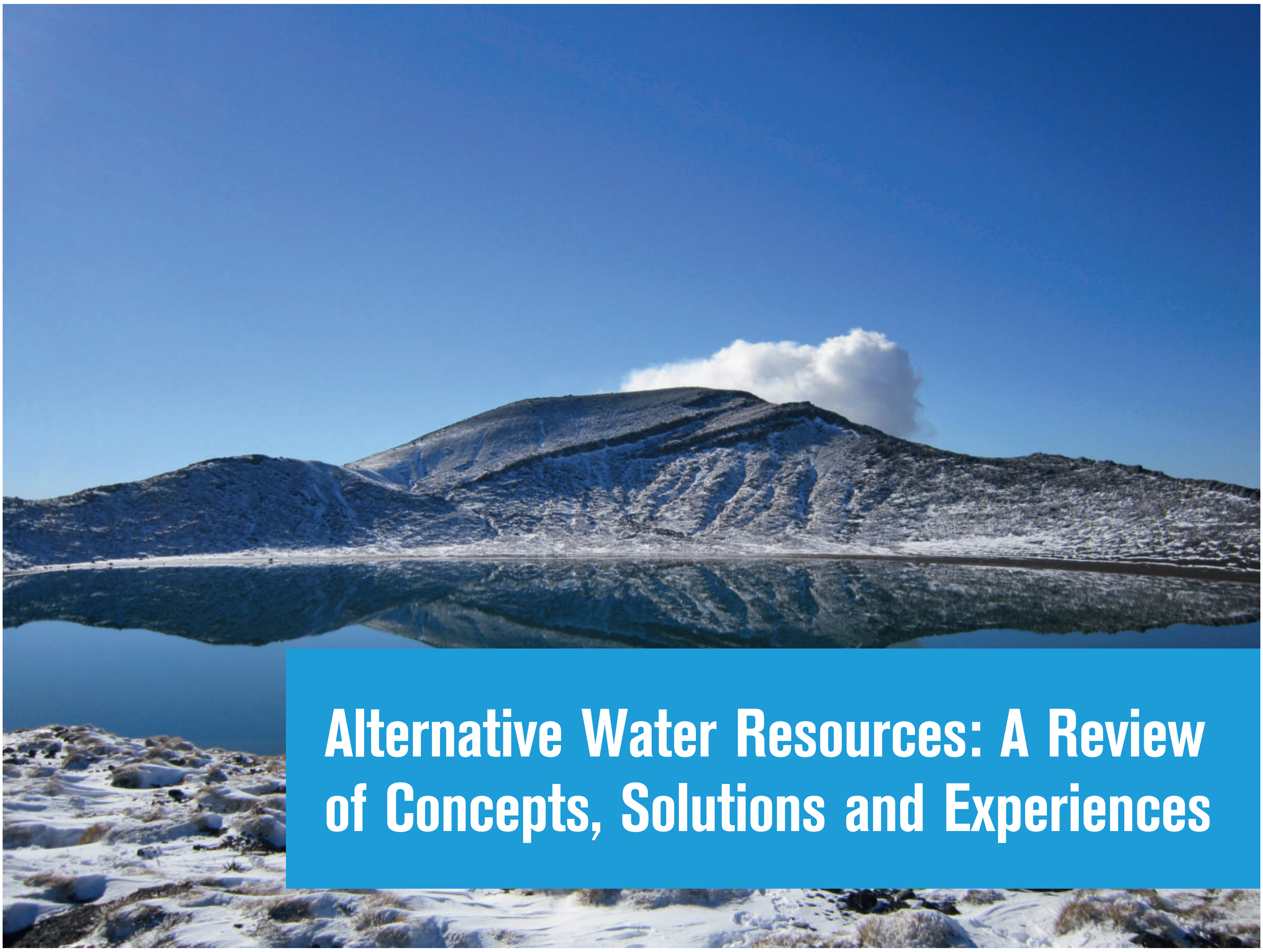
Alternative Water Resources Cluster



Alternative Water Resources: A Review of Concepts, Solutions and Experiences

Alternative Water
Resources Cluster

the international
water association

ALTERNATIVE WATER RESOURCES: A REVIEW OF CONCEPTS, SOLUTIONS AND EXPERIENCES

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International Water Association

2015

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PREFACE

Every resource used to supply water demand in an urban zone could be considered as alternative. Historically, since settlements were located some distance from water sources, a variety of sources and technologies for abstraction, conveyance, treatment and waste collection were emerging. Population growth and evolving enabling technologies led to new forms of alternative resources that were able to satisfy needs and specific requirements for water related activities. At the beginning, solutions were mainly focused on looking for additional reliable and good quality raw water resources without considering that large infrastructures were required to abstract, store and convey water to consumption points. Since cities and water demands were growing, potential solutions became more expensive, with high marginal costs and significant environmental impact. In some cases these solutions were just unfeasible or created considerable social reluctance.

All over the world, the search for affordable, acceptable and reliable solutions is today a common challenge for water supply planners. Therefore, having a sufficient quantity of water with appropriate quality is a common aim.

In this context, the water sector has been coping with different concerns throughout time. This way, finding average demand/resources balance was the first concern, especially for water-stressed areas. Then, reliability of available resources under droughts or scarcity scenarios became the key issue to cope with climate variability. Appropriate water quality for health protection and to fulfil specific requirements of every use was the following challenge. Thus, technology has been providing solutions to every problem, contextualised with different costs, impacts and consequences. Nowadays, some solutions such as desalination, reuse, greywater, artificial recharge or rain harvesting could be considered almost as conventional solutions as abstraction from pure streams or aquifers was long ago. There are many examples of use of those resources and their enabling technologies.

Additionally, demand management is the other component of resources/demand balance, and, in consequence, its contribution should be also analysed. If demand is considered as the total water that outflows from a water supply system, demand management must include policies to reduce both the global consumption and the different types of real loss.

Every context and city has a variety of options with different figures of marginal costs, (economic, social and environmental) and with different reliability for the availability/demand balance.

