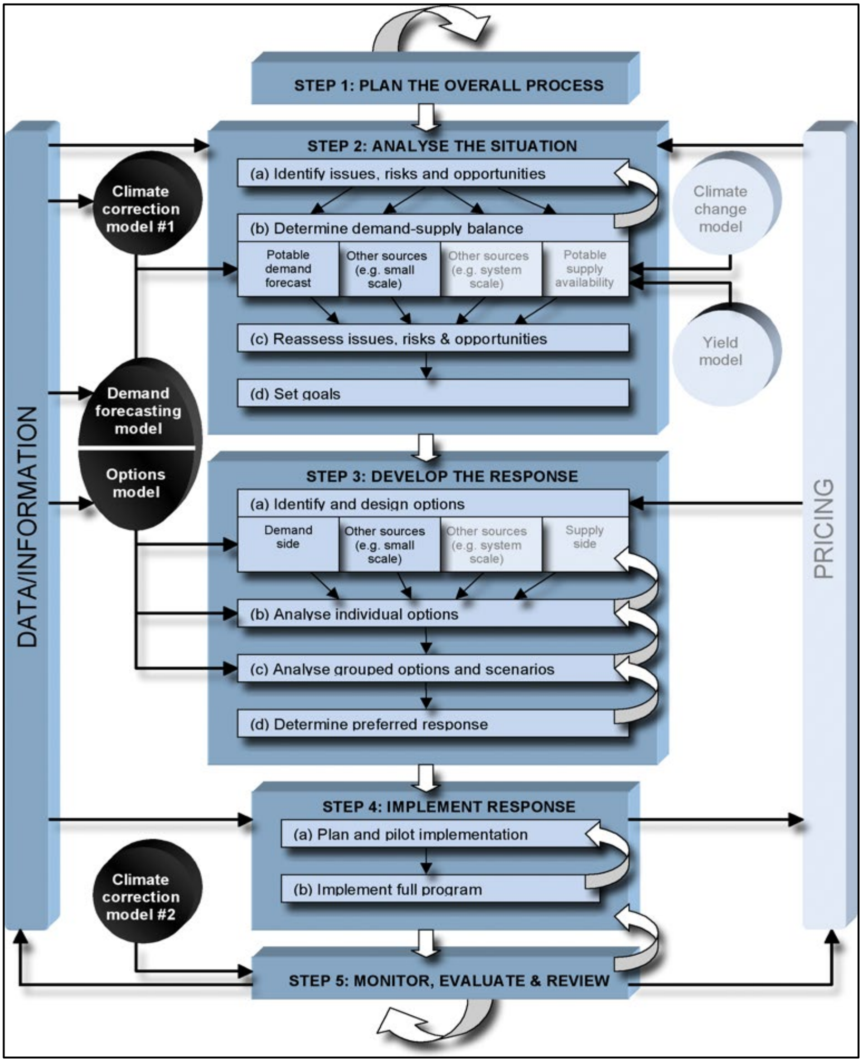

Figure 3.2 Integrated resource planning (Turner et al. 2010)

C. Local government and land use planning

Local government and land use planning can strongly support resilient water systems in a variety of ways.

Firstly, managing water in the landscape is often the responsibility of local municipalities, furthermore, improved water management through water sensitive urban design (Wong 2006) can maximize the efficiency of water use for irrigation, by slowing the progress of runoff water through the landscape and directing it where it can be most effective. This provides benefits in terms of urban green space, vegetation and urban amenity, including mitigating the urban heat island effect, as well as improving water quality. This means that new Greenfield developments give primary consideration to the hydrology, and after that consider the cadastral land planning.

Secondly, stormwater or rainwater can be captured for reuse, through dual use detention basins, where the objectives of reducing flooding and storing stormwater for later use can be combined through appropriate basin sizing and operation.

Thirdly, local municipalities in many cases have powers to impose development consent conditions to require new buildings and developments to have best practice water using fixtures and equipment, including toilets, taps, showers, urinals, cooling towers, irrigation systems and landscaping as well as third pipe plumbing for recycled water. An exemplary example of this is BASIX, a building and sustainability index, introduced in the State of New South Wales, Australia, in 2004 (NSW Government, undated).

These opportunities and levels of government are depicted in summary form in Table 3.1.

Table 3.1 Levels and types of planning for best practice urban water management

Planning	Levels of government or jurisdiction	Examples of best practice planning
Water resource planning	• National • State or provincial • Some catchment and river basin	• Licensing of abstraction including caps on water extraction based on sustainable yield, including water trading where appropriate. • Analysis and determination of impact of long-term climate change and requirements for environmental allocations. • Establishing processes for engaging water users, stakeholders and the community in water resources planning.
Water utility planning	• State or provincial • Sometimes national • Sometimes municipal	• Utilities undertake integrated resource planning, where supply and demand-side options are assessed on an equal basis, from a whole-of-society perspective. • Utilities integrate long term planning to maintain the supply-demand balance with short term contingency planning to manage drought.
Local government and land use planning	• Local or municipal • Sometimes state or provincial	• The water cycle considerations for new development sites are given primacy and lead the consideration of the land use planning aspects. • Use of water in the landscape to maximize water efficiency and minimize runoff. • Urban design reflects the principles of improving water efficiency, stormwater reuse, wastewater reuse, improving runoff water quality and reducing flood risk. • Development consent conditions for new buildings and precinct developments require best practice efficiency for water using fixtures, systems and processes.

The challenge of climate change in arid zones

Arid and semi-arid regions of the world offer particular challenges in urban water management. While traditional societies have managed to live and even flourish in areas with very low rainfall, as population grows and urban areas expand, this puts increasing pressure on water supplies and requires a different level of response and management. In addition, the impact of climate change is often to make climate less predictable, and to trend towards extremes. Due to low rainfall, there is often a reliance on groundwater resources, or water moved over considerable distances. Groundwater resources can be constrained as in the case of fossil resources, have long replenishment return intervals, be subject to saline intrusion, connected to surface water systems or groundwater dependent ecosystems. Water moved over long distances can be subject to very high pumping costs and energy usage, or high evaporation such as in the case of channels or physical leakage losses.

Climate change itself is reframing supply-demand planning, but there are differing perspectives on what this means. These differences are depicted in Figure 3.3.

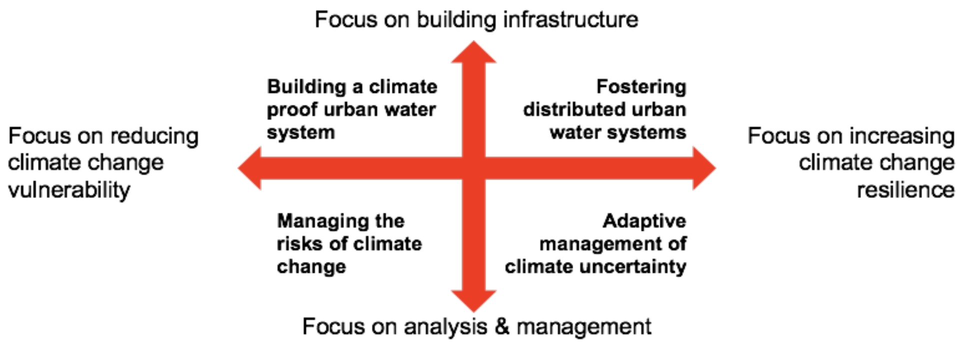

Figure 3.3 Different planning perspectives in responding to climate change (Fane & Turner 2010).

In this framework for understanding the response to climate change, the role of different forms of planning is clear to see. One form of planning aims to reduce climate change vulnerability, by attempting to 'climate-proof' the water system, for example, by building desalination capacity. The other extreme tries to make the system more resilient to climate change shocks by utilizing distributed systems. The other axis highlights the difference between a 'plan to build' strategy, with the focus on infrastructure and capital works, compared to a greater emphasis on analysis and management. All of these are planning approaches, however with a different emphasis, and often significantly different cost implications.

An example of the adaptive management of climate uncertainty is provided by the use of 'real options' planning (Borison & Hamm 2008), in which the security associated with new supply options is provided by the planned ability to build them contingent on outcomes in terms of water supply needs, rather than building them in advance. This was applied in 2006 in Sydney (White et al. 2006), where the analysis of the hydrology suggested that constructing desalination capacity in the drought could be postponed until dam levels dropped to 30%, assuming that all the planning and feasibility had been carried out already, and allowing approximately 2 years for construction. In terms of the probability of this ‘trigger level’ being reached the risk-weighted savings for the cost of supplying water in a reliable and secure way was approximately A$ 1 billion (US$ 0.7 billion) in 2006. In other words, planning and preparing to build the desalination capacity if needed, but not building it, provided the same water security as building it immediately but with significant cost savings. This is analogous to an insurance policy with a low premium (the cost of planning and preparing) but a large excess (the capital cost if the construction is triggered). Despite such careful planning the desalination plant in Sydney was built when the dam levels were at 56%, hence, care needs to be taken that political decisions do not override best practice planning (Giurco et al. 2014; Turner et al. 2016a).

Case studies for arid regions

The following case studies, conducted from the mid-1990s through to 2010 are based on experience of research and practice by the authors in water management and planning in arid regions. They demonstrate early and ongoing application of the principles of integrated resource planning in the arid context. Each case study has very different characteristics in terms of hydrology, governance, socio-demographic factors and water demand. However, there are important lessons from each of them for informing planning for best practice urban water management. The locations of the case studies are shown in Figure 3.4 and a summary of the key characteristics shown in Table 3.2.

A number of common lessons from these four case studies are drawn out in the conclusions section of this chapter.

Figure 3.4 Locations of the arid zone case studies

Table 3.2 Summary details of case studies

City	Country	Population	Average rainfall (mm/yr)	Main water source	Major sectors
Kalgoorlie	Australia	30,000	267	Inter-catchment transfer (pipeline)	Urban & mining
Alice Springs	Australia	25,000	281	Groundwater	Urban & tourism
Alexandria	Egypt	5,000,000	189	Inter-catchment transfer (canal)	Urban, tourism, port
Salalah	Oman	375,000	131	Groundwater (& desalination)	Urban, tourism, industry, port

A. Kalgoorlie-Boulder, Australia

Kalgoorlie-Boulder is a city in Western Australia, approximately 600 km east of the state capital, Perth. It is in an arid zone, with an annual average rainfall of 267 mm per year. The city has a population of over 30,000 and has had a strong history of mining, especially gold mining. In 1895 the Goldfields pipeline was constructed to pump water from the coastal water storages to the rapidly growing gold mining region. At the time, this was one of the largest capital works projects in Australia, and not without controversy (Blainey, 1993).

In 1994, the then Water Authority of Western Australia commissioned the Kalgoorlie-Boulder Water Efficiency Study (White 1994), which was the first analysis in this region of end use demand, and the development of options for improving water efficiency based on integrated resource planning. As a result of that study, the Kalgoorlie-Boulder Water Efficiency Program was implemented by the Water Corporation of Western Australia (Botica & White 1996).

The program comprised of a number of elements, including an indoor water efficiency program which included retrofitting of efficient toilets, taps and showerheads; an outdoor water use component which included elements such as rebates on mulch, drought-tolerant plants and tap timers; and water audits of the top 150 water using non-residential premises, excluding industrial and mining sites.

The application of planning principles features strongly in this case study. Firstly, the study was commissioned as a way to apply the principles of integrated resource planning. The water supply to Kalgoorlie-Boulder is highly constrained, especially in a peak month demand period, due to the size of storages and capacity of the pipeline. Augmentation of supply through duplication of the pipeline would be extremely expensive, at the time estimated around A$ 4/m3 (US$ 3/m3) in 1994 values. This means that a large number of water efficiency investment opportunities were more cost effective than new supply on a marginal cost basis, even including the typically more expensive option of retrofitting of toilets. This underlined the importance of integrated resource planning, and indeed was its first application in Australia, providing sufficient evidence for major cities such as Sydney to adopt the principles of integrated resource planning and similar programs in their world leading efficiency program which commenced in the late 1990s (Turner et al. 2016b).

A second aspect that relates to land use and water planning was the application of incentives for reducing lawn (turf) area for residential dwellings. Despite the high cost of water, the price was subsidized as was standard for rural areas, and there was a strong demand for large gardens and lawn areas. The incentive scheme was designed to support the reduction of lawn areas through replacement with water efficient landscaping. This scheme was also applied to new houses based on the difference between proposed and modified areas. This aspect of the program, however, did not demonstrate savings compared to the indoor water efficiency programs, in part because of the difficulty of ensuring compliance and an unavoidable selection bias for interested gardeners to participate.

In the long run, the impact of measures to reduce the demand for water can be tested in the change in average demand per person, or per household. Over a shorter period, this is not an accurate way to determine the impact of such an intervention, due to the strong influence of climate on demand, especially in Kalgoorlie-Boulder where the residential demand is strongly climate dependent. The evaluation of this Program used a climate model of demand, based on a reference year before the program, to strip out the influence of climate in subsequent years, and to see the underlying changes in demand had the climate been the same.

The results of that model indicated that, net of climate influence and the growth in mining sector demand, the bulk demand reduced by approximately 1,000-2,000 m3/d in the period after 1993-94. When the analysis was conducted this represented approximately 4 to 9% of total demand. The increases in demand during the period observed were due to climate and to the increase in mining demand. Had it not been for the influence of the water efficiency program and other factors subsequently introduced (i.e. restrictions) the demand would have exceeded the levels experienced by 1,000-2,000 m3/d.

B. Alice Springs, Australia

Alice Springs is a small city in central Australia, with a current population of nearly 25,000 and an average annual rainfall of 281 mm/yr. It relies on fossilized groundwater for its main water supply with the associated groundwater source not replenished by rainfall or runoff. By the early 2000s borehole water levels were at approximately 150 m below the surface and dropping at more than 1.5 m each year due to abstraction being over and above the sustainable yield of the aquifer. With the water levels dropping at such an alarming rate additional capital expenditure was required to extend the bores and additional ongoing expenditure needed due to the increased operating costs for pumping (Turner et al. 2007).

In the early 2000s the Northern Territory Government, Power and Water Corporation (the local water utility) and the Department of Infrastructure Planning and Environment (DIPE), recognized the need to use a coordinated approach to managing water resources in Alice Springs. Hence, they set up the Alice Springs Urban Water Management Strategy (ASUWMS), with the aim of using a combination of approaches to deal with the water resource constraints in the region. These approaches aimed to span water efficiency/demand management, alternative sources and effluent reuse to reduce both potable water demand and wastewater production in Alice Springs due to ongoing mosquito and pollution issues in the local swamp. Between 2002 and 2007 a suite of investigations was conducted as input to the ASUWMS.

The first study conducted by the authors in 2002/03 the 'Alice Springs Water Efficiency Study – Stages I & II' (Turner et al. 2003a) involved development of a detailed water demand forecasting model and options model and design of a suite of water efficiency options to assist in achieving specified targets for reduction of average and peak water demand and wastewater production. The main aim was to determine how much water would be needed in the future, determine how to reduce the rate of depletion of the groundwater resources in Alice Springs through water efficiency, reduce effluent overflow to the local swamp and identify the need for water services infrastructure augmentation. The study was conducted using the integrated resource planning approach (Turner et al. 2010).

A key feature of the investigations was to understand the water demand at an end use (micro component) level for single detached houses and flats (i.e. daily tap, shower, toilet, washing machine, dishwasher, air conditioner, pool and garden watering usage), sector level (i.e. schools, hotels, commercial customers) and system leakage level. An average single detached house in Alice Springs was found to use over 700 m3/household/year with 65% of the water demand associated with garden watering and a further 10% associated with air conditioning and household pools (Turner et al. 2003b). Due to seasonality these end uses also contributed to peak demand. Particular sectors, such as tourism also contributed significantly to water usage and peak demand. Understanding demand at such a detailed end use and sector-based level assisted in developing a more accurate forecast of demand, based on available data, and a suite of water efficiency options to reduce average and peak water demand as well as wastewater production. A total of 12 targeted options were developed including for example household indoor retrofits (similar to Kalgoorlie Boulder), top loading washing machine replacement incentive programs, garden efficiency tune-ups and pool cover incentive programs to reduce evaporation. Non-residential programs focused on hotel efficiency audits, hospital efficiency audit/action plans, school indoor retrofitting and garden irrigation/management.

The study found that potable water demand in Alice Springs, in a business as usual scenario, was expected to rise from 10 Mm3/yr in 2003 to approximately 12.5 Mm3/yr by 2021 due to the projected rise in population. The study developed two demand management program scenarios, which could reduce water demand by at least 1 Mm3/yr and 3.4 Mm3/yr by 2021 at an estimated cost of A$ 3.8M (US$ 2.6M) and A$ 10.2M (US$ 7M) respectively. The costs of implementing either of the program scenarios would be recouped by the energy savings obtained from reduced water pumping requirements alone. In addition to reducing the demand for potable water both programs would: reduce wastewater production with subsequent environmental and social benefits in relation to swamp overflows; reduce and/or defer capital investment required to augment the potable water and wastewater systems; reduce greenhouse gas emissions; and provide significant additional social and environmental benefits.

From 2005 to 2007 the Stage I & II investigations were expanded as part of the 'Stage III – Implementation of the Alice Springs Water Efficiency Program – Feasibility Study' (Turner et al. 2007). These investigations significantly broadened the suite of options developed and assessed both water efficiency and other options such as system leakage, source substitution (use of rainwater tanks and greywater systems), the expanded use of the non-potable Town Basin water supply and reuse options. Due to the large component of demand associated with outdoor water usage, expanding options to incorporate non-potable Town Basin and reuse options was seen as essential. A total of 31 options were developed and costed using four scenarios. Figure 3.5 shows a supply curve illustrating the options ranked in order of unit cost against the marginal cost of water (MC). The whole of society costs and quantifiable benefits were considered, provisional assessment of 'who pays' and cash flow, assessment of the potential distribution of costs and benefits to the community and financial implications to the utility together with associated potential price modifications. In addition, a broad level implementation work plan was developed identifying the key elements of work required for a Water Efficiency Program in Alice Springs. The ultimate aim of the investigations being to inform the ASUWMS Reference Group and NT Government decision makers on a range of possible grouped efficiency programs (Scenarios) that could be considered for implementation.

Scenario 3, with a present value cost of A$ 5 M (US$ 4.15 M), average unit cost of A$ 0.30 /m3 and potential savings of 2.4 Mm3/yr by 2030, was recommended as the preferred scenario. This was due to the relatively low cost and significant benefits that could be attained by society as a whole. For example, A$ 4.34 M (US$ 3.6 M) for avoided costs of reduced water and sewage supply and management, A$ 0.94 M (US$ 0.8 M) for reduction in greenhouse gases and A$ 2.44 M (US$ 2.1 M) for reduction in customer energy bills. The Scenario included a number of options that are important in terms of equity and constitutes a Scenario where the overall benefits significantly outweighed the costs.

The studies from 2002 to 2007 formed the basis of the ongoing Alice Water Smart program and later a similar program "Living Water Smart" adopted by Power and Water (the utility) and NT government in Darwin.

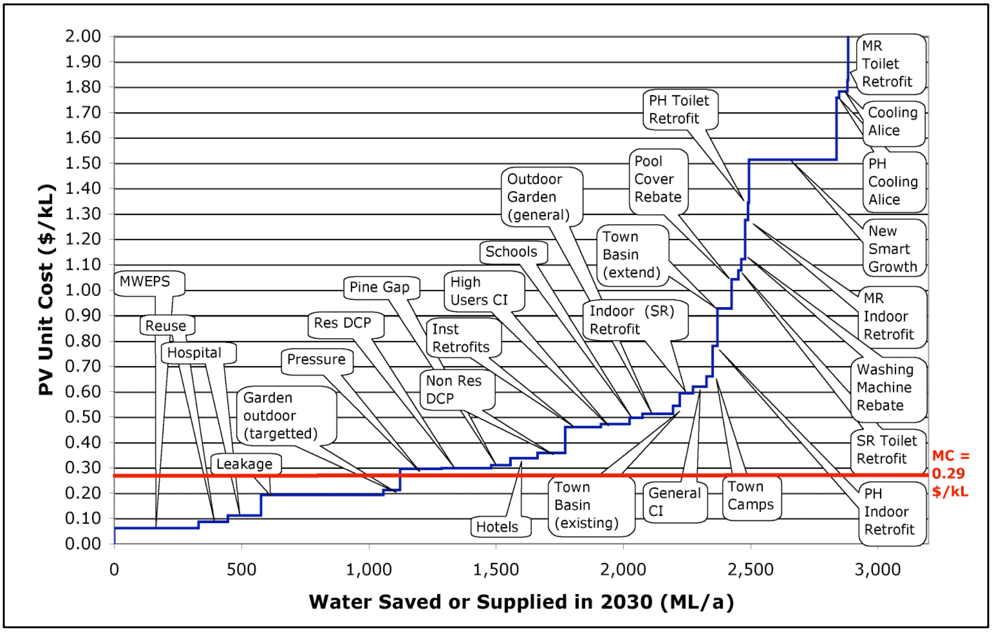

Figure 3.5 Supply curve of options ranked on unit cost (A$/kL) for the year 2030 (Turner et al. 2007)

Note: 1 KL = 1 m^3, 1 ML = 1,000 m^3, A$ 1 = US$ 0.9 in 2007

C. Salalah, Sultanate of Oman

Salalah is the second largest city in the Sultanate of Oman, with a current population of 375,000. It has extremely low rainfall, with average precipitation of only 131 mm per year.

In 2003/04 the authors joined a team of local and international experts to investigate how the constrained water resources could be managed as part of a large study, 'Detailed Water Resources Management and Planning Study for the Salalah Region' (GRC 2004), instigated by the Ministry of Regional Municipalities, Environment and Water Resources (MRMEWR) in Oman. At the time the population in the region was only 150,000 and urban water demand estimated to be 21.5 Mm3/yr. The agricultural sector at the time was the largest water user with 2,820 ha of net cropped area and a net water demand (NWD) estimated to be 60 Mm3/yr and gross water demand (GWD) estimated to be 110 Mm3/yr. Other large water users included a growing industry sector due to the expanding port and tourism.

As in many arid climates, both the urban and agricultural sectors in the Salalah region rely on a freshwater aquifer and a limited number of freshwater springs as the primary freshwater resource. This finite resource has suffered from over abstraction for many years. As a result, saline and brackish water intrusion from the coast and adjacent brackish water areas is a significant problem and in the mid-2000s causing agricultural land to become so saline that crop yields were reducing and in many cases the farms along the coast being abandoned. With the urban population and tourism expected to double between the mid-2000s and 2020, the saline intrusion issue was expected to only continue to grow and cause further tension between the urban and agricultural sectors and negative economic, social and environmental impacts.

The 2003/04 study (GRC 2004) aimed to both forecast demand for each sector and develop and cost a suite of options. The suite of options would then be tested against a groundwater model developed as part of the study to see which cost effective combination of options, focusing on water efficiency and source substitution (i.e. non-potable supplies such as wastewater reuse), could assist in providing sufficient water resources for the growing region and curb saline intrusion. The study was the first time in which the authors had combined the integrated resource planning methodology with a detailed geospatial groundwater model.

The water usage and demand forecast for the urban sector (i.e. residential households, commercial, government/institutional and industrial (G/I/I) properties and non-revenue water/unaccounted for water associated with system losses) was found to be very difficult to determine. This was due to the various ways in which the water from the available groundwater resource are abstracted and the non-centralized management and recording of the water used. A significant proportion of water used by the urban sector in Salalah is provided by a centrally managed Town Water Supply network. However, additional water is obtained from individual bores for large G/I/I properties and private wells for individual households for which, at the time, there are no records. Figure 3.6 shows the forecast estimate disaggregated by sector.

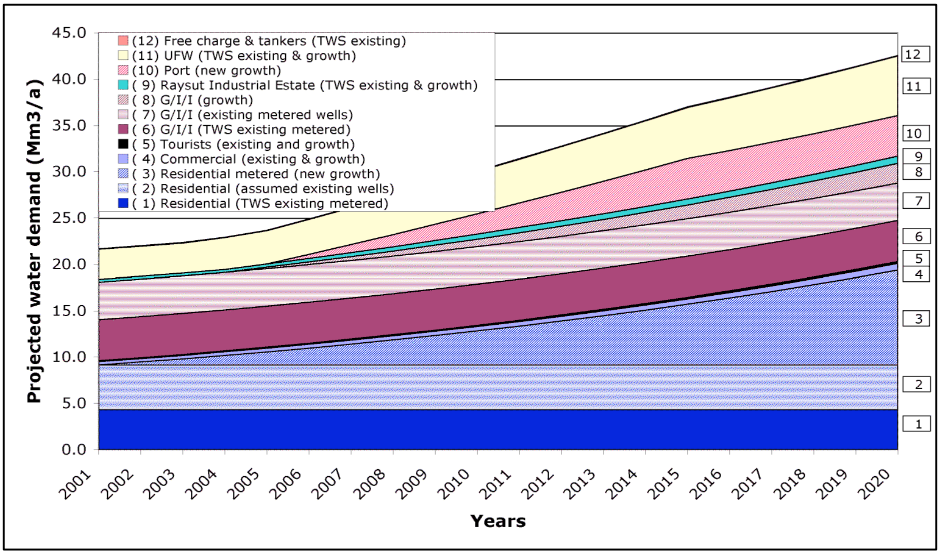

Figure 3.6 Urban Water Demand Projections (Turner & White 2004)

Notes – G/I/I government/industrial/institutional, UFW – unaccounted for water, TWS – town water supply

Estimating the water demand in the agricultural sector proved to be even more difficult. A small percentage of the water used for agriculture comes from channeled surface water springs. The majority is drawn from nearly 1,000 operational wells across nearly 800 agricultural properties. As common in many parts of the world, only a small percentage of the wells are actually metered (4% in Salalah at that time). Hence to estimate water demand in the agricultural sector, numerous assumptions were used to calculate the volume of water used including for example, net crop area, crop type, type of irrigation system, irrigation efficiency, percolation losses and evaporation losses. A National Well Inventory (NWI) from the 1990s that assessed the number of wells, area under irrigation, crop types, irrigation types and typical levels of efficiency, provided a snapshot that aided in estimating the water demand for the sector. Semi-structured interviews with stakeholders complimented the analysis to verify the assumptions in the NWI and ascertain how certain assumptions (e.g. crop areas, crop types and irrigation efficiencies) may have changed during the intervening period. It was established that the forecast for water demand in the agricultural sector was unlikely to change significantly but that water efficiency levels were low and thus there was significant opportunity to increase efficiency levels.

The Study estimated, using the best available information on population, land use, industrial growth and water demand records, that by 2020, in a business-as-usual or reference case scenario, the net water extractions would grow to over 100 Mm3/yr. This far exceeds the sustainable yield of the existing groundwater resources. Hence new sources of water were needed, the efficiency of water use improved, demand reduced in other ways or a combination of all three.

Over 30 water supply and demand management/water efficiency options were developed and modelled, the most detailed and comprehensive modelling of such options undertaken in Oman. The modelling included calculating the costs and benefits of the options, including the contribution to meeting water demand and reducing the supply-demand gap. The options were ranked on their unit cost to supply or save water. A reference case and two scenarios for water resource management were analyzed and tested using the groundwater model developed during the Study. The two scenarios were developed as a combination of the lowest cost supply, efficiency and demand management options. Scenario 1, saving or supply 36 Mm3/year, had a present value cost of 22 M RO (US$ 57M). The option comprised of a significant investment in improved water efficiency in the urban and irrigated agriculture sectors, removal of the large grass farm at Garsis, continued injection of wastewater in the coastal zone as a barrier to saline intrusion and moving the town water supply closer to the Jabal.

The groundwater modelling for the period 2004-2020 indicated that both the reference case and Scenario 1 resulted in a deterioration of the water quality in the current town water supply area, and an increase in saline intrusion in the agricultural areas in the coastal zone.

Scenario 2, saving or supply 47 Mm3/year, comprised the same options as Scenario 1, with the additional options of the removal of several other large farms and extension of the wastewater injection wells. Scenario 2, with a present value of approximately 46 M RO (US$ 119 M), was able to provide for sustainable water resource management within the planning horizon.

The Study recommended that six Groundwater Management Areas be defined, Salalah Plain East, Central and West each with separate coastal areas defined for the purpose of environmental protection of sensitive areas. It was also recommended that water allocations be established in accordance with the results of Scenario 2, providing a priority to the town water supply with an allocation in the Salalah Plain Central of 29 Mm3/year, reserved to meet urban demand to 2020; comprising of 21 Mm3/year for the town water supply and a further 8 Mm3/year for private wells.

To implement this sustainable water management strategy, a set of implementation actions were also recommended, including the establishment of a Management Committee chaired by a senior representative of the MRMEWR in Salalah, and comprising representatives of all the other relevant ministries and agencies. The establishment of a Reference Group, or Advisory Committee, to provide input to the implementation of the strategy by other stakeholders was also outlined. Other recommendations were made regarding budget allocations, metering and pricing, data needs and monitoring with an action plan developed outlining immediate actions required.

In 2012, a 69,000 m3/d (25 Mm3/year) desalination and power plant was opened in Salalah at a cost of US$ 1 billion and in 2018 it was announced that an additional 25 M gallon/d (100,000 m3/d, 36 Mm3/year) plant would be built for 60 M RO (US$ 1.56 billion). This brings into sharp focus the need to take action in regions with rapid growth. Since the 2003/04 study was completed the Salalah population has more than doubled. One of the key recommendations in the study was to take advantage of that growth and make every new water using appliance and building water efficient through efficiency regulations and building codes, incorporating water recycling where possible. Unfortunately, such options do not appear to have been taken-up to any great extent according to those responsible for installing the new desalination plant (Times of Oman, 2018), costing the country billions of dollars in supply that may not have been required if demand had been curbed in the mid-2000s.

D. Alexandria, Egypt

Alexandria is the second largest city in Egypt, with a population of approximately 5 million and an average rainfall of 189 mm per year. The allocation of the Nile River resources to Egypt is based on a 1959 agreement with Sudan that allocates 552 billion m3 of water to Egypt. This is supplemented by very small volumes of water from other sources. The majority of water is used in agriculture, but urban use is increasing. Egypt is an arid country, and Alexandria is at the very end of an extensive system of canals that provide water for agriculture, industry and urban uses.

From 2004 to 2010, the authors were engaged in research projects with key stakeholders in the region, including the Centre for Development and Environment in the Arab Region and Europe through the EU-SWITCH program, to analyze the future demand for water in Alexandria and to develop a list of options to improve the supply demand balance in future years (Retamal et al. 2011; White et al. 2011). Of significance in this work was the linkage between irrigated agriculture and urban use, as they draw on the same water supplies, although the marginal cost of improving efficiency in the irrigated agriculture sector is considerably lower than that for the urban sector. A second factor was the significant population that lived in informal settlements on the periphery of the city, with a variety of water servicing arrangements and therefore highly variable water use per person. As these areas develop, appliances and fixtures are added and water consumption rises. Leakage is significant, and there is a significant opportunity for water demand reduction if fixtures are efficient at the beginning.

The research showed that the extraction of water from the Nile system for the region of Alexandria can be capped at current levels, despite population growth, through to 2037. This could be achieved with a portfolio of options including water efficiency (demand management) and supply options. In the short term, the water efficiency options alone could have the effect of decreasing total extractions from the Nile by over 20%. The results showed that the most cost-effective options are those that improve the efficiency of water use in Alexandria, that is, the demand management options, including agricultural efficiency offsets. Many of these water efficiency options have a lower unit cost than the current operating cost of supplying water in Alexandria. This means that there would be a significant net financial benefit to the water utility (AWCO), and to the customers of AWCO, if these low units cost options were implemented.

Furthermore, the demand reduction levels estimated for these options are not the maximum possible. The estimates of overall savings are likely to be conservative, and further analysis would be likely to increase the estimates of participant take-up and savings. The implementation of the water saving options also has the effect of significantly reducing energy consumption, and therefore reducing greenhouse gas emissions, as described in Retamal et al. (2010). In addition, there is a significant opportunity for local economic development, in terms of the additional employment that would be generated in the implementation of these options, and also the potential for local manufacture of water saving fittings and fixtures.

Conclusions

There are several lessons arising from these case studies that indicate the important role of planning in best practice urban water management in arid regions.

A. Groundwater constraints

Arid zones often have a strong reliance on groundwater, and this means that constraints are often more complex due to the hydrology. Constraints include reduction in the water table due to lack of replenishment, which increases both capital and operating costs. Planning needs to take into consideration the real costs of utilizing ‘fossil’ or non-renewable groundwater sources, as well as the impact on other users and groundwater dependent ecosystems. Detailed hydrological investigations, and consideration of the interconnectedness of groundwater and surface water systems are needed.

B. Inter-catchment transfers

In the absence of groundwater resources, many arid zones have relied on inter-catchment transfers, often over long distances. This increases capital costs and pumping costs, and can place a strain on water resources in the source catchment. In such circumstances the marginal costs of water efficiency, and even wastewater reuse can be lower than operating costs, and certainly lower than the marginal cost when augmentation is required.

C. Variation in end uses

The local context for water use, including climate, socio-demographic, cultural and economic characteristics make a big difference to the demand profile and projections. For example, arid zones can have a large irrigation and cooling water load and high tourism demand can make for seasonal peaks in demand. In Alexandria, hosing down for dust suppression was a large end-use. In Kalgoorlie-Boulder mining represented a significant water using sector and in Oman large grass farms. Hence, gaining a detailed understanding of water demand in a region by sector and end use and how this is likely to change is essential when projecting future water demand.

D. Water source integration

In all the case study areas, the irrigated agriculture, urban use and industrial use relied principally on the same water sources, which means that actions to improve efficiency need to be compared across all sectors and planning integrated.

E. Limited efficiency and reuse

Despite the water resource constraints and high marginal costs of water, water efficiency levels and the reuse of wastewater were not especially high or optimized in the case study areas, despite significant potential. This is principally because the focus has traditionally been on supply-side options only, with the absence of an integrated resource planning framework to unveil the potential of demand-side opportunities.

Leakage assessment, and associated pressure reduction programs, as well as universal metering and cost reflective water pricing are essential foundation options, followed by water efficiency, and exploration of the potential for wastewater recycling. The regulation of the efficiency levels of water using fixtures and appliances and the use of development consent conditions for best practice efficiency in new buildings is also essential, especially in those areas with rapid growth, as demonstrated in the Oman case.

In arid and semi-arid regions with significant water constraints, often high-water usage and the difficulties associated with peak day and peak season system constraints, the use of best practice planning and urban water management is critical. When carried out using an integrated resource planning framework, it can unveil the significant potential of demand-side opportunities and the associated economic, social and environmental benefits.

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How to Reach Efficiency Managing Droughts in Water Supply Systems?

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Abstract

Climate change and population growth in cities are severely challenging the future of water supply. Satisfying water demand is increasingly difficult and frequent shortage episodes is now unavoidable. Ensuring water efficiency is necessary and has presented an opportunity to create more reliable and resilience water supply systems. The establishment of appropriate diagnostics and action plans are key to building efficiency to cope with these contingencies. Such diagnostics should provide answers to the following questions regarding water supply scarcity episodes: What is happening? Why is that happening? What will happen? And what could happen? In an attempt to answer these questions, two indices are recommended: Scarcity Risk Index and Reliability Planning Index. The optimal solutions to reach targets are based on the integrated analysis of both Indices.

Keywords: Drought, Efficiency, Resources management, Contingency, Water supply, Arid regions, Risk index, Reliability index.

Introduction

There are few water supply systems in the world that can guarantee to supply all their demands 100% of the time. This statement holds true particularly in arid and semi-arid regions. Climate change has exacerbated this in many places in the world, even in areas where some decades ago, water scarcity was not expected at all. For instance, countries like the United Kingdom which has traditionally been perceived as rainy, are currently concerned about droughts and their impacts.

Changes in rainfall patterns, which result in lower average precipitations or rivers runoff (both of which have new intensities, frequencies and durations of dry periods) are impacting the ability of water supply systems to provide the expected level of service. Overexploitation of groundwater is an additional challenge to supply systems that rely strongly on these resources.

Increasing population in cities contributes to the imbalance between available resources and demands, or raising concerns about the ability to supply short term forecasted demands. Consequently, scarcity and drought episodes are more likely to happen around the world.

There is a universal need to review operation and planning policies to manage water supply systems in coping with these new threats. Since episodes of insufficient resources are highly likely, procedures to prevent and manage scarcity and drought episodes need to be defined or updated. New scarcity assessment criteria must be applied with new methods and parameters in order to monitor and support decision making processes.

Various options, to cope with these situations, can be applied in any scenario, in which there are opportunities to improve the system's efficiency. These opportunities arise in the main stages of decision making when actions must be identified and implemented.

This chapter deals with these problems and proposes some of methods and parameters to find efficient solutions. This chapter begins by distinguishing droughts and scarcity episodes. It discusses the way in which useful diagnostics and effective analysis around drought management options can be conducted. It proposes two main parameters (indicators) to quantify scenarios and to set targets. It proposes methods to analyse contingency management options and finally, the chapter proposes recommendations of good practices for long term planning. It concludes by presenting the case study of Madrid Water Supply System in Spain with a history of successfully coping with droughts.

Making Accurate Diagnostics

The first step to understanding a drought episode is to conduct an accurate and complete diagnostic. A diagnostic should look to answer four main questions:

- What is happening?
- Why that happened?
- What is going to happen?
- What could happen?

Regarding the application of the first question "What is happening?" The answer may be simplified with statements such as:

a) It is a normal situation;
b) It is a temporary scarcity episode which cannot be managed through normal operation or;
c) It is a permanent scarcity situation that stops the provision of appropriate level of service.

The question "What is happening?" is not always an easy one to answer. Assessing the ability to supply all expected water demands from a supply system is complex, especially when it is unclear whether or not the situation is considered normal. A significant characteristic of scarcity episodes is that they never happen suddenly; they always occur gradually since one of the components of the hydraulic balance (resources available and demands) evolves differently than its "normal" or expected way. Hence there is not a sudden negative balance, but an increase in the likelihood of a deficit. In permanent scarcity systems the likelihood of imbalance is very high.

To get a clear answer to the first question "What is happening?" it is recommended to have previously identified a parameter and thresholds of reference that helps in defining the situation. If the thresholds are trespassed, it could be considered an anomalous scarcity episode and there is a need to trigger some special scarcity management actions. Thresholds will be different at least for every month or season and supply system.

Every supply system must identify the appropriate parameters of reference and their correspondent thresholds. The setting of these thresholds should be based on a definition of expected resiliency of the system to face and recovery from scarcity periods with a certain severity. Figure 4.1 shows the evolution of a supply system with normal and temporary scarcity episodes.

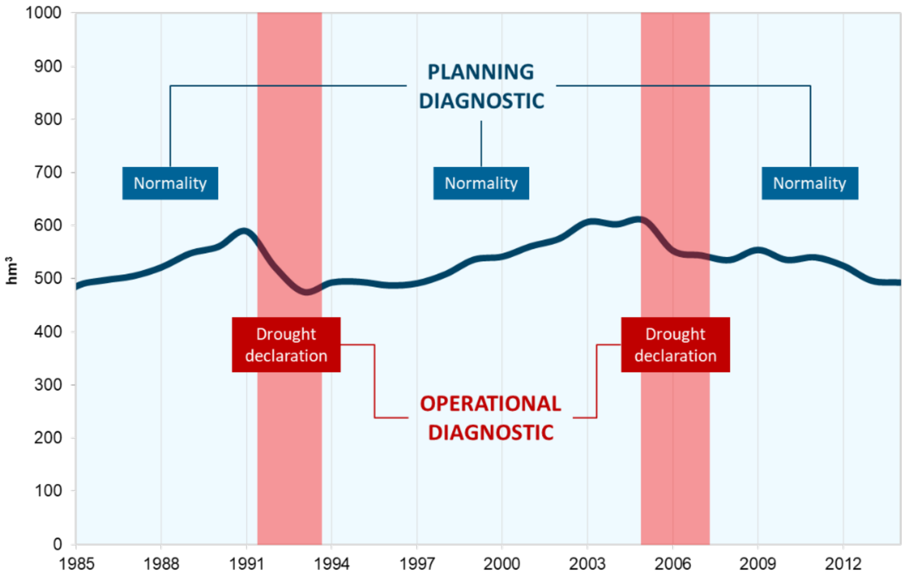

Figure 4.1 Scarcity Planning and Operational Diagnostics

Regarding the second question "Why that happened?" when the situation is clearly normal, it is a superfluous question, but when it is not clearly normal and there is a scarcity episode, this may be due to an abnormal low rainfall period. In this case it is properly called drought, since this meteorological anomaly is the most likely cause of the problem. Sometimes the supply imbalance is due to a faster than forecasted growth of demands, a decay of available resources or to a delay in the implementation of planned solutions. Often these imbalanced episodes are due to both causes or to the way hypotheses and scenarios of abnormal episodes of droughts were included in planning policies. They should be called drought episodes whenever they are clearly due to an abnormal low rainfall spell, and they should be called scarcity episodes whenever the cause is not clear. Nevertheless, experience shows that scarcity episodes are very often referred to as drought episodes.

Regarding the third question "What is going to happen?" it is an uncertainty problem linked to the first two questions. There is neither certainty about the future evolution of demands nor about future availability of resources, and consequently there is no certainty about the ability to supply all demands in the short term without any shortage or without significant impacts. The answer must be looked for, to some extent, in a risk assessment of the supply balance evolution, which assumes the application of operational policies as currently applied at the time of analysis, or following an already established operational schedule.

It is crucial to identify, at any time, the need and ability to impose some exceptional actions in the short term because of a scarcity episode is very likely. This short-term diagnostic must be differentiated from a generic medium to long term assessment regarding the likelihood of having to cope with scarcity scenarios in a supply system. The diagnostic focused on solving current scarcity episodes, can be called Scarcity Operational Diagnostic and the one focused on generic medium-term scenarios can be called Scarcity Planning Diagnostic. Figure 4.1 shows a theoretical evolution of a system using as a reference the amount of available storage resources. It differentiates episodes of scarcity and normality when Scarcity Operational Diagnostics must be applied under scarcity episodes, and Scarcity Planning Diagnostics must be applied under normal conditions on a regular basis. A Scarcity Planning Diagnostic must be always updated when a scarcity episode finishes.

Any Supply system must have drought/scarcity focused diagnostics (Planning or Operational), before during and after any scarcity episode. Efficiency must be searched in both types of scenarios but the main opportunity arises through the appropriate integration of these two types of diagnostics.

The answer to the fourth question "What could happen?" must be based on an analysis of options in every case. When the system is within a scarcity episode, considered options will be focused on solving the problem and recovering a normal situation, but when the situation returns to normal, options analysis must consider jointly how to reduce the likelihood of future scarcity episodes and how to solve those episodes if they become unavoidable. This is the best opportunity to look for an integrated efficiency.

Scarcity Operational Diagnostic

When a water supply system is not sure of being able to provide all expected demands reliably in the short term or the immediate future term, it triggers a declaration of a situation of drought or contingency. This statement usually results in some actions that lead to some impacts on citizens, customers, users, the environment and water related activities.

Decision makers do not wait for a zero volume of storage water to arise before making a drought declaration. It always starts when a situation of low storage or limited abstraction possibilities exist and this leads to the forecasting of an insufficient ability to supply all committed water demands in a certain time ahead.

As it has been mentioned, causes of those situations can be very diverse, but very often they are linked to a period of lower rainfall than normal and therefore they are usually called drought episodes. Effective solutions must identify the origin of the situations very well.

When scenarios of high likelihood of insufficient resources are approaching, water supply systems managers become concerned and start unusual preventive operational policies trying to avoid any direct impacts on users. These measures mean some increment in operational costs and the implementation of actions regarding preparations to cope with exceptional situations. If scarcity is caused by an abnormal low rainfall period, some impacts have already been produced in rain fed agriculture and related economic activities. Nevertheless, in an urban water supply system, a drought situation should not be acknowledged if any user is not constrained nor limited in some way in the use of water. For example, just launching campaigns asking for voluntary water savings, without any ban of uses or shortages should not be regarded as a drought scenario (from a water supply system point of view). A drought situation usually starts through a legal statement issued by the appropriate authorized institution with some compulsory measures that constrain the use and availability of water.