A review of the mentioned alternative options that focus on resources and demand has been compiled and described in detail in this Compendium. Likewise, case studies and parameters to assess their costs and benefits are described.

This Compendium is a good starting point for the activities planned in IWA's Alternative Water Resources Cluster. There are many identified ways to move forward within the cluster: new solutions for appropriate water balance, such as water trading, cloud stimulation, and applications of other smart technologies, new methods to assess reliability and to include risk parameters and principles, new criteria to compare in a consistent way potential options with all their significant parameters such as environmental impact, sustainability or social preferences. Perhaps at the end of this process we strongly acknowledge that we are not dealing with just alternative resources, but we will be dealing with reliable and resilient supply systems. Resources will probably be as alternative as they were in the past but solutions will be linked to energy, resilience and sustainability in a new comprehensive and efficient approach.

▪ FRANCISCO CUBILLO

Abbreviations

A^2O	Anaerobic–Anoxic–Oxic
ASR	Aquifer Storage and Recovery
AWR	Alternative Water Resources
BOD	Biological Oxygen Demand
CBA	Cost-Benefit Analysis
COD	Chemical Oxygen Demand
CSP	Concentrated Solar Power
CSR	Corporate Social Responsibility
CSU	Colorado Springs Utilities
CW	Constructed Wetland
DMA	District Metered Area
DPR	Direct Potable Reuse
ED	Electrodialysis
EIA	Environmental Impact Assessment
ESB	Engineered Storage Buffer
FESR	Fuel Energy Savings Ratio
FO	Forward Osmosis
GL	Gigalitre
GPT	Gross Pollutant Trap
GRP	Goreangab Reclamation Plant
GWF	Gippsland Water Factory
HKIA	Hong Kong International Airport
HSFW	Horizontal Subsurface Flow Wetland
IC	Internal Circulation
ICI	Institutional, Residential and Industrial
ILI	Infrastructure Leakage Index
IMS	Integrated Membrane System
IPR	Indirect Potable Reuse
IWA	International Water Association
IWRM	Integrated Water Resources Management
KDWS	Korean Drinking Water Standard
KGWS	Korean Gray Water Standard
kWh	Kilowatt Hour
LBSE	Lithium Bromide-water Simple Effect
LCA	Life-Cycle Analysis
LID	Low-Impact Development
MBR	Membrane Bioreactor
MD	Membrane Distillation
MED	Multiple-Effect Distillation
MEH	Multi-Effect Humidification
MENA	Middle East and North Africa
MF	Microfiltration
mg/L	Milligrams per Litre
Mm	Megametre
MNF	Minimum Night Flow
MSF	Multi-Stage Flash
MVC	Mechanical Vapour-Compression
MWh	Megawatt Hour
NAD	Natural Aeration Ditch
NF	Nanofiltration
NRW	Non-Revenue Water
NWD	No Water Day
ORC	Organic Rankine Cycle
PLP	Peak-Load Pricing
PSDP	Perth Seawater Desalination Plant
PV	Photovoltaic
RO	Reverse Osmosis
ROS	Regional Outfall System
RW	Rainwater
RWH	Rainwater Harvesting
SDG	Sustainable Development Goal
SNU	Seoul National University
SODIS	Solar Disinfection
SW	Stormwater
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
TWS	Triple Water Supply
UASB	Upflow Anaerobic Sludge Bioreactor
UF	Ultrafiltration
UV	Ultraviolet
VBFW	Vertical-Baffled Flow Wetland
VMD	Vacuum Membrane Distillation
WUE	Water Use Efficiency
WWTP	Wastewater Treatment Plant

Contents

1 INTRODUCTION

Water availability is an issue of increasing global concern. As usage continues to exceed sustainable rates and greater quantities of pollutants come in contact with once pristine water sources, more people are becoming concerned as to where their water will come from. An average of 3.3 million people die from water-related illnesses each year and, in 2008, 46% of people on Earth lived in homes without piped water (Macedonio *et al*., 2012). If current consumption trends continue, two-thirds of the global population will be living with severe water scarcity by 2025 (Macedonio *et al*., 2012). According to the United Nations World Water Development Report (UN Water, 2015b), demand for water is expected to increase in all sectors of production and, by 2030, the world is projected to face a 40% global water deficit under the business-as-usual scenario. In addition to this, climate change is increasing the frequency and intensity both of droughts and of storm events, while higher air temperatures necessitate greater water use for crop irrigation and livestock. For these reasons, alternative water resources (AWRs), such as rainwater harvest (RWH), water reuse and desalination, as well as moving towards more holistic, integrated approaches to water management are becoming more popular for meeting the global water needs that may not be satisfied by a single water source.

1.1 OVERVIEW OF CHALLENGES

In the field of water resources management, we are currently facing challenges relating both to the quantity and the quality of water sources. Challenges are diverse in their causes and effects, but must be considered to ensure greater sustainability in the water sector.

1.1.1 WATER QUANTITY

1.1.1.1 Resource Depletion

Not only is the global population increasing at an exponential rate, but economic development, urbanisation and globalisation have resulted in the average person having higher consumption patterns and weaker connections to the origin of their consumed resources. Meat-heavy diets are on the rise, increasing resource consumption, and an increasing proportion of the global population is concentrating in megacities, disproportionately straining resources in those areas (Butler and Memon, 2006). On an even larger scale, the amount of water needed to irrigate agriculture (which comprises over 70% of the world's freshwater use (Food and Agriculture Organization of the United Nations, 2013)) has had to increase to feed the growing population, and as countries strive to develop their economies, water needs in industrial sectors have increased as well. This demand has typically been met by increasing the extraction rate of freshwater from surface water bodies and underground aquifers, which – if it exceeds the rate of replenishment – leads to depletion of the resource, and can possibly cause land subsidence if groundwater is over-extracted. Conventional water resources are no longer sufficient to meet demand. According to Ng *et al*. (2013), global water demand is projected to increase at an average annual rate of 2%, leading to a demand of close to 7 trillion m^3 by the year 2030, as is illustrated in Figure 1.1. Given that water scarcity is a growing threat worldwide, this rising demand is likely to have detrimental effects on the global population and its water resources if it is not addressed.

1.1.1.2 Climate Change and Drought

Climate models predict that the trend of increasing global water scarcity will continue as climate change impacts become more severe. With these changes, precipitation patterns become more erratic, evaporation and transpiration rates rise with increased air temperatures and water resources therefore become more scarce and less reliable (Olsson, 2012). All over the world, particularly in arid climates, lakes are shrinking dramatically or disappearing completely, affecting both ecosystems and human use (Liu *et al*., 2013). Stern (2007) predicts that just a 2 °C increase in average global temperature could result in between 1 billion and 4 billion people – particularly those in developing countries – becoming victims of severe water scarcity. Some of the water-related impacts of climate change include diminishing freshwater supplies due to shrinking glaciers, decreased precipitation and increased drought propensity, higher frequency of flood disasters in some areas due to severe storm events and unreliable supplies of both food and water (Morrison *et al*., 2009; Olsson, 2012). These issues

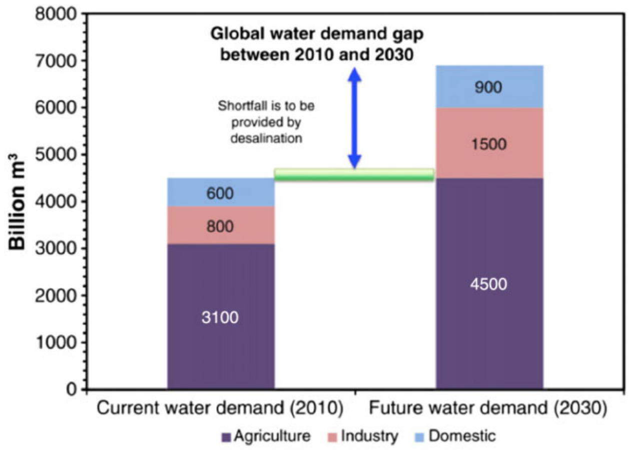

Figure 1.1 Global water demand in 2010 compared with projected global water demand in 2030 (Ng *et al.*, 2013).

will probably become exacerbated as higher atmospheric temperatures drive the need for increased water use in agriculture and livestock production, freshwater resources become contaminated because of seawater infiltration and pollutant discharge, and precipitation patterns become less predictable. If energy demand and carbon emissions are not reduced, all of the detrimental effects of climate change are likely to increase more quickly. Therefore, a more resilient water supply is needed, as is the proliferation of more energy-neutral practices within the water sector to help mitigate climate change.

1.1.2 WATER QUALITY

1.1.2.1 Risks to Human Health

The discharge of wastewater back into water bodies, dumping of industrial chemicals into those same sources and excessive runoff of stormwater over polluted areas have resulted in the contamination of groundwater and surface water that was once or still is used for drinking. In many areas, contaminants can be effectively removed with treatment technology. However, some regions either lack the capacity to treat their water to potable standards or the contaminants present in the supply – such as heavy metals, pesticides and even pharmaceutical compounds – cannot be removed by currently implemented technologies. Bangladesh is a prominent example of a country struggling to meet demand for freshwater because of source contamination. Arsenic contamination in aquifers has led to epidemic rates of cancer and other diseases, with an estimated 30 million people exposed to arsenic in concentrations greater than 50 µg/L. On top of this, much of the country's surface water has high turbidity and salinity, making it unfit for drinking and necessitating an alternative source of clean, reliable and accessible potable water (Karim, 2010a). However, Bangladesh is not the only country suffering from these issues; Pimentel *et al.* (2004) state that, in developing countries, 90% of all infectious diseases are spread through or related to water. Pollution in water sources constrains the use of these resources, and proper treatment technology or alternative sources of water are needed to overcome this issue.

1.1.2.2 Ecological Health

The excessive withdrawal of water from rivers, lakes and aquifers can be very disruptive to aquatic and surrounding terrestrial ecosystems. McKay and King (2006) state that ecosystems are highly sensitive to the alteration of hydrological flows, which occurs when water is extracted from riverine systems. Reducing depth and stream-wetted area may alter or destroy the habitat of certain organisms and decrease biodiversity in the ecosystem. It can also reduce dissolved oxygen concentrations, which can be detrimental to aquatic organisms. In addition to this, the discharge of poorly treated wastewater or saline brine into natural bodies of water can cause harm to aquatic ecosystems, especially with continual introduction. Compounding this issue further, the reduced volume of available water caused by over-extraction concentrates these contaminants because dispersion is limited. Finally, urbanisation often results in the removal of vegetation and riparian buffers, leading to further contamination from urban and agricultural runoff.

1.1.3 ENERGY AND CLIMATE

1.1.3.1 Water–Energy Nexus

Water and energy are inherently linked. Water is generally needed to produce energy (Mekonnen *et al*., 2015), and energy is needed to heat, pump, treat and distribute water. This relationship increases the complexity of both water and energy management. Additionally, human uses of water and energy are usually closely related. Hydraulic fracturing for natural gas, oil sands development and thermal energy generation are all important sources of energy needed to power industries around the world. However, both of these processes require large quantities of water, which – if returned to the natural environment – are discharged with significantly diminished quality. On the other hand, water scarcity is being addressed through the increasing implementation of reuse, desalination and more effective treatment processes, which are generally very energy intensive, thus the existence of the water–energy nexus.

In the United States, the largest withdrawal of water is for evaporative cooling in power generation plants, and the largest consumptive use of water is agricultural irrigation, much of which goes toward the production of feedstock for biofuels. Increasingly, reclaimed water is being substituted for potable water in these end uses to conserve existing freshwater stores, and there is much current research focusing on recovering resources to create more sustainable water and energy supplies. Clean water, as well as nutrients and energy, can be recovered from wastewater, and with technological innovation these processes will probably become more efficient. However, even in processes in which renewable energy is used, water use can be high, and many water-efficient processes still require a great deal of energy. For this reason, the relationship between these two resources is a vital consideration in all water and/or energy-related decision-making processes (Schnoor, 2011).