A declaration of a drought situation should be based on a reliable diagnostic (first and third question). The definition of a method to carry out a reliable diagnostic is the first step in searching for drought/scarcity efficient management. Low rainfall periods are frequent drivers of drought declarations but this is not always the main cause, or the only cause. That is why a diagnostic must start quantifying the real severity of rainfall and runoff in relevant river reaches, based on past meteorological and flow gauge records. Figure 4.2 shows an example of statistical assessment of yearly rainfall in one meteorological station. Figure 4.3 shows a characterization of rainfall spells with different duration and intensity in a meteorological station. This rainfall spells characterization could be used as a reference for drought characterization. Figure 4.4 shows a statistical assessment of an analysis of monthly cumulative runoff values flowing into the abstraction points of a system.

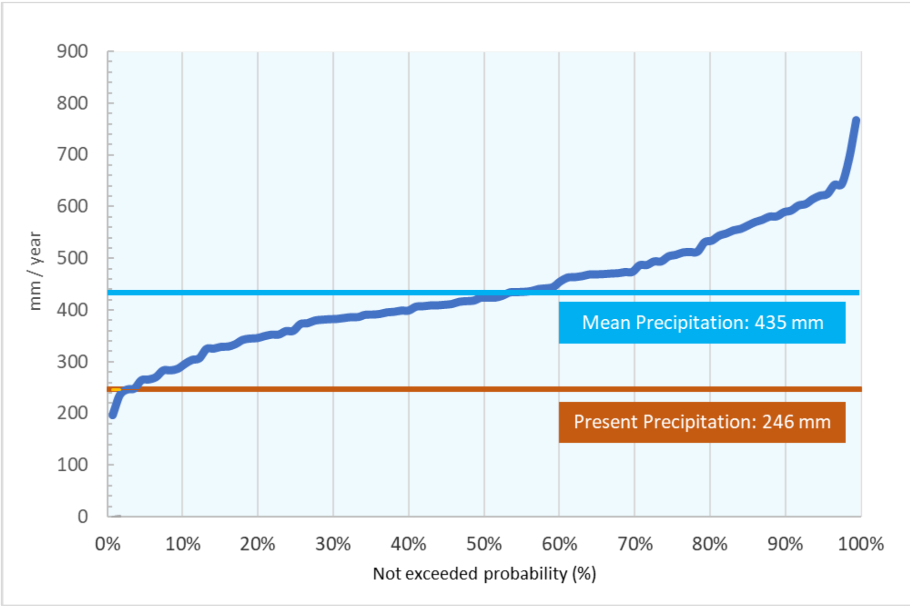

Figure 4.2 Statistic Analysis of Total Yearly Precipitations

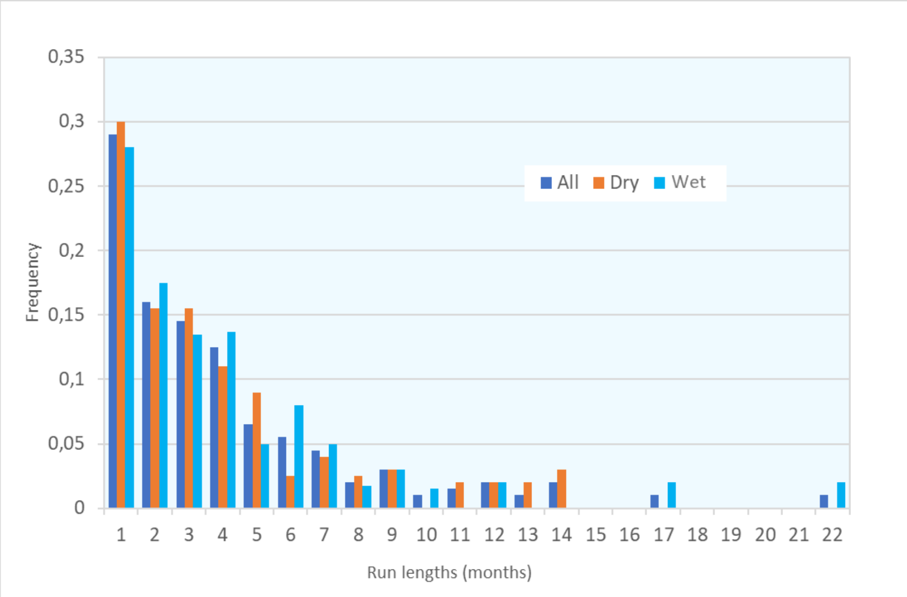

Figure 4.3 Observed Frequency of Run Lengths

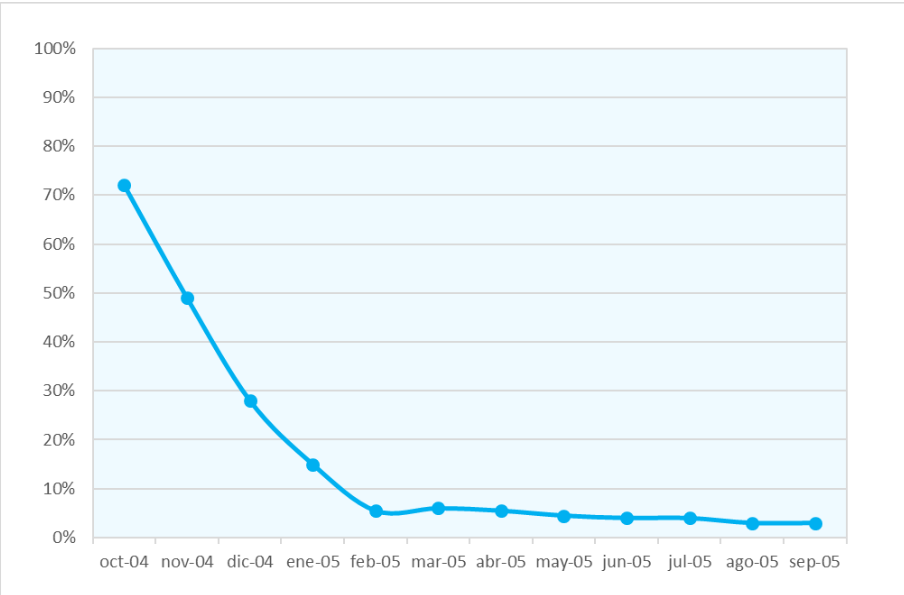

Figure 4.4 Not Exceedance Probability Evolution of the Monthly Cumulative Runoff

Rainfall indexes are helpful in assessing the real origin of the problem but they are never the most relevant parameters when an urban water supply system is concerned. At present, there are very good monitoring systems and indexes, like the Multivariate Standardized Drought Index MSDI (Hao, et al, 2013) that provides information about the severity of rainfall spells and their influence on soil moisture and conditions for vegetation, wildlife and crops, but this information is not necessarily useful in assessing an urban water supply condition nor its ability to satisfy demands.

To be less dependent on rainfall, many urban systems rely on their capacity to store water in reservoirs, pumping from groundwater, or their ability to abstract and treat water from rivers or desalinated seawater.

Nevertheless, it is important to know the real origin of an unbalanced situation in working towards the appropriate solutions. Solutions and management practices will be different depending on the causes of the problem. Unbalanced scenarios, due to inadequate demand growth planning or delayed implementation of structural solutions, will require different type of actions to cope with the problem than those to solve occasional unexpected short dry periods.

Droughts are linked to low rainfall and scarcity episodes are linked to resources/demand imbalance, but in most of the imbalance episodes a scarcity scenario will always be called a drought. Anyway, at the time of making management decisions it is important to know the reality.

An accurate Scarcity Operational Diagnostic will be based on an analysis of facts benchmarked with some values of reference. The establishment of those parameters and values of reference (thresholds) are key points in any identification of potential solutions or options. It will be useful to characterize the past hydrological period in terms of rainfall and runoff.

A Scarcity Operational Diagnostic can be solely based on the current situation and on previous evolution records. It is what may be called Facts to establish the baseline for decisions making. Volumes of total usable storage (considering water rights and multiuser agreements, etc.) are frequently used as parameters for a first diagnostic of a current situation. An indicator that relates current available volumes with average unitary demands could provide a useful diagnostic in foreseeing immediate term scenarios, but supply managers need to manage parameters that help them make efficient decisions; to do that, some special forecasting techniques must be applied. These forecasting techniques must consider at the very least:

- evolution of storage, reserves and abstraction capacities with several hypotheses of severe scenarios and
- demand evolution under different saving and shortages requirements

Forecasting available resources implies uncertainty management techniques and involves assumptions of abilities to abstract certain amounts of volumes and flows from every considered potential source.

Forecasting demand evolution requires techniques to estimate volumes and patterns of reductions (savings) that could be obtained through different kind of actions within a certain timeline.

Facts, Assumptions and Hypotheses will determine different forecasted scenarios. Diagnostics that involve forecasting the future are relevant in the making of preventive and mitigating actions, which is why it is important to distinguish Facts from Assumptions and Hypotheses. Facts to have information about the past and the current situation, to be used as a base line to forecast the future; Assumptions based on accurate and well-defined assessments of responses to potential measures and actions; Hypotheses to consider events with different levels of probability to build options analysis that aid the making of efficient decisions.

A useful Scarcity Operational Diagnostic should provide information about:

1. Hydro meteorological records regarding statistics parameters.
2. Current Demand pattern. Showing the present (recent past time) values of components of uses and demands for every type of use and supplied zone. This analysis must consider the influence of weather and the main explanatory variables that can be conditioned under compulsory scenarios. Figure 4.5 shows analysis of monthly demand patterns for every main type of use under average weather conditions and Figure 4.6 shows an analysis of real demand evolution with the normalized values (those that should have happened with the observed weather) in comparison with those expected under extreme and average weather scenarios. This comparison allows the assessment of the demand response to some other stimulus independently of weather influence.
3. The need to implement non-conventional resource operational rules within a certain timeline.
4. The likelihood of triggering some scarcity (drought) management declaration within a certain timeline. Figure 4.7 shows examples of these type of forecasting analysis.
5. The likelihood of triggering some more constraining drought management measures within a certain timeline. Every measure and stage will determine some impacts and damages with an estimated lasting time. Figure 4.8 shows examples of these type of forecasting analysis.

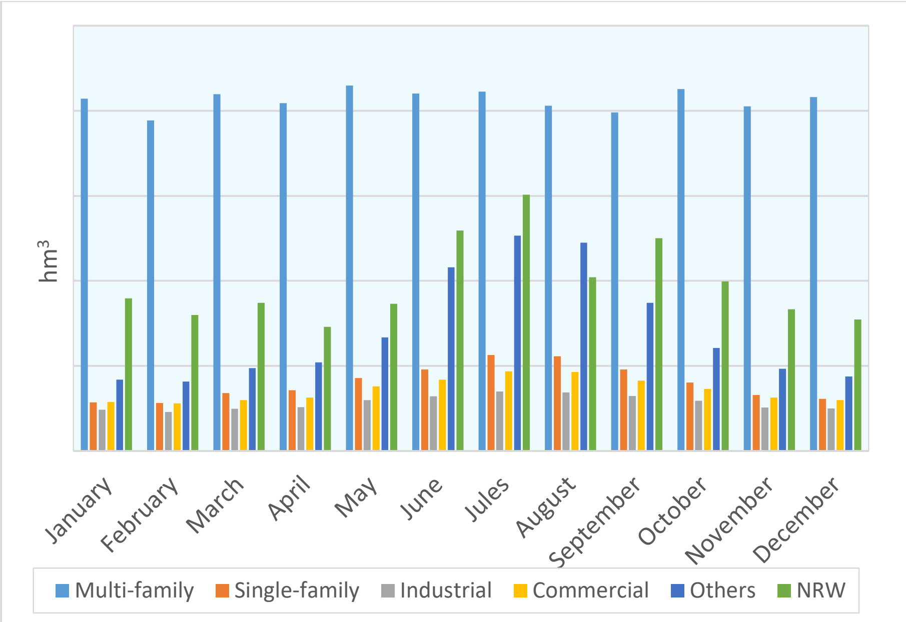

Figure 4.5 Forecasted Monthly Demand under Normal Weather Conditions

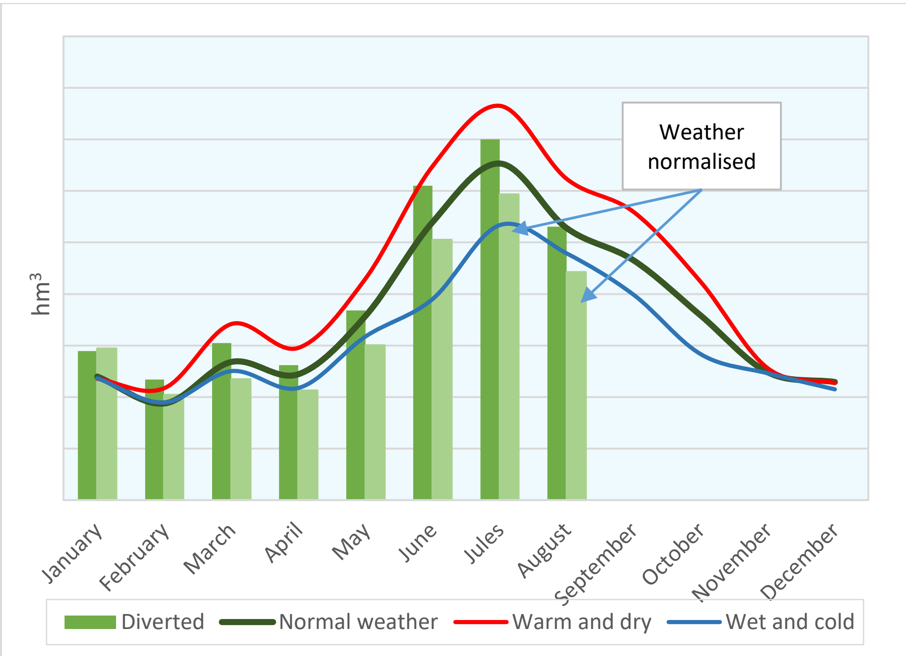

Figure 4.6 Comparison of real monthly consumption and normalized to observed weather with expected demands under different weather scenarios

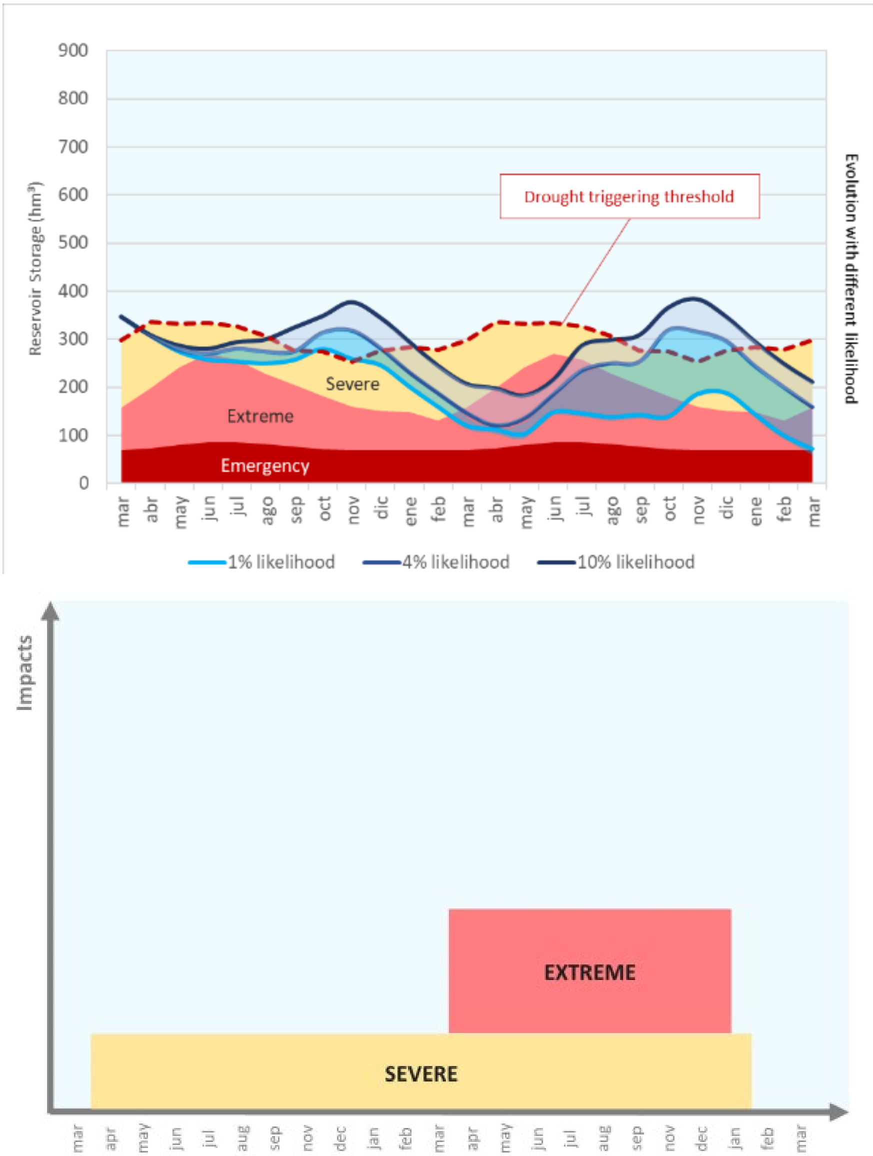

Figure 4.7 Forecasted impacts for 10% likelihood

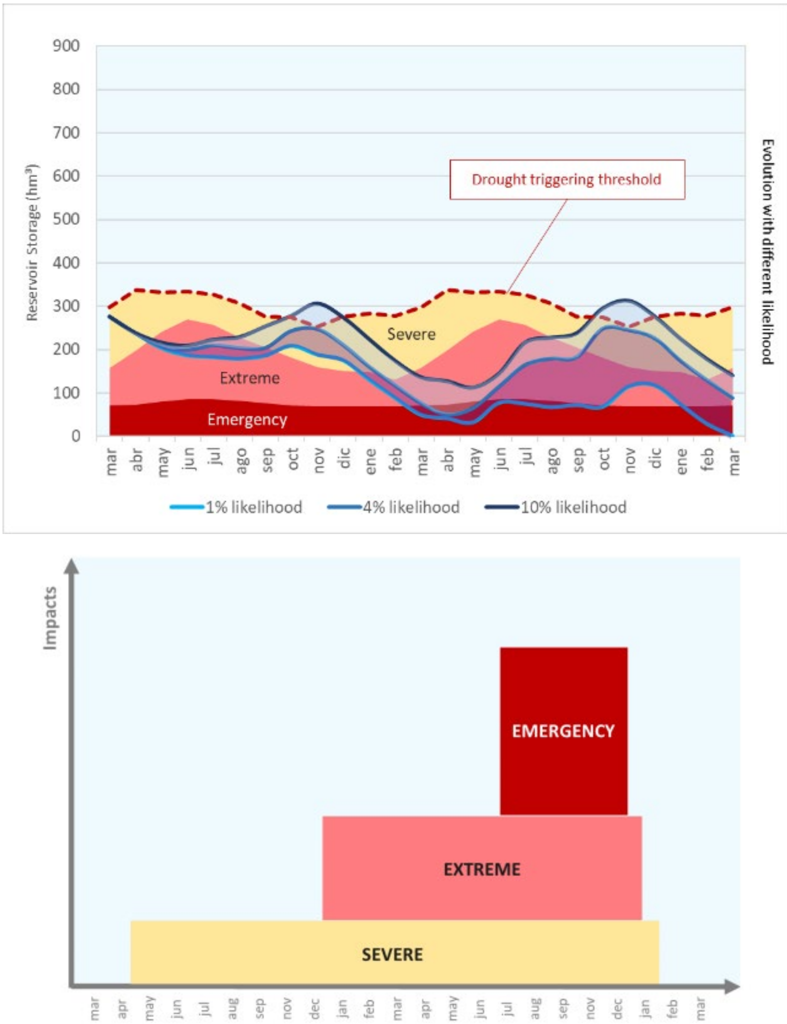

Figure 4.8 Forecasted impacts for 4% likelihood

Combination of the items 4 and 5 of the previous list will form the Operational Scarcity Risk Index. This index can characterize, monthly, the severity likely evolution of a scarcity episode under scheduled (according to protocols) solving and management measures.

$$SRI = \sum_{i=1}^{n} I_i \cdot \int_0^1 D(p_i) dp_i \tag{1.1}$$

SRI (Scarcity Risk Index): Sum of the impacts (damage and cost) for each phase of scarcity multiplied by the integral for the time of analysis of the duration of this phase, as a function of the probability (see Figure 4.9).

Where:

i Each of the considered phases of different degree of severity of the scarcity episode

n Number of considered phases

I_i Monthly impact (damages and total costs) related to the stage of severity i

D Duration (in months) of this stage, and related to a certain probability (pi) of remaining in this stage

Forecasted horizon should last at least the maximum expected time of drought. A Scarcity Operational Diagnostic should be carried out monthly under normal conditions and weekly under drought episodes. Every supply system should determine the mentioned basic parameters, stages and thresholds on a regular basis and keep them updated for its specific context and system. Assumption of monthly damages and costs (putting social and environmental damages in monetary terms) should be calculated based on established protocols and measures for every stage. Thresholds to trigger every stage are linked to the established achievable resilience and correspondent protocols.

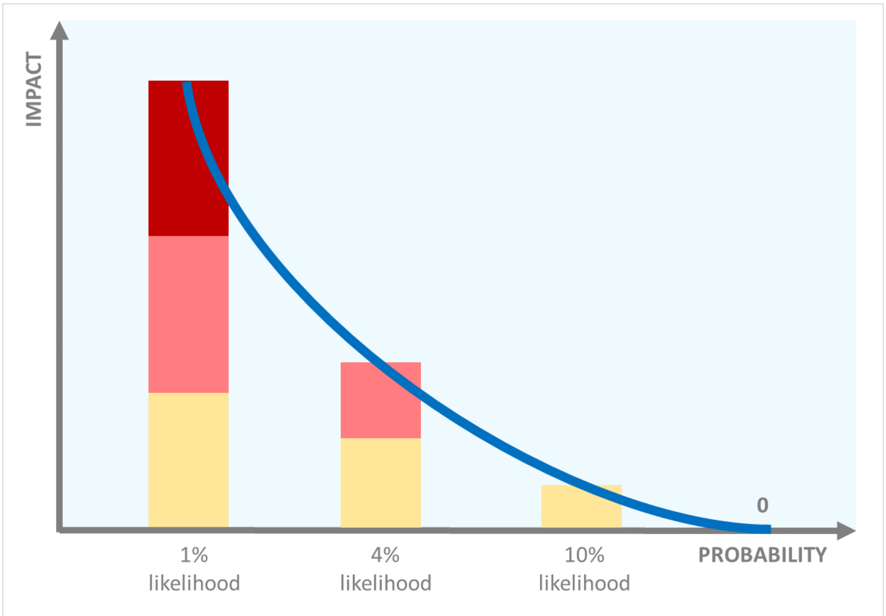

Figure 4.9 Operational Scarcity Risk Assessment

Scarcity Planning Diagnostic

A Scarcity Planning Diagnostic is carried out by the assessment of the ability to provide total demands in future generic scenarios and horizons. It is assumed that it is carried out under a normal scenario without any constrain linked to a scarcity or drought current episode. A Scarcity Planning Diagnostic is the assessment of the likelihood of having to cope with a scarcity episode and the analysis of several options to reduce the risk of scarcity of the system through the reduction of that likelihood and its related impacts.

A Scarcity Planning Diagnostic must follow a similar procedure to the Scarcity Operational Diagnostic but it must be focused on future horizons and scenarios and using generic time series of rainfall, runoff and availability of resources. Long term demand evolution and climate change scenarios are good examples of hypotheses to manage in planning exercises. This type of medium to long term planning diagnostics must be carried out and updated on a regular basis. A yearly frequency is recommended but it is crucial whenever there is information of relevant changes in new infrastructures for abstraction or storage and when it changes the assumptions about demand patterns or availability of resources. It is necessary to carry out this analysis when a drought episode finishes, which always means an opportunity for planning for the next drought episode and implementing preventive measures.

A water supply system should be able to know or calculate: The Generic Scarcity Risk Index in a Scarcity Planning Diagnostic and the current Scarcity Risk Index within a Scarcity Operational Diagnostic.

The Generic Scarcity Risk Index will be calculated for every horizon, scenario and hypothesis considered. Every scenario will involve: 1) resources availability (including climate change hypothesis), 2) abstraction and transport capacity based on existing and planned infrastructures and 3) amount of demands to supply with their patterns based on forecasted evolution of uses and achievement of demand management policies.

The result of the analysis will determine, for every horizon and scenario, the likelihood of triggering a scarcity episode (or drought episode) and the assessment of the duration and severity of the drought episode. It is a risk assessment, and in consequence the index must be a risk index which multiplies probability by impact. Figure 4.10 shows a Planning analysis based on this Generic Scarcity Risk Index for future horizons.

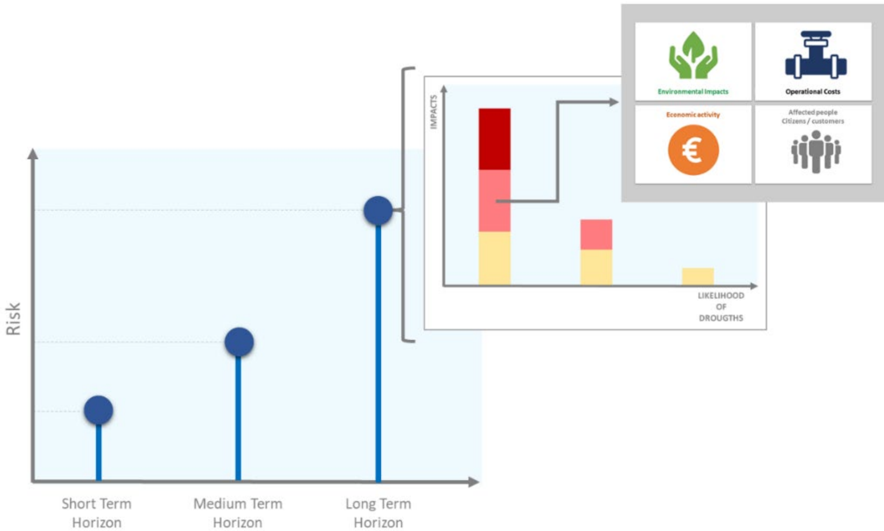

Figure 4.10 Assessing Generic Scarcity Risk Index for Planning Horizons

To assess this index, it is crucial to establish the procedure and the criteria to cope with the different severity of scarcity episodes in advance. The definition of such drought/scarcity management episodes must be carried out with a credible assessment of the consequences and results of implementing some measures. This capacity to recover from a problem or scarcity episode within a certain time and up to a certain amount of damages is called resiliency from the supply system to drought and it is described in another chapter of this book.

General approach to effectively managing droughts

Efficiency analyses are always based on finding the best options to fulfil specific targets in different horizons.

Best solutions will be those that create the less likelihood of social and environmental impacts with the minimum total cost (CAPEX and OPEX). Regarding scarcity and drought, the method of carrying out these analyses has two main characteristics: First, it is a problem that impact dramatically on the whole economy of a region and with remarkable influence in society and second, arid and semi-arid regions society and water suppliers know that it is impossible to guarantee 100 % of permanent supply to fulfil demands.

Therefore, Efficiency management must integrate conventional structural and operational solutions with contingency (drought/scarcity) management solutions since they are highly likely to be applied.

Setting Targets for Risk and Resilience

Looking for efficiency is always based on the analysis of different options to fulfil targets with the less global costs. Regarding droughts and scarcity in water supply systems, the targets must be established in terms of risk to provide a certain level of service. To assess that risk, the two main parameters proposed in previous paragraphs must be used: first, likelihood of starting a drought situation with some compulsory measures that impact on water related uses (reliability) and second, the amount of impact of those measures (resilience).

Setting these targets will require an assessment wider than just the own supply system. It will require joint analysis:

1. Within the basin, or basins, where the system is located or water is abstracted from;
2. With all entities and stakeholders that share resources with the supply system or receive its waste water;
3. With all stakeholders linked to the economic activity of the supplied zone and, most importantly;
4. With the citizens and users of the supply system that will suffer a direct impact on their level of service and commitments with them.

Public participation processes are crucial in the analysis of targets which include the cost of every target, its feasibility and direct and collateral impacts.

Options Analysis

Efficient solutions must look for two types of actions: a) those to reduce the probability of scarcity situations and b) those to improve resiliency and allocate preventive resources and options with the aim of resolving and recovering from a scarcity scenario. It is a combination of structural and operational solutions. These operational solutions must include normal and contingency management procedures, with assessment of costs that include all type of global costs.

Structural solutions mean not only actions of building new infrastructures for abstraction, pumping, drilling wells, treatment or inter-basin transfer, but also any action which adds a permanent contribution to the balance between resources and demands should be considered. An example are demand management measures that achieve a permanent saving and reduction in demands. Another example is reused water plans that reduce the consumption from natural resources.

Structural solutions are used to lasting long periods of time till they are fully operative, and therefore these types of solutions should never be considered as an Operational solution. In consequence, they are only considered for Planning analysis and their influence reducing the Generic Scarcity Risk Index.

Every structural option to consider must include at least its economic investment (capital cost), its operational cost (according to a forecasted operational role among other options), its environmental cost (Life Cycle Assessment techniques) and social costs. Additionally, it must include the horizon when it will be fully operative (regarding dams and reservoirs, the time when they will be able to regulate and provide water, not just when they will be finished but empty). And as a complement to all these costs, its contribution to the reduction of Generic Scarcity Risk Index.

Regarding operational solutions, at least two types of solutions should be considered: Those to improve normal operational efficiency and those focused on improving resiliency.

Solutions to improve normal operational efficiency will be those based on criteria and practices to be applied using available resources under conditions of normality. The use of different resources considering their operational and environmental cost, their ability to fit with the appropriate required water quality for every type of use, and their importance to be available to guarantee or reduce the likelihood of trigger a drought situation must be analysed. Reused water plans and water trading options contracts are a good example of solutions to improve scarcity index values.

Solutions focused on resiliency are within the framework of scarcity episodes' management procedures. These solutions must be included and considered in Drought/scarcity/contingency management protocols. These protocols will define procedures, responsibilities and the way to proceed and manage contingency episodes when a drought or scarcity situation is declared:

- Which actions should be triggered and when;
- How much water should be abstracted from every available source;

- Which demand reduction measures should be imposed for every scarcity scenario;
- Which uses to shorten and when;
- When to start water trading, etc.

All these actions and the way and circumstances to implement them are defining the potential impacts of a scarcity and the guarantee of keeping these impacts within the established amounts and scopes.

Every action will have some economic cost and social and environmental costs additionally to an assessment of their contribution to guarantee or improve the operational Scarcity Risk Index and to fulfil the established minimum achievable level of resilience.

Figure 4.11 summarizes for a certain horizon the different assessment stages to analyses options to improve resilience, options for costs saving at preventive operational measures and options to improve reliability, the combinations of these 3 analyses will facilitate the selection of the most efficient options.

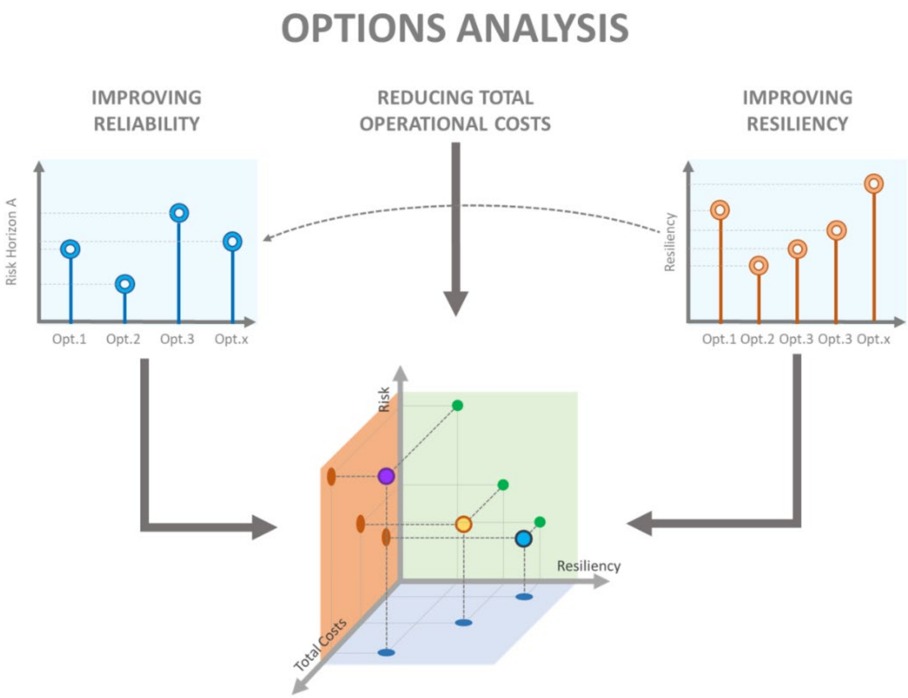

Figure 4.11 Assessment of Options in Scarcity Planning

Defining this group of solutions and their contribution to the management of potential scarcity scenarios are of a key importance in setting the resiliency of a system to drought. Likewise, social acceptance and knowledge is also crucial to reach expected results from every measure. It should be more than just an assessment of the social cost. Society must be involved in the definition of these measures and their potential impacts. In contingency management the public involvement, even more, the involvement of every potential affected stakeholder is a kernel issue.

So, efficient management of droughts must consider both type of options, structural and operational, with their interaction among them.

It is important to notice that, although every measure will have a contribution to reliability, resilience or both, there will be a "natural evolution" of demands, and perhaps in the availability of resources. Demands very likely will grow and resources could decay due to climate change or overexploitation of available resources happened. Assessment for every future year and horizon must consider these changes and evolution to calculate the expected index evolution under management as usual or with the implementation of some considered options.

For every assessed horizon there will be an optimum solution, based on a group of options that fulfil the targets in an affordable way with the less total costs and with the acceptance of society and stakeholders. Figure 4.11 outlines this type of analysis.

If a solution is not found among all options considered, a review of targets must be carried out and discuss. In general, the only choice is to assume a reduction in resiliency or a higher Generic Scarcity Risk Index.

Recommendations

Every water supply system must carry out accurate Scarcity Diagnostics (Operational and Planning) on a regular basis and when a scarcity episode happens. These diagnostics must provide at least answers to the questions: What is happening, why this happen and what is going to happen.

It must be assessed the feasible and realistic resilience of the system in coping with scarcity episodes. This assessment must be based on specific parameters of every supply system jointly to their thresholds of reference to identify scarcity episodes.

Since thresholds are determined, likelihood of trespassing these thresholds must be calculated either for current situation and future horizons.

The first step for any management strategy or policy is to set targets and commitments for likelihood of coping with a drought and the amount of impacts and damages to suffer from it. In a second step their feasibility and affordability must be analyzed.

In arid and semiarid zones, droughts and scarcity scenarios are one of the most relevant threats, in such a way that policies and practices regarding drought management are key issues to set targets and looking for efficient solutions.

To be efficient managing droughts, it is basic to have appropriate diagnostics before, during and after any episode of drought or scarcity.

Assessment of sufficiency of a water supply system in any future horizon and scenario must be quantified through the two main parameters used to determine the Generic Scarcity Risk Index:

1. Likelihood of start a drought situation with some bans, shortages or conditioning to water system direct or indirect users
2. Likelihoods of impacts with different severity and duration

The *Generic Scarcity Risk index* jointly with resiliency should be the parameters used as targets when setting strategies and Action Plans.

The processes to identify thresholds and severity scenarios is an opportunity for efficiency, because they are linked to all planning and operation practices and resiliency of the system.

The method to manage efficiently a water supply system should be based on integrated analysis of the three main pillars of its management: Planning (designing), Operational planning and Contingency management. Every process has some opportunity to improve efficiency, but the main opportunity is in the integration of all of them.

Planning for Resiliency and reliability should be based on setting values, preferences and acceptances from stakeholders and users. Once they are established, the task is to look for the optimum feasible combination of options and their thresholds.

Scarcity Operational Planning must be a systematic task, suggested monthly, looking ahead for possible episodes of triggering drought conditions and on weekly basis when the system is under a scarcity episode or contingency.

Contingency management, must be aware that drought episode could occur with worst conditions than in previous occasions, so it is important to forecast possible evolutions and anticipate measures to cope with longer and more severe duration and intensive droughts and scarcity. This assessment of evolution and forecasting likelihood of more severe situations must be quantified through the Operational Scarcity Index, which should help to make contingency management decisions.

Madrid Case Study

Madrid Region has a surface of 8.000 km2 with a population close to 6.5 million people distributed in 177 municipalities.

The Supply system has been threatened by dry periods and fast population and consumption growth. Episodes of scarcity that required mandatory reduction of consumption and efficient operational procedures were unavoidable in the last decades.

Applied solutions focused on all type of measures, structural, operational and for contingency management. All of them were managed in an integrated way, from long term planning to immediate operation decision making.

Figures bellow show some examples of the main episodes, use of resources, demand evolution, contingency solving and fulfillment of protocols to cope with the last drought episode in 2005-2006.

Figure 4.12 shows the front page of the 2 drought management manuals published by Canal de Isabel II. The first one was issued in 1992 and updated till 2003 when the new one was issued with an additional integration with planning and operational procedures. It has been updated on a yearly basis and applied and tested in several episodes of droughts or approaching droughts.

Figure 4.13 shows the management stages defined in the last Drought Management Manual.

Figure 4.14 shows the evolution of reserves in the reservoirs of Madrid supply system during last decades and the characterization of stages approaching or triggering droughts situation.

Figure 4.15 shows reserves evolution during 2005- 2006 drought, related to the average status.

Figure 4.16 shows the real evolution of reserves and different forecasted evolutions carried out when the 2005-06 drought had not started, and figures 4.17, 4.18 and 4.19 show different decision-making events and their impact on demand and on ecological flows.

Figure 4.12 Drought Management Manuals of Canal de Isabel II

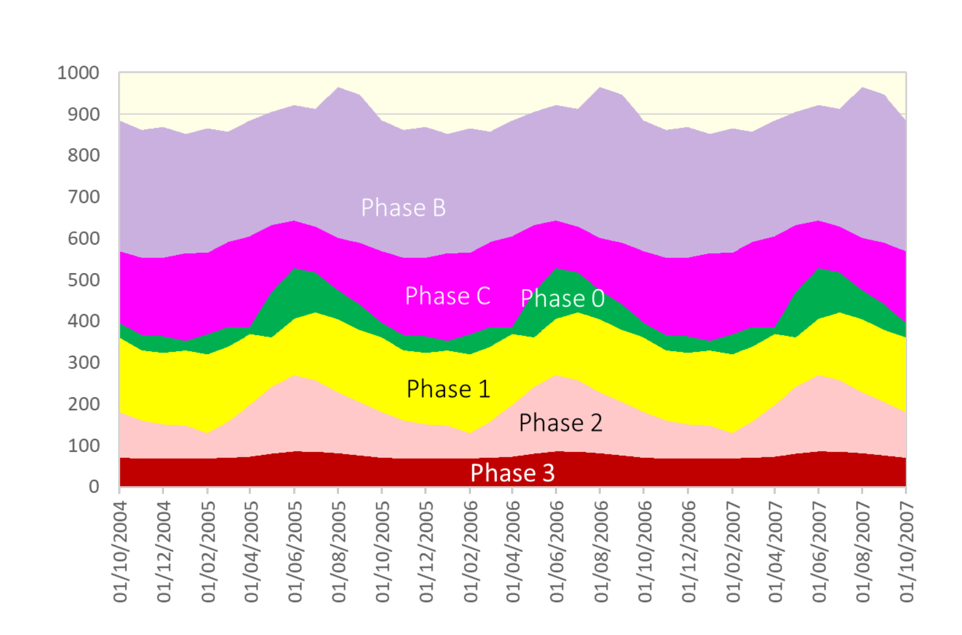

Figure 4.13 Management Stages Defined in the Drought Management Manual of Canal de Isabel II

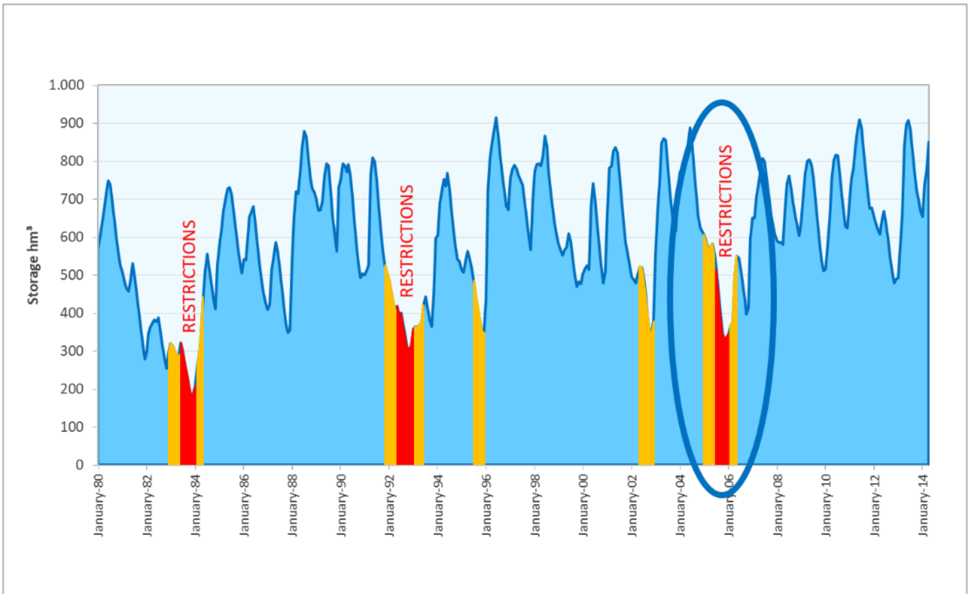

Figure 4.14 Evolution of Reserves in Madrid Supply System during Last Decades and Characterization of Stages Approaching or Triggering Droughts Situations

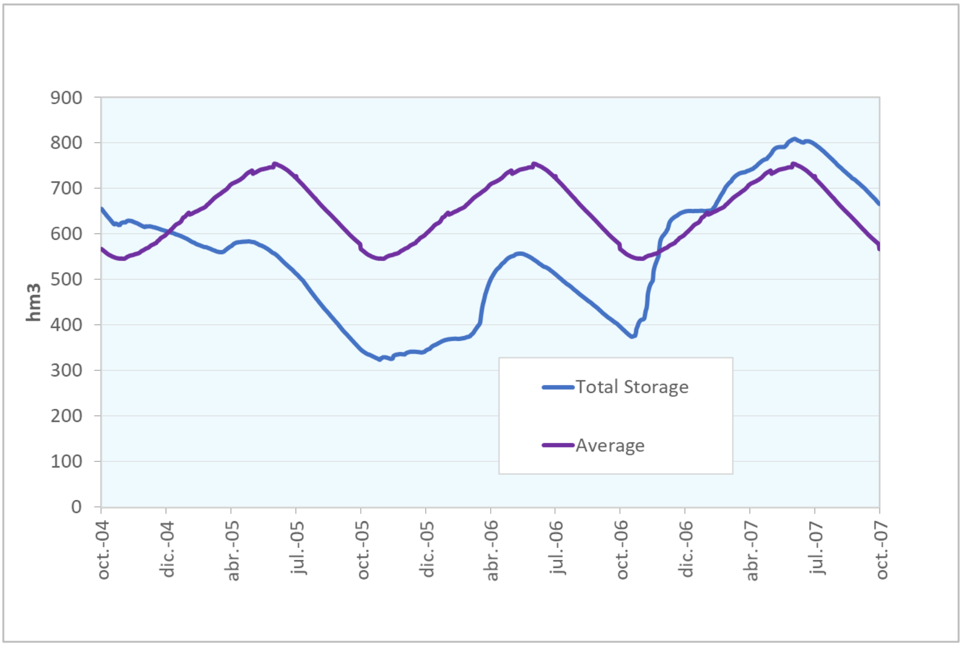

Figure 4.15 Reserves Evolution during 2005- 2006 Drought, Related to the Average Status