1.1.3.2 Non-Sustainable Water-Supply

Many methods of acquiring, treating and distributing water are powered by fossil fuels, which exist in finite supply and tend to increase in price as they become scarcer. Excessive energy use also contributes greenhouse gases to the atmosphere, worsening the impacts of climate change. Therefore, dependence on these sources to maintain water supply systems is not sustainable in the long term (Brown, 2013). Utilising renewable sources of energy such as wind, solar or geothermal can help to alleviate these problems, but they often require large capital expenditures. Therefore, if proper infrastructure is not in place and sufficient funds are not available, their implementation may not be feasible (Gude *et al*., 2010).

Another unsustainable aspect of present water supply networks is the need to transport water long distances from source to supplier to end user. Most municipal water suppliers are highly centralised, and therefore require a great deal of energy and piping infrastructure to supply water to users. Centralisation can also result in more water loss as there is more potential for leaks and inefficiencies in the system. A decentralised water supply that treats and distributes water locally is a more sustainable option, and therefore a shift to this kind of structure may be necessary.

1.2 DRIVERS OF AWR USE

The Organisation for Economic Cooperation and Development (Organisation for Economic Cooperation and Development, 2010) groups the drivers for the use of AWR into four categories: socio-economic changes, technological change, environmental/external stress and political change.

Socio-economic changes include population growth, demographic changes resulting in demand for better or more environmentally friendly water provision, expansion of urban areas and shifts in activity from public to private sectors or vice versa (Organisation for Economic Cooperation and Development, 2010).

Technological change drives the use of AWR because it often makes new options available which are safer, cleaner and possibly cheaper than existing structures. New techniques that improve the resource efficiency of water treatment/distribution, simplify processes, enhance ecosystem services, create more durable systems and reduce pollution have the tendency to mitigate costs in water sector operations, both in the short and long terms. However, this is not always the case (Organisation for Economic Cooperation and Development, 2010).

Environmental and other external stresses on water resources are becoming more common with habitual over-extraction, and climate change is likely to worsen this situation in many places. Many jurisdictional areas are responding to this increasing scarcity with the introduction of water reuse, desalination, demand management, etc. In some cases, it may not be a choice, but a necessity to meets the needs of the population (Organisation for Economic Cooperation and Development, 2010).

Political changes, particularly regulatory changes, are major drivers of AWR implementation. Included under this category are land use changes, water quality regulations, effectiveness of governance and revenue collection (Organisation for Economic Cooperation and Development, 2010).

Within all of these categories, cost becomes a main factor as well. Lower costs of relevant technologies generally increase uptake of these methods (Organisation for Economic Cooperation and Development, 2010), although forward-thinking water managers may make decisions based on long-term costs as well. For example, a higher-cost technology that causes minimal environmental damage is likely to induce lower mitigation or restoration costs in the future, and therefore may be favoured.

1.3 RATIONALE

The existence of the above challenges necessitates a more sustainable approach to water management, one that does not rely on a single source of water to meet all of an area's needs. Therefore, it is important to have information of the AWR options available and ways in which they can be used to create resilience within a larger system. This Compendium has been created to review alternative options focused on resources and demand, using evidence from scientific papers and real case studies to assess their costs and benefits. Current and future challenges to water supplies are also addressed, and recommendations are made for how to effectively and sustainably integrate AWR for the creation of a more reliable system.

1.4 SCOPE AND OBJECTIVES

Within the scope of this Compendium, all potential water resources, including surface water and groundwater are considered as AWR. However, owing to increasing strain on existing sources, more focus will be put on less conventional resources such as RWH, reuse and desalination. The use of these resources is considered as ways both to augment the drinking water supply and to create more secure water supplies for agriculture, industry and other end-users of non-potable water.

With the completion of an extensive literature review, best practices are identified, along with their advantages, disadvantages and examples of how they can be integrated into a sustainable water portfolio. The solutions discussed will range in their applicability from rural to urban systems and from low- to high-income countries. Case studies that successfully demonstrate the creation of more reliable water supplies are highlighted to show the viability of such projects and to inspire new projects of equal integrity. This will also help to enable the identification of gaps in knowledge and technology that must be addressed.

The document aims to cover a wide spatial scale, with examples from each major geographic area and a range of socio-economic conditions. The feasibility and applicability of different options for enhancing the resilience of water supplies vary drastically by location. Each country has different needs and resource availability, as well as unique political climates and economic capabilities. Therefore, attention will be drawn to these issues when discussing AWR.

Experts in relevant topics have contributed knowledge about the future direction of AWR use, and this information is summarised at the end of the Compendium. Finally, a set of recommendations are made for how to effectively and sustainably integrate AWR for the creation of a more reliable system.

The objectives of this Compendium include the following.

- Raising awareness within the water sector of the applicability of AWR use.
- Highlighting key issues that are affected or driven by non-sustainable resource use.
- Compiling and summarising information on AWR best practices to make it accessible to interested parties.
- Showcasing successful case studies to demonstrate different applications of AWR.
- Identifying key technology and knowledge gaps that exist within AWR-related sectors.
- Providing recommendations for decision-makers and water professionals to successfully implement AWRs into larger management plans.
- Creating a basis on which professionals and academics can collaborate to share knowledge and develop solutions.

2 RAINWATER HARVESTING AND STORMWATER COLLECTION/MANAGEMENT

Rainwater and stormwater are seen as promising AWR because of their low treatment needs relative to other AWR, minimal environmental impact and added benefits of runoff and peak flow reduction. The application of RWH dates back to around 2000 BC, where it was used in Israel, parts of Africa and India (Fewkes, 2006). This long history of use has resulted in many civilisations becoming quite efficient at using RWH processes, even without the help of advanced technology. It is also a source of water with minimal potential to create conflict, as transboundary and property rights issues are unlikely. However, problems arising in recent years – such as the presence of emerging contaminants, rapid population growth and climate change – have introduced new challenges for RWH that must be addressed in system design.

Despite the potential of RWH, its promotion is limited, probably because of misunderstanding of rainwater quality and unreliable water supply due to seasonal variation. However, good examples of RWH exist and scientific innovation is narrowing the gap between our current knowledge and future needs. When more than one purpose can be served at the same time – such as flood mitigation, water supply and contingency planning – or when rainwater is used to supplement the existing water supply, the adoption of RWH is promising. In all cases, sustainability, technological, economic and social aspects should be considered.

2.1 RAINWATER HARVESTING

2.1.1 UNLOCKING THE POTENTIAL OF RAINWATER HARVESTING

For the purposes of this report, "rainwater" will refer to precipitation that is collected before it hits the ground and becomes runoff. This is an important distinction to make because "stormwater", which has already become runoff, will generally have different collection systems, contaminants, treatment methods and end uses.

There is a lot of misunderstanding about the quality and quantity of rainwater. Evaporated water from the land forms clouds and eventually becomes rainfall, the quality of which is similar to distilled water. When it falls, it may contain some quantity of air pollutants and particulate matter, and in the use of rooftop RWH systems, some contaminants may be picked up from the roof, particularly if it is not cleaned well. Further chances of contamination are presented if rainwater runs off onto streets and driveways into streams and local catchments; the longer the distance (mileage) that rainwater has to travel, the greater the chance of contamination. In the water cycle, rooftop-harvested rainwater has the shortest mileage, and therefore has the lowest chance of acquiring dissolved and particulate matter, as shown in Figure 2.1.

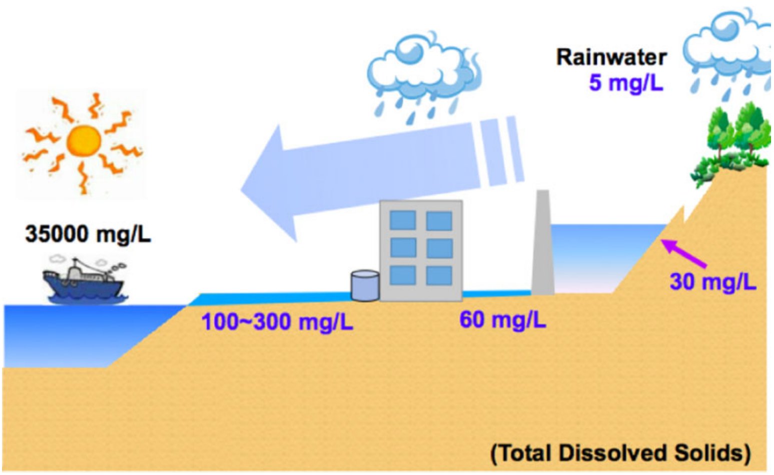

Figure 2.1 Mileage of rainwater and total dissolved solids (TDS) (provided by Mooyoung Han).

RWH collects rainwater from rooftops in a storage tank, but most rainwater storage tanks in operation have problems to do with water quality. The water is often turbid, containing suspended solids or even tiny insects that are easily observable to the naked eye. Sometimes, this is a result of poor design, which creates an obstacle to harvesting rainwater for human consumption.

Current progress in science and technology has created new opportunities for RWH to become a safe source of potable water. Rainwater is of high quality when collected properly, and poor-quality rainwater is not necessarily a result of the water itself, but of inadequate system design, poor maintenance of equipment (Dobrowsky *et al*., 2014) or incorrect sampling methods from rainwater tanks.

In general, the only contaminants in rainwater tanks are particles and microorganisms from the atmosphere (Kaushik *et al*., 2012), bird droppings or the roof catchment (Ahmed *et al*., 2012). Therefore, it requires minimal treatment before using it as drinking water. Many studies have even reported that rainwater can be a good quality drinking water source without any other treatment as long as the catchment and tank are managed well (Coombes *et al*., 2006; Lee *et al*., 2012).

There are several particle removal strategies used when collecting rainwater that maintain its quality in holding tanks. Specific examples are depicted in Figure 2.2 and are as follows.

1. Biofilm: biofilm inside the tank maximises microbial activities for self-purification (Kim *et al*., 2012; Kim and Han, 2013, 2014).
2. Calm inlet: to avoid re-suspension of sludge, inflowing energy is diverted upwards by using a two-elbow-type pipe, allowing the sediment to remain undisturbed.
3. Inlet barrier and drainpipe: sediment is kept in the first part of the tank, and from time to time it is drained away by opening a valve.
4. Floating suction: flower pollen can sometimes enter the tank and float on the water surface. By making the pipe inlet 10 cm below the water level, only clean water is collected.
5. Siphonic discharge: when the water exceeds a certain level, any scum floating at the surface is siphoned off.