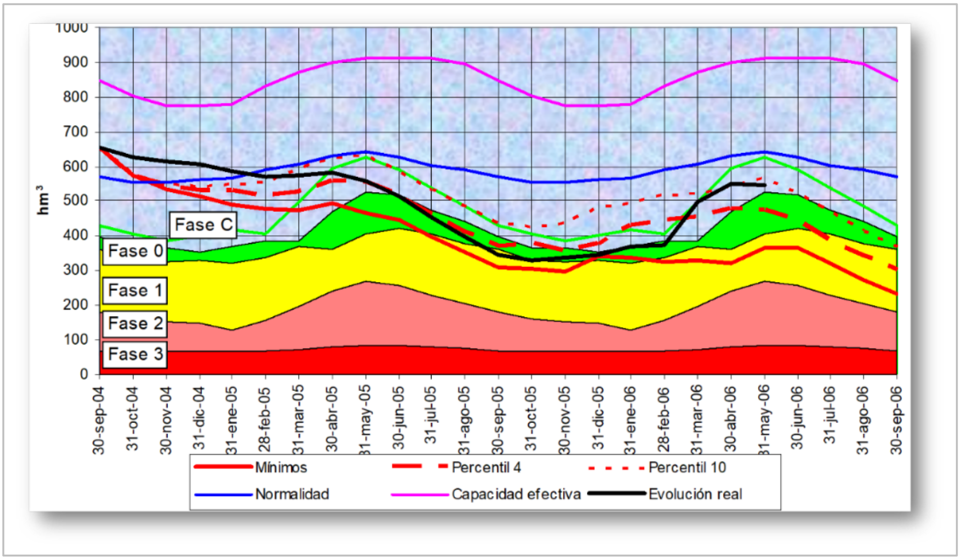

Figure 4.16 Real Evolution of Reserves and Different Forecasted Evolutions Carried Out When the 2005-06 Drought Had Not Started

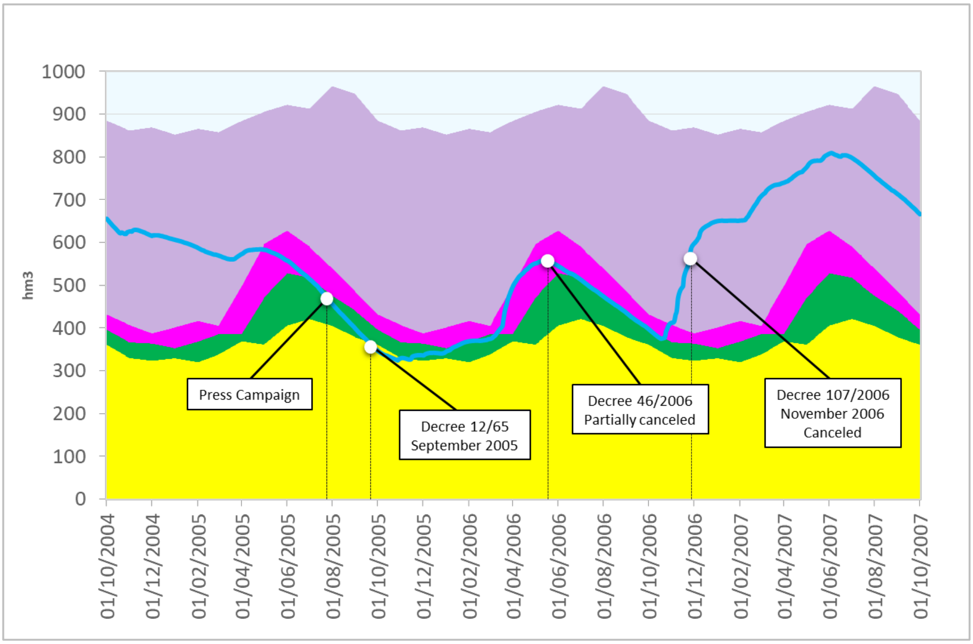

Figure 4.17 Evolution of Reserves, Stages and Times to Trigger Measures

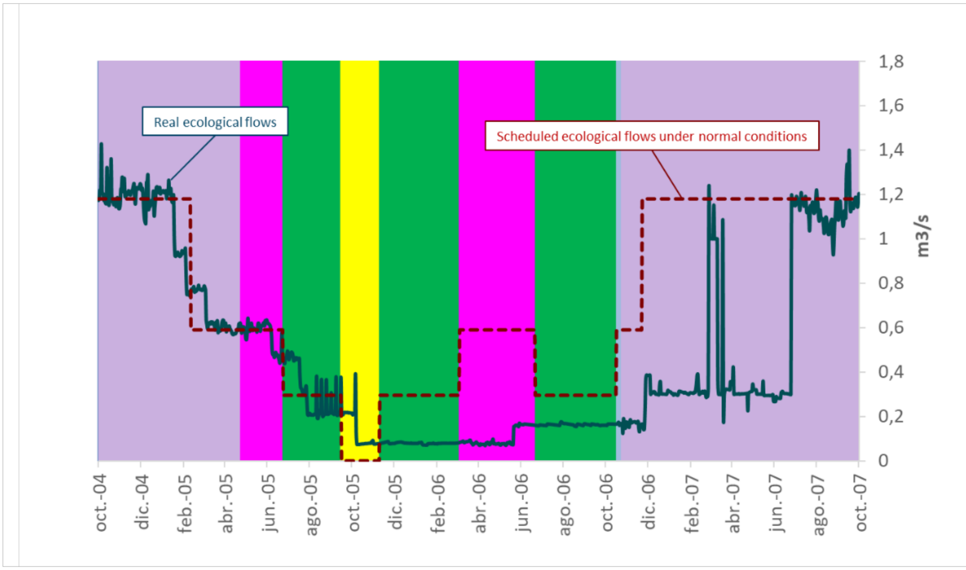

Figure 4.18 Changes in Ecological Flows under Drought Stages

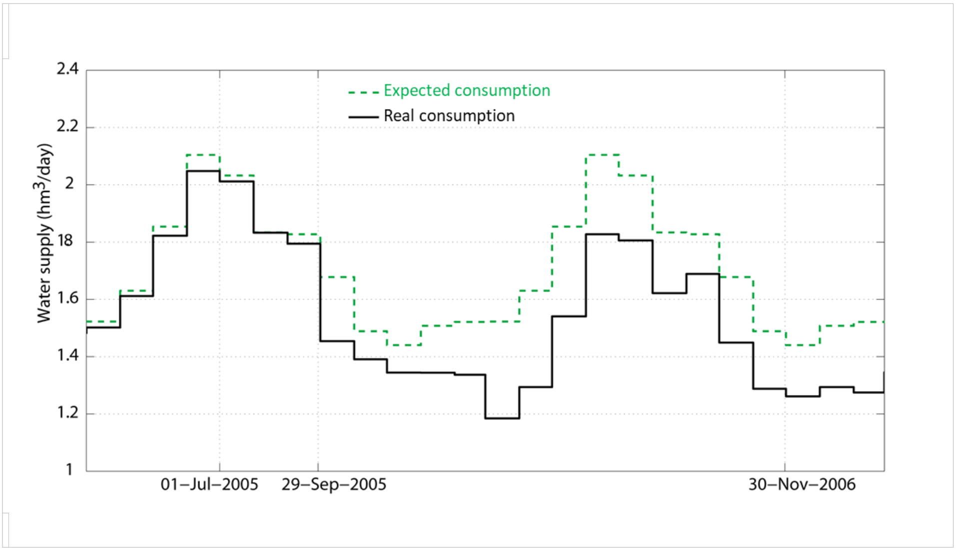

Figure 4.19 Expected and Real Consumptions

International Experiences

Every year some news about raising scarcity and drought episodes are issued around the world. Australia, South Africa, California, The United Kingdom and China are examples of recent droughts and scarcity episodes with different impact and type of solutions. Some documents related to those episodes are included in the following bibliography.

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How to Quantify Resilience to Droughts in Water Supply Systems?

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Abstract

Different meanings and interpretations of resilience are being developed. Every system shows a different level of resilience when it comes to coping different kind of threats. Water utilities are facing increasing challenges and should ensure overall resilience. Among the many threats that water utilities must face, droughts and their impacts and derived scarcity scenarios to water supply systems stand out as one of the more important to consider. A comprehensive calculation of resilience is presented in this paper. Resilience is defined in this paper as the capacity of a system to recover within delimited impacts in the aftermath of a disruptive event. Different types of threats are classified from the point of view of water service disruption: (A) water scarcity, (B) water supply discontinuity, (C) discontinuity of hydraulic conditions and (D) discontinuity of drinking water quality conditions. Some of them could rise simultaneously but this paper is focused mainly on those episodes related to droughts. The proposed method is to relate the capacity to recover from failures with quantified unavoidable, or scheduled, impacts. Hence, quantifying impacts is a key challenge to apply the method and that is why the method focusses on the way to quantify impacts. The method to quantify impacts rely on quantify the loss of appropriate level of service. The resilience concept is built on the existence of capacities based on applicable protocols to cope with failure episodes, resources, skills, technologies and operational procedures to keep updated and reliable abilities to resolve failures.

Keywords: Quantitative approach; Service disruption; System resilience; Water supply systems; Droughts; Resilience to droughts.

Introduction

Communities are exposed to disruptive events, including natural disasters (droughts, floods, earthquakes, hurricanes, tornados, tsunamis, wildfires, and winter storms, cyber and terrorist attacks, climate change, traditional threats and manmade accidents). It is necessary to face and overcome these hazards and develop systems able to cope with them and to ensure appropriate services and appropriate resilience, understanding resilience as a capacity to face and recovery from threats. But there is not a common use of resilience approach, such as appropriate, feasible, or socially accepted resilience. So, it is important to make an accurate definition of resilience for every system and threat and the way to quantify it in every case.

The concept of resilience has been used in a great range of disciplines, such as civil, structural and lifeline engineering, sociology, economics, regional science, policy research and decision science (Tierney et al., 2007), psychology (Henry et al., 2012), business (Hoffman, 2007), as well as in ecological and socio-ecological systems (Barnes et al., 2012). It has also been extended to the security disciplinary area (Prior et al., 2014). In addition, several definitions may be found in literature and its application is not evident as it was explained in Henry and Ramirez-Marquez (Henry et al., 2012). There is a specific resilience from every type of system to cope with different threats, additionally there is a different resilience to any type of threats depending on the severity of the threat. There are different approaches in the scope of analysis of capabilities, from those just focused on solving failures, crisis or disasters to those that include preparedness and risk management policies (Environmental Protection Agency (EPA), 2015).

The concept of resilience raised from the property of a material to absorb energy when it is elastically deformed and have this energy recovered upon unloading (Tsakiris, et al., 2012). This theory has been applied to many disciplines. The Community and Regional Resilience Institute (CARRI) interprets resilience as the capability to anticipate risk, limit impact, and bounce back rapidly through survival, adaptability, evolution, and growth in the face of a turbulent change (Fitzgerald, 2009). One of the most common definitions is related to the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions (White House. Presidential Policy Directive, 2015). Other authors focus on the ability of an entity or system to bounce back from an unforeseen event to establish a definition of resilience (Henry et al., 2012). From these definitions, different tools have been developed to assist water utilities for the purpose of assessing and planning response actions to face anomalies and traditional disruptions. Some of them tried to increase overall community preparedness by raising awareness (Travers, 2010), while others may specially consider climate changes (Environmental Protection Agency (EPA), 2012) and others are focused on the implementation of contamination warning systems (Murray et al., 2010), or on risk management (Brashear et al., 2010). Although these tools help water utilities improve their resilience to threats, they are not able to quantify the resilience of a system. A standard and measurable definition of resilience is required to assess and compare systems, prevent from unforeseen events, define operation and planning procedures and establish contingency management protocols.

In addition, several indicators have been defined to explain different attributes linked to resilience, such as robustness, redundancy, resourcefulness and rapidity (Tierney et al., 2007). The Argonne National Laboratory Resilience Index uses a great number of variables to measure the resilience of an infrastructure, like drinking water and wastewater systems (Petit et al., 2013). This index considers preparedness, mitigation measures, response capabilities and recovery mechanisms. These attributes may give rise to quantifiable variables (Francis et al., 2013). There are some other definitions just focused on distribution networks systems, (Todini, 2000) that proposes a “Resilience Index (RI)” and explains that, in water supply systems, failures or modified and increased demand conditions increase the internal energy dissipation, and if a surplus of energy is not available, there is a failure in the delivery. That author, Todini, defines resilience as the capability of the designed system to react and overcome stress conditions, as well as describes that an increase in resilience mean a decrease of the internal energy dissipation. The resilience index of Todini compares the amount of power dissipated in the network to satisfy the total demand and the maximum power that would be internally dissipated to satisfy constrains of demand and head. This resilience index is analysed by other authors as a measure of the capability of the water distribution network to cope with failures (Baños et al., 2011; Tsakiris et al., 2012). Jayaram and Srinivasan (2008) explain that the RI may not efficiently work for systems with multiple sources, so they proposed the “Modified Resilience Index (MRI)”. Prasad and Parker (2004) add the effects of surplus power and reliable loops to the RI and defined the “Network Resilience Index (NRI)”. However, these indexes only consider the flux of energy. Furthermore, a standard quantitative definition of resilience has not been standardized (Prior et al., 2014; VanBreda, 2001) and a mathematical approach has not been adopted yet (Environmental Protection Agency (EPA), 2015). It must be noticed that a quantitative metric is required to support resilience engineering (Francis et al., 2013) and it should be more comprehensive. Prior and Hagmann (2014) emphasise the importance of moving the resilience concept from the conceptual rhetoric to actual policy-making and explain several reasons for measuring resilience.

Some variables have been included in resilience models of water supply systems. Barnes et al. (2012) proposes a base model of first-degree expression with the components of a resilient water supply system. They explain that resilience may be expressed as a function that depends on water quantity, water quality, water demand and other variables (such as hydraulic head), though they do not seek to detail a definitive equation of the components of a resilient water system. The National Infrastructure Advisory Council defines infrastructure resilience as the ability to reduce the magnitude and/or duration of disruptive events (National Infrastructure Advisory Council (NIAC), 2014). Tierney and Bruneau (2007) explain that resilience may be measured by the functionality of an infrastructure system after a disaster and also by the time it takes for a system to return to its previous level of performance. The same interpretation is found in other articles (Ayyub, 2014; Castet et al., 2012), because resilience is presented as a combination of survivability and recoverability (Uday et al., 2014). As may be seen, the importance of including time variable when resilience is being defined is emphasized (Haimes, 2009; Haimes, 2006). Henry and Ramirez-Marquez (Henry et al., 2012) describe a delivery function to evaluate the performance of a system at a specific time. They define resilience at time t as the ratio of recovery at time t to the loss suffered by the system at a previous time. Baker et al. (2013) add the concepts of reliability, vulnerability, survivability and recoverability to the delivery function-time figure described in Henry and Ramirez-Marquez (Henry et al., 2012). They also consider time to recover as a stochastic variable. Francis and Bekera (Francis et al., 2013) propose a metric to quantify resilience that incorporates resilience capacities (absorptive, adaptive and recovery) and recovery time. The Department of Homeland Security: Science and Technology Directorate (2010) presents a resilience model (“bathtub” shape) to describe the behaviour of the system after being impacted. The total area within the resilience profile is used to compare the resilience levels, measured in performance-time units.

Water infrastructure is a vital public health and economic resource (Giannelli, 2011) hence the resilience of drinking water systems to face hazards and traditional service interruptions has been studied by several authors. However, there is not yet a common definition of the way to make assessments that helps water supply managers to include the concept in decisions making processes in planning and operation policies.

The proposed methodology in this article considers previous efforts to measure system resilience in a generic manner (Department of Homeland Security: Science and Technology Directorate, 2010; Francis et al., 2013; Henry et al., 2012; Rose, 2007; Whitson et al., 2009). The main objectives of this article consist of setting a definition of resilience for a whole supply system, proposing the need of rising different types of resiliencies for every type of threat and severity. A general model of resilience is proposed for this purpose and a metric named as impact factor is presented.

Proposed Definition of Resiliency to Drought

When a disruptive event occurs, the system responds with its absorption and adaptation capacity. If the system is not able to absorb disturbance, hazards causes failures and impacts on different users or related aspects. In this chapter, the resilience concept is related to the failure's occurrence and the solving and recovery process, so it is not associated with the search for absence of failures.

Although resilience is being related to dramatic threats, it is applicable to any disruptive event that impacts on the normal water service provision, such as pipe breaks or water quality failures, nevertheless this paper will focus mainly on drought and scarcity episodes

Figure 5.1 shows a theoretical disturbance episode, summarized as the loss of provided level of service.

Resilience is limited to the ability to manage failure episodes. Failures are part of the impact generated by a threat and, at the same time, the impact is a component in the risk assessment. Thus, it may be said that resilience is a constituent element in a risk analysis. Resilience is considered as an attribute of the system at a given time, but any change in protocols, resources or technologies of the water company may immediately change system resiliency.

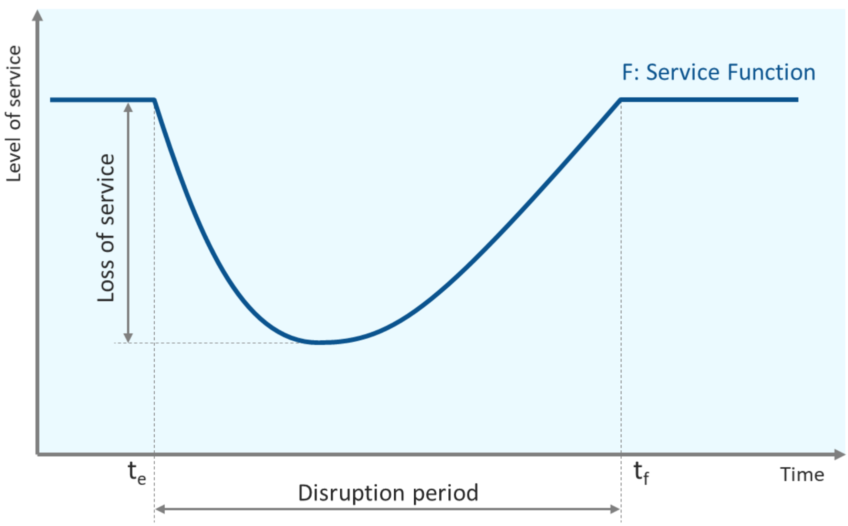


Figure 5.1 Loss of level of service along a disturbance episode

Since drought management strongly relies on operational procedures, resilience to drought is linked very much to the type of established procedures to prevent, mitigate ad solve scarcity episodes caused by droughts. These procedures involve the detailed sequence of actions or processes followed to cope with the operation of the system, both under normal conditions, during and after an impacting event. Solving protocols have a relevant influence on the response capability of the system, but to be effectives, they must be applied with rigor when they are triggered and they must be defined based on realistic assumptions and hypotheses. Response capacity is not only linked to protocols, there are some other components that influence the system resilience, the most relevant are next: (1) structural configuration, (2) operating availability of equipment, (3) technologies, (4) human resources (qualified and trained) and (5) updated solving contingency management protocols (with real application in the expected terms regarding timescales).

Different protocols will determine different loss of functionalities when coping with a specific threat. Figure 5.2 shows potential change in patterns of lost level of service depending on applied protocols and resources.

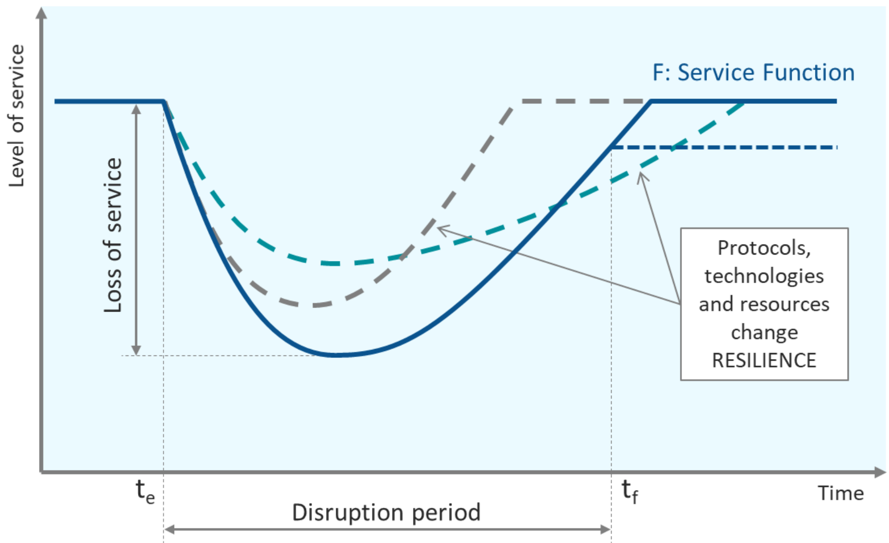


Figure 5.2 Shaping Loss of Level of Service with Different Protocols

It is evident that loss of level of service is not enough to quantify the impact of a failure, because lasting time of loss of functionality is a key additional variable to consider. To be more precise, it is important to distinguish the grade of lost functionality. To do this, it must be acknowledged that in many cases loss of functionality cannot be measured as a continuous function. In cases like drought management, protocols are applied following stages with different severity, triggering compulsory measures for different uses, imposing shortages or rationing, through statements or legal, statutory requirements. So, it is appropriate to consider different levels of loss of functionality tided to different constrains in the use of supplied water with their linked impacts. Figure 5.3 shows the impacts linked to a loss of functionality for different lasting times in a different way than in previous figures.

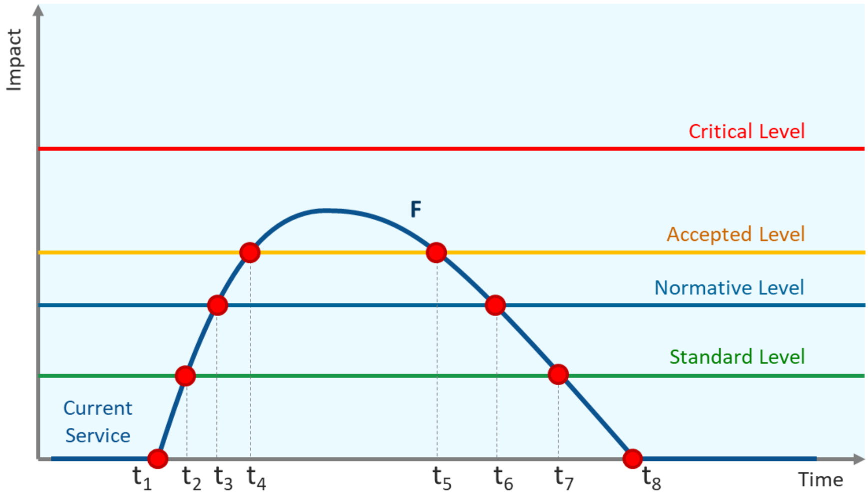


Figure 5.3 Impacts Evolution along a Disturbance Episode and Related Thresholds

In order to asses impacts of an episode of failure, based on loss of functionality and time, it is necessary to know different thresholds of reduced level of service. The proposed definition considers 4 thresholds: (1) standard level, (2) normative assumed level, (3) socially accepted level, and (4) critical level.

Impacts are not only produced on users of the water supply system, there are some others water related users that can be impacted by a scarcity episode or its solving procedures, such as environment, economic activities, operational costs or municipal and social activities. These impacts can be considered imbedded in the above-mentioned thresholds or have their own levels and thresholds.

Another major challenge is the definition of a performance or service function, which can be defined from the point of view of service disruption to the end user and could considers four main impacts of threats: (A) water scarcity with some kind of shortages, (B) temporary water supply discontinuity, (C) discontinuity of hydraulic conditions (like low pressure) and (D) discontinuity of drinking water quality conditions. All of them can and should be considered, but in this paper only water scarcity has been considered to make an easier understanding of the proposed methodology. The above-mentioned disturbances can be produced by an episode of drought or scarcity due to an inappropriate planning, but they can be generated by any other threat like an earthquake or just a burst. If the origin is different than a drought, the resilience should be assessed in a different way since the resilience to quantify would be the resilience to earthquakes or to bursts. There is in fact a set of attributes of the systems and each type of threat generates a different resilience factor. Anyway, the units of the impact factor are loss of service level and time, represented by the vertical and horizontal axes of the resilience model, respectively.

The system capacity could be assessed by the real or expected intensity and duration of loss of service that is able to guarantee the system to face a threat with a certain severity. The loss of service and time are the main parameters that are proposed to measure guaranteed maximum impacts.

Since it is necessary to combine records and expectations, facts, assumptions and hypotheses should be differentiated and considered to quantify limited impacts and resiliencies. Only facts, records and implemented measures of past events can be analyzed and quantified; based on these facts resilience to those happened episodes can be assessed. When current or future resilience wants to be assessed, assumptions and hypothesis must be considered, it is always an estimation and forecasting exercise. Resilience assessment relays on reliable assumptions like availability of expected resources, strategic reserves, operative technologies, citizens' collaboration or real applications of protocols. Happened disruptive events with different severities must be identified and used as a reference, they may be used to assess their impacts and to forecast impacts of other likely future episodes with similar conditions but with expected availability of resources and applicability of procedures and protocols. Every change in the system conditions (infrastructure, technology, resources, etc.) would modify resilience. If there were not available data related to a specific threat, resilience assessment should be estimated. Uncertainty increases in long-term estimates, because assumptions are necessary and some hypotheses have to be taken into consideration. The estimate of resiliencies requires adequate models for simulating real conditions and operations to face a disruptive event. In these cases, the resulted resilience depends on the capacity to anticipate resources and processes and the ability to reproduce the conditions of the simulation models. As an example, the system resilience to overcome an event related to water scarcity varies with the methods for forecasting of water inflow to the reservoirs, the availability of water reserves and the reactions of end-users to save water. Resilience should be a parameter to be considered in the planning and design process, due to the fact that failures always occur even in controlled situations. In order to meet this challenge, it is required to define criteria and failure thresholds with measurable parameters for different types of expected threats. Well-defined levels of service allow the establishment of failure thresholds.

To sum up, resilience is presented for water supply systems in this article as the set of system capacities to delimit impacts of disruptive events. Capacities are verified based on records and adapted to present circumstances or hypothetical scenarios. Patterns of maximum Impacts guarantee by a resilience may be measured by the duration and severity of the failure caused by a hazardous event. The severity of a failure is a loss of functionality under some reference values or levels of service, which allow the calculation of the impact factor. Resiliencies are calculated for every type of threats, and the system resilience is an aggregation of these resiliencies in consideration of the society´s perception of failures.

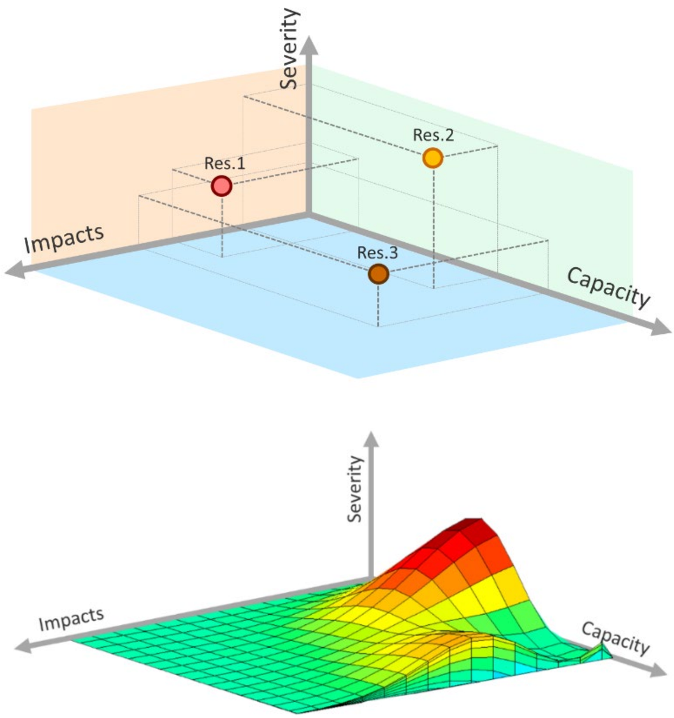


Figure 5.4 Severity of Events

Methodology

The proposed methodology is based on ways to build, for a water supply system, a trade-off between threats with a quantified severity and the guarantee maximum impacts on the level of service. The impact is quantified by the loos of service and this loss of service is measured by the impact factor, which is limited by the defined service levels and the severity and duration of the failure.

Types of Disturbances

The following types of consequences due to disruptive events should be considered in water supply systems, as they affect water service provision:

A. Water scarcity. Water scarcity is a general term that refers to permanent and temporary, natural and human induced phenomena of low water availability (Spiliotis et al., 2015). Water scarcity is connected to various phenomena: aridity, desertification, and drought and water shortage (Spiliotis et al., 2015; Tsakiris et al., 2011). It is linked to the availability of resources to satisfy the total demand in the short-term. An example is a drought, which is a natural hazard with temporarily can produce an imbalance water availability due mainly to low precipitation, what produce the reduction of water availability (Vangelis et al., 2011) and a high probability of not satisfying all expected demands in a short-term horizon. The impacts of droughts are immense and they produce significant losses in urban water supply (Wilhite et al., 2014).

B. Water supply discontinuity. It means the structural or hydraulic impossibility to attend flow requirements of some end-users that need water supply continuity. The supply discontinuity may be due to a pipe break or a failure in a service connection over their total mean downtime or the lack of resources in a unique source to a supply zone.
C. Discontinuity of drinking water quality conditions. The discontinuity may be produced in any part of the water supply cycle since the water quality conditions do not comply with standards of the company or the drinking water law. Some scarcity scenarios that requires the use of unusual raw water could create episodes of inadequate quality of water.
D. Discontinuity of hydraulic conditions. The cause of discontinuity may be caused by a high demand, an inadequate operation or a failure, and as a consequence, the pressure/flow conditions are affected. Some drought management practices impose reduction of pressure in a supply zone to reduce consumption and real losses, in these cases there are two types of loss of level of service, the linked to water shortages and the linked to pressure reduction.

In a water supply system, disturbances may be assessed independently or in conjunction. All above mentioned service disturbances can happen individually or combined, could happened due to a specific problem or combined due to a scarcity episode. In this paper all those possible causes will be summarize as if they were due to a unique scarcity episode.

Failure Thresholds

Under normal operation, regulation framework or company`s commitment establishes that water must be delivered in certain conditions of quantity (water supply), continuity, pressure and quality. The fulfilment of these commitments implies operational and capital costs for water utilities. Failure in water supply systems is associated with the non-fulfilment of normal conditions. In this article, failure is mainly related to the lack of supply of all expected demands to a service zone. Other environmental, economic and social factors should be included in a more comprehensive assessment but here are not specifically mentioned. A failure is usually a loss of functionality under some reference values. However, these service levels are not always defined in detail. As said, resilience is linked to an amount of failure occurrence. Its magnitude depends on the severity and duration of the failure, though there is always some ability to manage failures and this statement should be considered in the protocols followed by the water company. A failure is an evidence of the system`s risk, but when a failure starts, a current updated risk analysis may be also assessed. In order to classify the severity of an impact to the service, it is recommended to fit a set of reference thresholds of service level. Four failure thresholds are proposed: (1) a standard level that explains when a failure starts, (2) a normative assumed level applicable to failure scenarios and defined by a law or statutory definition, (3) a social accepted level under exceptional episodes, and (4) a critical level under which the system is not able to be elastically recovered, which in fact is the limit of resilience. The critical level corresponds to a dramatic situation with relevant social and economic implications. It should guarantee a minimum service to end-users (basic needs) that must not be low down in any circumstance. The failure thresholds divide the levels of severity of the analysed threat into level 0 (above the standard level), level 1 (between the standard level and the normative level), level 2 (between the normative level and the accepted level), level 3 (between the accepted level and the critical level) and level 4 (below the critical level), from less to more severe. In each of these levels of severity, different measures should be taken in order to overcome the threat with the established resilience.

Quantifying Resilience

In this article, resilience is presented as the capacities of the system to guarantee that the consequences of a hazardous event are limited in time and damages. Although potential hazards may produce different impacts on water supply systems and related water users, the presented methodology is mainly focused on service disruption to end-users. Under anomalies, a quantitative metric to measure resilience is proposed. The set of protocols, resources and technologies are linked to each hazardous event in such a way that they are fixing the resilience for this type of threat. The recorded data should be a basic reference to assess the expected resilience in hypothetical future episodes and scenarios. The loss of service level and the disruption period due to a threat are represented, as well as how the protocols of contingencies, technologies and resources may set discontinuities linked to every stage of management and inconsequence modify resilience. The disruption period is the time between the start of the service disruption due to the occurrence of a disruptive event, t_e, and the final time when the system is finally recovered, t_f. After recovery measures are taken, the service function may reach the same level of service as before the disruptive event. However, it may be below it, if it is over the standard level of service. It is shown how protocols, technologies and resources may vary the duration of the disruption or its severity.

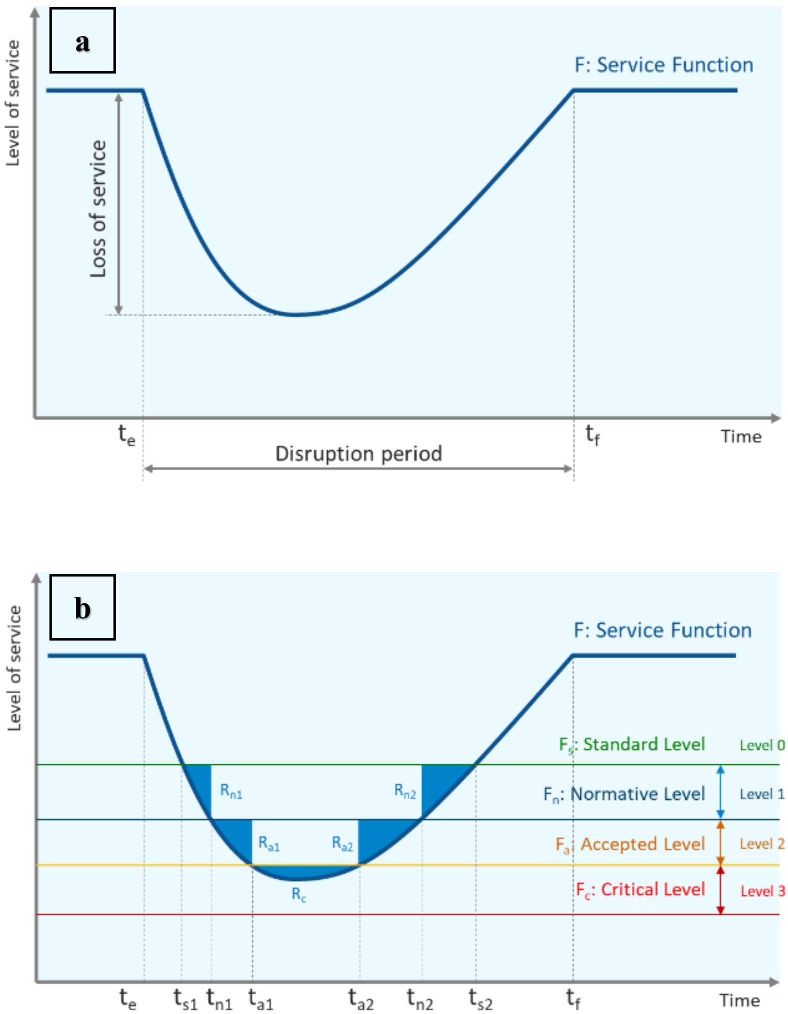
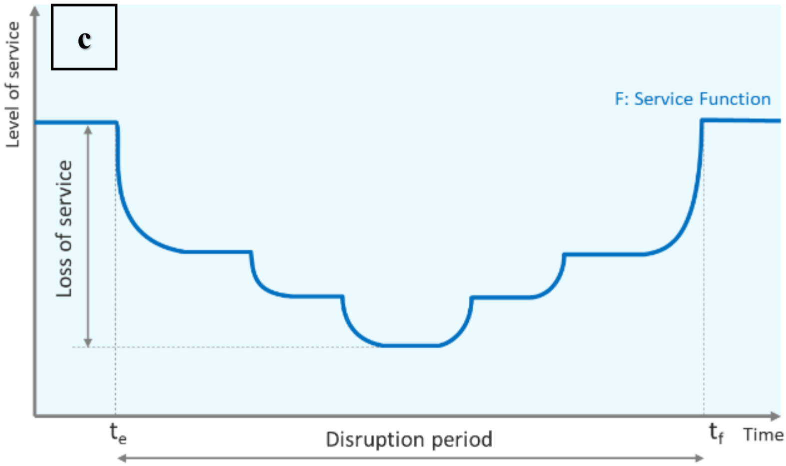


Figure 5.5 a) (Level of Service in a Duration) and b) (Service Function)



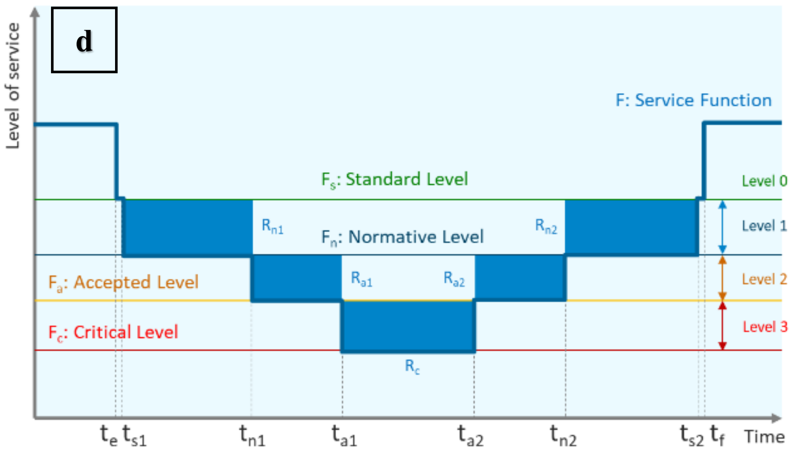


Figure 5.5 c) (2nd Type) and d) (Schematic of Different Levels)

Figure 5.5 a) And c) Resilience models, with the representation of the loss of service and the disruption period. b) and d) Calculation of the impact factor. The level of service (standard level, normative level, accepted level and critical level) and the levels of severity (level 0, level 1, level 2, level 3 and level 4) are shown. In these cases, the normative impact factor, R_{fn}, is the sum of R_{fn_1} and R_{fn_2} and the accepted impact factor, R_{fa}, is R_{fa_1} plus R_{fa_2}. The critical impact factor, R_{fc}, is also presented.

Figure 5.5 b) and d) reflect how the impact factor is calculated for a specific type of threat and for the two cases shown in Figure 5.5 a) and c. In the case of water scarcity, the service level is under the standard level when the water supplied is less than the required in normal conditions; the normative level could be the risk considered at the hydrological planning; the accepted level is referred to an acceptable maximum reduction for end-users, identified through public participation processes; and the critical level only implies the provision of basic needs. In those cases, the loss of service can be determined with the percentage of water supply reduction over the disruption period or by the reduction of expected consumption in a number of properties. In the case of structural, hydraulic and quality discontinuity, the failure thresholds account the number of affected properties without the normal conditions of supply, which vary with the type of threat and the thresholds that are considered. The loss of service is calculated with the number of properties under the fixed thresholds.

It should be noted in Figure 5.5 b) and d) that the service function in the original state when the threat occurs may be above the standard level (level 0 of severity). That is the reason why the service function may reach the standard level sometime after the occurrence of the disruptive event. The instant of time when these two functions intersect (the service function and the standard level) may be defined by the variable t_{S_1}. In the same way, after recovery measures are taken, the service function intersects with the standard level at t_{S_2}. The recovery function represents how the service is being gradually recovered to reach at least the standard level of service. It should be mentioned that if the normal operation conditions when the hazard occurs were the conditions of the standard level, the time t_{S_1} would be the same point as the occurrence of the event, t_e. Similarly, if the normal operation conditions in the recovered state were coincident with the ones related to the standard level, the time t_{S_2} would be the same point as the final recovery time, t_f. The service function intersects with the normative level at t_{n_1} and t_{n_2}, and with the accepted level at t_{a_1} and t_{a_2}. The general analysis procedure to calculate the impact factor for a type of threat, based on Figure 5.5 b) and d), is the following:

$$\begin{aligned}(R_{f_n})_A &= (R_{f_{n_1}})_A + (R_{f_{n_2}})_A \\ &= \int_{t_{S_1}}^{t_{n_1}} (F_{S_A}(t) - F_A\,(t)).\,dt \\ &+ \int_{t_{n_2}}^{t_{S_2}} \left(F_{S_A}(t) - f_A(t)\right).\,dt \\ (R_{f_n})_A &= (R_{f_{a_1}})_A + (R_{f_{a_2}})_A \\ &= \int_{t_{n_1}}^{t_{a_1}} (F_{n_A}(t) - F_A\,(t)).\,dt \\ &+ \int_{t_{a_2}}^{t_{n_2}} (F_{n_A}(t) - F_A\,(t)).\,dt \\ (R_{f_c})_A &= \int_{t_{a_1}}^{t_{a_2}} (F_{a_A}(t) - F_A\,(t)).\,dt\end{aligned} \tag{3.1}$$

Where R_{f_n} is the normative impact factor, R_{f_a} is the accepted impact factor and R_{f_c} is the critical impact factor. F is the service function; F_S, the standard level; F_n, the normative level and F_a, the accepted level of service. The subscript A is referred to the type of threat A. This formulation is applicable to other cases, whereas it is considered that the normative impact factor is calculated with the area delimited by the standard level and the service function, in consideration of the time where the service function intersects with the normative level. The accepted impact factor is the area between the normative level and the service function, delimited by the time where the service function intersects with the accepted level. The critical impact factor is the area within the service function and the accepted level. It is possible that a threat remains in the first level of severity. In this case, the normative impact is the unique impact factor that has to be calculated. The impact factor for the type of threat A is obtained with the normative, accepted and critical impact factor:

$$(R_f)_A = W_{n_A}(R_{fn})_A + W_{a_A}(R_{fa})_A + W_{c_A}(R_{fc})_A \tag{3.2}$$

Where W_{n_A}, W_{a_A} and W_{c_A} are specific weights for the type of threat A that multiply each partial impact factor ($(R_{fn})_A$, $(R_{fa})_A$ and $(R_{fc})_A$), which are calculated within a certain level of severity (level 1, 2 and 3, respectively). If the level four is reached, the system is not able to be recovered in an elastic way, so there is no resilience. The specific weights have to be analyzed in each case study, due to the fact that the measures that should be taken in each level of severity to recover the system have different impact on the end-user. The system impact, as reference to assess resilience, should be the result of the sum of the impact factors calculated for each type of disturbance that occurs at the same time in the water supply system. Specific weights (W) should be considered to aggregate the impact factors and more research is needed to define quantitatively them. If four types of disturbance (A to D) occurred at the same time in the system, the impact factor of the system would be: In a similar way some other impacts of the environment, economic activities or similar can be included through additional weights for every specific impact.

$$R_f = R_{f_A}W_A + R_{f_B}W_B + R_{f_C}W_C + R_{f_D}W_D \tag{3.3}$$

The global impact factor, R_f, should integrate similar levels of severity to represent the society´s perception of failures. It has to be considered that a drought impact on the whole water supply system, whereas a low pressure or a water quality failure affect a number of end-users. Thus, different weights should be used for each type of threat (W_A, W_B, W_C andW_D). The impact factor may be zero and this value corresponds to three different cases: (1) there is no perturbation of the service function in the aftermath of a hazard, (2) the service function after a hazard is above the standard level of service, and (3) the service function over the disruption period is coincident with the standard level of service. Impacts and resilience must be linked, but resilience must be well defined in terms of resources and procedures to apply in every case, their definition will be a commitment with users and society, a commitment to be able to keep within the correspondent impacts if the threats occur with the considered severity. Protocols to cope with threats include assumptions of available resources, timescale to implement measures, responsibilities to make decisions and to carry out tasks, etc. In some way protocols are a comprehensive commitment with resilience, this is a reason to be public domain and to be discussed in public participation processes. Water utilities may use the impact factor to quantify how they are prepared for certain hazardous events; how resilient they are.

Assessing current and forecasted resilience of a water supply system is the main foundation to build investment plans and to review operation and contingency management policies. The lower the impact factor is, the more resilient a system is considered. The comparison between different water companies is also possible, as long as the same levels of service are defined.

Case Study

The resilience of a supply system is described by its protocols to cope with every type of threat. But the credibility of those protocols can only be proved when a threat happens and the correspondent disturbance to service must be managed. Every new episode is an opportunity to test the established resilience and any way the opportunity to update and tune all assumptions and hypothesis. The water supply system of the Autonomous Region of Madrid (Spain) is managed by Canal the Isabel II, which is the water utility that supplies water to more than six million people in this region. The managed water supply system has 14 big reservoirs, near 100 wells, some abstraction rights in two additional rivers, 14 treatment plants, more than 17,000 kilometers of main pipes, 321 water tanks, and about 760,000 service connections.

Canal de Isabel II defined protocols to face droughts from 1992 when finished a 2-year severe drought. Since then those protocols were updated and integrated with planning and monthly operational procedures. In 2003 a new protocol was issued and published with defined responsibilities to keep it updated, reliable and fully operative. This protocol defined the impacts and resilience of the system to different severity of droughts. In 2005-2006 a severe 2 years' drought happen with a return period of 20 years. The case study highlighted in this article is a test of that drought in contrast with the proposed methodology in this paper.

Specific actions to restrict the water supply were required. The Spanish Decree 97/2005 was enacted the 29th September 2005 to establish exceptional measures to manage water supply in the region of Madrid, because a drought had been declared. Previously, Canal Isabel II had founded a Drought Committee in May 2005, and had launched a campaign called "The challenge of water" addressed to end-users for saving water in July 2005. Another campaign with the same objective was launched in April 2006. Finally, the Decree 46/2006 of the 30th November 2006 repealed the exceptional measures to manage water supply in the Autonomous Region of Madrid.

The system resilience for that drought is determined with the protocols established by the company for that type of threats. Canal de Isabel II water utility has published the protocols to be followed in the aftermath of a drought (Cubillo et al., 2003). The resilience established in these protocols was contrasted with real data over the disruption period.

Protocols of drought management of the water company that manages the water supply system of the Autonomous Region of Madrid (Spain) define different failure thresholds for a drought event according to the severity of the disruptive event: (1) in the standard level, the water company supplies water to the 100% of end-users; (2) in the normative assumed level, the water supply should be reduced by 9.4% over a year; (3) in the accepted level, the water supply should be decreased in 26% over two years, and (4) in the critical level, the water supply should be reduced by 51.4% over a year (Cubillo et al., 2003). Therefore, protocols define how to manage a general drought event, as the level of service is reduced over a certain period to overcome the studied threat. The analysed hazardous event is a drought that remained in the first degree of severity. The occurrence time, t_e, is the day when the Decree 97/2005 was enacted to establish exceptional measures to manage water supply in Madrid; that is the 29th September 2005. When a drought reaches the first level of severity (represented as the level 1 in Figure 5.5 d), some measures should be taken to reduce the water supply in 9.4% over the following 12 months. The main actions consist of banning some outdoor uses and non-essential uses, additionally, a campaign asking for voluntary changes in habits of end-users related to water use was launched. Figure 5.6 shows the evolution of reserves and the dates when some legal measures were taken.

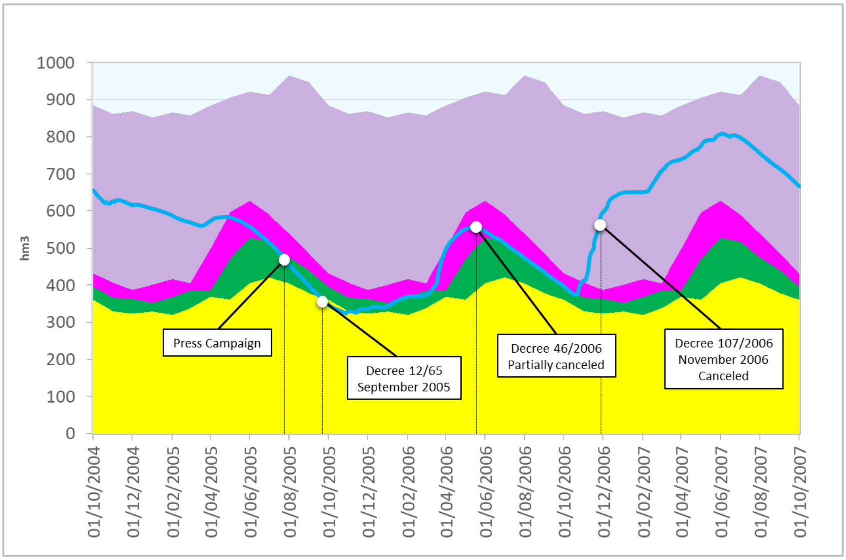


Figure 5.6 Evolution of Reserves and Dates of Triggering Measures

The reduction of 9.4% (normative level) is represented in Figure 5.7 b), since the 29th September 2005 until one year after this date. The initial service function defined by the protocols was coincident with the standard level, so the occurrence time of the disruption, t_e, is equal tot_{s_1}, where the standard level of service intersects with the service function (29th September 2005). In Figure 5.7 b), the normative allowed impact factor is also presented, which is defined as:

$$(R_{f_N})_A = 9.4\% \times 12 months = 112.8\%\, month = 9.4\%\, year \tag{3.4}$$

If the specific weight W_{n_A} is considered as one, the impact factor for the analysed type of threat A is:

$$(R_f)_A = W_{n_A}(R_{f_N})_A = 9.4\% year \tag{3.5}$$

In the first level of severity, the impact factor was actually less than or equal to the normative impact factor. However, the company took actions to reach a normative impact factor of 9.4% $year$.

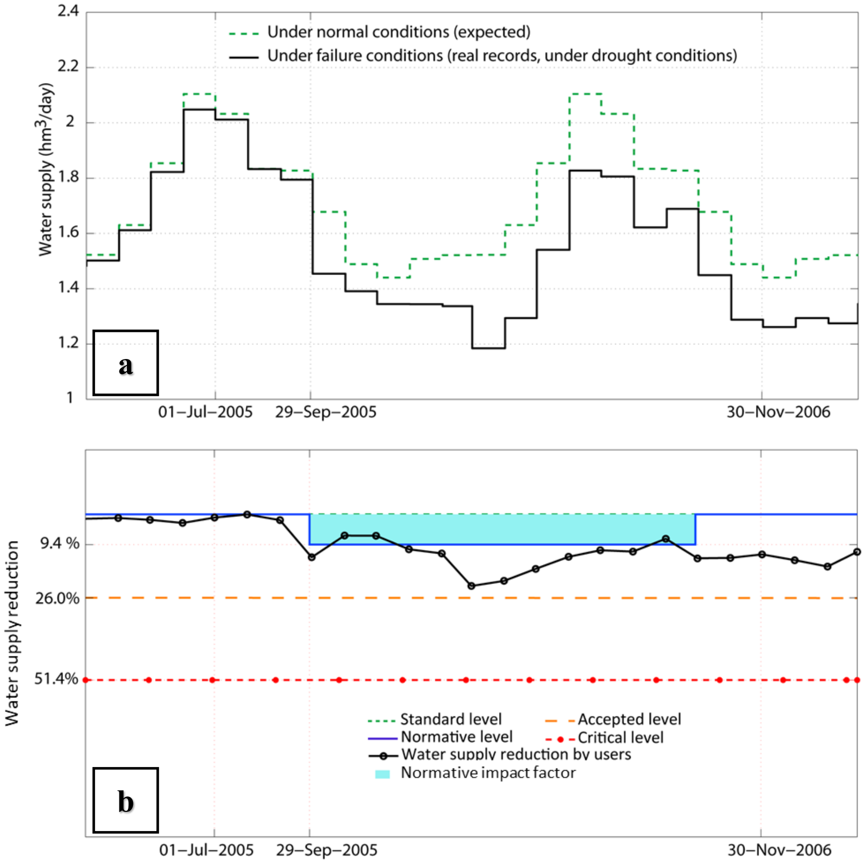


Figure 5.7 a) Water Supply (m^3/s). b) Normative Allowed Impact Factor and Evolution of Water Supply Reduction

To test the management protocols of contingencies for the analyzed type of disturbance (Figure 5.7 a)), the water supply over the disruption period was compared to the expected water supply under normal conditions. The aim was to reach the target of 9.4% reduction of water supplied. Figure 5.7 a) shows the real monthly water supply evolution and the expected ones under normal conditions. The water supply values in normal conditions were determined based on records of previous years without unusual events, adapted to the real climatic conditions of the analyzed period by means of demand forecasting models. The water supply in normal conditions represents the standard level of service in terms of total volume supplied and it is shown in Figure 5.7 b). The deviation from this level allows the assessment of the effectiveness of protocols. Specifically, the percentage reduction of water supplied is calculated as follows:

The percentage reduction of water supply is also shown in Figure 5.7 b) over the disruption period (water supply reduction by end-users). It is observed in Figure 5.7 a) that it is not until the enactment of this law when the real water supply differs considerably from the water supply under normal conditions. The obtained results allow contrasting the effectiveness of protocols followed by the company in the first level of severity due to water scarcity. The water company Canal de Isabel II expected a reduction of water supply represented by the impact factor for the drought event. It may be observed in Figure 5.7 b) that the reduction of water supply was higher than the expected by the protocols. Thus, it is concluded that protocols in the case of water scarcity were effective. In Figure 5.7 b), it is also represented the date of July 2005, because the water company launched a campaign called “The challenge of water” addressed to end-users to save water. As may be seen, some months after this campaign, it was maintained a significant reduction of water demand. In addition, when the Decree 107/2006 repealed the exceptional measures, the 30th November 2006, the normal conditions of operation were recovered. However, the water supply was below the standard level of consumption. The main reason was that although end-users could consume the same quantity of water as before the drought, they were accustomed to use less water for satisfying their necessities than they used to consume before the drought period. They became aware of their environmental responsibility to save water and this was achieved, in a great manner, by means of influencing change in behavior towards water use. After this change in behavior, the protocols for future drought events should be updated to calculate resilience.

Level of service should not be quantifying only by reduction in water consumption. Low pressure in some properties, inadequate drinking quality, environmental, social and economic impacts are relevant components of the level of service that should be considered when total impacts are assessed. All these components should be included in the assessment of impacts and in resilience. As an example of one of those impacts, Figure 5.8 shows the reduction in ecological releases from reservoirs along the tested drought.

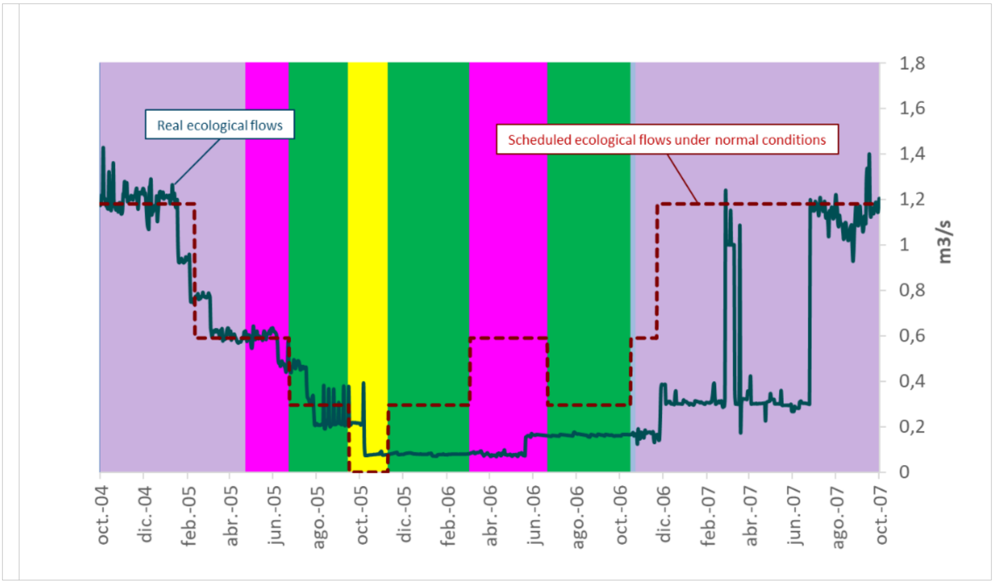


Figure 5.8 Evolution of Scheduled and Released Ecological Flows

Water companies should analyze their protocols, resources and technologies to know how their water supply system is going to perform under anomalies and fix their failure thresholds. Furthermore, these thresholds classify the level of severity produced by a threat and are necessary to know what type of measures should be taken to recover the system to normal conditions.

Conclusions

Assessing resilience for water supply systems is proposed as the response capacity of a system to delimit impacts in the aftermath of a disruptive event. Resilience is determined by the resources, technologies, skills and protocols to cope with every type and severity of threats. Quantifying expected and scheduled impacts is the way to quantify resiliency to every disturbance. Regarding water supply, it is concluded that it is necessary to categorize the types of disturbances and the following classification is suggested: (A) mandatory demand shortage, (B) water supply discontinuity, (C) discontinuity of drinking water quality conditions and (D) discontinuity of hydraulic conditions. The establishment of failure thresholds is required to determine different measures to be taken to overcome every scenario. The recommended failure thresholds are the following: (1) standard level, (2) normative allowed level, (3) accepted level and (4) critical level. When these thresholds are exceeded, the system is under the level of severity 1, 2, 3 and 4, respectively. In addition, a resilience model that allows assess an impact factor is proposed. It measures the loss of service level and considers the disruption period. It is proposed an impact factor, defined by an integral of a product of two factors: loss of service level (service disruption to end-users) and time. The lower this factor is, the more resilient a system is considered.

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Groundwater as a Strategic Reserve for Water Supply Systems

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Canal De Isabel II

Abstract

In many parts of the world, the sustainable use of groundwater in arid and semi-arid ecosystems is still an unresolved issue. In regions with little, infrequent and irregular rainfall, and a high evaporation rate, the natural recharge of aquifers is insufficient, making it difficult to compensate for the effects of water usage, especially in those aquifers that include a large unsaturated area.

The groundwater management for urban usage in arid and semi-arid systems requires specific planning that guarantees both the sustainability of the resource and the correct development of the necessary infrastructures for its exploitation. This entails the establishment of appropriate exploitation and maintenance guidelines and plans in order to guarantee efficient and safe management of the facilities, while at the same time ensuring the water supply.

In this context, groundwater may be used jointly with other sources, in order to guarantee the water supply in scenarios of water scarcity or as a precaution against the future occurrence of such scenarios, as well as security or mitigation against structural contingencies in supply systems that could eventually lead to critical situations.

The fact that groundwater is as a strategic reserve implies that its usage may be temporary – even though at times the exploitation periods may be quite long –, calling for a quantitative and qualitative compensation of the effects caused by the exploitation. In this case, the condition of strategic reserve must be applied also to the collecting and exploitation infrastructures, and hence these have to be included as such in the investment planning.

Among other aspects, this chapter deals with the importance of an appropriate establishment and control of the parameters and indicators that will allow us to evaluate the systems' performance and sustainability –aquifer and groundwater including collecting and operating infrastructures–, in order to ensure a guaranteed water supply.

Keywords: Groundwater, Exploitation system, Strategic reserve, Strategic infrastructure, Operation planning, Guaranteed supply, Availability indicators, Operational functionality indicators.

Introduction

The water scarcity issue in arid and semi-arid regions must be approached by including both surface water and groundwater, as well as regenerated and desalinated water, into the supply systems. The joint usage of all these resources will make the system more stable and at the same time guarantee the water supply.

To achieve this, the resource management must be unified and transformed into one single large system to manage resources in the short-term, medium-term and long-term. However, each supply system has to be dealt with individually, depending on the different possibilities offered by its specific resources, as well as on the existing demand for it.

Groundwater plays a wide range of roles in urban water supply. Depending on the different kinds of supply systems, it may be used as priority resource, strategic resource or part of a joint usage system next to other resources.

The following data will illustrate just how important groundwater is for urban water supply. They make it clear that its role in arid and semi-arid regions is essential and that it might constitute a perfect guarantee for the population's water supply.

- 25% of the amount of groundwater used worldwide goes into urban water supply. Many of the large cities in arid and semi-arid regions use groundwater to provide their drinking water.
- Almost 48% of the water used domestically around the world is groundwater, of which 2.54% is non-renewable (UNESCO 2009, p 100).
- This percentage of usage is much higher in certain countries, mostly those located in arid and semi-arid regions, where the number might even reach 100%. For example: on the island of Malta, 100% of the water supply comes from groundwater; in Saudi Arabia. This proportion is 99%; in Tunisia 95%, in Morocco 75%, etc.

However, groundwater usage and exploitation have connotations that are quite different from those of other water sources, especially those of surface water. The fact that this resource is "invisible", even more so if the aquifers are very deep, makes it more difficult to monitor its evolution and detect the consequences of inappropriate usage. In some cases, the results may even be irreversible.

The shortage of rainfall makes it impossible for the aquifers to recharge naturally and to allow the usual replacement of the extracted resource. This is why appropriate planning and operation within a framework of sustainability is so important, in order to make the resource available in times of necessity, and under the appropriate conditions of quality and quantity for the assigned destination. Climatic change may contribute to make this situation even worse due to its new scenarios with a rise in temperatures and a marked decrease in rainfall in many regions, adverse conditions that seem to have stabilized, thus reducing the aquifers' ability to refill naturally.

This chapter deals with the importance of the condition of groundwater as strategic reserve for ensuring a guaranteed supply in the case of water shortage. To achieve this, it is basic to integrate all the components into the system: both the groundwater aquifer and the infrastructures necessary for its abstracting and operation. Such a unified management would allow to handle successfully the relationships among all components, in order to accomplish a supply that is both sustainable and efficient.

With the purpose of making such a complex system operable and quantifying its functionality at different points in time, several indicators shall be proposed, for the resource's availability as well as regarding the environment and the infrastructures of the system. These indicators will make it possible to manage the exploitation according to the groundwater's reaction capacity in sudden episodes that may be critical for the supply service, as well as situations of shortage that may imply a lengthy pumping activity in order to guarantee the resource's availability.

Resources Options for Water Supply Systems: The Importance of Groundwater

The water supply systems in arid and semi-arid regions have to deal with the challenge of guaranteed supply to cover the demand within an adverse context of shortage and unpredictability of rainfall. To tackle this challenge, these systems must rely on infrastructures and resources that have to be able to lessen the effect of this variability and to ensure the supply required by urban water usage.

Other resources with a higher stability – but not a lower cost –, such as desalinated water or regenerated water, are making a constantly growing contribution to urban water systems, but at present they are still unable to cover the entire needs of a majority of countries. At the same time, surface water is a resource of unreliable availability in general, and an increasing shortage in arid and semi-arid regions; this is why groundwater, in spite of its own variability, especially in the cases of shallow and unconfined aquifers due to their difficulty in recharge naturally, can be considered an important alternative within the joint usage of resources.

The existing joint usage policies that depend on several sources tend to give priority to those resources that imply lower operating costs, sometimes even leading to their deterioration or complete exhaustion, which is a strategy that cannot be recommended.

In some other cases, groundwater is assigned to the concept of strategic reserve, usually applied to resources that are used irregularly or only in certain situations of contingency, drought or probable shortage.

Appropriate resource planning necessitates identifying situations that make it possible to use a certain kind of resource – or a part of it – as a strategic reserve. The use of strategic reserves should always be associated with the definition of thresholds that determine the circumstances in which they should be used and to what extent (Cubillo González and Ibáñez Carranza, 2003).

Groundwater meets the appropriate requirements to be considered a strategic reserve. Besides, the effects of climatic change increase even more the importance of groundwater in this respect and as an undeniable strategic resource in order to mitigate the consequences of severe droughts.

Availability Indicators

In the context of shortage and scarcity, an exploitation of groundwater that is both sustainable and efficient should be able to answer the following questions, and thus indicate its availability:

- What is the capacity of the groundwater system?
- When is it possible to exploit it?
- For how long can it be exploited?

Establishing these availability indicators will help to design an appropriate operational strategy. The following indicators are suggested here:

- **Probable available volume during an annual cycle**: shows the system's capacity on a short-term operational horizon.
- **Assured continuous available volume during a multiannual cycle**: includes temporary sustainability criteria for the system's capacity on a medium-term and long-term horizon.
- **Immediate available volume in case of shortage or scarcity**: reflects the capacity for immediate abstracting, usually considered as strategic reserve.

Figure 6.1 represents the different scenarios of resource usage in a water supply system with stable resources that maintain a constant flow of supply, surface resources of priority use in normal situations, complemented by groundwater from shallow aquifers, as well as deep groundwater as a strategic reserve for critical situations.

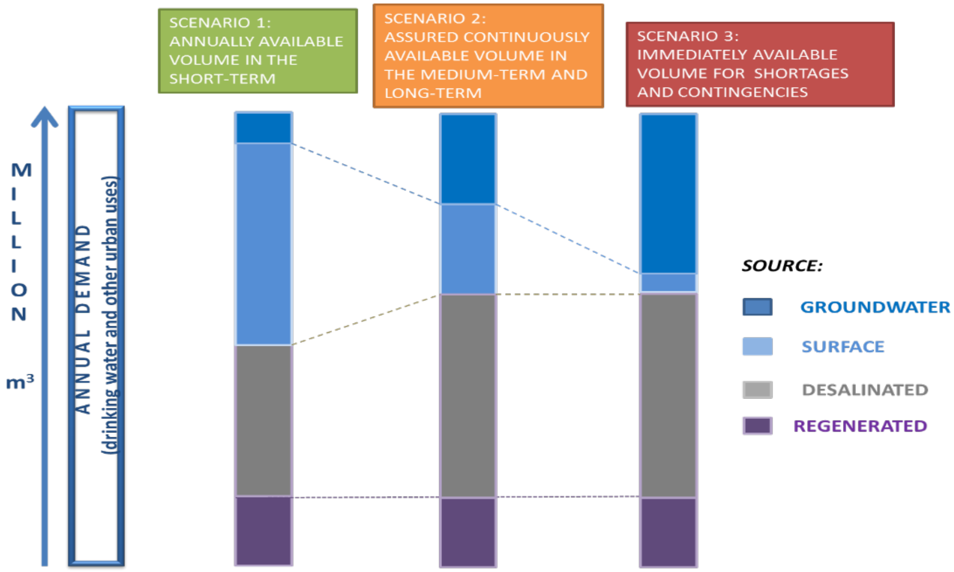

Figure 6.1 Example of using various resources by means of joint usage in an urban water supply system in an arid region (drawn up by the author)

All the above considerations show clearly how important the integration of groundwater into the planning and operating scenarios of the water supply systems in arid and semi-arid regions really is. On the other hand, the operational capacity and sustainability of these systems depend directly on the characteristics of the resources and the aquifers or geological formations where they are located.

Considerations on the Aquifer/Groundwater Unit

An appropriate groundwater management must be based on a profound knowledge both of the aquifers that are going to be exploited and of the availability and other characteristics of the water they contain. The unit made up of aquifer and groundwater is the backbone that supports the entire groundwater exploitation system, because it conditions the usage of the resource, the typology of abstracting, and **the operation rules that are necessary to exploit the resource efficiently**.

Figure 6.2 is a schematic diagram of the interrelationships of the aquifer/groundwater/abstracting system unit, with regard to covering the guaranteed supply, showing the necessity of an environmentally sustainable management and a planning process for the supply system operation, based on risk management techniques and strategic reserve allocation.

Figure 6.2 Concepts Associated with Groundwater Exploitation for Urban Usage (drawn up by the author)

Many of the most important aquifers in the world that are used for water supply are located in arid and semi-arid regions, and some run the risk of being overexploited or contaminated due to the lack of appropriate planning and operating. In many cases, there has been no sustainable usage of the resources. For a long time, the volume of extraction has exceeded the volume of recharge, and the non-renewable aquifer reserves have been used up, revealing one of the major problems that exist in arid and semi-arid regions: the delicacy of their ecological balance due to deterioration or exhaustion of water reserves.

Overexploitation due to poor planning or inappropriate practice may lead to a substantial and constant decrease of the piezometric level, which in turn may cause important economic, social and environmental disasters that may be impossible to overcome in the short-term or medium-term. Not only could the consequences be higher pumping costs or a reduction of immediate groundwater availability, but other important phenomena could also be caused, such as ground subsidence, decrease in water quality, or saltwater intrusion in the case of coastal areas, etc. (Downing, 1993).

A recent example of this can be observed in the Kingdom of Bahrain, an island state located in the Persian Gulf, with an area of 770 km2 and a very high population density of 1,627 people per km2. With 51% of its water coming from reverse osmosis (RO) plants, 47.7% from desalination, and 1.3% from groundwater, the country today has one of the highest water prices in the world, and the water production causes an enormous energy consumption

(Al Maskati, 2018). In less than fifteen years, an intense management of non-renewable water resources has led to a decrease in groundwater usage from 39% to 1% of the total water volume supplied.

The most important characteristics of the aquifers and their storage formations that must be known in order to achieve an appropriate exploitation management, are the following: extension, lithological composition, structural characteristics, storage capacity, as well as physical and hydrological limits, degree of confinement, hydrogeological properties of both the aquifer and the upper formations, and hydraulic gradient and thickness of the unsaturated layer (UNESCO y AIH, 2005).

In general, shallow aquifers are less interesting as strategic reserves than the deeper ones, because they are more vulnerable to being polluted and show a higher dependency on rainfall variations, even though they do play an important role as regulating element.

With regard to the characteristics of groundwater, the following aspects should be ascertained: origin, age, whether it is fossil or renewable, water quality and its evolution during exploitation, possible treatment as drinking water, feasible extraction volume, exploitation flow and usable reserve quantification. All these data will be useful to ensure a guaranteed supply, because the use of groundwater for water supply in critical situations will be safer if its planning is appropriate.

The quality of any water volume, both on the surface and underground, depends on natural factors as well as the influence of mankind. In order to ensure the supply of clean and healthy drinking water and to protect human health (ONU, 2014), it is necessary to take appropriate measures to protect the resources against pollution and deterioration. It is true that groundwater is less likely to be contaminated than surface water, but if it is, the remedies are much more expensive, complex and sometimes not even feasible. This would be even worse in the case of deep aquifers due to their higher average age (from dozens of years up to several thousand, if the water is not fossil).

A big advantage of groundwater aquifers compared to surface water consists in the role they can play as important water regulating elements that provide flexibility to the system by limiting the effects of climatic variations and ensuring a guaranteed water supply. Against this background, the application of artificial recharge techniques, both on the surface and underground, is very effective and can contribute to greater availability, especially in arid and semi-arid regions with large aquifers that have abundant storage capacity and a slow water flow whose evolution is easy to control.

Every aquifer/groundwater system reacts differently to its exploitation, according to the different possible operation scenarios (long-term, discontinuous, etc.). With regard to these reactions, the following aspects at least should be analyzed and quantified:

A. Piezometric evolution during exploitation, both during operation and temporary halts, as well as in recovery periods after exploitation.
B. Evolution of water quality during exploitation. Even though groundwater quality is usually stable and rarely shows any significant ion variations, there may occasionally be elements whose concentrations increase during exploitation in comparison to the initial

values, due to natural geochemical processes. Quality control is particularly important in the case of drinking water.

C. Control of incidents of isolated or widespread pollution. A useful tool would be the drawing up of water health plans to map out the basic guidelines to guarantee the quality of the resources that will be used as drinking water, in order to prevent pollution, or at least avoid its spreading. Such plans would help to create protocols of preventive action in order to measure the evolution of groundwater quality by means of wide monitoring networks, to evaluate the risk of quality decrease, and to take possible measures if necessary.
D. Control of incidents of ground subsidence caused by groundwater exploitation, which could affect surrounding buildings or the underground infrastructures of the water supply system itself.

Environmental Functionality Indicators

Establishing indicators helps to create protocols and guidelines that will contribute to ensure the sustainability and efficiency of the strategic reserve's management.

Among these environmental sustainability indicators that describe the functionality of the aquifer/groundwater system and are able to tackle the issues mentioned above, the following ones are suggested here:

a) Filling Level of the Aquifers (Figure 6.3): estimated with reference to the existing range between the highest historic value of the static level and the highest acceptable dynamic level. With this indicator it will be possible to quantify the effects caused by pumping, and to analyze the aquifer's recovery. It will thus be possible to evaluate the suitability of its exploitation.

This indicator conditions when to start abstraction and the reduction or limitation of the volume extracted (Sánchez Sánchez and Gómez Gálvez, 2016).

Figure 6.3 shows the piezometric variations of a deep aquifer during different periods of water extraction. As can be clearly seen, the filling level suffers great changes from one phase to another.

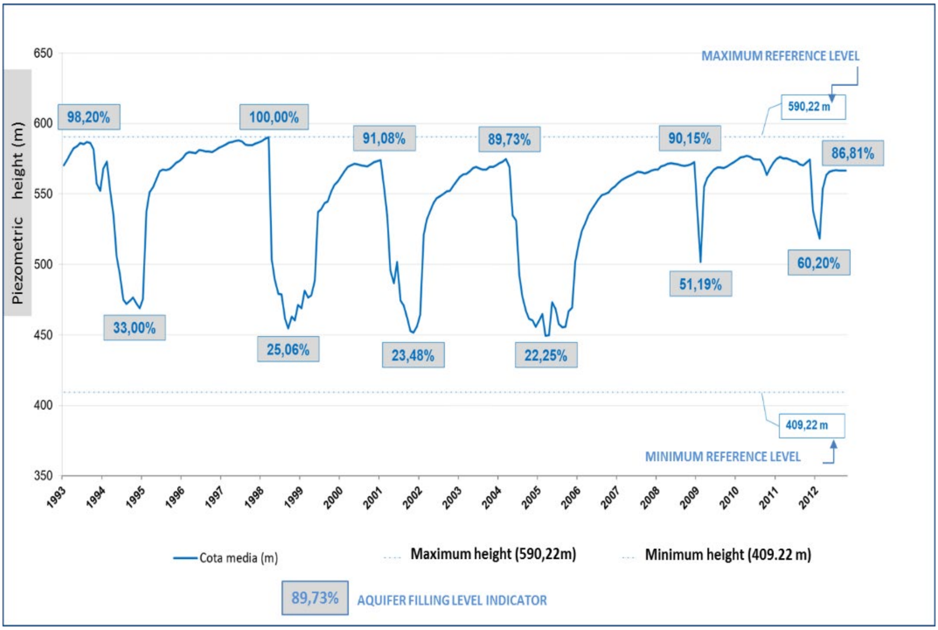

Figure 6.3 Peizometric Variations in a Deep, Semi-Confined Aquifer in Different Scenarios of Exploitation and Recovery, Indicating the Filling Level (in %) for the Different Phases of Activity (halt or extraction).

b) Indicators of Water Quality Variations: the quality of the extracted water is a factor that influences the operational capacity. A sampling plan should be established with intervals of no longer than three months in order to check the quality of the water as a whole during the cycles of continuous pumping.

The slowness of groundwater flow causes few variations in the water's composition during exploitation in the short-term and medium-term. However, it may be wise occasionally to increase the number of controls of certain parameters during water abstraction just before introducing it into the system. One interesting example of variation during exploitation could be that of arsenic, due to the fact that there are certain geochemical phenomena of anion exchange in some underground water with high pH values, which could cause the unblocking of arsenic and an increase in its concentration (see Figure 6.4).

A variability indicator quantifies the temporary variations in the concentration or value of a certain parameter, and should make it possible to establish relevant preventive or correction measures at the delivery point.

The quality indicators of water for urban usage should be established both for the delivery points and for the abstraction itself. During groundwater abstraction, specific indicators have to be established in order to be able to observe even small variations, and to be used as a basis for the monitoring at the points of treatment, usage and consumption.

c) Subsidence Indicator: monitors the annual variability of ground level with regard to a reference level. This indicator should take into account the piezometric level at the beginning and end of the pumping periods, as well as the volume of water extracted. This could be especially important after lengthy periods of pumping.

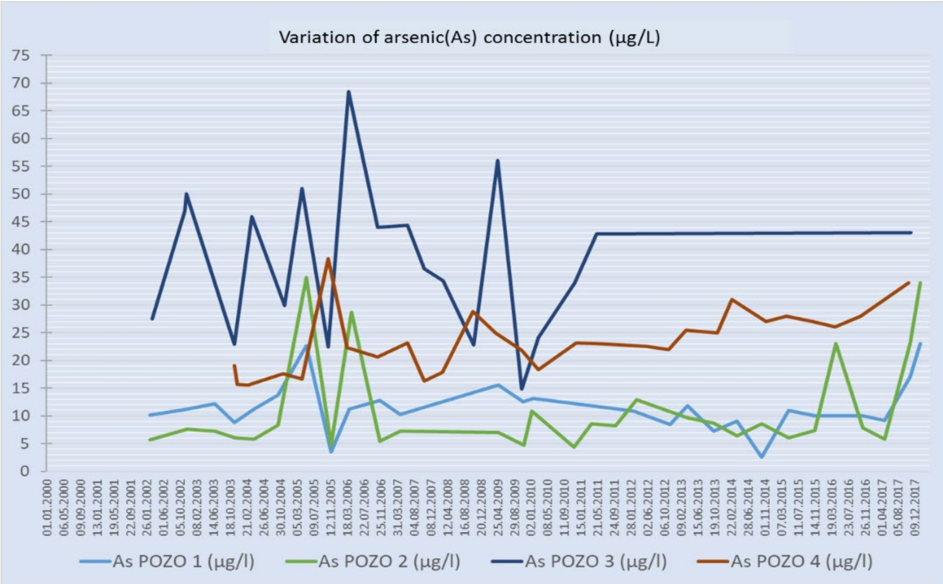

Figure 6.4 Evolution of Arsenic Concentration in the Water Extracted from Different Wells of an Unpolluted Detrital Deep Aquifer

Considerations on Groundwater Exploitation Systems

The design of a sustainable and efficient groundwater exploitation system should take into account both the abstracting infrastructures and the associated facilities necessary to convey episodes the extracted water to the delivery points, as well as the monitoring of the operation parameters. The associated facilities may well be rather complex and add an important extra cost to the initial investment. However, the use of optimized equipment in the design can help to reduce the operating cost and improve efficiency.

The complex system that interrelates all the elements included will depend on the characteristics of the aquifer exploited, the primary usage assigned to it, and the policies used to operate it.

In view of this chapter's focus on the operation of strategic reserves, it does not deal with the abstracting systems of shallow aquifers that can so frequently be found in many arid and semi-arid countries, consisting of vast horizontal galleries that have served, due to gravity, as the main source of supply during thousands of years. Lately, serious droughts have led to the overexploitation of these shallow aquifers, and in many cases these important systems of "intelligent" abstracting have had to be abandoned. However, an attempt should be made to recover them for the future. To this end, it is necessary to establish guidelines and operations that assign different roles to each aquifer, according to their capacity, while at the same time avoiding an inefficient and over-intensive exploitation.

Basically, this chapter deals with wells of medium and great depths, which exploit the groundwater of aquifers with the highest strategic potential.

The strategic use of groundwater requires exploitation systems that are both resistant and diversified, with a complete network of many wells, in order to be able to cover the demand whenever it is necessary. With this in view, it is convenient to distribute the wells over the entire surface of the aquifer, to avoid a centralized extraction and to allow the lamination of the effects caused by the exploitation. Also, in order to ensure the supply, “emergency wells” should be drilled, which would only be used in case of dire necessity.

In many arid and semi-arid regions, the strategic underground reserves are located in very deep aquifers that, due to their special characteristics, make it extremely difficult to extract the water. The wells can be very deep, even more than 500 meters, with drilling diameters of up to more than 600 millimeters and enough filtering tubes to avoid the weakening of the main pipe column. The well outlet, drilled with a diameter of up to 800 millimeters and a casing of 700 millimeters, must have a circular space of at least 20 meters, cemented with mortar. Also, the wells usually have an electro pump at a great depth (up to 300 meters and more), so the size of the piping must be appropriate, allowing a high-capacity electric pump unit, impulsion pipes and peizometric pipes for level monitoring to be installed. It is also advisable to install cathodic protection systems both on the surface and in depth, to lengthen the life span of lining pipes and impulsion pipes.

Figure 6.5 is a schematic diagram of the main construction elements a deep well for groundwater exploitation is made up of. As can be seen, the electric power system for working the electric underwater pump unit at great depth is very important, and in this context it must be mentioned that a high voltage power supply can improve the system’s performance even more, in order to avoid voltage imbalances and to employ three triple-pole cables instead of six single-pole cables (Muñoz García and Pérez Martínez, 2001). This would make the installation even more efficient. It is also advisable to include among the main equipment speed regulators to improve the facility’s operational possibilities as well as the installation's energy efficiency, with a performance of 97 to 98% in these elements (Pérez Martínez, 2000).

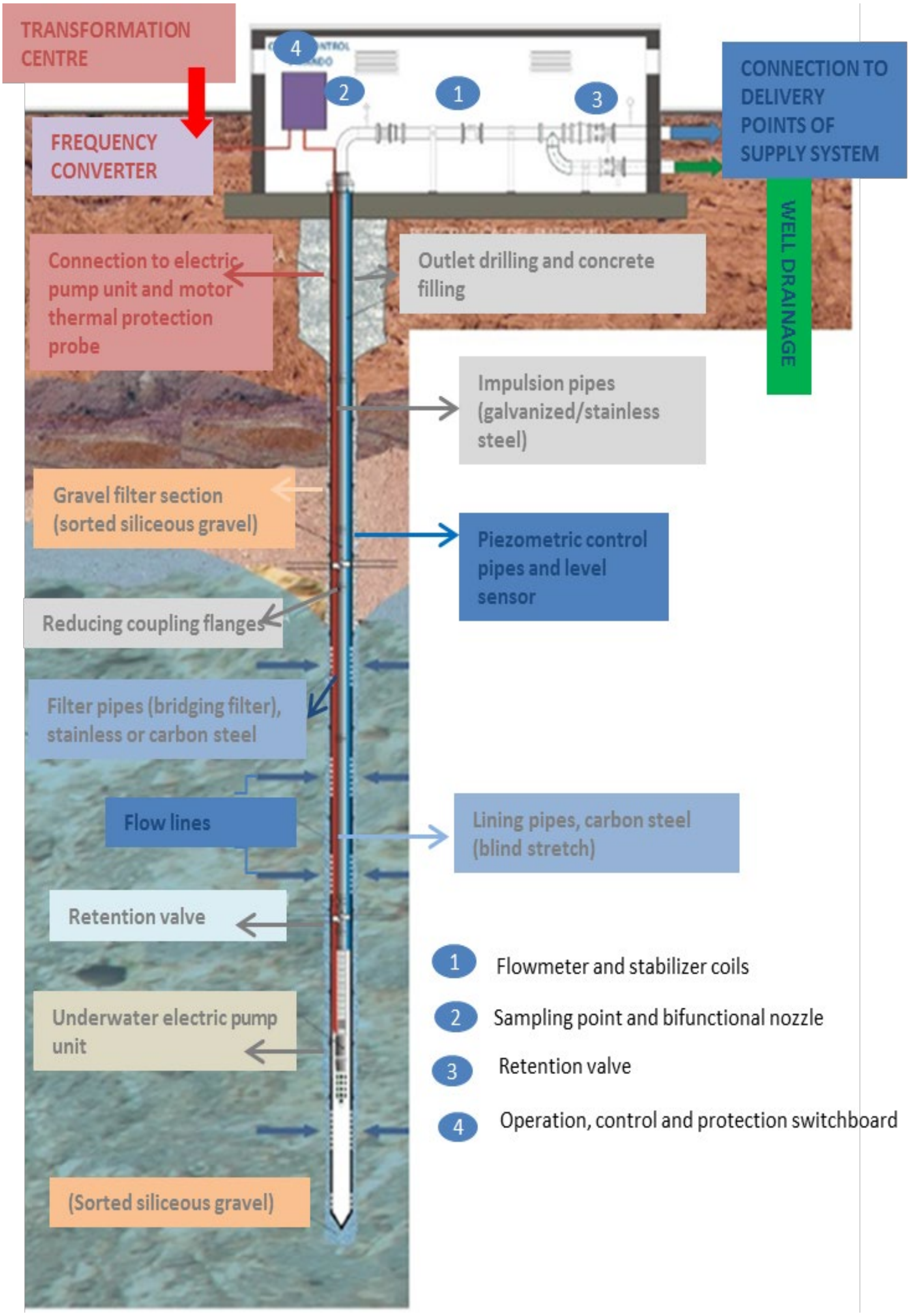

Figure 6.5 Example of the Construction Diagram of a Deep Well

An appropriate abstracting system management requires monitoring equipment and a safe communication network to oversee and analyze the operation parameters.

Only the immediate and prompt follow-up of these control parameters makes it possible to know exactly the operational development and hence to evaluate its efficiency. The same communication networks will be used to detect present and future breakdowns and possible performance loss during the abstracting. For this reason, the monitoring and communication networks are basic tools that are essential to the operating capacity and the maintenance plans.

The parameters for operation monitoring should include at least the following: essential electric parameters, water quality parameters, peizometric values from the exploited aquifers, impulsion pressure in critical spots, instantaneous, optimum and peak flow values, supplied volume at delivery points, etc.

The data must be monitored in real time regarding all parameters that offer the possibility to install alarm systems and establish operation protocols for emergency situations (maintenance protocols, operation halt, incorporation of new abstracting, etc.). Since water management has a crucial influence on society, its monitoring and control is fundamental to prevent potential negative consequences. Telecontrol systems, together with hydrologic data base management systems, are appropriate tools to know the current operative status and performances of every well in real time (Sánchez Sánchez, et al., 2006).

One of the most notable operation parameters for a groundwater exploitation facility is its energy index. This indicates the energy needed by the facility to bring up one cubic meter of water to a pressure height of one meter. The recommended values are below 5.5 Wh/m3 for flows bigger of more than 10 l/s (Pérez Martínez, 2000). This index includes the characteristics of the equipment, and hence its production efficiency. It is complementary to the specific abstraction flow (l/s/m).

Considerations on the Delivery Points

The delivery point is the supply system's infrastructure where the groundwater enters the system after its extraction from the aquifer, and is especially relevant to the operation's functionality. In urban systems with joint usage of several sources, the delivery point is used to be sharing by various resources.

Several types of delivery points are possible according to the settings of each urban supply system (drinking water treatment plants, piping, service reservoirs, distribution networks, etc.).

Figure 6.6 is a schematic diagram of the different points of groundwater supply in an urban supply system with joint usage of several aquifers and various surface resources.

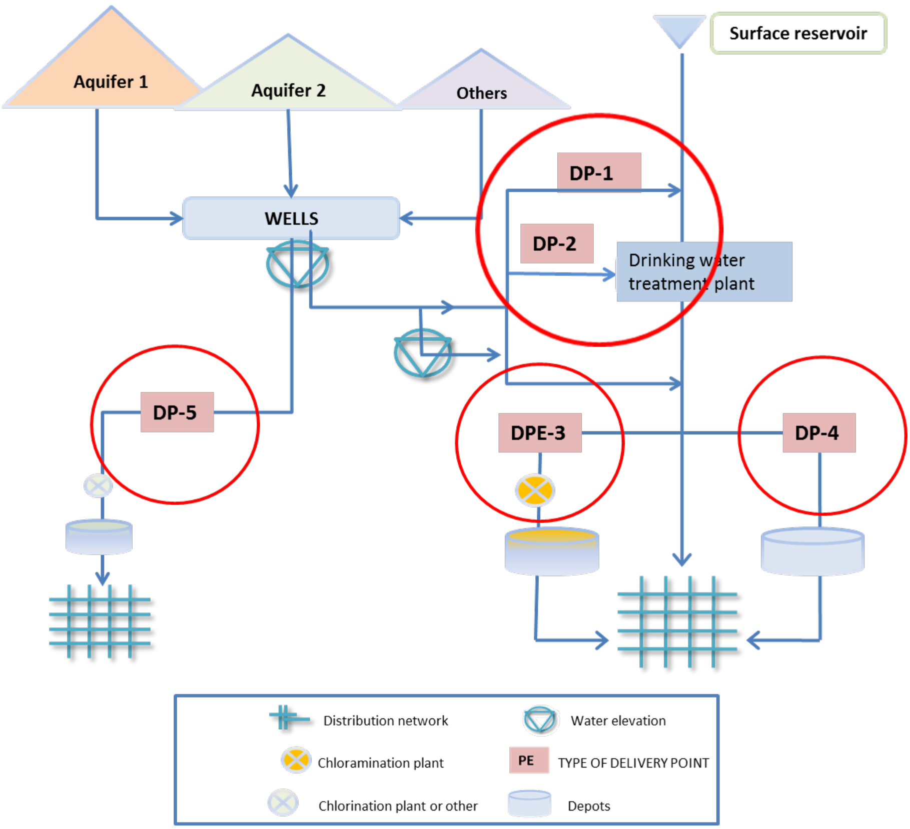

Figure 6.6 Types of Groundwater Delivery Points in a Joint Usage Supply System

Strategic Infrastructures and the Importance of Maintenance

The exploitation systems of strategic reserves for urban use can also be considered to be strategic infrastructures in the event of critical supply situations, such as breakdowns, contingencies or immediate shortage situations. Considered as such, they acquire a new role because they have to provide water immediately and with the highest guarantees.