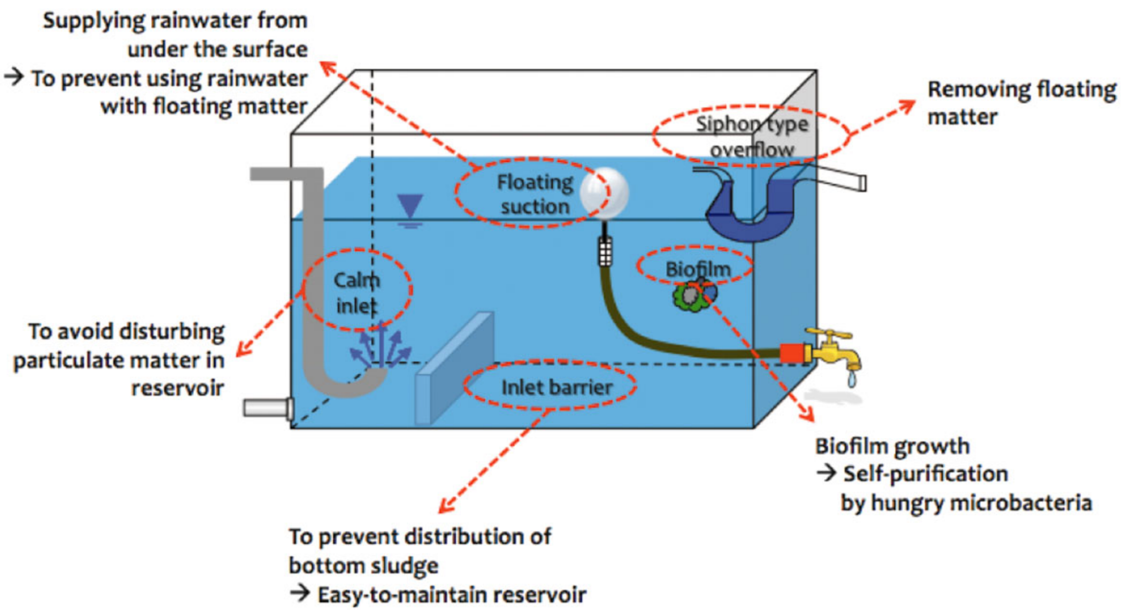

Figure 2.2 Technical innovation in particle removal (provided by Mooyoung Han).

Finally, a very useful method of removing possible pathogens from rainwater is solar disinfection (SODIS). This involves exposing rainwater in 2-L polyethylene terephthalate bottles in a solar collector to sunlight for about 4–8 hours. Complete disinfection can usually be achieved, even under weak weather conditions, by adding inexpensive food preservatives such as lemon and vinegar (Amin and Han, 2009, 2011).

2.1.2 TACKLING RAINWATER SHORTAGE IN DRY SEASONS

One of the barriers to using rainwater to its full potential is irregular rainfall distribution over a calendar year. Rainwater is not considered a reliable water source because of the shortage of precipitation during the dry season. Adding to this problem, in many rural areas, local rainfall data – which are an essential input for determining efficient system design – are not available.

To cope with water shortage during dry periods, systems can be carefully designed through simulation modelling (Mun and Han, 2012). Optimum tank volume can be calculated with catchment area mapping and the input of rainfall and water consumption data. Strategies to restrict water consumption based on the remaining water in the tank can then reduce the number of no water days (NWDs) that occur (Mwamila *et al.*, 2015). Another way to reduce water shortage is to develop a site-specific water supply system with dual sources: for example, rainwater for drinking purposes and groundwater for other domestic purposes at sites contaminated by arsenic (Nguyen and Han, 2014).

2.1.3 CHALLENGES AND CONSIDERATIONS IN RWH IMPLEMENTATION

RWH has long been a popular practice at small to medium scales, particularly in rural and peri-urban areas. Adoption rates for RWH practices are now rising in urban areas, and the scale of these solutions is increasing. According to Belmeziti *et al.* (2014), 15% of the inhabitants of France are connected to a RWH system. They investigated the quantity of potable water that can be saved by applying RWH to a large urban area, in this case the Paris agglomeration. Using geographic information system (GIS)-derived estimations of total rooftop area, annual precipitation and total water demand, they concluded that about 81 million m^3 per year – 11% of the area's potable water demand – can be replaced by rainwater for non-potable uses.

Biswas *et al.* (2009) conducted a similar study in Dwarka, and identified average potential water savings of 16.8% through RWH. The most effective areas in which to harvest and use rainwater are those that are densely populated because this maximises the ratio of inhabitants to rooftop area, allowing water to be used more fully if collection systems are efficient (Chanan *et al.*, 2010). However, these findings do not speak to the economic feasibility of full implementation; incentives often still need to be in place to encourage installation of RWH systems.

Historically, RWH has been most commonly implemented in arid and semi-arid regions because of the lack of freshwater in ground and surface water reserves, but climate change and population growth have resulted in the depletion of water resources in many humid regions that were formerly perceived as water rich. This has necessitated the use of RWH systems in areas such as the United States and Western Europe, and the additional benefits of runoff and peak flow reduction make these setups more attractive to businesses and municipalities. RWH also creates opportunities for decentralisation, as it can be used close to the source, reducing the need for large-scale treatment and distribution systems (DeBusk *et al.*, 2013).

De Busk *et al.* (2013) stated that automated RWH systems that withdraw water at regular intervals for specific end uses and are linked to a backup water supply are superior, as they prevent system overflow, decrease potable water demand and reduce or eliminate the labour needed in their operation. In addition to this, it is recommended to have an alarm or warning light that alerts users when a system malfunctions, water levels are low or potable water is being used in place of rainwater.

In areas that do not suffer from severe water shortages, there is sometimes a lack of incentive to implement RWH because the cost of implementation in these regions may exceed potential water savings – a problem that is exacerbated by subsidisation of water supplies. RWH systems also have limited efficacy if the collected water is not used. If systems are kept at capacity and not subject to regular withdrawals, overflow events will be prone to occurring and the system will yield fewer benefits (DeBusk *et al.*, 2013).

The responsibility of homeowners to clean and maintain their RWH systems is essential. In many parts of the world, it is common for houses to have rooftop RWH systems, but not all users take necessary safety measures. This mostly becomes an issue when the systems in question collect water for potable uses. A study by Stump *et al.* (2012) assessed the demographics and practices of household RWH system users in the United States and found that testing of water quality in the tanks was infrequent. In fact, the results of the study showed that 64% of participants never tested for contaminants in their rainwater tanks. Although these setups usually do have treatment systems suited to the expected end use, certain contaminants may persist, including lead, which can harm young children and foetuses, even in very small quantities. In the study by Stump *et al.*, lead was present in some of the collected samples, but the use of a first-flush device decreased concentrations significantly, suggesting that atmospheric deposition is occurring.