Strategic infrastructures play a fundamental role in the management of supply systems. Due to their very nature, they may work with interruptions or for only short periods, which necessitates the establishment of annual maintenance plans to ensure the facilities' immediate functionality in case of a sudden emergency. Such planning must include the facilities' main elements: well equipment and associated abstraction infrastructures (water disinfection systems, drinking water treatment plants, pumping elevation stations, pipes, electrical installations, etc.).

The maintenance plans have to make it possible to detect faults in the equipment, to acquire experience regarding possible operational issues, to observe the aquifer's reaction during the exploitation, to detect possible quality variations in the extracted water, and, most importantly, to assess the reaction of other supply system infrastructures related to the groundwater exploitation system.

To ensure the immediate and effective availability of these infrastructures, the maintenance plans need to include a sufficient testing period under real productive working conditions. This is why this kind of strategy is called Productive Maintenance Plan, a basic strategy in operational planning that shows the high management capabilities of those companies and institutions that make use of it.

Operational Indicators

Given the complexity of many water supply systems, it is advisable to establish indicators that are able to create protocols and guidelines that will ensure an effective operation of the strategic resource, in order to tackle serious situations such as droughts or other contingencies or emergencies by means of an immediate supply at the delivery point. Here the following scenarios will be analyzed (Sánchez Sánchez and Gómez Gálvez, 2016):

a) The groundwater system's capacity to supply water immediately in situations of contingencies or other supply necessities. This means being able to guarantee a certain water volume at the system's various delivery points as soon as possible.
b) To this end, the so-called indicators of immediate production capacity are suggested: these indicators would permit the assessment of the real supply capacity within no more than 24 to 48 hours, indicating units of volume and/or a percentage of the capacity with regard to a maximum tested volume of the wells that may be introduced into the urban system during that time.

The strategic reserves' production capacity in situations of drought or shortage, ensuring a steady volume level during a long period.

This indicator of production capacity for long-term exploitation permits the measurement of the groundwater abstraction system's real annual capacity in order to tackle situations of shortage. It is expressed in units of annual volume and/or a percentage of the capacity with regard to the maximum available volume.

Such a situation, as has been shown, requires the application of availability and sustainability criteria, in order to avoid problems in the exploited aquifers and to allow the recovery of the groundwater level and quality.

Conclusions

There are at least three basic questions that define the main operation planning lines and the reaction capacity of the supply systems in different situations: how much, referring to the resource's availability; how, referring to the lines of operation and functionality; and when, referring to the evolution of availability and actual usage.

An appropriate planning of resources conditions the availability of the different sources, depending on the various probable scenarios of the hydrological situation. To achieve such a planning, it is essential to take into account the abstraction capacities in the short term, as well as their sustainability in the medium and long term.

Establishing various availability indicators makes it easier to reach the right decisions when defining the operation scenarios. This article suggests a series of indicators based on the resource's availability for tackling different temporary risk situations:

Probable available volume during an annual cycle: shows the system's capacity on a short-term operational horizon.

Assured continuous available volume during a multiannual cycle: includes temporary sustainability criteria for the system's capacity on a medium-term and long-term horizon.

Immediate available volume in case of shortage or scarcity: reflects the capacity for immediate abstracting as strategic reserve.

In arid and semi-arid regions, groundwater plays a relevant role in reaching the values of the indicators mentioned above. It guarantees a regular contribution to the overall supply, as well as serving as an emergency measure in the event of contingencies and scarcity, but only if its management is able to ensure this availability with regard to a pattern of existing natural or artificial recovery. This implies assigning the role of strategic reserve to the groundwater, and limiting its usage to the reaction to risk situations of shortage or to the prevention of these risk situations in the short-term (Cubillo González and Ibáñez Carranza, 2003).

To achieve this, guidelines and protocols must be established that help ensure the sustainability of the resource in situations of urgency and its availability, while maintaining the necessary quality requirements for urban usage. In this respect, the following indicators have been suggested, which cover various key aspects of the exploitation:

- The aquifers' filling level, offering data regarding their state, development and reaction to the exploitation.
- These measurements should be monitored at least once a month during the exploitation periods, although monitoring should really be carried out on a daily basis.
- Groundwater quality variations: any change in the composition of the extracted water, due to both natural or artificial reasons, that could lead to the risk of not complying with the established quality standards has to be detected, and its causes and consequences for the supply systems have to be analyzed.
- The readings have to be taken individually for each parameter, and a quarterly sampling should be sufficient, while a higher frequency could be applied in certain cases.
- Another useful tool would be the drawing up of water safety plans to map out homogenous protocols of action in the event of incidents and alarms concerning water quality, and to prevent possible scenarios of quality loss.
- Phenomena of ground subsidence caused by groundwater extraction. These should be analyzed during long periods of exploitation of large volumes.

To be able to manage groundwater exploitation appropriately and efficiently, it is most important to have an extensive knowledge of the combined aquifer/groundwater unit. All the associated aspects must be taken into account for drawing up investment plans and taking the right decisions for operation planning. In many cases, aquifers have been used inappropriately and overexploited due to glaring ignorance, causing important economic, social and environmental disasters that offer no solution at all in the medium-term and long-term.

To avoid such disasters, groundwater has to be given its due importance in the water supply planning of arid regions, in order to guarantee the volumes available during multiannual cycles, instead of using it on a short-term basis, except in cases of breakdown or other contingencies in the supply systems. In these exceptional cases, the exploitation systems turn into strategic infrastructures with the aim of achieving an immediate supply for the urban system (usually within less than 24 hours).

Against this background, the facilities' functionality and operational capacity become very important. Given the fact that groundwater exploitation systems usually work with interruptions or during short periods, it is advisable to establish annual Productive Maintenance Plans that could guarantee an immediate functionality in case of necessity.

Such plans should include both the abstraction facilities with their specific fittings and all the other infrastructures associated with the exploitation system: monitoring and control networks, pumping stations, power supply systems, treatment and/or disinfection plants, transport mains leading to the delivery points, etc.

Finally, the operational or real capacity indicators will be derived from the availability indicators and environmental functionality indicators, together with the monitoring network which relates the groundwater system to the rest of necessary supply system infrastructures.

The operational indicators allow the determination of the real reaction capacity of the groundwater system at any moment, taking into account all the relating factors.

In this context, two scenarios can be established, represented by two different indicators:

- The groundwater system's immediate capacity to collect water in situations of contingencies or other supply necessities. This indicates the maximum flow that could be supplied to the different supply areas through the strategic infrastructures within no more than 24 to 48 hours.
- Its readings should be made on a daily basis and be assessed in real time.
- The strategic reserves' production capacity in situations of drought or shortage, ensuring a steady volume level during a prolonged period.
- Its readings should be updated monthly.

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City Connections for Water Resource Management: A Regional Planning Perspective

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Abstract

Regional planning focuses on spatial and governance systems of territories. It is an integrated approach of development that promotes the interrelations between cities, intermediate towns and rural settlements. Different than the balanced development that promotes an equal development in each part of a region or a country, the integrated approach mobilizes natural and human resources of each area to base economic development on comparative advantages. Some key activities are specific to some areas (tourism, heritage, mining, agriculture), others harness the advantages of large cities. Regional development is not homogeneous and synergies are requested between localities and sectors to foster a fair sharing of wealth.

The legal system is a key factor to support water management. The Romano-Germanic legal system is based on a hierarchy of texts, giving priority on sectors to others. For example, in France, master planning at the regional level should follow planning documents related to Water basin management, Flooding risks management, Climate and Energy regional schemes and charter for regional natural parks. Moreover, the European directives impose an Environmental assessment for master planning with a monitoring system. This hierarchy provides guarantees to hinder economic development when challenging natural resources and risk management. Regional planning is a tool driven by the legal system that organize the relation between water resource management and the network of human settlements.

Keywords: Urban planning, Legislation systems, Basin management, Water resources management

National Disparities of Human Settlement Management

The spatial organization of human settlements takes different shapes[1]. Some countries have historically a strong concentration of human settlements with one or two city primacy (Algeria, Egypt, Saudi Arabia, Syria, etc.), others have a more dispersed network of cities (Germany, Australia, etc.). To better balance the urban hierarchy several countries adopt national urban policy[2] can have effect after decades. The human settlement pattern has a strong inertia.

For example, Ethiopia prepared a national urban development scheme in 2016. It proposed a better-balanced development around secondary cities to counterbalance the development of Addis Ababa that is the engine of growth of the country. Highlands are more populated than

1 Managing system of secondary cities, B. Robert, Cities Alliance, 2014.
2 See https://unhabitat.org/urban-initiatives/initiatives-programmes/national-urban-policies

low arid lands, mainly due to climate conditions for agriculture and disease conditions, especially malaria that cannot reach highlands. The large population growth (+50% in 20 years) with 45 million additional populations, will have a structural effect on human settlement organization. Rural area has few capacities to accommodate more population. The rate of urbanization is expected to reach 40% of the national population (20% in 2011) with a pace of urbanization similar to China or Indonesia in the past 20 years (+ 1%/year). Urban population will triple and the effort of the national, regional and local governments will focus on urban infrastructures to provide jobs and housing and increase economic development rate.

When a relatively dense pattern of settlement already exists, the logistic corridors based on industrial development and large communication infrastructures can have a direct effect on the economic development and the urban development along these corridors with emerging towns and cities. To facilitate regional development, large cluster of cities is organized along these corridors to manage public services and economic development. Here the concept looks for sharing costs for facilities and utilities for the benefit of each region, and sharing benefits based on specific assets of each region.

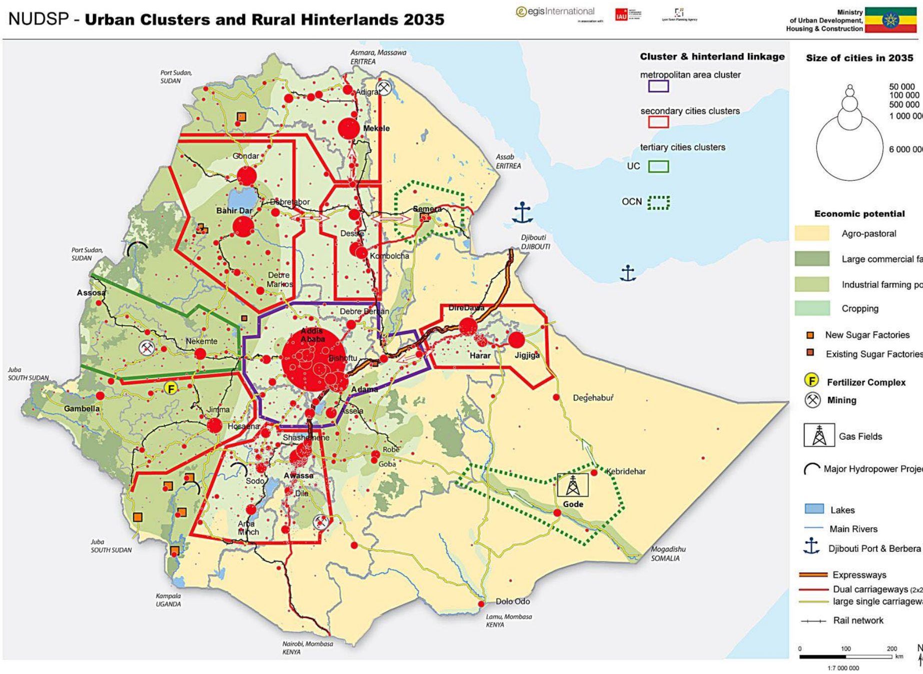

Figure 7.1 Urban Clusters and Their Rural Hinterlands in Ethiopia for 2035

(Source: National Urban Development Scheme, 2016)

In Saudi Arabia, the urban corridor concept was adopted in 2001 for the National Spatial Strategy. But it never works because of the specific organization of the country: logistic corridor didn't foster emerging towns or cities in the desert area for the lack of existing human settlements. The corridors are following a tunnel shape effect, concentrating population and activities on the main cities, mainly Riyadh, Jeddah and Dammam. It is correlated to the type of economy based on oil rent and its related redistribution in public administration and services that convert more than 80% of the economy. The urban network reflects the natural constraints and the type of economy. In that context, village clustering proposed for the National Spatial Strategy 2030 in strongly linked with their proximity to cities and large towns. Considering distance and time to connect large towns and city centers, the 17,000 human settlements were classified with "suburb villages" inside the administrative urban limits, "city orbital villages" and "city satellite villages" located near large urban agglomerations, "village clusters", "village orbital centers" and "village satellite centers" near large communication infrastructures and "isolated villages". Given the existing shape of human settlements in Saudi Arabia, there are very few isolated villages located far from large urban agglomeration or main roads. The main supports for villages are based on large agglomerations that provide services and economic opportunities.

Example of Village Classification

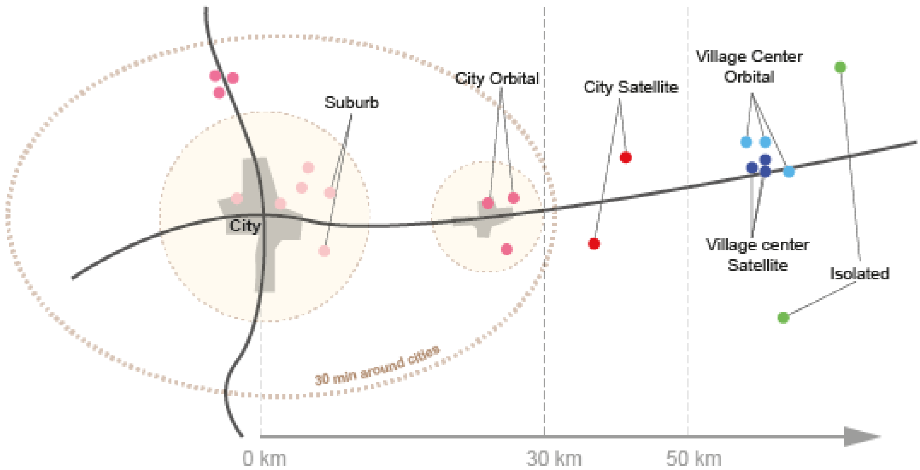

Figure 7.2 Proposal of Village Classification for Saudi Arabia
(Source: Institut d'aménagement et d'urbanisme d'Ile-de-France, 2018)

In Lebanon, the National Physical Master Plan[1] adopted in 2009 protects mountain summits to preserve water resources, river sheds that are the main ecological connections between mountain summits to the sea. It also defines national and regional natural parks to manage protected landscapes and base the sustainable development of these areas on natural and cultural heritage assets. Beirut accommodates half of the national population and two third of the population is concentrated on the coastal areas. The urban sprawl is one of the main concerns with few regulations on the real estate speculation. The management of water resources and pollution is difficult (few wastewater plants operating in the country). Regional planning plays an essential role to define protected areas.

1 http://www.cdr.gov.lb/study/sdatl/sdatle.html

In that context, how territorial pattern affects water resource management? How water resource management is a taken into consideration by local governments? How water resource is an asset or a constraint for development?

Metropolis, Linking Urban and Rural Areas

Worldwide, half of the urban dwellers lives in metropolitan areas[1]. The metropolis definition is based on a concept of functional areas well defined by OECD[2] that gathers urban and rural areas well connected with city centers. It is mainly based on economic activities and their related mobility. Metropolitan areas are attractive because of their large job market and their higher level of productivity. They are the main support and beneficiary of the globalization process and offer more possibilities for innovation[3]. Clustering cities, towns and villages are promoted to share services and base economic development on shared comparative advantages of each territory. Then, cities, towns and settlements connection is a key element in the contemporary territorial pattern.

Different Systems to Manage Network of Cities

The relation of metropolitan areas to the water varies given their specific geography. For example, Casablanca, Algiers and Tripoli-Libya have four main challenges regarding flooding: rising of the sea level that increase coastal erosion; marine submersion that increase flooding in wadis and coastal areas; higher salinity of underground water given sea intrusion; drought that reduces water resources. Metropolitan planning hinder urban expansion, protects river banks, underground water and coastal areas to reduce vulnerability of human settlements in urban and rural areas. Planners are working for compactness of cities. Climate change imposes to review adopted standards regarding rainfall and then the level of risks. Opening space for river expansion replace the previous channelization of rivers. Other resources and water management are mobilized: reuse of urban waste water; lower consumption of water resource in agriculture (change of crops, higher efficiency in irrigation systems); desalinization plant using water from the sea for potable water.

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1 UN's World Urbanization Prospects, 2018, UN, New-York, 2018.

2 OECD approved in 2011 a methodology to identify the functional urban areas that is a harmonized definition of urban areas as “functional economic units”. It is based on a core urbanized areas or ‘urban high-density clusters’, ignoring administrative borders based on a population grid of 1 km². An urban core consists of a high-density cluster of contiguous grid cells of 1 km2 with a density of at least 1,500 inhabitants per km2 (1,000 inhabitants in Canada and USA) and the filled gaps that could be mono or polycentric (when more than 15% of the population commute to another core urbanized area). A municipality is defined as being part of an urban core if at least 50% of the population of the municipality lives within the urban cluster. The hinterland of a metropolitan area is defined as the worker catchment area of the urban labour market, outside the densely inhabited core. The size of the hinterland, relative to the size of the core, gives clear indications of the influence of cities over surrounding areas. Urban hinterlands are defined as all municipalities with at least 15% of their employed residents working in a certain urban core. Municipalities surrounded by a single functional urban area are included and non-contiguous municipalities are dropped.

3 For a good synthesis of the metropolitan issues, see: Co-creating the Urban Future. The agenda of metropolises cities and territories, UCLG, 2016, Barcelona.

Figure 7.3 Corridor

Figure 7.4 Metropolitan Area

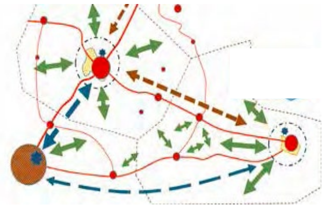

Figure 7.5 Town Clustering

The governance complexity of territories is increasing due to the emerging power of local authorities. Local governments play an essential role to manage local development. The large number of actors and the frequent changes in technologies, economic patterns, challenges and political players require a flexible governance system.

Water Resource Management and Regional Planning

Water resource management is a key component of regional planning. Regional planning balances water management between a structural constraint and an asset. It can fix important constraints for human settlements expansions to manage flooding and landslide that affects human settlements. Demographic growth and related urban expansion increase vulnerability due to a larger risk exposure of human habitats and economic activities. Specific measures are taken to hinder urban sprawl and avoid urbanization on flood prone areas. It can also define constraints related to drought and water scarcity that affect human settlements and economic activities. Water is an absolute necessity for city and industrial developments. Then cities mobilize new water resources from other water basin or from the sea with desalinization plants to ensure their development. If most of the water resource is used by agriculture that should be optimized, priorities are given to provide water for towns and industries because of their higher productivity. The relative stability of rural population and the very fast rate of urbanization in developing countries change the relation between actors to face water scarcity, drought and flooding.

Solutions adopted by countries reveal their relation to the environment. Saudi Arabia feed desert cities with desalinization plants and pipes (Riyadh is located 400 km from plants along the Persian Gulf Coastal Areas). Libya pump large underground water fields in the desert to feed coastal cities located at several hundred kilometers from the wellfields. India gives priority to land availability than the protection of water reservoirs (several industrial areas have been developed just above water reservoirs). France adopts water basin strategies to control pollution and monitor water resource with national and local actors. Ethiopia focuses on energy production (Renaissance dam and other dams) with few considerations of the desertification effect of these infrastructures.

Regarding the large effects of climate change, water resource management will become a top priority for governments. Cities and towns should manage better their pollutions and water uses (consumption, recycling, and urban planning). Algiers protects the western part of the Mitidja plain to limit urbanization and pollution on arable land and wellfields. Tripoli in Libya implement a large sewage system to reuse on large extend urban waste water for agriculture irrigation. New towns in the Egyptian desert reuse urban waste water to expand green forests in the surroundings.

Territorial Governance for Water Resource Management

Given their expansion, cities are more dependent to their hinterland and exchanges. Pollutions affects river sheds and underground water. Overconsumption of urban wells and pollution due to the lack of sewage systems affects quality of the underground water that are used for drinking water, industry and agriculture. So, all efforts done by cities regarding utilities for water supply and sewage system are crucial for the quality of life of urban dwellers, capacities for industrial development and available resources for agriculture.

Political and economic relations are generally not following the delineation of water basin. Water resource management cannot be considered only at the urban or municipal levels. Given these geographical discrepancies, water basin management challenge is an opportunity to create new solidarities between territories. There are common responsibilities of national and local authorities, economic and social actors regarding pollution and utilization of water resources for a same water basin. The interrelations between local, regional and national actors covering regions and municipalities, and between different economic sectors (agriculture, industry, services) encourage to implement a specific territorial governance.

Shared platforms for cities, towns and rural areas should be implemented to fuel the public debate to fix challenges and priorities, and support decision makers to elaborate policies, strategies and action plans. It should be supported by a high level and permanent dedicated territorial expertise to support decision makers (examples of territorial planning agencies[1] in France, Mexico, Korea, Algeria, Morocco, USA, Egypt, and China...). These strategic technical bodies play different roles: think tank, permanent territorial observatory, urban lab, resource center open to the public, public policy provider. They are crucial to monitor the development and prepare decisions to anticipate water crisis through territorial planning, to manage during crisis (alert, aid…) and to recover after disasters. Monitoring systems, based on indicators and permanent observation of the territorial dynamics, are essential to provide flexibility in policies and strategies.

Conclusion

Regional planning considers water resource management a key factor for development. The integrated approach fosters relations between urban and rural areas, large cities, intermediate towns and villages to manage sustainable development. The territorial focus of regional planning facilitates connections between cities and their hinterlands. It necessitates a governance system including different level of government, covering economic development sectors and different territories. Water resource management, especially for regions suffering of water scarcity, is a typical regional planning concern. Looking for a better territorial management of water basin is an excellent way to better manage regions and networks of human settlements. Regional planning and water resource management are intertwined.

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1 Metropolitan and Territorial Planning Agency (www.mtpa-network.org) global network has been launched during Habitat 3 conference in Quito for fostering and implementing territorial planning agencies. For example, Paris Regional planning agency (www.iau-idf.fr), Seoul Institute, Regional planning association (New York), Emplasa (Sao Paolo).

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B. Case Studies

Oman Efforts and Achievements in Managing Water Scarcity

By: Ahmed Said Al Barwani

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Abstract

Oman is situated in the south eastern part of Arabian Peninsula, surrounded by United Arab Emirates (U.A.E) from North West, Saudi Arabia from the west, Oman Sea and Arabian Sea from the east and south east. As in all arid and semi-arid areas, Oman is characterized by an extreme low annual average rainfall (<80mm), low groundwater recharge rate and limited water resources. Nationally, the consumption of indigenous water is 25% more than the resources currently available from renewable resources, desalination and treated wastewater. The agriculture sector is the dominant water-using sector accounting 95% of total renewable conventional water (83% of the total conventional and non-conventional water usage). All agriculture in Oman is irrigated. In many areas, demand for water exceeds natural replenishment. Where this situation exists, the demand is met by withdrawals from aquifer storage with consequent decline of groundwater levels. In coastal areas, over-abstraction has led to saline water intrusion with adverse impact on agricultural production and the environment.

Water is, and will remain, one of the nation's most valuable resources. Effective water management will be of vital importance in present and future. Limited water resources, increased water demand within the economic diversification program, increased of urbanization, low agriculture return to water use and groundwater pollution are the main challenges facing water resources sector. In order to counteract these challenges, the government efforts focus on finding the balance between water demand and water supply taking into consideration the environmental and social effects. This includes applying the concept of integrated water resources management and the augmentation of both conventional and non-conventional water resources. This accompanied by applying several legislation and institutional reforms.

The Omani government efforts and achievements in managing its water resources are reviewed in this paper so as to highlight its experiences and the necessity of a more sustainable approach to be applied to integrated water resource sustainable use.

Keywords: Water Resources Management in Oman, Water Supply, Capacity Building

Introduction

Oman, with an area of almost 309,514 km2, is situated in the south eastern part of Arabian Peninsula, surrounded by United Arab Emirates (U.A.E) from North West, Saudi Arabia from the west, Oman Sea and Arabian Sea from the east and south east, Figure 8.1. The total population is about 4.6 million (2018), of which around 26% is rural. Population density is about 9195 inhabitants/km2 (Zekri, 2014). Oman is a leader in the Region in the fields of water resources assessment and management and has excellent record in related legislation and institutional capacity-building. Optimization and strategic management of the water sector was seen as a key dimension of the Omani Economic Diversification Strategy at the vision “2020”. Due to its location Oman classified among the driest regions in the world. Day time temperature is high, generally above 30 C and seasonally above 40 C. Potential evapotranspiration varies from 1,660 mm/yr. on the Salalah plain at the southern part to 3,000 mm/yr. in the interior and 2,200 mm/yr. at the northern part of the Sultanate (MRMWR, 2012). Rainfall is limited and irregular over much of the country. Mean annual rainfall in the coastal plains and desert areas is relatively low, less than 50mm, and highly sporadic. In mountain areas, however, where rainfall is greater, up to 350mm, and relatively frequent. It provides a source of natural recharge to a number of aquifers including those in the interior and coastal plains. The southern regions of the Sultanate are exposed to south westerly monsoon winds originating in the Indian Ocean. The resulting mist and drizzle (Khareef season) are limited to the south side of Dhofar mountains and the plains between the mountains and the sea (MRMWR, 2013). Droughts of two- or three-year’s duration are not uncommon. However, in the interior and coastal plains despite, recharge from the mountains, aquifers can become stressed in some areas.

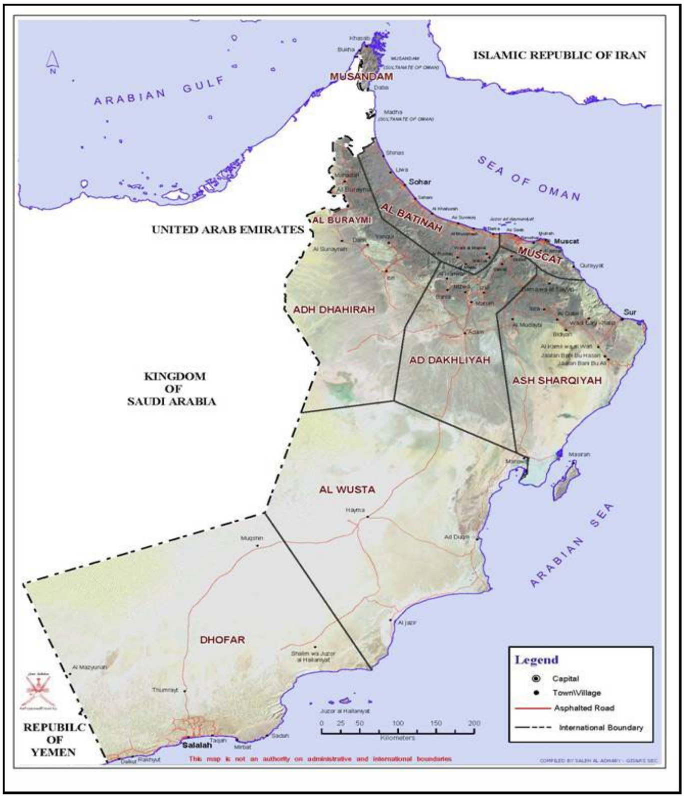

Figure 8.1 Location Map of Oman

There has been a rapid development of the water resources of the Sultanate during the past forty years. The growing economy has brought an increase in urbanization with a demand for high levels of service and quality for water supplies. The main challenges facing the water resources are limited water resources, increasing water demand, and low agriculture return to water use and also groundwater pollution (MRMWR, 2000). It has long been recognized that the successful and sustainable future development of water resources in Oman depends on a thorough understanding of the available resources to meet potential demands. In order to balance between supply and demand a significant investment has been made over the past 45 years in monitoring, inventory, resource exploration, assessment and water balance calculation to establish an appropriate technical foundation for resource development, planning and management.

Since the early 1970's the Sultanate of Oman has progressively moved forward with a series of policy reforms and strategies to achieve national goals and priorities in the water sector. While there has been significant progress in some areas of the sector there are also a number of challenges facing the sector and country to meet increasing demand for water, particularly the domestic and industrial use. Optimization and strategic management of the Water Sector was seen as a key dimension of the Omani Economic Diversification Strategy at the "Vision 2020" To assist in meeting the Vision 2020 strategy and maintaining the country's water security, a National Water Resources Master Plan has been prepared. The plan adopts the widely accepted Dublin (1992) principles and meets the requirements of The Hague Declaration (2000). The purpose of the Master Plan is to provide a sound basis for planning horizon 2020 and takes account of the need to provide for sustainable development and security of supplies beyond this date. The aim of this paper is to assess the latest water resources situation in the Sultanate of Oman, highlights the main challenges facing the water sector and the efforts and activities accomplished to maintain and secure water sources for sustainable water use. Also, to highlight the government efforts particularly in applying the concept of integrated water resources management in Oman and its experiences in this field.

Water Resources

Unlike many countries in the region, Oman does not depend significantly on Transboundary Rivers or underground water flow from neighboring countries. Rainfall is the major source of water in the Sultanate of Oman. The annual average of wadi flow is estimated at 330 Mm3. There are two main types of water resources in the Sultanate, conventional water resources (natural). This is the predominant water resources representing about 87% of the nation's water resources including groundwater occurring in aquifers within alluvium and hard rock representing 92% of the total conventional water where surface water representing 8% and occurring as Ghaily falaj and few permanent wadi flows.

Non-conventional water resources including desalination produced 196 Mm3 in 2011 and treated wastewater with a total annual volume of 62.2 Mm3, of which 24.2 Mm3 is used for landscaping, 3.3 Mm3 are being injected in the coastal aquifer at Dhofar Government to combat seawater intrusion and 34.7 Mm3 discharged to wadis (Assessment Report, 2014). Both of desalinated and treated wastewater accounts for 13% of the nation's water resources. Nationally, the consumption of indigenous water is 25% more than the currently resources available from renewable resources, desalination and treated wastewater. In areas where aquifers have limited groundwater storage, domestic and other priority supplies are at risk. Total replenishment of the renewable resources estimated to be about 1,318 Mm3/yr.

(MRMWR, 2013). The annual replenishment is equivalent, to about 500m3/capita, this is approaching a condition of extreme water stress according to international indices.

The quality of water available for agriculture varies from region to regions of Oman. On the coastal plains where groundwater overdraft has been most severe, saline intrusion has occurred. The saline front is advancing in some coastal areas and is stationary in others but in general the quality of water drawn from wells within 12 km of the coast is deteriorating (Al Barwani and Helmi, 2005). In the interior regions water quality also worsens in dry periods as water levels fall and pumps draw older water from deeper aquifers. The fossil water in the large undeveloped aquifers is of potable or near potable quality; the Nejd aquifer suffers from high fluoride and high sulfate levels. There are no major problems of artificial contamination.

Water Demand

In Oman agriculture is by far the largest water consumer, estimated to account for 1,546 Mm3/yr. (MRMWR, 2013) which is 83% of the annual national demand of 1,872 Mm3 (Table 8.1). This water irrigates a cropped area of 59,448 ha (MWR, 1998) with approximately 64% and 36% supplied principally from wells and aflaj respectively. Cropped area, particularly on the Batinah and Salalah coastal plains expanded during the 1980's and early 90's as part of land allocation and development programs, resulting in increased water abstraction.

Table 8.1 Water sources used to meet gross water demand

Water source	Amount (Mm3/per year)	%
Agriculture groundwater abstraction	1060	57
Falaj flow	486	26
Urban groundwater abstraction	88	5
Desalination supply	196	10
Treated wastewater use	42	2
Total	1872	100%

Because of the absence of surface water bodies all irrigation occurs with groundwater withdrawn from sedimentary aquifers. During the last 50 years, the agricultural cropped area increased by more than doubled. Cultivated area was 20,000 ha in 1961 (FAO, 2005) reaching 70,000 ha in the beginning of the 1990's (MNE, 2004). Zekri on 2014 stated that in 2005 cropped area is 55,597 ha, of which 92% in coastal areas. The latest statistics released by the Ministry of Agriculture and Fisheries 2012-2013 estimated the cropped area of 55,673 ha (MAF, 2014). In 2013, MRMWR updated the water balance for the Sultanate and the results showed that there is increase in water demand of about 35% compared with estimates of water demand for the year 2000 despite the reduction in cropped area. This reflects the urgent need for better estimation of actual water consumption particularly in agriculture sector. Table 8.1 shows that agriculture demand is met by water supplied from Falaj flow (26%) and abstraction of groundwater using wells (57%). Desalination is used to meet the drinking water supply where treated wastewater is used for amenity purposes and aquifer recharge in some areas.

On the other hand, urban water demand has increased more than four folds during the last decade in Oman. This increase in demand concerned the industrial, commercial, municipal and tourism sectors. This is due to the economic growth of these sectors. In fact, the urban water demand was around 86 Mm3 in 1998 and reached 399 Mm3 in 2010. The increase in demand in these sectors essentially met through supply increase of non-conventional desalination sources (MRMWR, 2013).

Water Balance

An updated water balance for the Sultanate conducted by the Ministry of Regional Municipalities and Water Resources based upon the characteristics of Oman. A modeled methodology developed to account for the most important feature of the water resources of the country. The water balance (MRMWR, 2013) shows that, in many areas, demand for water exceeds natural replenishment (Table 8.2). Where this situation exists, the demand met by withdrawals from aquifer storage with consequent decline in groundwater levels (and, locally, falaj flows). The stress, currently imposed by over-abstraction, exacerbated during periods of drought. This situation currently occurs in Al Batinah, Salalah and the inland areas of Ad Dhahirah, Ad Dakhliyah and North Sharqiyah regions.

Table 8.2 Water Balance by Governorates in Mm3

Water Assessment Areas	Volume of rainfall	Agriculture abstraction	Excess/Deficit
Musandam	333	30	26
North Al Batinah	1243	515	-257
South Al Batinah	329	138	-90
Muscat	518	72	-23
Al Buraimi	569	58	25
Ad Dhahirah	1423	158	-142
Ad Dakhliyah	4627	249	-57
North Al Sharqiyah	1136	172	-55
South Al Sharqiyah	296	23	48
Masirah	43	5.2	5
Al Wusta	1894	0.1	94
Al Nejd	2028	16	134
Salalah	362	109	-24
Total	15,841	1,546	-316

It is estimated that the total average rainfall falling over the Sultanate is 15,841 Mm3. Of this total, 79% evaporated leaving just 2,398 Mm3 as effective rainfall generating runoff and direct infiltration to the groundwater resources, which means that direct recharge, is 15% of rainfall on average; the remainder is lost to evaporation, initial absorption and runoff. Table 8.2 shows the water balance distribution per water Assessment Areas (WAA). In fact, agriculture is the major use of conventional water in the Sultanate. The total deficit reached 648 Mm3 per year, conversely there is a surplus of water in few areas accounts for 332 Mm3. Thus, the net water balance at the Sultanate is consequently an average deficit of 316 Mm3 per year. We also, have to take into consideration that the areas showing a surplus of water are located within the more hyper arid desert areas with low abstraction rates. Moreover, water quality distribution map showed that this abundance of water is of poor quality water.

Challenges Facing Water Sector

In Oman, agriculture water use (1,546 Mm3) is a major user of the renewable conventional water resources equal to approximately 95% and the rest is domestic water supply by groundwater wellfield. Lack of good agriculture practices and irrigated water management is one of the main challenges facing water sector in the Sultanate. Furthermore, we can summarize the main challenges facing the water resources and its direct related agriculture activities in the following issues:

- Limited water resources
- Effects of climate changes on water resources availability
- Increasing population growth and water demand
- Balance the gap between supply and demand
- Water use efficiency in agriculture sector and low productivity
- The conflict of objectives between agricultural (food security) and water policies (Water security)
- Degradation of groundwater quality and
- Estimating the actual groundwater abstraction by agriculture sector

Integrated Water Resources Management in Oman

Sustainable water resources management in the Sultanate is a priority policy issue given natural water scarcity and increasing water demand for different development activities. Implementation of Integrated Water Resources Management (IWRM) principles is a framework for the sustainable development and management of water resources for the whole society and plays a key role in social and economic development, particularly in sustainable development and poverty alleviation. The key to encouraging an IWRM-oriented civil society lies in the creation of shared visions, through joint diagnosis, joint creation of options, joint implementation, and joint monitoring. Figure 8.2 showing the different elements of the IWRM experienced in the Sultanate of Oman. In order to achieve the Oman's vision for water resources, in 2000 a Water Resources Master Plan had been executed. The purpose of the Master Plan is to provide a sound basis for development and management of the country's water resources. Although it has a planning horizon of 2020 the Plan also takes account of the need to provide for sustainable development and security of supplies beyond this date. The Plan prepared for the Ministry of Water Resources but the responsibility for development, management and use of water is not limited to the MWR.

The Plan takes into account the roles of other Ministries and the private sector in meeting national objectives. The Plan developed and comprises of more than twenty components, including the following four key elements:

- Establishment, development and protection of secure sources of potable water supplies for all towns

- Increase in water resource availability
- Establishment of sector water allocations, and
- Management of agricultural water demand (through the introduction of quota system in areas irrigated from wells) and improvement in aflaj systems

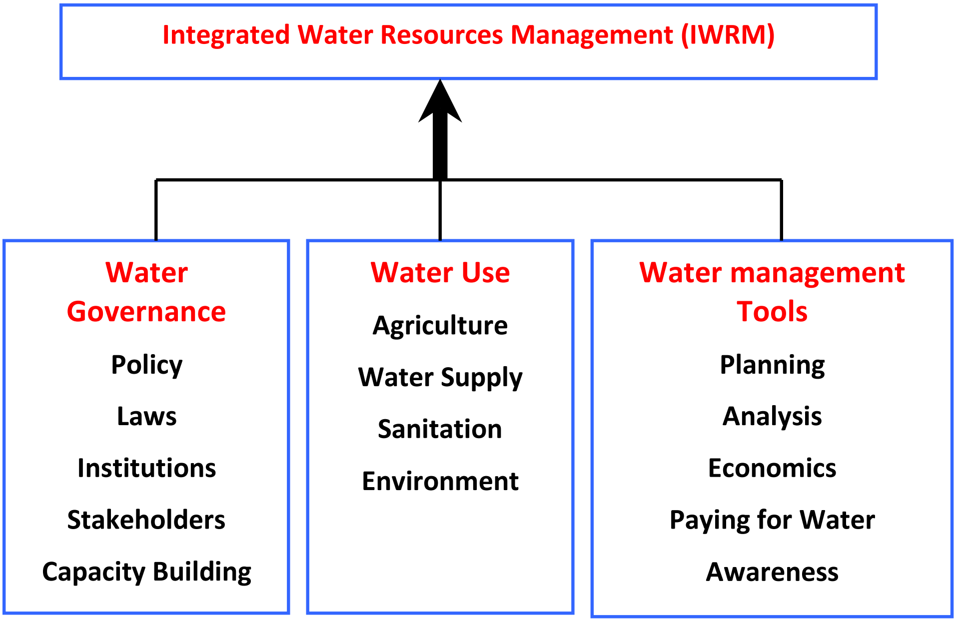

Figure 8.2 Schematic diagram for the IWRM Principle (after ESCWA, 2005)

These key elements of the Plan are to be supported through the implementation of appropriate institutional changes, amended legislation and regulations, continued human resources development, training and public awareness campaigns. The Plan assumes that water infrastructure development, agricultural advice and support to farmers and associated water sector activities will achieved through a program involving inter-Ministry coordination (MWR, 2000).

Water Resources Management Experiences in Oman

Since 1989, the strategy of the sustainable development, management and conservation of water resources in the Sultanate started. The technical basis for the water management comprises the assessment of water availability, development potential and demand for water. It also, has to appraise the extent to which the country should allocate its scarce water resources towards improving food security or towards making water supplies available to encourage other economic investment. Accordingly, water resources management relied on the followings main pillars:

- Institutional Framework Reforms
- Implementation of Laws and Regulations
- Demand Management

- Provision of Additional Water Resources
- Water Conservation and Public Awareness

On the following sections, we summarize the Oman's water resources practices during the last 20 years since the formulation of the Ministry of Water Resources (MWR) on 1989 as a part of the Water Resources Master Plan 2020.

Institutional Framework

The three main sources of water in Oman, natural resources, desalinated and treated wastewater. Their subsequent use is managed under different government ministries and their associated legal and regulatory arrangements. At the national level, conventional water resources fall under the remit of three central Ministries: **Ministry of Regional Municipalities and Water Resources (MRMWR)** has the responsibility of groundwater and surface water assessment, development, management and conservation and **Ministry of Agriculture and Fisheries (MAF)** is responsible for developing agriculture, crop and livestock production. Its role in water use restricted to irrigation management in farmers feed by wells or traditional Falaj system and **Ministry of Environment and Climate Affairs (MECA)** is responsible for protecting natural water resources from pollution. In general, it is not always clear where the role and responsibility of either MRMWR or MECA ends or the other begins (Zekri, 2014). On the other side, at the national level non-conventional water resources fall under the remit of two entities: **Ministry of Regional Municipalities and Water Resources (MRMWR)** and two private companies; Oman Waste Water Services Co (HAYA) and Salalah Waste Water Services Co. For domestic water use the **Public Authority of Electricity and Water (PAEW)** is responsible for securing and distributing fresh water. Until recently the organizations involved were all public sector, but in the last few years, there has been an increasing involvement of the private sector in desalination and treated wastewater. Such moves have been designed to expand infrastructure and to increase effectiveness and efficiency in areas such as costs and service delivery.

Regulations and Laws

Since 1988, the governmental laws and regulations had a very important role in protecting Oman’s water resource from either depletion or pollution. The Sultanate had taken several important actions regarding conservation of water resources, through many progressive regulations in order to control the demands, abstraction and protection of water resources (MWR, 2000). The following are the most important ones:

Royal Decree 82/88, refer to “the water of the Sultanate of Oman is a national resource to be used according to the restrictions made by the Government for organizing its optimum utilization in the interest of the state of comprehensive development plans”.

- Royal Decree 29/2000, refer to a new water law “Water Protection Law” emphasis on regulations for wells and aflaj, and regulations for desalination units on wells.
- Royal Decree 114/2001, organize the disposal of solid and dangerous wastes, environmental pollutant and untreated sewage wastes without a permit.
- Royal Decree 115/2001, refer to organizing disposal of liquid and solid waste products.

- In 2001, a series of Ministerial Decrees, refer to the implementation of water supply well fields protection zones at several regions of the Sultanate.

Demand Management

A need to reduce agricultural water use established in many areas. A number of measures that could be used to achieve sustainability targets are summarized in the followings:

- Demand management on farm properties "water savings": Improvement can be made by adapting cropping pattern and through the introduction of modern irrigation systems.
- Abstraction Control: this can be achieved through control actual water use and introducing water quota particularly for farmers using water from wells for irrigation. The target is 160 Mm3/year, which is equivalent to 20% of the national consumption.
- Sector Water Allocations: with the increasing demands on conventional water resources, the strategy establishes the prioritization of water use as Domestic, Industrial/Commercial, Environmental, Aflaj and Agriculture irrigated from wells.
- Water Tariffs: water charges and tariffs are widely used throughout the world in connection with irrigation schemes, introduced with variety of objectives. Tariffs could be introduced in Oman with the aim of reducing water consumption providing an incentive to farmers to look more carefully at their cropping patterns and farm budgets and make decisions to maximize their returns on the water charged, without necessarily reducing consumption.
- Changing Cropping Patterns: water saving can be made through a change in cropping pattern by reducing the area planted with dates and other tree crops, replacing Rhodes grass and alfalfa with annual fodder crops. This will reduce the water consumption and produce water savings in the range of 8,000 to 15,000m3/ha/year.
- Change Land Use: small farm size leads to less efficient production systems because of diseconomies of scale. While growth, of urban areas consumes arable land. During 2005-2010, the urbanization of agricultural land has consumed around 11,595 feddans (only in Al Batinah) which represents almost 9% of the total agricultural area in Al Batinah.
- Improvement of Aflaj Systems: this is done through establishing protection zones around the “mother well”, the source of water to the falaj and providing support, both financial and technical for repair and maintenance. Since 1989 up to the end of 2011 the MRMWR had supported 1864 project for falaj maintenance.
- Integrated Water Resources Management: applying IWRM principle on 3 main catchments in Al Batinah area through cooperation between MRMWR, MAF, Dresden University-Germany and local community.

Provision of Additional Water Resources

The water resources that are currently available can be augmented in a variety of ways, some of which are being implemented as in the followings.

Conventional Measures

Recharge and Storage dams: Oman has a fairly large number of dams to serve different purposes including: Groundwater recharge, Irrigation water requirements, Flood control and Water Supply. Most of the dams built in Oman are multipurpose in the sense they meant for aquifers' recharge, flood protection and as a barrier against seawater intrusion. Since 1985, groundwater augmentation by artificial recharge of floodwaters has been a major component of water policy, with the construction of 46 recharge dams with a combined reservoir capacity of 95.42 Mm3. These recharge dams since they were built till end of 2014 retained about 1,401 MCM or equivalent annual volume of 47 MCM. Also, ninety-six small retentions or storage dams, with reservoir capacities of less than 10,000 m3 were constructed in upper catchments of the Al Hajar Al Gharbi Mountains of northern Oman for water supply to remote communities. It is worth mentioning that according the monitored results of the operation of these dams, we can say, they have not only achieved their intended purpose but some of them have realized greater dividends, as the dam value recovered. In Addition, the government has constructed a major storage Wadi Dayqah Dam in Wilayat Quriyat near Muscat the capital with a total capacity of 100 million cubic meters. The dam will provide 35 million cubic meters per year of water, of which 10.4 million cubic meters be utilized for agriculture purposes by the village downstream of the dam, 3.9 million cubic meter will be used for domestic uses at Wilayat Quriyat and 20.6 million cubic meters for domestic uses at Muscat. The dam lake will be able to secure water supply for three consecutive years during drought periods. In terms of water, the dams have positive impacts such as reducing saline intrusion, increasing groundwater, availability and improving standard of living of mountain area residents in addition to preserving the stability of such communities.

- Recharge Wells: The artificial recharge of excess wadi flows or wastewater through wells, rather than through construction of dams or some other method of surface spreading, has some potential to provide significant quantities of renovated water for selected agricultural purposes, for recharge of aquifers. Example is the injection of 20,000 m3/day of treated wastewater to tertiary level at the coastal aquifer at Salalah plain.

- Interception of Groundwater Losses: A flow of groundwater to the sea is necessary to maintain a stable seawater interface. However, in some areas where natural groundwater flow still exists, it may be possible to effect reductions in flow losses to the sea by 50% and still maintain a groundwater balance.

- Water Transfers: Refers to the transfer of water by pipelines from an area with a surplus or good quality water to an area of deficit. Examples in Oman are the two projects (Al Masarrat and Ash Sharqiyah wellfields). Those are the first large scale municipal water supply network, fed solely by groundwater, in the Sultanate of Oman and one of the largest municipal groundwater supply schemes in the GCC countries. They both provide more than approximately 200,000 residents with fresh save drinking water on the first stage of the projects. The groundwater volume reaches 12 Mm3/year (MRME&WR, 2005).

Non-Conventional Measures

- Desalination of Seawater and Brackish Water: In Oman, desalination plants make an important contribution to water supplies where natural water resources are unavailable or inadequate. During 2011 desalination provides about 196 Mm3 (70%) of the potable water supplied nationally. Plants installed since the early 1970s, primarily to provide potable water to communities but also to supply industry. They are located both on the coast and in the Interior, primarily of seawater for Muscat and some other coastal towns and of brackish water in the Interior (PAEW, 2011).

- Sea water flushing: Seawater distribution systems to duplicate water networks installed in some cities for sanitary flushing so that the domestic demand for fresh water supplies can reduced by 30%. In many coastal cities of Oman, the water used for flushing as not only of potable standard but also comes from desalination. In future, the use of seawater flushing considered as one of the options for coastal towns.

- Reuse of wastewater: Wastewater from municipal areas represents an important non-conventional resource to the water budget. The treated volume generated till 2030 will reach 100 Mm3 per year which deemed to represent a significant potential source. The acceptance of the use of treated wastewater for irrigation must also be sought as a consensual approach.

- Fog collection: Fog is harvested by intercepting, condensing and collecting the fine moisture droplets of fog-clouds from a screen. The MRMWR and other government bodies have implemented many of experiments whether those relevant to collecting water fog from the trees used to irrigate some fenced agriculture areas by MAF, re-vegetate the fenced mountain areas and for livestock drinking purposes (MRME&WR, 2005).

Capacity Buildings and Awareness

Public awareness has an essential and effective role in orienting Awareness constitute an important factor in the application of programs, plans and policies aimed at rationalizing water consumption, and the development of programs and the development of water resources management in the Sultanate. The awareness and information department in the Ministry had attention to this aspect through coordination and follow-up with their representatives in the different Directorates General. The implementation of awareness programs through direct contact and indirect contact includes:

- Implementation of lectures, seminars, field visits and establishment of labor camps for the maintenance of aquatic sites
- Implementation of meetings, reports, news and appeals guidance through the various media (TV and radio)
- Many publications annually issuing guidance about the importance of water and the need to rationalize consumption through the presentation of the methods of rationalization, and the definition of water facilities and to highlight the efforts and programs implemented by the Sultanate to preserve water resources

On the same while, the ministry attaches great importance to the development of skills and capacity building for all the technicians and specialists' sector of water resources. This achieved through the implementation of several training programs in various disciplines and sending some to academic studies inside and outside the Sultanate within the framework of a general plan to improve the efficiency, increase the skills, and gain information. During the past five years the total number of trainees (447) and the number of envoys in academic studies (40) of them (20) and graduate (20) are continuing in the study

The Ministry has taken a great importance to developing the skills of the technical staff of Oman in the areas of water resources through effective participation and contribution in many Arab, regional and international organizations concerned with water resources. In addition to participating in international conferences and forums that discuss water issues, especially in arid and semi-arid countries and its problems as well as hosting many of these conferences in the Sultanate.

Conclusion

Water is a key for sustainable development. His Majesty has already spelt out the dangers of ignoring the water problem, saying, in 1991, "The use of this vital resource throughout the world can have a great impact on future development strategies, and indeed could become a decisive factor in political tension and thus world security". This statement represents the general framework for the different strategies pursued by the Omani government to manage water resources in the Sultanate. Across the last forty years, the Government executed great efforts to ensure water security for the sustainable development goals. Therefore, Development of the country's water resources should be sustainable in the long term, not just technically but also economically, environmentally and socially. In evaluating the potential for the development of water resources in Oman, a number of basic principles continuously applied. These principles summarized as followings:

Sustainability

Development of the country's water resources should be sustainable in the long term. Where resources already degraded due to over-consumption or pollution, the water balance of the aquifer should be restored to sustainability by acting appropriately. Saline intrusion in coastal areas halted or largely retarded by controls on consumption. A number of major aquifers in Oman hold large volumes of groundwater but receive very limited recharge (e.g. the non-renewable resources of the Najd, Sharqiyah-Wahaybah in Al Batha and Al Masarrat). These major aquifers resources in Oman should form a strategic reserve and those of potable quality be allocated only for priority domestic and industrial use. Their development should be planned in distinct stages with adequate intervals for evaluation of the aquifer response to pumping.

Priorities for Water Use

The development of water resources is based on the principle that the provision of domestic and industrial water supplies has priority over its use for agriculture except where resources are used in aflaj areas where the current supply of water will be maintained.

"Virtual Water" Imports

The water, that would be otherwise have been used to irrigate crops and fodder fed to animals by the import of the equivalent amount of food and livestock from abroad is already considerable in Oman. It is now estimated to be over three times the indigenous water currently consumed by the country. The major challenges facing water sector is the dichotomy between the stated policy objectives of self-sufficiency in food and the elimination of water balance deficits needs to be resolved. As indicated by virtual water imports, total self-sufficiency in food production, may be unattainable goals, but a focused policy(s) towards food security, and production of higher value and more water efficient crops would make a significant contribution to the national economy and reduce dependency on food imports.

In addition to the above three pillars, facing challenges in agriculture sector should be overcome to improve water use efficiency in such sector. These are crop pattern management, low crop production, well-managed irrigation systems, land management, and farm size.

The future outlook for the management and promote of water resources in the Sultanate include the comprehensive treatment of sewage which can produce an effluent complies with the Omani Standards for Wastewater and Reuse, and be valuable local contribution to water resources. The main use for the effluent is agriculture or municipal landscape irrigation and aquifer recharge. In addition, to reduce water losses through surface outflow by construction of recharge dams. Moreover, implement the Integrated Water Resources Management concept as a part of ensuring environmental sustainability. So far, in Oman, consensus building has been largely via conventional public awareness campaigns of lectures, newspaper articles, radio and TV broadcasts. While these are valuable in raising awareness, particularly amongst the younger generation, they need to be future developed and targeted to the main stakeholders, the farming community. Oman is confident that, in the long term, following the tradition of peaceful cooperation that has characterized development since the Renaissance of 1970, this goal has been achieved.

Finally, we can say that Oman has dealt with the challenge posed by the continued increase in the demand for water resources of each sector through the adoption of the Platform seeks to harmonize the requirements of development and water resources available. First to focus on, supply management through the implementation of national programs for water resources assessment to identify all available resources and the development of infrastructure. This also included effort to regulate the use of water, expand water quality monitoring network, and the Sultanate recently expanded its scope to manage demand by encouraging all activities aimed at preserving the water resources in all sectors., and increasing efficiency in the field of water and uses supply, and the promotion of sea water desalination and waste water treatment. It was the implementation of all of these activities in the main objective of sustainable development, which aims to maintain and rational use of natural resources and strict quality control for the benefit of present and future generation framework.

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Glossary

Aflaj (single falaj):	A surface and/or underground channel fed by groundwater/spring or stream built to provide water to communities for domestic and/or agricultural use
MAF:	Ministry of Agriculture and Fishers
MECA:	Ministry of Environment and Climate Affairs
MRME:	Ministry of Regional Municipalities and Environment
MRMWR:	Ministry of Regional Municipalities and Water Resources
MRME&WR:	Ministry of Regional Municipalities, Environment & Water Resources
PAEW:	Public Authority of Electricity and Water

The Role of Education in Water Security: Case Study from Uzbekistan

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Abstract

Water security of Uzbekistan, located between two main rivers, Syrdarya and Amudarya, faces challenges of global, regional and local levels. Since 1960's through 2010, the global climate change has caused the depletion of the third part of glaciers in the upstream of the rivers. It is projected further reduction of the glacier extent in average by 50% to 2050 as compared to 2010, which may result in reducing the river flow by 20-45% during summer months (Punkari et al., 2014). The unmet water demand to 2050 may amount 50% of total demand in Amudarya River basin and 33% in Syrdarya River basin. This may be followed by a significant cut in crop production and an increase in the unmet food demand. Water and energy nexus is the major challenge for developing the basin-scale water cooperation in Central Asia. While the upstream states, facing a shortage of fossil energy resources, make steps forward developing the hydropower, the downstream states, prioritizing food crop production, try to preserve the irrigation-based basin water management. Recently, Uzbekistan, the downstream country and Tajikistan, the upstream state, made first steps forward in developing the upstream hydropower for mutual benefits and managing its potential negative consequences to the downstream crop production and the environment. At the local level, subsidizing energy and water, and conventional irrigation practices are among constrains for efficient use of available water resources. While overall irrigation application amounts are in line with crop evapotranspiration rates, the irrigation schedules do not fully coincide with crop water requirements. As the consequence, unutilized water losses recharge groundwater and form drainage flow. Increasing the productivity of available water resources is considered to be the way to meet growing water demand and the adaptation strategy to a new environment.

The government, adapting water management to a new environment has transformed administrative water management into basin management. Basin administrations created within hydrographic borders have taken responsibility for water resources planning and allocating among water consumer associations. Administrations of main canals became responsible for delivering water to Irrigation System Administrations (ISAs), and ISAs to water consumer associations. It was expected that District Water Administrations will provide extension services to the farmers. However, in 2017, to simplify the process of water governance, the level of the ISAs was excluded and their responsibilities were transferred to DWAs.This caused complications in the water supply of farmers and water distribution among the water consumer associations in the summer of 2018. The changes of responsibilities of DWAs were due to a lack of qualified staff able to deliver consultancy services to farmers.

At the farm-level, the government adopted the program of wide scale adaption of drip irrigation. The area under drip irrigation is projected to increase from 28,000 ha in 2018 to about 600,000 ha by 2030. The key role in shifting to drip irrigation is given to clusters, representing contractually linked cotton lint processing factories and farmers. The government removed custom taxes for importing any equipment to produce the drip systems and guaranteed low percentage credits for purchasing and installing drip irrigation. The lack of qualified local consultants able to deliver the training services to farmers for the operation and maintenance of drip systems may become one of the main constrains for accelerating the program.

Given above examples indicate the importance of high education/ universities role in sustainable and more productive water use at all levels. This study describes several alternatives which can contribute to building the capacities of the water institutions to meet water security challenges.

Keywords: Water security, Capacity building, Integrated Water Resources Management

Introduction

Water security of Uzbekistan, located between two main rivers, Syrdarya and Amudarya, faces challenges of global, regional and local levels. Climate change impact, increasing demand and competition for water between different water uses are among them. The objective of this paper is to determine the role of education in the process of transforming the water management. This study summarizes the current and potential impacts of the challenges on human activities and environment. The institutional and technical measures taken by the government to adapt water management to a new environment are highlighted. Two of them, introducing integrated water management (IWRM) in Fergana Valley and wide scale adoption of drip irrigation are discussed in detail. Introducing IRWM principles in the Fergana Valley followed by the extensive capacity building programs clearly showed the way of achieving the goal. The program of wide adoption of drip irrigation technology recently taken by the Government indicates the needs for diversifying and revisiting the education process.

Water Management

Available water resources of Uzbekistan are at 51 km3/yr in average, of which 46.8 km3/yr, or about 90%, is allocated for agriculture. Because 80% of available water resources originate in the upstream states and belong to transboundary water courses, the operation regime of the upstream reservoirs plays important role in securing the water supply. In addition to the upstream reservoirs, Uzbekistan has 31 in-bed and 27 off-bed reservoirs with a net capacity of 16 km3. The water management infrastructure in Uzbekistan is represented by 180,000 km of canals, 140,000 km of drainage, 1620 pump stations with annual power requirements of 8.2 billion kWh, 4100 wells for irrigation and 4300 wells for drainage purposes. Over 41,000 staff is involved in water management.

Global Challenges

Since the water resources of Uzbekistan are mainly transboundary, the impact of global climate change is given for water resources at the regional scale.

At current, about one-third of the river flow originates from mountain glaciers that are quickly losing their volume due to global climate warming. Glaciers cover 18,128 square kilometers (km2) in the Aral Sea Basin, and they have an important hydrological role because they release melt-water, especially during the dry summer months. During the past decades the rivers received a significant amount of excessive water from glacial melt, but in the future, this source may be lost as a consequence of vanishing glaciers. In the future, water shortages are expected to be a serious problem for the national economy and the environment. Demand for water will increase at the same time as the river flow diminishes (Punkari et al., 2014).

The ADB made projections, until 2050, indicate that the mean temperatures will rise throughout the years in the Central Asian region, with an annual mean temperature rise of about 3oC. The projected changes in annual precipitation were relatively small until the year 2050 and varied from model to model. The already-dry southwestern parts of the region were projected to become even drier, especially during summer time. Uzbekistan's climate is predicted to become more arid. Since, Uzbekistan uses substantial amounts of water from the Amudarya River for agriculture, the foreseen decrease in these water resources can have a severe impact on the country's economy (Schlüter et al., 2013). The large-scale irrigation systems are already suffering from water shortages, and higher temperatures will increase the volume of required irrigation water.

Based on the future melting rates of glaciers in the Aral Sea Basin, predicted using Global Climate Model Projections and hydrologic modeling, the glacier extent in the Aral Sea Basin is projected to reduce to 2050 by 50% as compared to 2010 (Punkari et al., 2014). Table 9.1 shows the contribution of the different sources to the total river flow. In the Amudarya River basin, glacial melt is an important contributor to the entire flow, especially in the smaller streams at higher elevations. Total water resources generated in the upstream parts of the Aral Sea Basin indicate that for the upstream Amudarya almost 40% of the total flow is generated by glacial melt, while for the upstream Syrdarya this figure is just over 10%.

Table 9.1: The relative flow contribution of the four components for the upstream Syrdarya and upstream Amudarya rivers, 2001-2010 (%) hydrological component Syrdarya River and Amudarya River (Punkari M. et al., 2014)

Hydrological Component	Syrdarya River	Amudarya River
Direct runoff[1]	31	16
Base flow[2]	23	19
Snow melt[3]	35	27
Glacial melt[4]	11	38

1- Rainfall flowing overland directly into the streams;

2- Rainfall infiltrating into the soil and flowing through the soil into the streams, or available as groundwater;

3- Precipitation falling as snow and flowing into the streams when it melts;

4- Precipitation feeding glaciers and that eventually melt and flow into the streams.

The data given in Table 9.1 indicates that the glacial recession caused by climate change will have a major impact on total flow and the timing of flows. The analysis shows that inflow into the downstream areas will decrease by 22%–28% for the Syrdarya River and 26%–35% for the Amudarya River by 2050. The range of the projected decreases reflects the uncertainty in the climate projections.

The major user of fresh water in Uzbekistan is irrigated agriculture. About 94% (48 km3/yr) of water resources is consumed by irrigated agriculture, while other sectors such as households and industry consume about 3 km3/yr (Ahmadjanov, 2017). Climate change will reduce available water resources and increase the demand of crops since higher temperatures lead to elevated evaporation rates. The total water demand in the Syrdarya Basin is projected to increase by about 3%–4% by 2050, while demand in the Amudarya Basin will increase by about 4%–5%. It is expected that water shortages will be higher in the downstream of the rivers having major irrigation systems in the region. These data show needs for actions to secure sustainable water use in Uzbekistan.

Regional Challenges

At the regional/country level the water challenges are associated with growing population and increasing demand. From 1980 to 2010 the population of Uzbekistan doubled which accordingly increased demand for water, energy and food, and reduced water availability per capita from 3200 to 1500 m3/yr. The water and energy nexus associated with competition for water between the upstream hydropower and the downstream agriculture complicates the situation. Limited fossil energy resources induce the upstream states to change the operation regime of the key upstream reservoirs from agriculture to hydropower generation mode. As the consequence, this may change the river flow regime downstream — more water may come in winter and less in summer. The downstream human activity, which at present is mainly irrigated farming, may face increasing water shortages. Uncertainties, such as climate change, scarcity and sharp fluctuation in water resources availability, may increase the competition for water between human and environmental needs.

Local Challenges

At the local level, conventional furrow irrigation practices cause high infiltration losses. Often, irrigation applications depend on water supply regime rather than crop water requirements. This results in groundwater table rise and secondary salinization of the irrigated land. About 31% of the irrigated land is prone to salinization. Other barriers for efficient use of available water resources are as follows:

- High number of farmers complicating water distribution process
- Most of water consumer associations (WCA) created on administrative base
- Poor financial status of WCAs
- Aged infrastructure
- Lack of flow monitoring infrastructure
- Coarse land leveling practices

In water short environments farmers widely apply alternate furrow irrigation and/or plastic sheets to cover furrow beds. At WCA and DWA levels time-based water rotation is in practice between WCAs and farmers, accordingly. Unfortunately, these measures are not sufficient to cover water shortages, especially in the tail ends of the irrigation systems.

Actions taken to meet water challenges

The government has introduced the combination of the institutional and technical measures, such as:

- introducing limit-based water use permits;
- water administrations shifted from administrative approach to basin approach;
- basin management administrations of irrigation systems are created at the small river basin level > following level is irrigation system administrations > district level water administrations > water consumer associations> farmers;
- replacing high water consumptive crops. Cotton/alfalfa crop rotation is replaced by cotton/winter wheat cropping sequence;
- modernizing water infrastructure;
- strengthening legal basis of water management and use;
- wide adoption of water saving (with focus on drip irrigation) is on the way;
- strengthening of formal and informal institutions;
- prioritizing measures for amelioration of salt affected land.

The water administration at current represents the mixture of basin and administrative approaches. The water management above district level takes into consideration the hydrographic boundaries, while DWAs and WCAs are created on the administrative base. During water short years/periods the water allocation is according to the limited water use rule, which applies the equal cut of water permits based on the availability of water. The advantage of this rule is simple practical solution, while the shortage is that the rule does not consider the development phase of crops.

Having water shortages and prioritizing food independence policy since 1993 the state shifted from cotton/alfalfa crop rotation to cotton/winter wheat cropping sequence and increased grain production on the irrigated land. Main infrastructure, installed in 1970-1985s is aged and requires renovation. The state one by one reinstalls water intake and other structures while WCA and farm levels require financial inflows. Two initiatives described below to highlight the role of education in meeting the water challenges are integrated water resources management (IWRM) and wide scale adoption of drip irrigation.

Integrated Water Resources Management in Fergana Valley

I IWRM principles were tested in Southern Fergana Canal command area in the Fergana Valley, the Syrdarya River basin. The canal takes water from the Andijan reservoir on the Karadarya River. The total length of the canal is 120 km. The command area of 83844 ha belongs to Andijan and Fergana provinces of Uzbekistan, except about 2500 ha belonging to Osh province of Kyrgyz Republic. This irrigation transfer action was funded by SDC and implemented in the cooperation by the Scientific Information Center of the Interstate

Coordination Water Commission and the International Water Management Institute. The project was implemented step-wise from 2002-2012.

During its inception phase, 2002, the project analyzed the existing water management issues in Central Asia, selected and justified the project sites, made initial contacts with key stakeholders and specified the IWRM principles to the local context. The key findings of the inception study were as follows: declining the state funding to maintain the base level of the irrigation systems; an increasing number of farmers, after collapse of the ‘kolhoz’ system, led to the institutional gap in the water management below the district level; the inefficiencies in the water management practices cause low water productivities (IWRM in Fergana Valley project, 2009).

During the implementation phase, 2003-2004, the project initiated major institutional reforms, such as the establishment of a unified canal management organization along hydrographic boundaries, involving water users in the canal governance, creating hydrographic water consumer associations (WCA) using bottom-up social mobilization approach. Along with the institutional measures, actions were taken to increase water productivity and adopt irrigation schedules meeting crop water requirements (Dukhovny and Stulina, 2012).

The phase III (2005 - 2008) concentrated on strengthening both vertical and horizontal linkages. Public participation was integrated at all levels of the water management hierarchy. Aiming for the inter-sectoral integration, emphasis was given to consultation efforts. At the national level the project established multidisciplinary and inter-ministerial groups. A transboundary small river component was added to the project’s agenda (SIC ICWC/ IWMI, 2008).

The capacity-building activities became the main component of the project. Over 100 training events were conducted under the project with over 8000 participants (Fig. 9.1). Main attention was given to training of WUAs staff, canal administrations and farmers.

The phase IV of the project focused on improving the water productivity and strengthening water management in small river basins. Institutional innovations supported by technical interventions and the intensive training program guarantied the success of the project (Fig. 9.2). Forty-seven WCAs were shifted from administrative to hydrographic boundaries during the project life in 2004 through 2007. Irrigation applications were reduced from 12700 m3/ha to 6700 m3/ha in average. Significant reduction of number of infection illnesses, such as Hepatitis A, Diaries, and Dysenteries, also would be not possible without the intensive capacity activities.

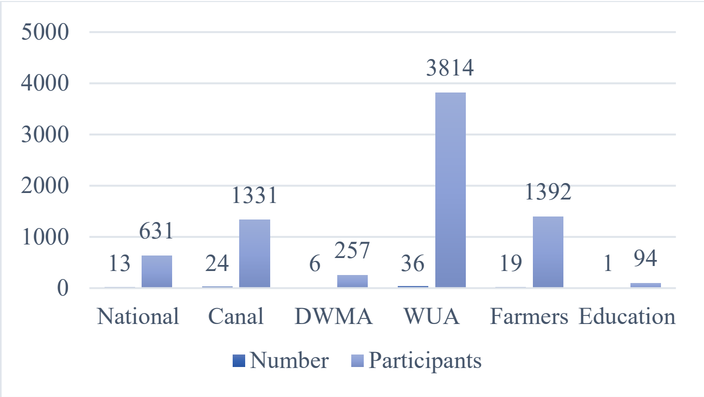

Figure 9.1 Number of Events and Participants of the Training Programs During the Third Phase of the Project (2005-2008) (After Mirzaev, 2011)

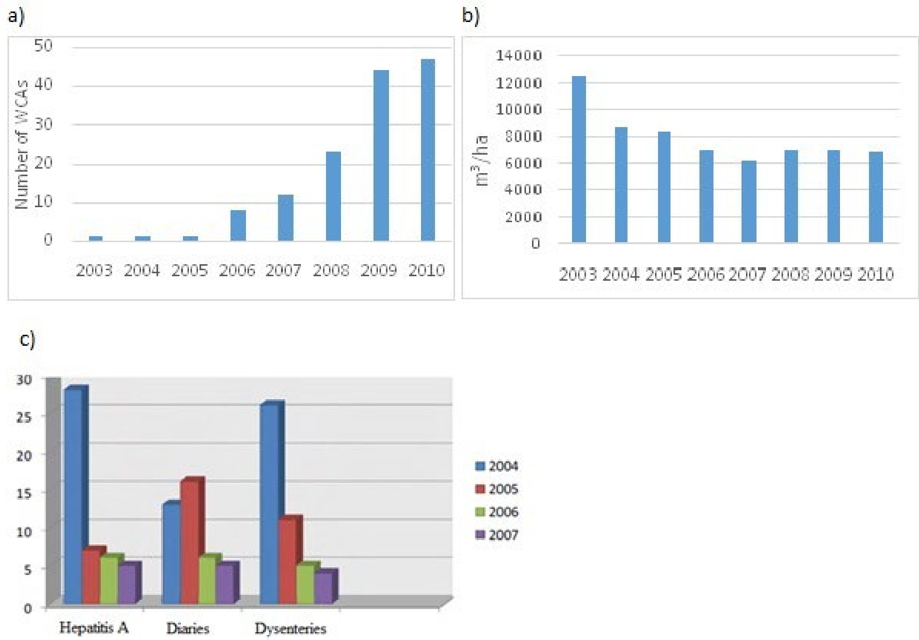

Figure 9.2 Number of WCAs established on hydrographic base (a), changes in irrigation applications (b) and number of infection illnesses among the population (c). (IWRM, 2008)

Issues Identified in Introduced Water Management Principles

Along with the successes, some issues identified were as follows:

- Unclear sharing responsibilities between different levels, especially between irrigation system administrations, canal administrations and district water administrations (DWA). DWAs had similar responsibilities with ISAs but at the district level;

- Incentives for water savings were not introduced. Water was delivered to WCA gates free of charge. Farmers paid fees only for WCA's services;
- Capacities of DWAs to lead the WCAs and water users forward adapting water saving technologies and improving water productivity under the growing water shortages were not strengthened;
- Capacity building program did not cover high education (University level);
- Capacities of district water administrations were not in place to deal with the facing challenges;
- Financial situation of WCAs did not reach the level to maintain/ modernize infrastructure.

These issues require consideration and actions. The project outcomes indicate that the development through institutional and technical interventions is to be supported by the strong capacity-building programs insuring the successful reaching the aims.

Wide Scale Adoption of Drip Irrigation

This is another example demonstrating the role of education in development. The company 'Shurtangas', specializing in exploring natural gas and producing plastic material, such as polyethelene and PVC, has taken the initiative of demonstrating the advantages of drip irrigation in Uzbekistan. Aiming to increase the market for plastic materials, which the company produces, in 2010, the company purchased the equipment for making drip lines and hired the staff. Starting from 2011 through 2013 the company installed demonstration sites of drip irrigation of cotton on 150 ha area total in 2011 in Bukhara, Navoi and Kashkadarya provinces and 100 ha in 2012, and for irrigation of 11 ha orchards in 2013 (Fig. 9.3). Except for highly salt affected areas, the yield of cotton exceeded 4 t/ha against 2.5-3 t/ha under furrow irrigation (Karshiev, 2018). This significant increase in crop yield was demonstrated to the farming communities, and then the demonstration sites were transferred free of charge to farmers. Impressed by the cotton yields on the fields belong to the company, in 2014, neighboring farmers took credits for purchasing and installing drip systems for orchards, vegetables and cotton. However, gradually the interest of farmers to drip irrigation is reduced due to several issues, including high maintenance costs, the lack of incentives to save water and the lack of knowledge to maintain and operate the drip system.

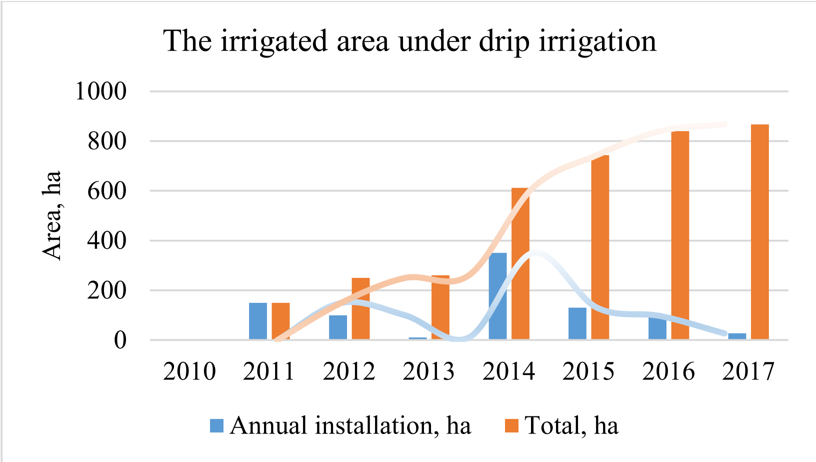

Figure 9.3 Installing Drip Systems at farm fields bythe company "Shurtangas" (modified from Karshiev, 2018)

Facing the water shortages, the government declared the program of wide scale adoption of drip irrigation. It is planned increasing the area under drip irrigation from 28,000 ha in 2018 to 500,000 ha in the nearest future. The key role in shifting from furrow to drip irrigation is given to clusters, representing the linkage between farmers and cotton lint (or fruits/vegetables) processing enterprises (Fig. 9.4).

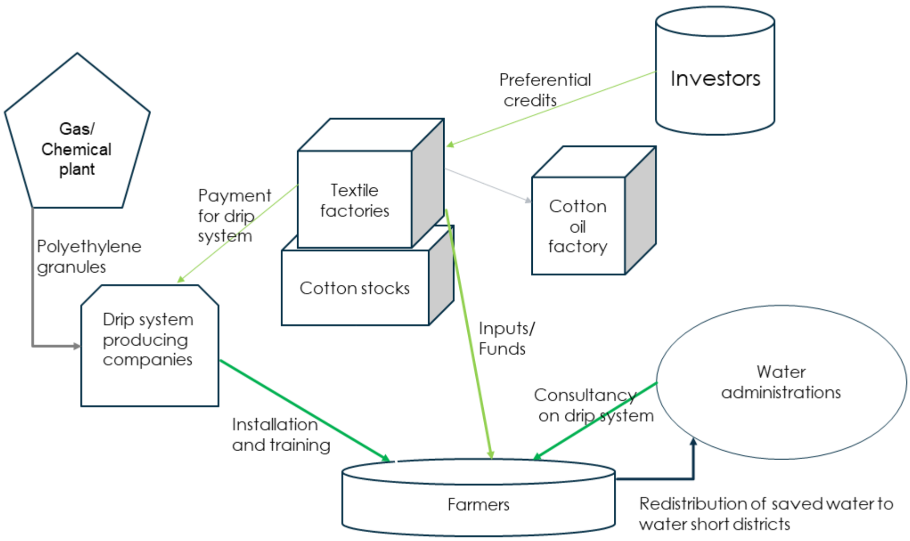

Figure 9.4 Cluster Approach to Wide Adoption of Drip Irrigation

The cluster linkages indicate needs for quite different skilled developers who can understand win-win situations along the resource use>crop production> processing line. From one side, it requires specialists in narrow fields, such as drip systems – in design, installation, maintenance and operation. From the other side, specialists of new areas are required such as value chain analyses. According to this scheme, District Water Administration's advisory support for farmers is important in successful maintenance and operation of drip systems. The implementation of the approach requires a skilled staff of the water administrations/WCAs and farmers' advisory services.

Conclusions

Given two examples indicate, that along with the institutional and technical interventions, the importance of revisiting education and capacity building programs, including water management courses for securing water resources in Uzbekistan. Introducing innovations and advances in water management requires narrow oriented rather than wide profile specialists. At the same time, specialists are required in new areas such as water diplomacy, value chain analyses, high technologies, including GIS and remote sensing. Cooperation in education is another efficient way in capacity building of new water generation.

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Sudan National Strategy to Adapt with Water Scarcity

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Abstract

The main challenge for the coming decades will be the task of increasing food production to ensure food security for the steadily growing population, particularly for non-Nilotic areas in Sudan. Water harvesting methods and techniques can be generally defined as hydraulic systems designed, implemented and operated to achieve the most efficient use of rainwater for productive purposes.

The purposes of water harvesting can be for agriculture, domestic use, drinking purposes for people and animals, flood hazard mitigation and for combating desertification by afforestation, fruit tree planting or agroforestry. Rainfall shortage and variability constrain crop production of smallholder farmers in Sudan and climate change may even aggravate this problem. The paper presents the parameters that are used in assessing water harvesting projects, such as climate, hydrology, topography, soil, and socio-economy.

Many areas in Sudan are suffering from water scarcity specially in dry season (November-May), especially in the non-Nilotic regions although there is a considerable amount of rainfall during the rainy seasons with high flood potentials. On the other hand, desertification is located at the northern part of Sudan and also at the western part of Sudan, as verified by recorded rainfall data. Therefore, water harvesting projects are categorized as high priority schemes in those regions.

The national strategy of Sudan to adapt with the water shortages (scarcity) is mainly focusing through implementing a huge water harvesting project called 'zero thirst', for the period 2016-2020. The aim of this project is to implement about 5000 projects to provide water through water harvesting (small dams, hafirs, and water wells), with a total budget of about one billion dollars.

Keywords: Water security, Sudan national strategy, Water resources management

Introduction

Water harvesting is the collection, concentration and storage of water that runs off a natural or man-made catchment surface. Water harvesting methods and techniques can be generally defined as hydraulic systems designed, implemented and operated to achieve the most efficient use of rainwater for productive purposes.

Since gaining independence in 1956, Sudan has had two civil wars (from 1955 to 1972 and 1983 to 2005). According to the 2005 peace agreement, the citizens of South Sudan will hold a referendum in 2011 on the issue of independence from the north. With over four million internally displaced persons (IdPs) and international refugees, Sudan has the largest number of displaced people in the world today. The separate conflict in Darfur in 2003 has displaced nearly two million and caused an estimated 200,000 to 400,000 deaths.

Climate change presents an additional stress for Sudanese people already struggling with poverty, post-conflict recovery and environmental degradation. Straddling north and sub-Saharan Africa, with the Sahel running through the center of the country, is a country of extreme geographic and climatic contrasts. However, rainfall and the length of the dry season are the most significant climatic variables.

Collection and concentration of rainwater and runoff and its productive use

Sudan has huge rainwater harvesting projects (Fig. 1), for different usage, such as for:

- The irrigation of annual crops, pastures and trees
- Domestic consumption
- Livestock consumption
- Fish and duck ponds

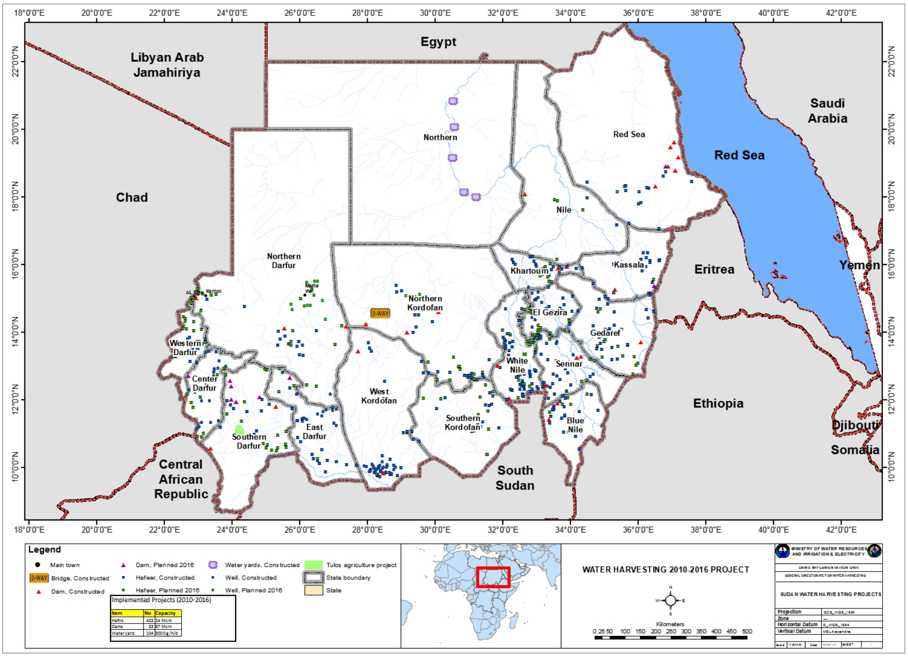


Figure 10.1 Rain Water Harvesting Projects in Sudan

Purposes of Water Harvesting

There are different purposes of water harvesting, these can be summarized in:

- For agriculture
- For domestic use
- For drinking purposes for people and animals
- For flood hazard mitigation

- For combating desertification by afforestation, fruit tree planting or agroforestry

Types of Water Harvesting

The main Water Harvesting systems that can be distinguished are:

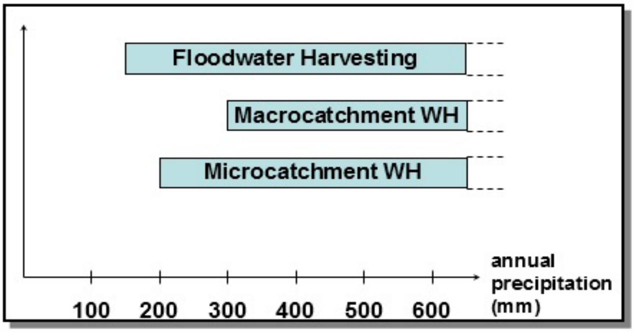
- Rain Water Harvesting.
- Flood Water Harvesting.
- Underground Water Harvesting.
- Fog Water Harvesting.

Water Harvesting Assessment Parameters

Different parameters can assess water harvesting; these are:

Climate: two main climate factors for potential water harvesting assessment are existing, these are:

- Rainfall: all of the total annual rainfall, rainfall patterns (min., max, duration of rainy season, etc.). Rainwater Harvesting is an effective tool option to gather the rain water and store it appropriately. Advantages of rainwater harvesting: Reduces flood hazards; Direct solution to drinking water crisis; Mitigates effects of drought; Rise in groundwater levels and local solution for climate change adaptation, and evapotranspiration which depends on the temperature, humidity, and the wind should be considered.



Annual precipitation ranges for different types of water harvesting in summer rainfall areas (Source: Prinz 1994, altered)

Figure 10.2 Annual Precipitation Ranges for Different Types of Water Harvesting in Summer Rainfall Areas

Hydrology

The below transparency shows the hydrological cycle. The cycle can be visualized as beginning with the evaporation of water from the oceans. The resulting vapor is transported by moving air masses. Under the proper conditions, the vapor is condensed to form clouds, which in turn may result in precipitation. The precipitation which falls upon land is dispersed in several ways. The greater part is temporarily retained in the soil near where it falls and is partially returned to the atmosphere by evaporation and transpiration by plants, partially percolating through the soil and underlying rock to an aquifer (= ground water). A portion of the water finds its way over and through the surface soil to stream channels, from where it flows farther into the ocean. The same happens to water of near surface aquifers. However, substantial quantities of surface and underground water are returned to the atmosphere by evaporation and transpiration before reaching the oceans.

Phreatic surface (ground water table) acts as the boundary between the saturated and unsaturated zone.

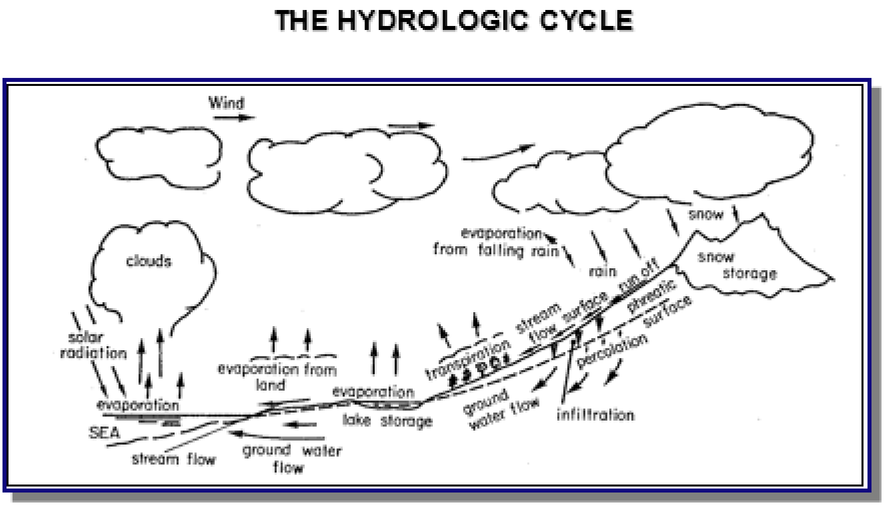


Figure 10.3 Schematic Diagram of Hydrologic Cycle

Topography

Generally, land escapes in arid and semi-arid regions are comprised of four important landscape types:

- Rocky top slopes and isolated rock outcrops (45 degrees or greater)
- Medium slopes (between 10-20 degrees)
- Low slopes (between 1-10 degrees) usually broad and shallow
- River channel (sand rivers), seasonally flowing, mostly having steep banks up to several meters high.

Soil

Water harvesting captures runoff in order to infiltrate it where it is needed. In the catchment area, every drop should be collected, and in the cropping area, as much as needed should infiltrate. In areas with similar rainfall, the amount of runoff and infiltration depends largely on the soil characteristics.

Runoff and infiltration are closely related. Most of the water that does not infiltrate runs off.

The cropping area should take up all the water, i.e. have a high infiltration rate. However, if the water infiltrates and moves on through the soil into deeper layers, it is useless. Therefore, the ability to hold the water - a high storing capacity - is needed.

Finally, we need sufficiently fertile soil in order to guarantee a good plant growth.

The above statements are true for macro-catchments, micro-catchments and floodwater harvesting. Micro-catchments would ideally require different properties on a small area, which is hardly found in nature. The farmer has to compromise and / or treat the soil.

Earthworks are crucial because they have to withstand floodwater. Once a damage occurs, it quickly gives rise to subsequent damages. Without intact earthworks, the whole system might be useless.

The soil used for earthworks should therefore be stable and not be subject to piping.

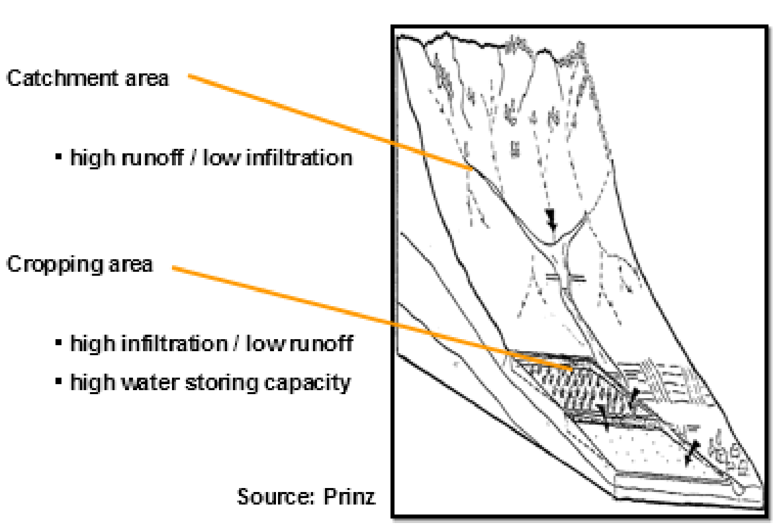


Figure 10.4 Required Soil Properties for Water Harvesting for Agriculture

Socio-Economy

The figure No. 5, describe all parameters related to socio-economic process.