2.1.4 FUTURE OF RAINWATER HARVESTING

2.1.4.1 RWH as a tool to increase the resilience of urban water systems

Decentralised RWH has high potential in increasing the resilience of urban water systems. It can be used as a backup system when the water supply has temporarily stopped owing to a sudden power failure, pipe breakdown or natural disaster. RWH can also mitigate flooding without increasing the existing sewer capacity, and locally stored rainwater can be supplied for firefighting to extinguish fires in their early stages. Reducing potable water consumption from the main water supply by substituting rainwater for non-potable uses can also reduce the energy required to treat and distribute water, thereby reducing the carbon footprint of the whole network. Furthermore, when rainwater is used to supply clean water in developing countries, it contributes to the United Nations' Sustainable Development Goal (SDG) 6, ensuring availability and sustainable management of water and sanitation for all.

2.1.4.2 Multi-purpose RWH and management

Although there is growing global awareness of the benefits of RWH through successful RWH projects, more effort put into raising public awareness is needed in the form of more tangible incentives to promote the installation of RWH systems.

The main reason for the slow promotion of RWH is the economic feasibility; the cost of tap water is often too low to justify the initial setup costs of most RWH systems. This is true in most developed countries where water supply systems are generally very established and comprehensive. However, by taking into account other benefits such as flood mitigation and contingency planning, multi-purpose RWH systems can be seen as more economically feasible. The case of the Star City multi-purpose RWH system is an example, and will be discussed in greater detail in section 6.10.

Providing economic incentives such as subsidies, tax exemptions or equivalents may help to encourage RWH as a practice. Public awareness can be increased, especially among children, by offering environmental education in schools, and including information on water conservation, harvesting and reuse.

2.1.4.3 Rainwater management using IT

Seoul City announced a new regulation to enforce the installation of RWH systems in December 2004, a schematic of which can be seen in Figure 2.3. The main purpose is to mitigate urban flooding, and the secondary purpose is to conserve water. As a result, it aims to ensure the safety of the city and improve the wellbeing of citizens. As part of the programme, the city asks citizens to voluntarily cooperate by filling and emptying rainwater tanks according to directions from the disaster prevention agency.

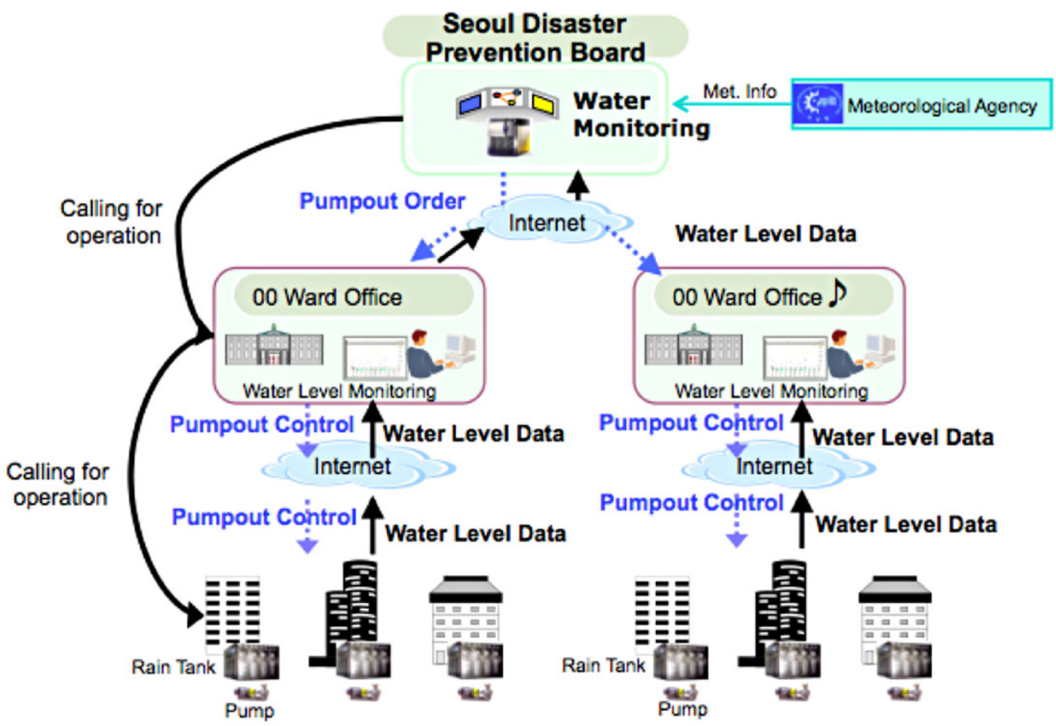

Figure 2.3 Monitoring of a multi-tank system for urban flood prevention and water conservation using IT (provided by Mooyoung Han).

A special feature of the new system is to provide a network for the monitoring of water levels in all water tanks by the central disaster prevention agency. Depending on the expected rainfall, the agency may issue an order to building owners to empty their rainwater tanks fully or partly. An incentive programme is in place for those who follow the government's instructions and there is some punishment for those who do not. After a storm event, the stored water can be used for firefighting and/or miscellaneous purposes such as toilet flushing and gardening.

2.2 STORMWATER COLLECTION AND MANAGEMENT

Stormwater runoff can also be collected for use, but treatment methods generally differ from those used in rooftop-harvested rainwater. Constructed wetlands (CWs) – consisting of vegetation, supporting substrate and living organisms – are a frequently used system both to treat and to store stormwater. Macrophytes facilitate the sedimentation of solids and remove certain pollutants from the water; water columns transport pollutants to active biological zones and provide ideal environments in which biochemical treatment processes can occur; and living organisms present in the wetland system aid in the transformation and recycling of some chemical substances found in stormwater runoff (Chanan *et al*., 2010). The added recreational and aesthetic value makes constructed wetlands ideal for urban areas where development has led to a loss of green space.

The collection of stormwater runoff can be an effective way to reduce flooding, stream bank erosion, water pollution, sewer overflow and other issues linked to increased runoff generation, and may even help to supplement the existing water supply. However, some experts warn that the over-extraction of stormwater can be detrimental to stream health and environmental flows. Stormwater collection regimes should be optimised both to meet urban water requirements and to restore the hydrological profile of the area to as close to pre-development conditions as possible (Fletcher *et al*., 2007).