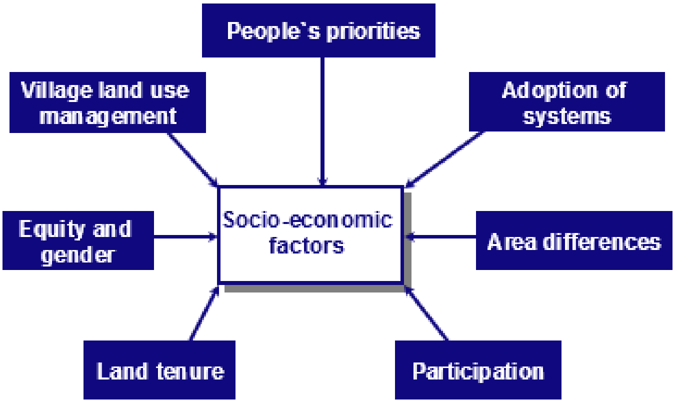


Figure 10.5 .Socio-economic factors

Water Harvesting for Agriculture

Water Harvesting for agricultural purposes is used to secure water supply in dry areas where other water resources (surface or groundwater) are not available or uneconomical to develop, in order to:

- increase the productivity of arable and grazing land which suffers from inadequate rainfall
- increase yields of rain-fed farming
- minimize the risk of crop failure in drought prone areas

There are two main water harvesting systems, these are rainwater harvesting and flood water harvesting. Figure 10.6 shows the factors affecting surface runoff:

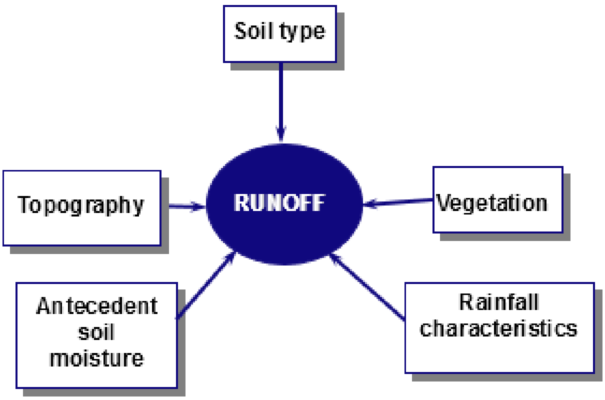


Figure 10.6 Surface Runoff Factors

Water Harvesting for Rural Areas

There are different problems associated with water unavailability in rural areas:

- Public health: connection of clean and sanitary environment to water availability

- Poor health
- Illiteracy: No time for school! Water first.
- Poverty

Sudan National Strategy to Adapt with Water Shortages

The majority of Sudan's people as well as Sudan's economy are reliant on natural resources. The availability of water, pasture, and forests is essential for rural livelihoods, for agriculture and livestock. This is a problem because Sudan's natural environment is rapidly changing and degrading. Water is scarce and can taste salty, the lack of pasture causes local conflict, trees are cut down for firewood, the soil blows away, and the farmland becomes a desert. This will increase poverty and vulnerability, and will impact on the economic growth of the country. Some of the causes are population growth, conflict and displacement, overuse of water resources, deforestation, land-use changes and weak governance and management. In addition, the variable and changing climate in Sudan is making the situation worse, causing droughts as well as floods, and in the longer-term increasing temperature and reducing rainfall. This will reduce the viability of rain fed agriculture and livelihoods.

To adapt with water shortages and to satisfy of the immediate need for safe drinking water, settlement of nomads and pastoralists to avoid conflicts with farmers, within Sudan and with bordering countries, and to increase the minimum per capita share of domestic water, to be in line with country strategy in terms of quantity & quality, the Sudan establish a zero thrust project, which aiming to implement about 5000 small projects to provide water through water harvesting; small dams with about total capacity 93.2 MCM, hafirs with about total capacity of 24 MCM, and water wells with average pumping rate of 3000 gallon per day through five year (2016-2020).

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Integrated Decision Support Tools for the Demand Management Making Groundwater Sustainable

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Abstract

Groundwater management in India and as a matter of fact in many countries, is the bigger issue than its availability due to the fact that the groundwater is hidden and not completely as well as precisely mapped and the absence of any regulation, there is no control on its withdrawal. A novel idea has been developed to involve the farmers since beginning of the study, allow them to collect a few data that can be easily collected by them. Then explain to them the scientific study and its outcome using a number of options so that they have the freedom of analyzing a number of scenarios and their results. Thus, with a detailed scientific outcome, farmers are explained the consequences and get convinced to adopt a scenario that helps better management practice and sustainable condition of the aquifer system.

This practice however needs more precision to establish the trust and confidence from the farmers. Thus, is why the lumped model used initially has been improved to integrate with a numerical aquifer modelling and make it discretized model. This has helped two folds; (i) the discretized simulation has provided a better groundwater balance and (ii) the area for taking decision has become small being a realistic size for taking a single decision.

Keywords: Groundwater management, Decision support systems, Demand management

Introduction

Water resources, no doubt, is the topmost priority for any nation as this is an essential commodity for life and its availability varies in time and space. If a sustainable development is to be assured for SDG of UN Goals for 2030 for water, it is mandatory to know how much water is available in the dynamic state and balancing it with the corresponding demand at all scales. Surface water is visible and can be assessed to a great extent but groundwater is hidden; often are misunderstood and misjudged for its judicious use endangering the sustainability.

Water deficiency are the major issue of most of the part of a number of countries with degradation of its quality. About 70-90 % of total water of the South Asian countries is used for the irrigation purposes (Babel and Wahid 2008). In this regard, India is one of the largest groundwater users in the world. As estimated India uses more than 60% groundwater for irrigation purpose and about 85% for drinking purpose. The agriculture sector occupies 43% of India's total area and contributes 16.1% to its GDP (Government of India 2010) and in many areas agriculture solely depends on the groundwater. Groundwater development is growing with high pace and mostly through private initiatives. Water level depletion in hard rock is most common problem in our country as compare to multilayer aquifer system or alluvium region but expansion of deep private tube-wells in multilayer aquifer system is a growing and major issue facing the country because we cannot pump deep aquifer blindly. Behavior of deep aquifers is totally different that of shallow aquifers. If we would go more than limit of abstraction, serious leakage may occur in the respective regions. So deep aquifer management is also much important as shallow aquifer.

Already established Climate change, impacts both the surface water and groundwater availability. It is widely observed that due to climate change the extreme meteorological events have become frequent and have adverse impact for the water system. Generates, more runoff that flows through the streams to sea. The same event due to high intensity generates reduced infiltration and hence less groundwater recharge. Thus it is utmost important that all these components are estimated accurately using the best approach available. Then the balance of the water availability and demand are determined particularly for the groundwater. The positive and negative nature of the groundwater balance decides the course of action for the next water cycle. However, if the negative balance of the groundwater system is too large, then demand management becomes obvious in addition to enhancement of groundwater recharge artificially. Accomplishing this, needs prediction of the groundwater balance and implementing the same needs a tool for making a decision by the water users or the farmers.

Using a lump model, a Decision Support Tool (DST-GW) has been developed for a reasonably small watershed and all the fluxes acting on the groundwater system were estimated at the present scenarios as well as predicted using probabilistic values of the rainfall as well as other inputs. The rainfall forecasting has been used taking the best suitable model for the Climate Change in the area. This tool allows the farmers and water users to design a number of scenarios of the groundwater utilization and test in the model for their respective impact in the next 10 to 15 years. Based on the satisfactory and acceptable impact, the corresponding scenario is adopted. This method has been effective in making decision to change the agriculture as that is only way to manage the demand. The model has been validated and handed over to the local authority so that the groundwater user or a user association jointly make a decision and decide the groundwater utilization. The model (DST-GW) also allows to include the other fluxes for example enhanced recharge by artificial means. Rigorous exercise has been made to refine and increase the accuracy of estimating the fluxes. The comparisons of the scenarios have been made based on the socio-economic aspect also. For example, if the farmers are suggested to change the cropping pattern then it has been possible to compare the revenue generation with the market price of the newly introduced crops. Often to convince the farmers, a few translated parameters have also been utilized. For example, instead of taking decision based on groundwater levels, we have used the number of bore wells getting dried up. This has a direct relation as the bottom of the wells were known and has been extremely effective in convincing the farmers.

Lumped Model for Decision Support Tool

For a sustainable groundwater management, it is necessary that precise estimation of its various components is made in the present condition and are projected with careful and consulted efforts so that judicious decision is taken, uncertainties are minimized or removed and the loss to the crops are avoided. Thus, the objectives of the present study could be:

- Estimation of aquifer fluxes and their spatio-temporal variation.
- Assessment of long-term change in storage of both shallow and deep aquifers.
- Preparation of water budget and generation of possible scenarios both demand and supply based.

The Study Area

Maheswaram watershed located 30 kms. south of Hyderabad city agglomeration is about 55 km2 in area (Figure 11.1). There are no prominent rivers in the area, though streams fill the depressions (forming tanks) during the monsoon period of about 4 months. The weathered column is distributed unevenly but is in the range of 3 to 15 meters. The over-exploitation of the groundwater resources has eventually resulted in the decline of water levels beyond the weathered zone. There are more than 700 bore wells presently in the area and the yearly draft is about 1.0 million cubic meters (MCM).

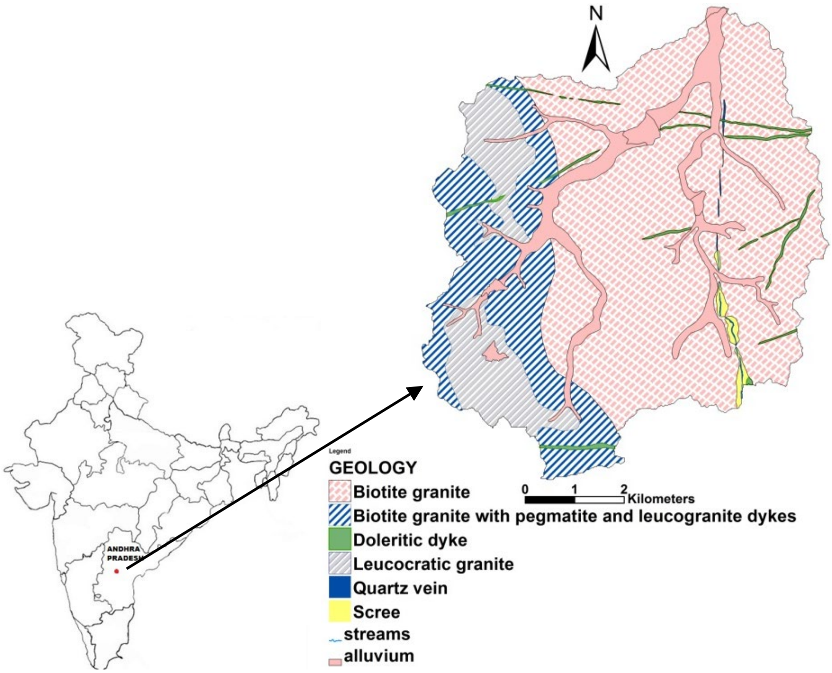

Figure 11.1 Geological map of the Maheshwaram Watershed (Courtesy-IFCGR)

Natural recharge to aquifers of Maheswaram watershed was measured for 1999 monsoon using tritium injection method. The mean recharge value obtained from measurement at 14 sites was 22.2 mm for the effective seasonal rainfall of 350 mm occurred during July to October, 1999 (Rangarajan & Prasad Rao 2001). The total recharge quantum over the effective infiltration area of 55 km2 is calculated as 1.22 MCM.

The soil infiltration properties in terms of its rate of percolation were determined at 38 places in the Maheswaram watershed. The infiltration rate varied from 848.8 to 1.7 mm/hr. indicating non-uniform properties of the soil profile.

The general elevation of the area ranges from 620 m amsl to 600 m amsl, although the hillocks in the southern portions (south of Maheswaram) occupy higher elevations around 640 to 660 m amsl. Geomorphological areas of higher elevation have shallow pediplain features. In these the weathered zone thickness is less than 10 m below ground level (bgl) complexes are often observed in the area. In general, these complexes are also spheroidically weathered and form poor aquifers. The undulating topography of the granite can be advantageously utilized for furrowing and contour bunding, thus increasing the residence time of the surface water. A fairly good correlation exists between mapped lineaments and well capacities. Since there is sufficient recharge near tanks or discharge areas, the well yields have been observed to be substantial. The existing geologic, topographic, geophysical and borehole information have been integrated; minimizing the risk of poorly located well sites.

Fairly good estimates of draft could be made through the process of well inventory. But the estimations of recharge require the knowledge on several factors like (a) the lithologic properties (b) aquifer characteristics and (c) rainfall patterns that contribute for recharge in an area. The water level fluctuation, area of influence and the specific yield of the aquifers obtain the total recharge in the watershed. But the estimations of specific yield could go wrong by an order of magnitude. Despite the numerous studies determinations of recharge fluxes in (semi-) arid regions remain fraught with uncertainties. The values of transmissivity (T) on single well tests and well field tests varied from about 35m2 /day to about 245 m2/day (Ledoux et al. 2002).

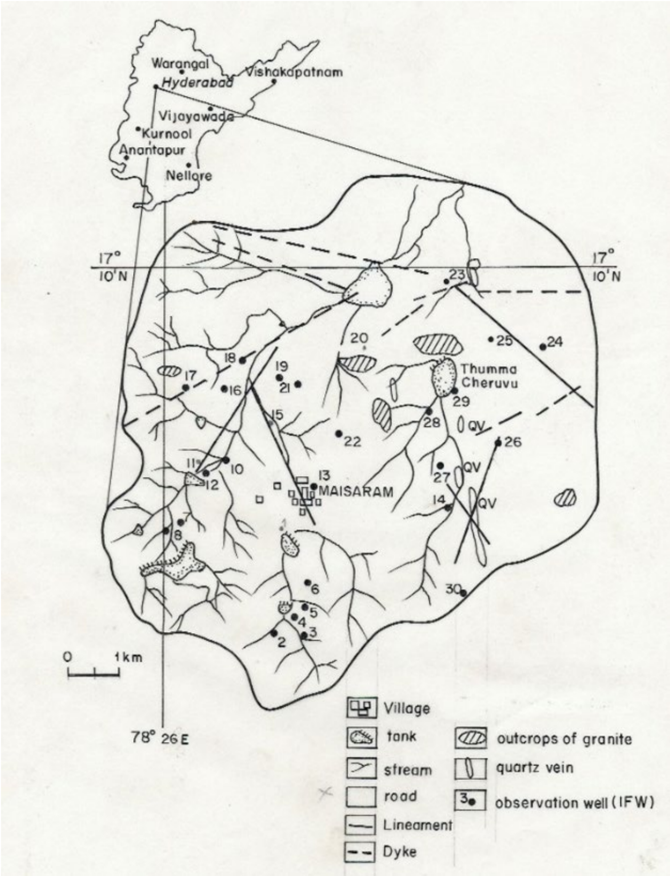

Figure 11.2 Location of the Maheshwarem Study Area with Drainage and Structural Features as well as with Monitoring Wells

The area has a typical set-up of the hydrological system in granitic terrene of hard rock. There are 3 to 4 orders of streams present in the area (Figure 11.2). The drainage system has 9 tanks (surface reservoirs) to store runoff water during the rainy season and use them for irrigation after the rains are over. In the early days a large amount of water could seep down to the groundwater but due to poor maintenance thick silt is accumulated and almost no seepage is taking place now and the tanks are mostly evaporation tanks.

Data and Methodology

The groundwater budget method focuses on groundwater flow. Although groundwater flow is linked to surface flow such as precipitation, evaporation and runoff, the latter do not appear directly in the budget. Changes in groundwater storage can be attributed to recharge, irrigation return flow and groundwater inflow to the basin minus baseflow (groundwater discharge to streams or springs), evaporation from groundwater, pumping, and groundwater outflow from the basin (Figure 11.3). These fluxes are arranged in the following equation based on their nature as influx or out flux.

$$R + RF + Q_{in} = E + PG + Q_{out} + Q_{bf} \pm \Delta S \tag{10.1}$$

Where,

R = Groundwater Recharge

RF = Irrigation return flow

Q_{in} = Inflow of groundwater

Q_{out} = Outflow of groundwater

E = Evaporation from water level

PG = Groundwater Abstraction

ΔS = Change in groundwater Storage

Q_{bf} = Base flow

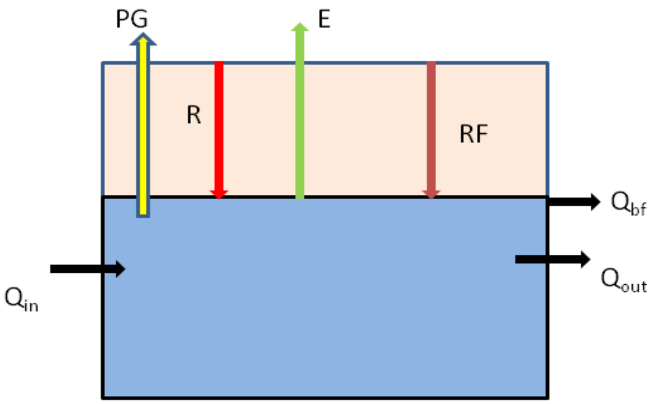

Figure 11.3 Various Fluxes Acting on Groundwater System with the Sign of Their Entry or Exit

The relationship between change in groundwater storage (ΔS) with resulting water table fluctuation (Δh).

$$\Delta S = S_y \times \Delta h \tag{10.2}$$

Where S_y is the specific yield.

In these two equations, change in storage (ΔS) and water level fluctuation (Δh) are taken as unknown parameters. Other budget components are estimated independently. This method is called water table fluctuation method.

Methodology for Estimating Other Budget Component

Groundwater Abstraction (PG): Groundwater abstraction (PG) corresponds to groundwater pumped for agriculture as well as for industrial and domestic use. For the estimation of PG (Agriculture) is to realize a borewell inventory with the instant discharge of each borewell. Then information on daily pumping duration (may be recorded by the electricity provider) and number of pumping days during the dry/rainy season. Agricultural pumping can also be estimated by land use map using Remote sensing techniques. For PG (Domestic) estimation, the easiest way is to make use of census data for population and livestock and then use daily consumption standard norms usually provided by governments. For the estimation of PG (Industry), a field investigation may be required.

Groundwater Recharge: The recharge parameter forms an important aspect of the assessment of groundwater resources evaluation. It involves hydrometeorological hydrological process taking place on the surface and also involve sub-surface lithological characteristics (Baweja and Karanth 1980). Groundwater level data in the basin at specific interval of time leads to estimation of the infiltration using basic relationship between balance over a given period and resulting water level fluctuation (Healy and Cook 2002).

$$R = Geographical\ area \times Sp.Yield \times \Delta h \qquad (10.3)$$

Irrigation return flow (RF): Irrigation return flow is defined as the excess of irrigation water that is not evapotranspirated or evacuated by direct surface drainage, and that returns to the aquifer. Irrigation return flow coefficient is defined as the ratio between the irrigation return flow and the abstracted flow: $C_f = R_F/P_G$. It varies from more than 50% for rice cultivation to about 15% for sugarcane cultivation.

Evaporation from water table (E): when water levels are shallow, evaporation from phreatic aquifers is one of the main components of the groundwater budget (Coudrain et al. 1998). Annual evaporation flux is expressed as an inverse power function of the water table depth below the surface, independently of the soil characteristics.

$$E = 71.9 \times z^{-1.49} \qquad (10.4)$$

Where E is the water table evaporation (mm/y) and z, the water table depth (m)

Groundwater horizontal Flow: Groundwater horizontal flow estimates using Darcy flow equation.

$$Q = T \times (dh/dl) \times dw \qquad (10.5)$$

Where,
$T = Transmisivity$
$dh = Head$
$dl = length\ of\ the\ cell$
$dw = width\ of\ cell$

The above methodologies are suitably modified to suit to the aquifer system as well as to include the surface water bodies to develop the tool for an effective groundwater management.

Reliability of the Model

As it has been pointed out, the accuracy of the hydraulic model involved in the DST is closely linked with the accuracy of the data acquired in the field. Calculation of a clear error component is rather cumbersome given the fact that a large amount of data from different sources is used. However, data errors may also get counterbalanced. The way we used to approach the accuracy of the model is (i) to check if S_y and R are coherent with the existing bibliography for the same lithological and climatic contexts, and (ii) to repeat the DWTF method on several hydrological years, which leads to make other estimates of S_y and R under different aquifer stresses or rainfall conditions. While R may change due to different rainfall, S_y should be constant if the water table fluctuations during the different dry seasons take place in the same aquifer.

S_y estimates are, 0.0094 in 2002, 0.0140 in 2003 and 0.0138 in 2004, all are evaluated in Rabi seasons for the same part of the aquifer, between 610 to 620 amsl. The small difference between S_y evaluated in 2002 and the two other seasons is most probably explained by less detailed maps in 2001. Indeed, in 2001 most of the observation wells were located far of pumped areas (upstream areas), which led to overestimates of the mean levels and in turn underestimate S_y. Consequently, only the mean value of S_y estimated in 2003 and in 2004, has been kept as calibration parameter in the DST (S_y=0.0139). S_y values from DWTF method are realistic for fissured granite aquifers and are of the same order of magnitude as values estimated at sub-basin scale through global modelling (0.01) and at well-scale through pumping tests (from 0.003 to 0.02, 0.0063 in average).

During the three hydrological years of monitoring, the recharge coefficient (R/Monsoon Rainfall) varies from 12 to 19%, which is similar to results obtained in India under comparable climatic conditions for a coastal aquifer in Karnataka (13-24%, Rao et al., 2004), for an alluvial aquifer in Uttar Pradesh (6-19%, Kumar and Seethaphati, 2002) and the value prescribed by the Central Ground Water Board for hard-rock aquifer (12%, CGWB, 1998).

Recharge values from DWTF method were also compared to recharge estimate using tritium tracer (Rangarajan and Athavale, 2000). However, while DWTF method gives estimation of the total recharge at basin-scale, the tritium technique, a local approach, gives only the minimum recharge (direct recharge) and do not take account of both indirect recharge (percolation trough rivers and tanks beds) and localized recharge (intermediate form, percolation through local geological or topographic variations: trenches, dugwells, lithological contacts). This is why values from the DWTF method are higher than the linear trend defined by the tritium recharge in hard-rock regions of India.

In the DST, total recharge (R) is evaluated every year from the total rainfall (TP) according to the linear trend that links the two variables ($R[mm] = 0.197 \times TP[mm] - 56.65$; $linear\ regression\ coefficient = 0.96$).

Sensitivity of the Model

Once mean annual flow components, mean S_y and annual rainfall vs. recharge trend are computed (here from 2001 to 2003: 'calibration' period), mean annual levels are simulated according to Equations1 & 2, and compared to observed data. The difference between observed (h_{obs}) and simulated (h_{sim}) levels, which depends on the accuracy of S_y estimate, but also on the variability of both annual recharge (or rainfall) and annual flows components (e.g., annual variation of pumping, of return flows, etc.), gives the sensitivity of the model $\left(Sensi\% = \overline{\left(\frac{|h_{obs_i}-h_{sim_i}|}{h_{obs_i}}\right)}\right)$. In the case of Maheshwaram, the prediction of levels is valid at 0.18%, which considering a mean h value of 600 amsl corresponds to an accuracy of about 1m. The 2004 mean annual groundwater observation falls in the range of the predicted water level. This shows the good accuracy and the robustness of the model.

Demand Management through a Lumped Model

Impacts on groundwater levels with groundwater abstraction & Recharge

Considering no apparent climatic changes (same annual rainfall pattern since the last 20 years), two scenarios are presented in Figure 11.4: ‘current trend’ with no change in both groundwater abstraction and cropping pattern, and ‘present rate of agricultural development’ where the irrigated area is increasing at a rate of ~1.3%/year according to (FAO, 1997); cropping pattern remains also identical. In the first scenario, the mean groundwater resource limit, below which the aquifer cannot be exploited, will be reached by the year 2010 if the current pumping is maintained. This scenario will also entail the loss of about 50% of the bore wells with accompanying serious socio-economic consequences that the reader can easily imagine (rural exodus, poverty, diseases, etc.). This limit will be reached earlier if the groundwater exploitation by pumping continues at the present rate of development.

Considering no change in both groundwater abstraction and cropping pattern, Figure 11.5 presents simulations with two different climatic conditions: one with two consecutive weak monsoons (annual rainfall: 2005=450 mm and 2006=400 mm) and the other with two consecutive good monsoons (2005=1000 mm and 2006=1100 mm). The simulated groundwater levels show that whatever the monsoon the problems will occur sooner or later, and maybe faster than expected. Drying up of bore wells are about 50% in 2006 in case of ‘Weak’ monsoons and about 40% in case of ‘good’ monsoons. These simulations as well the ones presented in Figure 11.4 show that realistic solutions have to be found quickly.

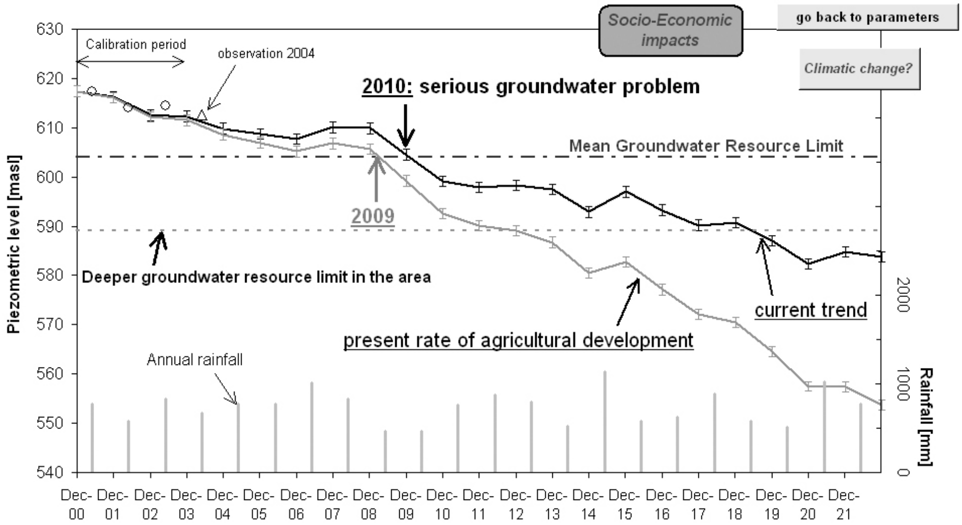

Figure 11.4 Pulation of Water Levels in Maheshwaram Watershed with Current Trend and 'Present Rate of Agricultural Development. The Vertical Bars Depict The Sensitivity Of The Model (0.18% Of The Piezometric Level)

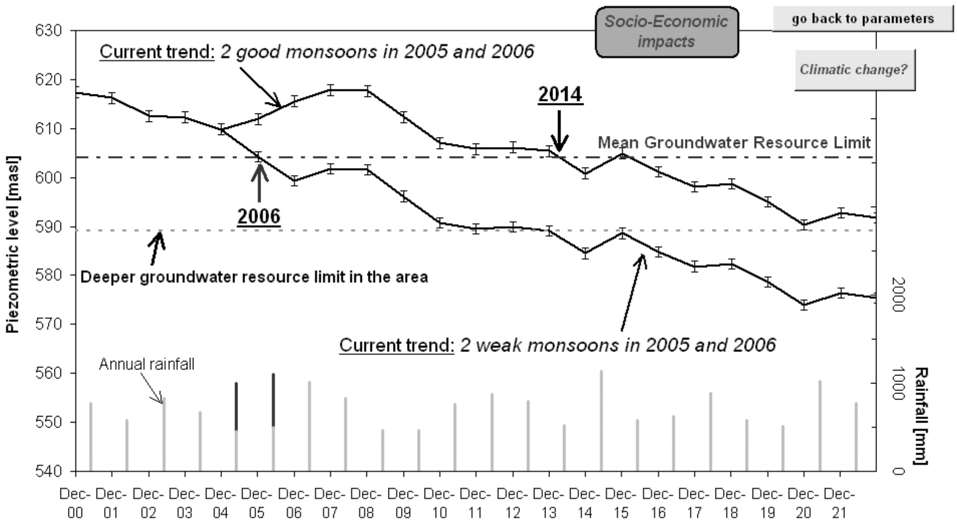

Figure 11.5 simulations with two different climatic conditions: one with two consecutive weak monsoons (annual rainfall: 2005=450 mm and 2006=400 mm) and the other with two consecutive good monsoons (2005=1000 mm and 2006=1100 mm

With the predicted groundwater levels this catchment is overexploited. To avoid a dramatic situation in this area in the near future, decisions have to be taken to improve the groundwater management. As, the area is overexploited either the evapotranspiration of irrigated crops has to be reduced (decrease PG-RF) or/and additional artificial structures have to be created. However, the authors want to point out that building high number of rain harvesting structures (water tanks, dug wells, etc.) may have serious negative impacts for the downstream areas.

This section presents one of the most interesting options of the developed tool: assess the impact of both changing cropping pattern of irrigated culture scenarios and artificial recharge structure. DST enables the increase or decrease of surface area of irrigated crops present in the watershed. In order to avoid non-realistic scenarios, which could not be accepted by the farmers because of profitability or cultural issues, the DST has been designed to enable the input of actions plan for several years under various socio-economic criteria. Figure 11.6 present two examples of scenario that considers a 15-year action plan scenario where 6% decrease of the rice cultivated area every 2 years and at the same time 20% increase of vegetables and flowers cultivated area. In this scenario paddy field area is reduced by 40% and area of vegetables and flowers is increased by 300% at the end of the plan. The first scenario –scenario 1- considers the changing cropping pattern only, and into the second – scenario 2- artificial recharge structures, have been added, 2 mm/year at the watershed scale. This 2 mm/year may correspond to about 25 hectares of additional tanks or about 30 defunct dug wells where run off is diverted (dug well dimension: 10x10x13m; supposed fully-filled up 3 times a year); moreover, it might be the improvement of irrigation techniques or consequences of a public awareness program (water conservation). While scenario 1 is just able to maintain the mean groundwater level above the mean groundwater resource limit, adding some rain harvesting structures (scenario 2) now significantly maintained the water levels above.

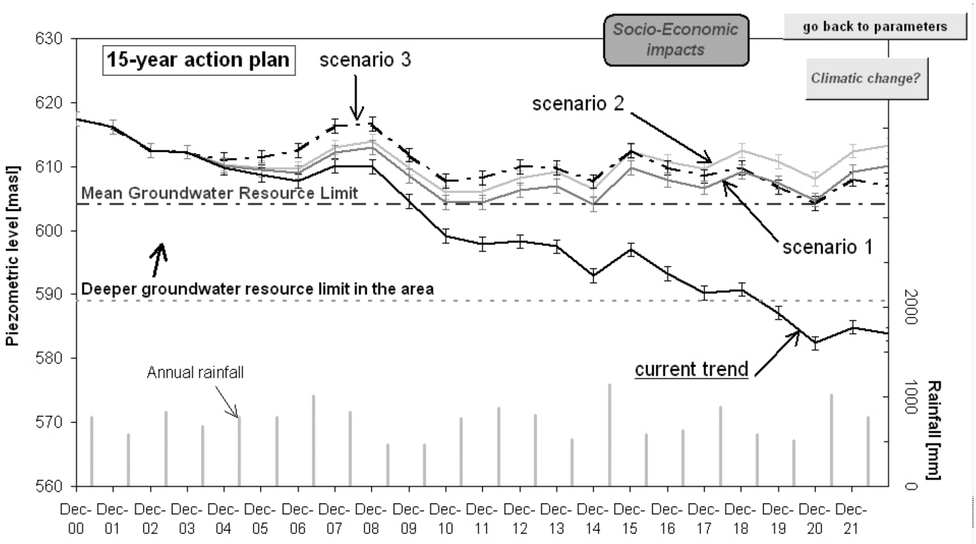

Figure 11.6 Simulation of Water Levels in Maheshwaram Watershed scenario 3 where only rain harvesting structures are built to stabilize groundwater level decline

Scenario 3 presents the results of a scenario where only rain harvesting structures are built to stabilize groundwater level decline (Figure 11.6). However, about 230 hectares of tanks (or 270 dugwells) are required. This non-realistic scenario shows that the artificial recharge cannot be considered as the only solution. One may question in such a semi-arid context the efficiency of groundwater management only based on such a solution.

One may conclude that in the present situation of Maheshwaram watershed, which is not an isolated case in the country and not an area recognized as an extremely or under overexploited area, reasonable solutions can be found by a package of solutions, i.e. combining changing cropping pattern, improving the irrigation techniques, new rain harvesting structure, etc. The water levels would be more or less maintained before getting back their original levels at the end of the plan; therefore, this would induce a sustainable solution.

Shortcomings in the Lumped Model Approach

Although considering the lumped model makes the study easy with some averaging of the parameters or fluxes. But due to very high variability and heterogeneity of the groundwater system a single value can be representative of the watershed firstly if the watershed area is small enough.

The error in prediction or in the water balance should be minimum so that the outcome of the respective scenario meets the predicted values or becomes very close to the predicted outcome. If this does not happen, the convincing of the farmers will be very difficult and the entire beauty of such a tool will be lost.

Second serious issue with a large area is the problem of decision. If a very large area is considered for a particular Decision Support Tool, the field within the study area may be belong to several farmers and hence taking a single decision or implementing any scheme uniformly becomes very difficult. Of course, at the same time the model cannot work on the scale equal to the farming field of a single farmer. Thus a trade-off will be to have an area belonging to a group of coherent farmers. In India there exists “Panchayat”, a group of neighboring villages. This could be an optimal one. Of course, the natural boundaries too have to be considered. These issues have overcome in the integrated DST.

Integrated Model for Decision Support Tool

Groundwater development is growing with high pace and mostly through private initiatives. Expansion of private tube-wells is a major issue facing the country. Water level depletion in hard rock is most common problem in our country as compare to multilayer aquifer system or alluvium region but expansion of deep private tube-wells in multilayer aquifer system is a growing major issue facing the country because we cannot pump deep aquifer blindly. Behavior of deep aquifer is I different from shallow aquifer. If we would go more than limit of abstraction, serious leakage may occur in the respective regions. In my case of study, shallow aquifers are highly arsenic contaminated. As a result, deep aquifer would also be contaminated. So deep aquifer management is also much important as shallow aquifer. Groundwater irrigation has increase since 1960 and has enhanced productivity, ensured food security and induced commercialization of agriculture. Groundwater withdrawals in India have surged from less than 20 km3 in 1950s to more than 150 km3 presently, making India by far the largest user of groundwater in the world.

Due to changing climatic conditions, less rainfall, more water requirements, and more water consuming agricultural practices and groundwater management issues, groundwater is facing depletion in most of the country which poses threats to the sustainability of this important economic sector of the country. In the current situation of depleting water resources, agriculture sector of India is also under threat. Groundwater resources need to be managed with appropriate methods in regions where existing or future demand for groundwater may exceed renewable reserves.

The study area

Southern flood plain of Ganga-Son interfluves is located in Bhojpur district, Bihar and lies between 25° 23’ 60” to 25° 49’ 12”N latitude and 84° 30’ 0” to 84° 56’ 24”E longitude (Figure 11.7). The study area monotonously represents flat terrain and topographical elevation of land surface is 39 to 74m above mean sea level.

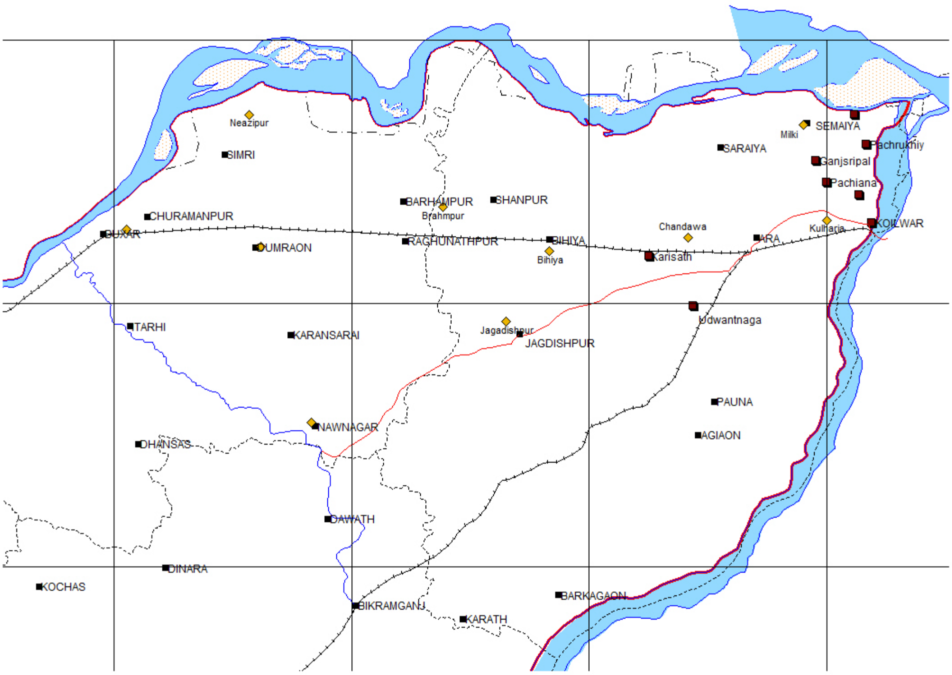

Figure 11.7 Study Area of Son-Ganga Confluence in Bihar for IDST

The climatic type of the district is Humid Sub Tropical. The hot weather begins in the middle of March, when westerly winds begin to blow during the day. The months of April and May are extremely hot. In a normal year, the monsoon sets in by the second week of June and the rain continue with intermissions till about the end of September or the early part of October. The rainfall of the area influence by South-West Monsoon (http://gov.bih.nic.in/profile/climate.htm). The cold weather starts from November and end up to the February. January is the coldest month when temperature comes down as low as 10 °C. From the month of April till the first break down of the monsoon, the district experiences occasional thunder-storms also. Humidity varies from 24.7% to 83.45% (Govt.

of Bihar 1994). Average annual rainfall is 1,061 mm and 88% of which is controlled by southwest monsoon (June to September). Population density of the area is 724person/km2 (Govt. of India 2001).

The area is underlain by unconsolidated formation which is Holocene in age and it lies in the Newer alluvium. The presence of kankar and fine sand at places render the top clay zone semi-pervious in nature, where ground water occurs under phreatic condition. These aquifers are made up of fine to medium grained sand, occasionally coarse with thin layers of gravel at some places (CGWB 2013).

Numerical Modelling of the Aquifer

The study area includes the Bhojpur, Buxar and parts of Kaimur and Rohtas districts of Bihar. The boundary of the area is formed by the river Ganga in the north, the Sone in the east, Karamnasa River in the west while the southern boundary has been taken as the basin margin areas of the Kaimur hills.

Boundary conditions of the study area: A three layered aquifer system has been considered.

Layer I: In the first layer, groundwater occurs under unconfined condition. This layer is bounded on three sides by perennial rivers and as such constant head boundary can be assigned to this layer on its northern, eastern and western boundary.

Layer II: Layer II is an aquitard which separates the Layer I from Layer III.

Layer III: In layer III groundwater occurs under semi-confined to confined conditions. The boundary of this layer towards west and east may be assigned as no flow boundary following the groundwater flow lines on these sides. The boundary on the southern and northern side can be assigned as flux boundary with water entering the model domain from the southern part and leaving through the northern part.

Sources and Sinks of Water

Areal Recharge: Areal recharge to the aquifer can be considered as equal to precipitation minus (1) runoff into streams, (2) evaporation, and (3) evapotranspiration from plants in the soil zone. Infiltration of precipitation probably accounts for the largest amount of recharge to the aquifer.

Hydraulic Conductivity: Hydraulic conductivity of layer III ranges from 50 to 305 m/day on the basis of pumping tests carried out. The K value increases toward the north. For Layer I the hydraulic conductivity can be estimated on the basis of the grain size data and using empirical equations. Lithological logs typically show an increasing particle size in the lower parts of the aquifer and the hydraulic conductivity is greatest in the coarse sand and gravel near the base of the aquifer.

Storage: Specific yield (applicable to unconfined conditions) and specific storage (applicable to confined conditions) are both required to characterize ground-water flow in the alluvial aquifer. Specific yield is the amount of water released per unit decline in hydraulic head; specific storage is the amount of water released from storage resulting from the compression of the aquifer matrix per unit decline in hydraulic head. The storage coefficient for confined aquifers vary in the range of 0.005 to 0.00005 (dimensionless) and the specific yield in the unconfined aquifers can be considered as 0.12.

Water Use: Pumpage of water from the alluvial aquifer has increased since the early years of development and is used mostly for irrigation. Estimate of this can be made from the Ground Water Resource Estimation reports based on GEC 1984 and subsequently on GEC 1997 recommendations.

Initial Water-Levels: For layer I the initial water levels representing conditions that probably existed before ground-water development began in the early 1970's can be taken from the historical records of the HNS data of Central Ground Water Board. The hydraulic regime prevalent during the early 1970's in this area can be taken as those representing the predevelopment or initial development conditions). For Layer III, however, there are only limited data representing the conditions of the pre-development stage. Further these data are not of the same period for the entire study area. Geostatistical techniques could be of much use in having an estimate of the initial water levels of this layer.

Groundwater models are mathematical and digital tools of analyzing and predicting the behavior of aquifer systems on local and regional scale, under varying geological environments (Balasubramanian 2001). Models can be used in an interpretative sense to gain insight into the controlling parameters in a site-specific setting or a framework for assembling and organizing field data and formulations ideas about system dynamics. Models are used to help establish locations and characteristics of aquifer boundaries and assess the quantity of water within the system and the amount of recharge to the aquifer (Anderson and Woessner 2002).

Mathematical models provide a quantitative framework for analyzing data from monitoring and assess quantitatively responses of the groundwater systems subjected to external stresses. Over the last four decades there has been a continuous improvement in the development of numerical groundwater models (Mohan 2001).

Numerical modeling employs approximate methods to solve the partial differential equation (PDE), which describe the flow in porous medium. The emphasis is not given on obtaining an exact solution rather a reasonable approximate solution is preferred. A computer program or code solves a set of algebraic equations generated by approximating the partial differential equations that forms the mathematical model. The hydraulic head is obtained from the solution of three dimensioned groundwater flow equation through MODFLOW software (McDonald & Harbaugh 1988).

Mathematical modeling involves four basic steps namely (i) formation, (ii) approximation and transformation (iii) computation and (iv) application.

Formulation: Formulation refers to the process of deriving or selecting the basic equation(s) governing the flow and solute transport of groundwater, with the domain specification and initial boundary conditions.

Approximation: Approximation refers to the selection of a numerical method which can be used to solve the system of algebraic equations. Finite Difference, Finite element and

Integrated Finite-difference (IFD), methods are the widely used solution strategies for modeling the groundwater systems.

Computation: Computation is the most important step in the process of modeling. This part refers to the process of obtaining a solution to a large number of differential equations. This is done using a digital computer and a method of coding the steps, in a computer programming language.

Application: The application part of groundwater modeling includes calibration or history matching of the observed and simulated heads, sensitivity analysis and prediction, sensitivity tests are to show how the model reacts to various extreme values of transmissivity, storage coefficient and recharge/discharge volumes.

The aquifer modeling of alluvial aquifers of Ganga basin in western Uttar Pradesh had been carried out in krishni-Hindon interstream region (Gupta et al, 1979) and Daha region (Gupta et al, 1985). They have assessed the stream aquifer interaction as well as conjunctive use of surface water and groundwater in Daha region. The initiation of groundwater flow modeling studies in parts of central Ganga plain is carried out with dual objectives to understand the complex hydrodynamics of the flow regime and work out groundwater budget estimation including small components like subsurface horizontal flows.

The groundwater flow modeling studies is commenced with the objective to establish and quantify groundwater recharge and discharge to the system and thus to establish an effective and realistic groundwater budget. The realistic groundwater budget is essential for implementation of any groundwater management plan. Groundwater budget studies in alluvial areas often present unrealistic figure as various inflows and river-aquifer interaction is not carefully dealt with.

Finite Difference Approximation

In finite difference method (FDM), a continuous medium is replaced by a discrete set of points called nodes and various hydrogeological parameters are assigned to each of these nodes. Accordingly, difference operators defining the spatial-temporal relationships between various parameters replace the partial derivatives. A set of finite difference equation, one for each node is, thus obtained. In order to solve a finite difference equation, one has to start with the initial distribution of heads and computation of heads at the later time instants. This is an iterative process and fast converging iterative algorithms have been developed to solve the set of algebraic equation obtained through discretization of groundwater flow equation under non-equilibrium condition. The continuous model can be replaced with a set of discrete point arranged in a grid pattern. This pattern more often known as finite difference grid. The general flow equation for unsteady flow of groundwater in a confined condition in the horizontal direction.

$$T_x \frac{\delta^2 h}{\delta x^2} + T_y \frac{\delta^2 h}{\delta y^2} = S_y \frac{\delta h}{\delta t} \pm q \qquad (10.6)$$

When Equation 6 is applied to an unconfined aquifer, the Dupuit assumptions are used: (1) flow lines are horizontal and equipotential lines are vertical and (2) the horizontal hydraulic gradient is equal to the slope of the free surface and is invariant with depth. It is understood that $T_x = K_x h$ and $T_y = K_y h$, where h is the elevation of water table above the bottom of the aquifer.

$$K_x \frac{\delta^2 h}{\delta x^2} + K_y \frac{\delta^2 h}{\delta y^2} + K_z \frac{\delta^2 h}{\delta z^2} = S_s \frac{\delta h}{\delta t} - R \qquad (10.7)$$

Where K_x, K_y and K_z are components of the hydraulic conductivity tensor. S_s is the Specific storage, R is general sink/source term that is intrinsically positive and defines the volume of inflow to the system per unit volume of aquifer per unit of time.

The flow of water in an aquifer can be mathematically described by equation. This is the partial difference equation in which the head h, is described in terms of variables, x, y and t. They are solved by means of mathematical model consisting of the applicable governing flow equation, equation describing the hydraulic head at each of the aquifer, and equation describing the initial conditions of head in the aquifer. Finite difference method for solving partial difference equation is much-agreed subject. With the development of high-speed computers, finite difference method for solving partial difference equation can be operated to solve problems in subsurface hydrology.

The basic idea of these methods is to replace derivatives at a point by ratios of the changes in appropriate variable over a small but finite interval.

Thus,

$$\frac{d\Phi}{dx} = \frac{L_t}{\underset{\Delta x}{\Delta x \rightarrow 0}} \frac{\Delta\Phi}{\Delta x} \approx \frac{\Delta\Phi}{\Delta x} \qquad (10.8)$$

How small Δx may be for above equation to be an acceptable approximation depends on the particular problem. This type of approximation is made at the finite number of points and reduces a continuous boundary problem to a set of algebraic equations.

The data required for groundwater flow modeling is presented below (Moore, 1979).

A. Physical framework

1. Geologic map and cross sections showing the areal and vertical extent and boundaries of the system.

2. Topographic map showing surface water bodies and divides.

3. Contour maps showing the elevation of the base of the aquifers and confining beds.

4. Isopach maps showing the thickness of aquifers and confining beds.

5. Maps showing the extent and thickness of stream and lake sediments.

B. Hydrogeological framework

1. Water table and potentiometric maps for all aquifers.

2. Hydrographs of groundwater head and surface water levels and discharge rates.

3. Maps and cross sections showing the hydraulic conductivity and/or transmissivity distribution.

4. Maps and cross sections showing the storage properties of the aquifers and confining beds.

5. Hydraulic conductivity values and their distribution for stream and lake sediments.

6. Spatial and temporal distribution of rates of evapotranspiration, groundwater recharge; surface water-ground water interaction, groundwater pumping, and natural groundwater discharge.

Demand Management in the Integrated Model

For this case, we have chosen an area in Alluvium aquifer and usually such aquifers are very large, no concept of watersheds. Thus, selection of an area for a uniform or single decision for a lumped model would have been impossible. The problem and issues of this area is the determination of an optimal pumping from the second aquifer that contains Arsenic free water whereas the first aquifer contains Arsenic contamination. The two aquifers are linked with a thick clay layer but with highly varying thickness and hence vulnerability of leakage. However, since the second aquifer is under tremendous confining pressure, the peizometric head of the second aquifer remains much higher than the first aquifer and hence the leakage is usually from the second aquifer to the first aquifer and the second aquifers remains safe from contamination. However, this is a dynamic situation and an indiscriminate pumping from the second aquifer that is happening, may lower the peizometric head so much that there is a leakage reversal with a disaster of contaminating the second aquifer also.

Thus numerical modelling has been employed with variable grids (keeping dense in the Arsenic affected areas and course elsewhere) simulating the multi-layered case of the groundwater system. The modelling with all desired data were employed as described in the section above.

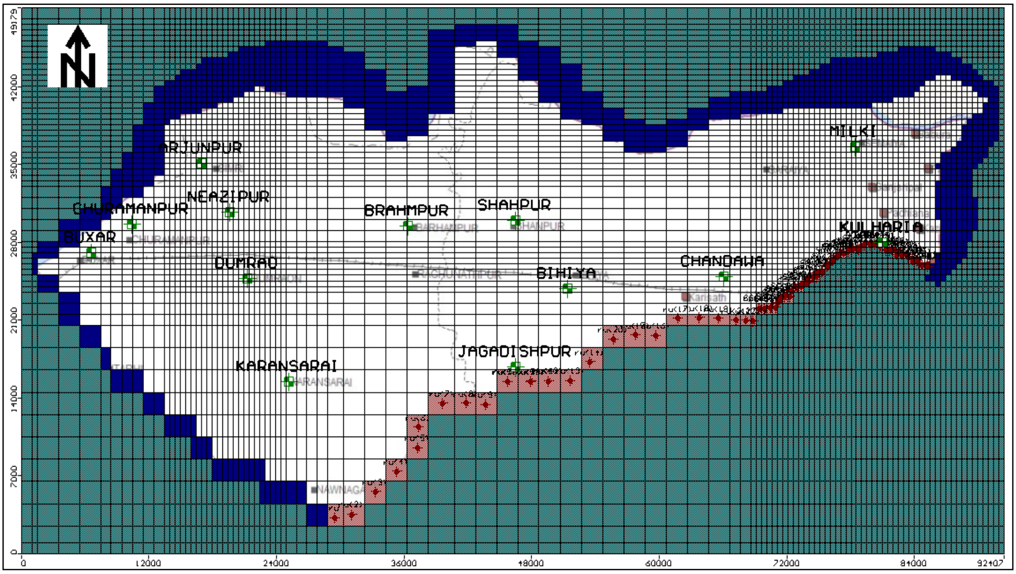

Figure 11.8 Numerical Model of the Area with Variable Grids; Dense In the Arsenic Affected Areas and Course Otherwise

The groundwater flow has been simulated under steady-state and transient condition simultaneously in both the aquifers including the possible leakage between the aquifers. After the model has been satisfactorily calibrated (Figures 11.9 and 11.10), the prediction was made for a number of years and with several scenarios considering (i) equal withdrawal from both the aquifers (withdrawal only from the 2nd Aquifer and vice-versa. Each time the leakage from the second aquifer to the first aquifer has been observed and plotted in the entire area.

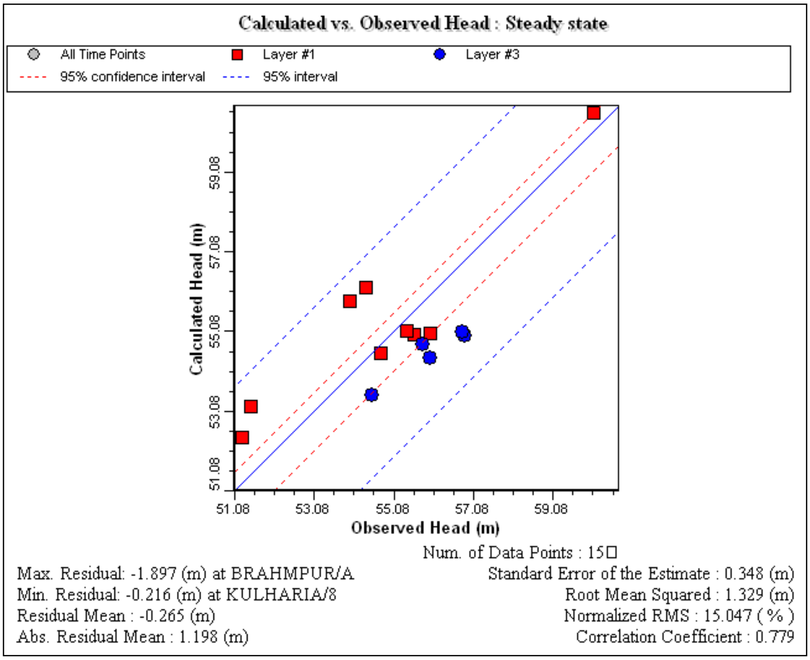

Figure 11.9 Results Of the Calibration under Steady State for Both the Aquifers Simultaneously

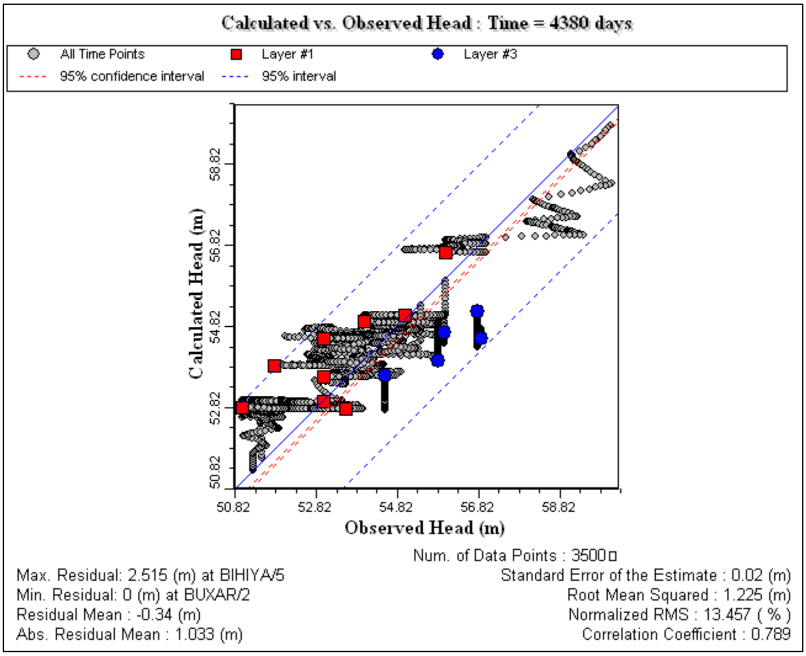

Figure 11.10 Calculated Versus Observed Heads for 1st And 2nd Aquifer (Pre-monsoon 2000 to Post-monsoon 2011)

This approach of IDST have thus both the facilities. One can check the entire aquifer system for any outcome for example leakage from the second to first aquifer. One may also prepare a zonal groundwater balance and prepare the DST as earlier. The zone consists of a one or several grids representing the area belong to one or two villages. Thus, this model will serve both the purpose; the entire model as a whole or take out a combination of grids making them as zone equivalent to the area of the farmers from one or from a few villages and hence the decision can be taken.

In this area the objective is to determine a suitable scenario of pumping from both the aquifers that maintains the positive leakage i.e. leakage from the second aquifer to the first one. Figure 11.11 depicts that following a particular scenario, the leakage from the second aquifer reverses and actually it becomes from the first aquifer to the second aquifer (represented by the red colors). Thus, the map indicates that due a particular pumping scenario, some areas have become vulnerable to the complete Arsenic contamination. Thus, another scenario may be run and based on the acceptable outcome, a particular scenario is selected for practice. This can be done on a zone or on the entire area.

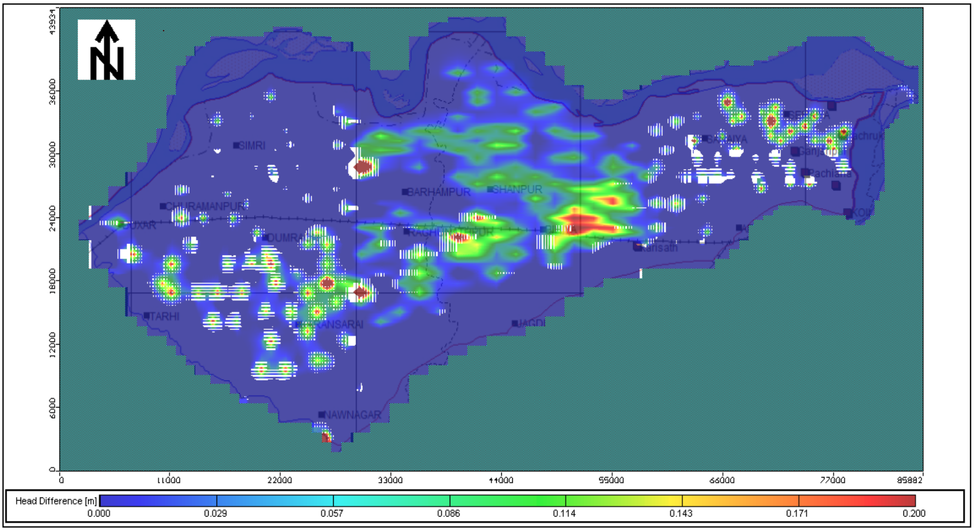

Figure 11.11 Map Showing the Leakage From The Second (Arsenic Free) Aquifer To The First (Arsenic Contaminated) Aquifer. The Red Colors Indicate the Reversal of the Leakage

The following scientific steps are thus followed for an Integrated Decision Support Tool (IDST-GW):

1. Considering all the possible fluxes and understanding their processes in a surface coupled groundwater system.
2. Simulating the groundwater flow under an appropriate initial and boundary condition starting from a regional scale numerical model but judiciously discretized; variable size grid should and could be possible.

3. Understanding and quantifying the impact of Climate Change and revising the methodology of estimating various fluxes with adequate data, mostly process based to incorporate the extreme events.
4. Considering additional fluxes to the system e.g., base flow and boundary's in and out flows that were hitherto ignored. This will reduce the errors and uncertainties in the ground (water) balance.
5. Also, the water harvesting and groundwater augmentation schemes and the resultant or corresponding fluxes to be estimated.
6. Precise and extensive knowledge of the sub-surface through advanced geophysics are advantageous; as most of the artificial recharge structures became defunct as they were decided on adhoc basis.
7. Once a regional model with appropriate boundary and initial conditions is calibrated and water budget is determined, smaller area for which a decision Support System is to be prepared, can be taken out from the regional model. This area could be a single grid or a combination of several grids that will form the model for the IDST-GW.
8. A large number of scenarios then can be generated as per the requirement of the local stakeholder and the resultant aquifer status for the next 10 to 15 years can be predicted and a decision is then taken to select the best scenario to have a satisfactory and acceptable predicted condition of the system.
9. Since the decision is from the users and the stakeholders, its implementation is obvious.
10. The size of the area selected for IDST-GW should be such a way that a single decision from the selected scenario could be taken. In India, area belonging to a few villages falling in a single Panchayat is the best for this.
11. The plume movement of the contaminated groundwater could also be studied in a similar way and a waste disposal site can be planned and associated scenario may be decided such a way that contaminated water does not flow towards the habitation.

Advantages and Conclusions

There are two very important aspects exist for such study and outcome (i) as the generation and adaptation of scenario will be purely made by the water users; they will ensure its implementations and (ii) this being an Integrated DST, the base will be a calibrated through established numerical model so the error propagation to the area of interest will be minimum. The regional model may be prepared basin wise.

Once the stakeholders and users are involved since beginning of the study, they will help in collecting the periodical data and updating the scenarios to make the best use of this new approach and the IDST-GW model.

Although the lumped model has worked very successfully in conveying the message to the farmers that groundwater is finite and it has to be used judiciously, it has suffered with a few drawbacks. The entire area of study to take decision should have been represented by a single value of various parameters that became a very strong assumption and the natural variability of the parameters were to be suppressed. Later to enhance the accuracy in the estimation and reduce the impact of uncertainties, a simulation model has been integrated with the Decision Support Tool. This has been useful in the two following ways:

A. To have a larger area for the study that will be anyway discretized in to smaller sizes.
B. To keep the errors and uncertainty produced from the parameter's variability, away from the area of interest.

This integrated model thus has two steps in execution; first the simulation of groundwater flow as well as mass transport on a regional scale, validate the same to complete with calibration. The model can be rigorously calibrated and validated to enhance the reliability. Then one or a number of grids forming a zone could be decided based on the extent of the geographical area in the field where single decision is possible and is to be taken. Then a zonal balance providing the change in storage in the form of (ΔS) is determined on the designated zone for a large number of scenarios. Although this procedure has the freedom of generating a large number of scenarios but the scope of making major modification is possible only in demand.

Such a procedure has been applied to an area that uses extensive irrigation for producing sugarcane. The area was discretized and groundwater flow was simulated using appropriate boundary and initial conditions. Initially the model was discretized into 2 Km by 2 Km grid; representing an area, on average covered by the farms lands belonging to one Panchayat (an administrative unit with a group of villages). The Panchayat being an administrative body could play an important role in taking decision and implementing the model results.

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The Intrinsic Connection between Gender and Urban Water Security

By: Laurens Thuy

The UNESCO World Water Assessment Programme (WWAP)

Introduction

Global water insecurity[1] is expected to significantly increase into the future due to a manifold of key drivers such as continuous population growth, rising water consumption and pollution rates, which, compounded by climate change and variability, lead to the dwindling availability of clean freshwater resources. This comes at a time when already 80% of the world's population faces serious threats to its water security and hundreds of millions of people suffer daily from acute water insecurity (WHO, 2014).

Over half of the world's population (3.9 billion) lives in an urban setting, a figure projected to increase to two-thirds (6.3 billion) by 2050, mainly as a result of rural-to-urban migration (UN Water, 2018). The bulk of the aforementioned growth in urban population will be accommodated by towns and cities of less developed regions in the timespan of few decades, thereby fuelling the growth of informal settlements. The latter often already struggle to encompass the needs of their inhabitants, and are frequently characterised by inadequate water and sanitation services. Indeed, the number of city dwellers that live without access to safely managed drinking water has reached 156 million: an augment by over 50% since 2000 (UN Water, 2021). Meanwhile, phenomena that manifest themselves globally within the urban context, such as ageing water infrastructure, urban sprawl, and loss of natural environment, further contribute to the challenge of providing adequate water and sanitation services to its inhabitants.

Shortcomings with respect to water-related services bring about far-reaching consequences in terms of health and economy that may not be limited to the communities or groups being 'left behind', but rather perpetuate widely beyond in society. So has the critical role of access to safe and reliable water services in human settlements, and the repercussions of a lack thereof, been painfully illustrated during the global COVID-19 pandemic which commenced in 2020.

Women make up half of the global population and are the primary providers and users of water, while playing key roles in ensuring its quality and preservation, in the urban as well as rural setting. Despite this, they are disproportionally underrepresented in terms of decision-making at all levels of the water sector. Aside of negatively impacting women's empowerment through a vicious cycle that reinforces gender inequalities, this underrepresentation hampers the efficiency of water-related institutions, which in turn threatens water security as well as related advancements in the field of poverty reduction and sustainable development.

Along these lines, this chapter will explore the social dimension of water security, and more particularly, its gendered nature. After exploring women's current representation in the water domain, as well as their potential role in water management, the case will be made for a more

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1 A lack of adequate water in terms of quality and quantity, to meet the needs of diverse sectors and stakeholders concerned, either by physical shortage or improper access to water

gender-inclusive urban water sector and how it could improve urban water security while advancing the global objective of sustainable development.

The Social dimension of urban water security

As discussed throughout the other chapters, a wealth of approaches exists to the concept of water security in function of the context and discipline. It may however be stated that generally, particular emphasis is placed upon the physical dimension among the cultural, ecological, political and social dimensions of water security. As early as in 2007, the UN Committee on Economic, Social and Cultural Rights (CESCR), highlighted the importance of considering the social aspect of water security (CESCR, 2008). Despite sufficient and clean water being a key enabler of poverty and vulnerability reduction, limited attention has gone so far to the role of social determinants in measuring and addressing water security.

The strategic importance of access to adequate water services, and its role in ensuring water security at different levels is however evident from any water security approach. One such example that moreover incorporates societal factors comes from the 2013 Asian Water Development Outlook report (ADB, 2013). The proposed water security framework consists of five dimensions to measure national water security: Household Water Security[1] – Economic Water Security – Urban Water Security – Environmental Water Security – Water-related Disaster Security (Figure 1). Urban Water Security in turn is determined by 5 key factors, among which access to water supply, access to sanitation, affordability, drainage/floods and environment; corresponding to the determinants of the Rural Household Water Security dimension. Indeed, access to WASH services at household-level may be considered a major determinant to water security in both the urban as well as rural context.

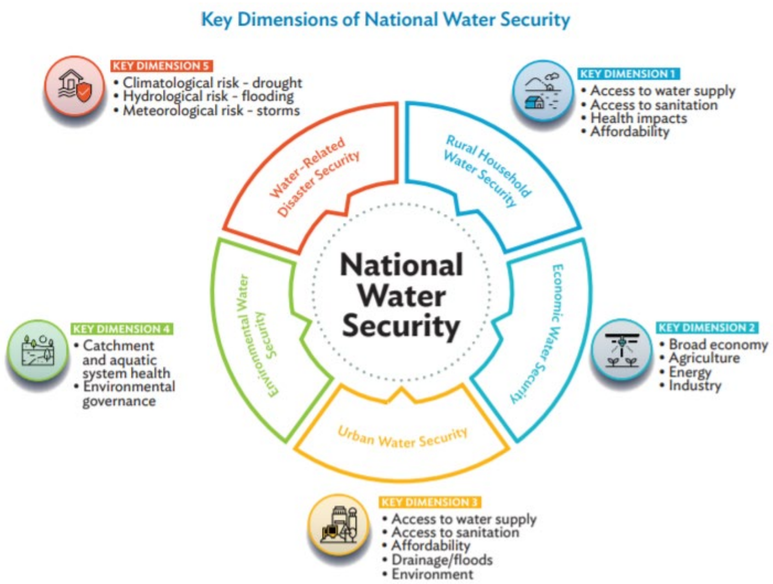

Figure 12.1 The AWDO Water security framework with five interdependent key dimensions (ADB, 2013)

1 The access by all people at all times to enough water for an active, healthy life, including, at a minimum : (a) the ready availability of water of adequate quality and safety; and (b) the assumed ability to consistently acquire water. (Tsai et al., 2015).

However, access to safe water services is far from the only determinant to urban water security. Romero-Lamkao and Gnatz (2016) proposes a framework that defines urban water security through five interacting social and environmental domains: Socio-demographic (social practices and location), Economic (wealth, and access to water and other assets), Technological (water infrastructure and water efficiency measures), Ecological (water/land endowments, and climate regime), and finally Governance (water/land use regulations and management). Within this concept (Figure 2), the five domains which determine the urban water regime are not only interdependent upon one another, but moreover subject to both societal drivers and environmental impacts. Examples of the former drivers are e.g. global urbanization or shifts in governance regimes, whereas the latter may be e.g. climate change and regional or local changes in hydrology. In line with this, urban water scarcity may be considered to be a complex function of both physical and social drivers, the latter which this chapter will focus upon.

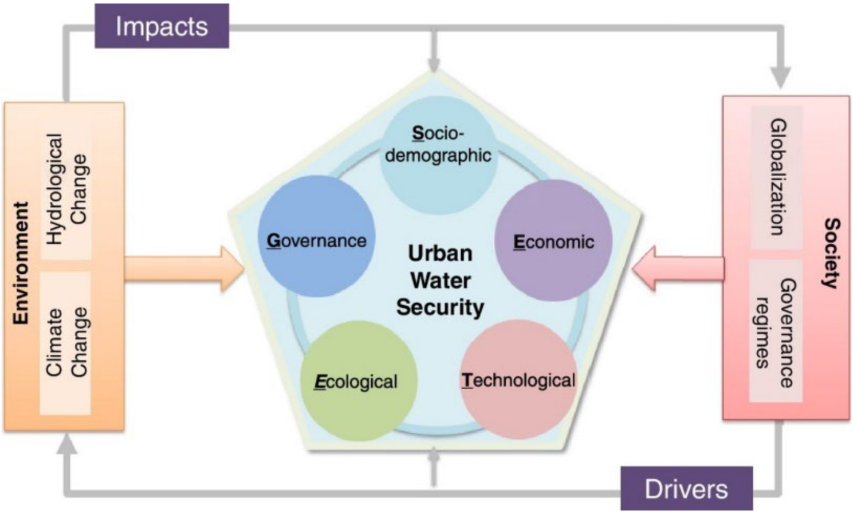

Figure 12.2 Urban water security framework shaped by five interacting social and environmental domains (Romero-Lamkao and Gnatz, 2016)

The gendered nature of urban water security

Despite access to ‘sufficient, safe, acceptable, physically accessible and affordable water’ being a basic human right (UNGA, 2010), universal access has been far from achieved. In 2017, 90% of the world population (6.8 billion people) used at least basic drinking water services, 73% (5.5 billion) had access to basic sanitation services and merely 60% (4.5 billion) had a basic handwashing facility at their disposal at home (UNICEF and WHO, 2019). What concerns the access to water on a household level, over 156 million city dwellers live without access to safely managed drinking water.

Despite its worth for indicating progress on the global or national level, such population-level data mask inequalities. For instance, access to water may differ considerably among diverse segments of society, communities, or even individuals in function of physiological factors (e.g. gender, age, ethnicity) and situational variables (e.g. living place, household composition, resources) (Grasham et al., 2019). Aside of other disadvantaged groups, particularly women and girls have been shown to face greater barriers towards accessing WASH services and to be disproportionally affected by the lack thereof, due to a range of biological, social, gendered, and economic factors. For instance, culturally assigned roles and responsibilities lead to women being in charge of water collection in 61 to 79% of households (Pouramin et al., 2020; Geere et al., 2018). Data is scarce, but this figure may be lower in the urban setting, where women are reported to be the primary responsible in 46% of the households and children in 12% (Geere and Cortobius, 2017).

The act of water fetching does not only bring along significant physical and psychological health issues, it is moreover a time-consuming task, diverting time away from income-generating activities, education or training, thereby creating a negative and self-reinforcing vicious cycle which is detrimental to women empowerment. In addition to this, households of cities or districts with inadequate water service provisions, or poor households that completely lack access, often rely on shallow groundwater wells, which are at elevated risk of biological contamination through leaking sanitation infrastructure (Hoekstra et al., 2018). However, gendered differences extend well-beyond solely ‘access to water services’, into virtually all domains that determine urban and even national water security.

Indeed, women are not only disadvantaged in terms of water access, and disproportionally impacted by the lack thereof, they are also highly underrepresented in terms of employment and participation within the water domain. For instance, women constitute on average less than 17% of the paid WASH workers and only about 22% of water utilities staff, a number that is even lower when considering technical or high-level positions. Moreover, their salary is significantly lower -up to 27%- than their male counterparts’ (UNESCO/UN-Water, 2016; World Bank, 2019). Despite the fact that women are highly underrepresented in the water sectors’ work force, paradoxically, a shortage of human resources exists, notably in the fields of management, accounting, finance and engineering (IWRA, 2014). For instance, the UN-Water Global Analysis and Assessment of Sanitation and Drinking Water (GLAAS) report found that 60% of utilities had insufficient staff to uphold their urban drinking water systems (WHO and UN Water, 2014). An example of women’s marginal participation to water governance can be found in the fact that as little as 12% of environment-related ministries is led by women (IUCN/EGI/UN Women, 2015). On a more local level, water user associations and water community boards also continue to be mainly composed by male members. Such gendered data on the urban level is scarce, but reportedly follows the same, above-mentioned, dynamics of unequal representations and power distribution (Adams et al., 2018).

In other words, women’s central role in domestic, agricultural and social water-related activities is often not reflected in water-related policy-making, and hence, their perspectives and roles are rarely taken into consideration in the management of these very water resources and in associated development programmes. Indeed, the water domain is a male-dominated environment within which women are largely excluded, or in the best case underrepresented, from decision-making processes. This means that related policies and outcomes are generally also male-dominated, with far-reaching impacts on the delivery of water-related services, as well as the distribution and allocation of related funding. That is to say, gender imbalances in water governance may be mirrored within the water institutions they regulate, and finally lead to gendered inequalities with respect to who gets water, how and when, as well as who benefits. Failing to properly represent the entire user community may not only strain the concerning water institutions’ decision-making power, but moreover compromise their effectiveness in addressing challenges on the ground (Imburgia et al., 2020). Such a lack of representativeness may moreover reduce support on the ground, enlarging the policy-practice gap and hampering efforts to safeguard urban water security.

The aforementioned gap is the direct result of governing socio-cultural values that are place- and time-dependent but deeply rooted in society. Overall, these give rise to common beliefs on gender roles, also called gender stereotypes, which have a substantial impact on women's role in the water sector. For instance, they may falsely dictate how jobs in the technical or engineering field are more suitable for men whereas other fields such as communication or social science would be more suited for women. Exactly because of the widespread and deeply rooted nature of such stereotypes, they are not easily eradicated nor are the associated gender inequalities. Consequently, women face disparate constraints to join water-related institutions at all levels. The barriers they encounter can be manifold: e.g. an unfair recruitment process, skewed HR policies, a discriminatory or gender-blind work environment, or even harassment. Even when forming part of such institutions, women's role and involvement may be questioned, or their inputs may not be given the same level of consideration. On the other hand, women themselves may be more reluctant to pursue a water-related job, or may be less inclined to assume an active role in decision-making processes.

Highlighting women's role in urban water management

Urban water security is a complex function of different variables that encompass environmental, social, technical and institutional factors. It is therefore crucial that the development of relevant policies goes beyond biophysical matter to include information stemming from relevant social processes, taking into consideration all stakeholders involved. Since women are disproportionately affected by water insecurity, their underrepresentation throughout the water domain should be overcome. But what role can women play in urban water management, and what benefits can this unlock for the particular case of urban water security?

Evidence shows that women leaders, in comparison to men, tend to emphasize social issues such as WASH and human development at national level, and tend to invest more in water infrastructure and water use efficiency at community level (Jalal, 2014). This may come forth from the fact that cross-culturally they are more in charge of domestic water provision and management, and therefore understand how the significant time savings associated with proper water access can be invested in remunerated work, education and training, communal activities or leisure. Women moreover hold vital knowledge on the equitable use and sharing of water, which may in turn promote water security on the national, regional, local and urban levels (Das, 2017).

In particular, urban water user or community groups may benefit significantly from women's participation and leadership. For instance, water committees with women board members have been shown to meet more frequently, to be linked to better-functioning water systems, and to apply a more effective fee collection, when compared to user groups governed by men-only boards (UNICEF, 2017). Such groups form an important first step in harnessing women's potential as entrepreneurs or grassroots[1] leaders, employing their knowledge to improve livelihoods (do Livramento Gonçalves, 2019). In addition, community groups can provide invaluable information on the quality and representativeness of water services and

1 "Grassroots women is a term used for women living in poor rural or urban communities, characterized as part of a group susceptible to risks and vulnerabilities because of their economic, social, and political marginalization"

their management. Since women are the water sector's primary users, their practical feedback regarding needs and concerns is instrumental to review and fine-tune the design, operation, and maintenance of water systems (Deloitte, 2017). As illustrated by the example in Box 1, such a 'user-centred' approach is essential to improve the accessibility to -and quality of-service, eventually augmenting user satisfaction and willingness to pay: one-by-one critical elements to ensure a sustainable and durable service provision.

Box 1. Including women in Malawian tap committees

In the 1980's, an innovative community management system was set up to bring piped water to low-income households through the construction of 600 Communal Water Points in 50 districts. The tap committees which were charged with the management of the water points were composed of over 90% men, whose involvement in water management matter prior to the initiative had been low. While the approach worked in delivering water to households, the collection of payments was disorganised and carried out in a somewhat intimidating manner, money was mismanaged and fell short to meet delivery costs. As the committees rarely met, water points functioned poorly, and membership fell. In an effort to overturn this situation, a gender approach was applied that prescribed tap committees to be composed of 60% women and 40% men. Participating women were offered capacity development courses in topics as: leadership; community participation; financial management; WASH; and operation procedures. As a result, membership to communal water points and the payment of bills improved significantly, while user satisfaction grew.

Overall, 24.000 low-income families across the country gained access to reliable water supply. The introduction of the aforementioned gender approach led to the system becoming more efficient, effective, equitable and financially viable.

Source: Maharaj et al. (1999)

As early as in 1993, evidence has shown that the effective participation of women to projects not only leads to better services and financing, but also to enhanced women's leadership and eventually to better hygiene, working conditions and status (IRC, 1993). These findings were validated by a World Bank evaluation of water projects that estimated women's inclusion to render such projects six to seven times more effective (World Bank, 1995). However, those new roles and associated tasks must be properly compensated in terms of an enhanced degree of power or financial remuneration. Even on a corporate level, gender-balanced leadership has been shown to significantly improve performance on areas such as employee engagement and customer satisfaction, when compared to male-dominated management. Likewise, companies with gender-balanced management are reported to be 21% more likely to outperform in terms of profitability and 27% more likely to have superior value creation. Moreover, women leaders are more often attributed behaviours, regarded as key for meeting future challenges. Examples of those are: being 'inspirational' by presenting a convincing future vision and inspiring optimism, promoting 'participative decision-making' by building a team atmosphere that is encouraging and participatory, and to clearly define expectations, responsibilities and rewards (McKinsey & Company 2013; 2018).

Unfortunately, the aforementioned benefits associated with women's involvement in water management at different levels and domains are generally not adequately acknowledged nor valued.

Towards a gender-inclusive urban water sector - turning the tide

Women's affinity and knowledge with relation to water should be matched proportionately to their representation within water-related decision-making, in order to break the vicious cycle of male domination within the domain. This section will explore potential methods and strategies in a number of key domains to help overcome this gendered gap, for the benefit of urban water security.

To advance gender equality within water governance, the latter must equally take into consideration the priorities, needs and perspectives of both women and men. In other words, a gender-responsive approach should be applied throughout. To accomplish this, several elements are indispensable.

The first is the existence of solid, goal-oriented legislative, regulatory and policy frameworks to guide the design, implementation and evaluation of gender-responsive water policies, projects and initiatives. An example of such a comprehensive international policy framework is the New Urban Agenda (NUA), which was adopted by a record number of Member States at the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in Quito, Ecuador, on 20 October 2016. The NUA aligns with the Agenda 2030 for Sustainable Development, and is to guide global urbanization policy until 2030 with as main objective to make cities more sustainable and inclusive. Among major obstacles to sustainable development in human settlements, the NUA lists issues such as the persistence of poverty, growing inequalities, social exclusion and environmental degradation while recognizing (young) women as key agents of change in creating a more inclusive and sustainable future. It contains a number of key recommendations to improve water security, in part by harnessing women and girls' vital contribution therein. In line with this, the NUA can be regarded as a valuable blueprint for the development of similar urban development frameworks on national or regional level (Box 2).

Box 2. The New Urban Agenda (UN, 2016)

The Quito Declaration on Sustainable Cities and Human Settlements for All, calls upon all national, subnational and local governments for action in the implementation of its New Urban Agenda (NUA). A grasp of its recommended actions to advance urban water security that make specific mention to women and girls:

"20. We recognize the need to give particular attention to addressing multiple forms of discrimination faced by, inter alia, women and girls […] indigenous peoples and local communities, slum and informal-settlement dwellers […];

61. […] Ensuring more and better opportunities for their [girls, boys, young women and young men] meaningful participation will be essential for the implementation of the NUA;

90. […] We will take measures to promote women's full and effective participation and equal rights in all fields and in leadership at all levels of decision-making, including in local governments;

119. We will promote adequate investments in protective, accessible and sustainable infrastructure and service provision systems for water, sanitation and hygiene, sewage, […], urban drainage, […] to improve safety in the event of water-related disasters, improve health, ensure universal and equitable access to safe and affordable drinking water for all, as well as access to adequate and equitable sanitation and hygiene for all and end open defecation, with

special attention to the needs and safety of women and girls and those in vulnerable situations;

148. We will promote the strengthening of the capacity of national, subnational and local

governments, including local government associations, as appropriate, to work with women and girls, […] in shaping organizational and institutional governance processes, enabling them to participate effectively in decision-making about urban and territorial development;

155. We will promote capacity-development initiatives to empower and strengthen the skills and abilities of women and girls, […], for shaping governance processes, engaging in dialogue, and promoting and protecting human rights and antidiscrimination, to ensure their effective participation in urban and territorial development decision-making."

Source: UN, 2016

Since both gender equality and access to safe water and sanitation are internationally recognized human rights, States are required to work towards their achievement. However, to be applicable on the national level, the modus operandi are to be formulated in country-specific legal frameworks, desirably following the principles of non-discrimination and equality, information, participation and accountability (UN Special Rapporteur on the human right to safe drinking water and sanitation, 2014). However, the presence of gender-responsive frameworks and policies is not a guarantee for the achievement of gender-responsive water management on the ground. As discussed in section 2 (i.e. the gendered nature of urban water security), also water governance institutions need to adapt such gender-responsive and inclusive character.

Water utilities for instance, both public and private, which are in charge of water infrastructure management and the distribution of sufficient and clear water, are to make efforts to balance their staff composition in terms of gender. Central to the establishment of such 'gender-sensitive' staffing are equitable HR policies that promote gender diversity, e.g. through gender diversity targets, equal pay for equal work, transparent hiring processes, and gender awareness training for all staff to put an end to workplace discrimination. In addition to equality measures, specific policies that safeguard women must be in place, e.g. against discrimination during pregnancy and maternity leave, alongside with the possibility to opt for flexible work schedules, or for extended leave. In addition, capacity building or vocational training can be offered to female staff to allow them to develop or reinforce their leadership skills, or gain expertise on specific topics of interest for their career development. It is worth noting that the aforementioned recommendations of enhancing the knowledge, skills and abilities of staff do not only apply to water utilities, and are applicable to all workplaces, projects or programmes, public or private, to reduce the manifestation of gender inequalities therein, protect workers' rights as well as promote dialogue. The same holds for awareness-raising on the potential of women leadership and participation within the water domain which must not only target relevant stakeholders in the water domain, but can be of value to the general public. A practical example of the benefits resulting from women's participation and inclusion in WASH projects and of the beneficial outcomes of capacity development and vocational training can be found in Box 3.

<u>BOX 3: Case Study - Urban Water Supply and Environmental Improvement Project</u> (ADB, 2015)

The Urban Water Supply and Environmental Improvement Project aimed to rehabilitate and expand urban water supply and sanitation (UWSS) systems in 4 cities in Madhya Pradesh, India, to provide better service to the urban communities, and in specific to women and the poorest residents. Alongside, the project intended to plan and manage UWSS in a more effective, transparent and sustainable manner. Emphasis was put on women's active participation within the project, and to addressing the gendered impacts from the lack of safe water and sanitation.

Gendered roles were identified as follows: in 60% of households, women acted as primary responsible for household water management, exposing them to physical injuries and sexual violence during water collection. The lack of sanitation facilities constrained them to rely on open defecation, with its associated security concerns. Despite this, women remained unaccounted for in water management structures, faced disproportionate obstacles to join productive or community initiatives, and were discriminated against when pursuing employment. WASH institutions were found to lack capacity on gender equality issues.

The lack of WASH services was addressed through municipal action plans, enhancing coverage for poor (informal) settlements by connecting them to the city infrastructure, along with capacity building to promote overall public participation and awareness. The key project components that addressed gender inequalities were: a gender mainstreaming strategy to plan and implement pro-women community-based initiatives; a gender action plan including participation targets, prioritization of women's needs and gender awareness training for all project staff; a practical gender field manual; and a social mobilization for public awareness and participation that prioritized women and vulnerable communities. In addition, the project accommodated: institutional commitment to promote gender-sensitive working conditions such as equal pay for equal work and safe working conditions; gender expert staff and capacity development to enhance awareness on social and gender issues; and vocational training.

The project benefited over 5.6 million people in terms of improved water supply through an annual membership. In particular women and girls reported increased frequency in bathing and clothes washing (which would previously be mainly men's privilege), improved hygiene practices thanks to individual or communal toilets, and substantial time savings thanks to reliable and safe water services. Additional achievements were: the enhanced participation and leadership of women in Community Group Committees and their overall empowerment; reduced safety risks for women and girls in water-related activities or tasks; benefits from institutional, communal and individual capacity training; a positive change in gender relations reported by both men and woman; and finally an increased understanding of gender issues in water access and sanitation among project staff and public representatives.

Source: ADB, 2015

The monitoring of progress on the ground is an essential tool to evaluate the level of practical implementation of policies, and to measure the success of related frameworks and institutions. This can for instance be accomplished through local stakeholder consultations and the collection of relevant water-related field data. Indeed, consultative processes with community leaders, water user association boards, or other relevant stakeholder representatives may be valuable, if not essential, to inform policy-making. Not only can this significantly enhance the latter's inclusive and participatory nature, it can moreover help better align institutional action with the situation and challenges experienced on the ground. Evidently, the consulted groups must themselves respect a gender-responsive approach, for instance through women and other vulnerable or minority groups being meaningfully integrated in their management structure and member base.

The collection of local field data, on the other hand, is a similarly indispensable asset for the formulation of evidence-based policies, as well as for tracking progress towards predefined goals. Of particular interest is gender-disaggregated data as it allows the establishment of a deep and solid understanding of the nature and extent of gendered disparities with respect to water-related topics, such as the level of access to - and benefit from- water-related services and interventions, or involvement in related decision-making. Moreover, due to its erratic nature that is a function of physiological and situational variables, water security is best considered on the smallest scale possible, preferentially down to the intra-household level. Despite its value for the formulation of gender-responsive actions, at date, no country collects sex-disaggregated data on intra-household water uses and WASH access. Such data may provide insights on how to reduce gender inequalities within households, communities or districts, and its scarcity is an important concern for monitoring progress towards the Agenda 2030 for Sustainable Development and its specific Goals (Miletto et al., 2019). Methodologies and indicators to collect gender- or sex-disaggregated data do however exist, an example of which being the 2019 UNESCO WWAP Toolkit for sex-disaggregated water data collection.

In addition to the wide array of aforementioned approaches and actions that may benefit inclusiveness and gender equality at different levels within water governance and management, their success is dependent on a number of enabling factors. One of these is political will and strong leadership to drive action on the incorporation of gender considerations within decision-making, but even more importantly so, on the formulation of adequate implementation strategies to accomplish their practical application on the ground. Along with this goes evidently the allocation of sufficient financial resources to allow the realization of the predefined objectives and goals. The actions discussed throughout this chapter, such as the establishment of representative water-related institutions and overarching frameworks; the gender mainstreaming of laws and policies as well as their reinforcement; the adoption of measures to promote women's participation in water management and their overall empowerment, as well as the collection of gender-disaggregated data, each have a price. A price which may however be well-worth paying in return for the significant gains in water security they may bring about.

Conclusion

Urban centres and their inhabitants are facing mounting challenges with respect to water security due to a range of drivers such as rural-urban migration, changing life standards and global climate change and variability. Despite the common conception that water security is merely a matter of improving water infrastructure and implementing technical advances, social determinants down to the individual level play an influential role. Women and girls are disproportionally impacted by a lack of access to adequate water and sanitation services, making water security a gendered phenomenon. Despite, the water domain is clearly male-dominated and characterised by an underrepresentation of women within water-related decision-making and jobs at virtually all levels and domains. Not only does this tend to reduce the aforementioned bodies' representativeness, it moreover stands in shear contrast with women's central role in water resources management and evidence that their larger involvement increases the efficiency and sustainability of water-related services, projects and programs. Overcoming the aforementioned challenges will be necessary in order to unlock women's potential in the water sector, and to bring about the associated improvements in water security at all levels. As top-down method, an integrative gender-responsive approach will need to be applied throughout overarching legal frameworks, policies and national as well as urban-specific water institutions, in order to stimulate progress on the ground. The incorporation of consultative and participatory processes with female and male representatives of local stakeholders, as well as gender-disaggregated field data will prove crucial for the achievement of evidence-based and participatory decision-making. Simultaneous bottom-up action will also play a critical role, for instance by targeting persisting stereotypes through public awareness-raising on water- and gender-related issues, along with capacity development and vocational training for women to stimulate their entry in the water sector workforce, or enhance their participation in related decision-making.

The achievement of women's equal representation in the water domain is not only a moral obligation, it is indispensable for the achievement of an inclusive, equitable and sustainable water sector and to ensure urban water security while unlocking the related social and sustainable development.

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Water Security in Human Settlements

Best Practices and Lessons Learned in Arid and Semi-Arid Areas

Regional Centre on Urban Water Management (RCUWM)

Tehran, Iran

This publication is the outcome of an expert-group meeting organized by Regional Centre on Urban Water Management (RCUWM) under the auspices of UNESCO with the aim of providing practical advice to improve water security in human settlements, using best practices, lesson learned and effective tools, specifically in arid and semi-arid areas. This book describes what such best practice planning and management might involve, and uses several case studies undertaken by the authors in arid regions including valuable experiences on urban water management. The book is a contribution to UNESCO Intergovernmental Hydrological Programme (IHP).

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