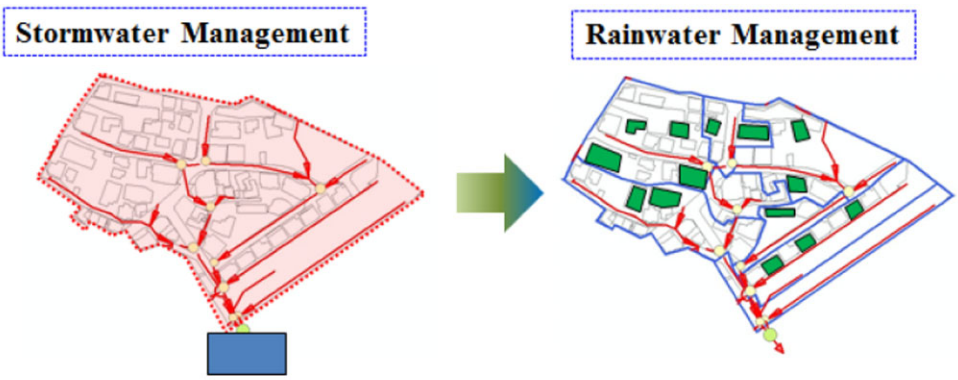

Figure 2.4 Differences in runoff pathways between water collected by storm drain and water collected by rooftop RWH. Collected stormwater passes over more impermeable surface area than rainwater, and therefore tends to have lower quality (provided by Mooyoung Han).

One of the barriers to collecting stormwater runoff – particularly in urban areas – is the high-level contamination that is generally present after it has passed over dirty, impermeable surfaces (Figure 2.4). For this reason, stormwater is generally only collected for non-potable uses (McArdle *et al*., 2010).

Both rainwater and stormwater can be used for crop irrigation, reducing potable-quality water use in agriculture. However, they must be used efficiently, as the collection of precipitation solely for irrigation can become problematic for several reasons. The first of these is the propensity for tanks to overflow and create runoff-related issues during non-growing seasons. Additionally, in many countries, the time of year when the most water is needed for irrigation is the time when the least precipitation is received. Therefore, rainwater for irrigation is best stored using large tanks with controls to enable the slow release of water, and to have a backup usage for the collected water to prevent overflow during rainy seasons (DeBusk *et al*., 2013).

2.3 INFILTRATION AND GREEN ROOFS

The encouragement of natural infiltration processes is a way in which many regions choose to manage stormwater. Not only does enhancing the infiltrative capacity of an area reduce peak flows, flood risk and runoff, but this process speeds up the recharge of aquifers, thus contributing to the usable freshwater supply. Low-impact development (LID) measures such as permeable pavements, infiltration galleries/trenches, bio-retention substrates and grass swales are popular and effective means of increasing infiltration rates.

Liao *et al.* (2013) completed a study comparing the efficacy of five different (mostly infiltration-based) LID methods in reducing peak flow and controlling runoff in urban sub-catchments with greater than 80% imperviousness. The methods included bio-retention, infiltration trenches, permeable pavers, grass swales and rain barrels. The results of the study are displayed in Figure 2.5, and suggest that infiltration trenches and rain barrels (i.e. RWH) are the most effective methods of reducing peak flow, and these two, as well as permeable pavers, are the most effective methods of reducing the runoff coefficient of sub-catchments.

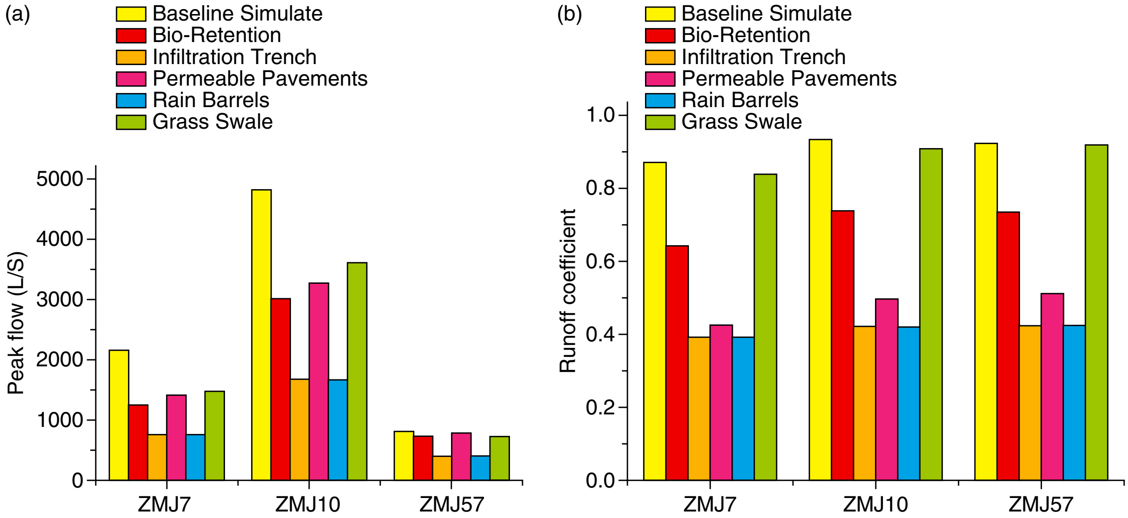

Figure 2.5 Effects of five different LID stormwater management techniques on peak flow and runoff coefficient (reprinted from *Water Science & Technology* 68 (12), 2559–2567 (2013) with permission from the copyright holders, IWA Publishing).

In some arid or semi-arid regions in which conventional RWH systems are not feasible, but greater water availability is needed for agriculture, infiltration-based *in situ* RWH practices may be used. These methods involve creating micro-catchments in farm fields as well as manipulating vegetation cover to reduce evaporation, enhance infiltration and increase the availability of water at the root zone. An example of such a method is the half-moons or *demi-lunes* pictured in Figure 2.6, which capture rainwater and keep it on the field (Vohland and Barry, 2009). Vohland and Barry (2009) performed a study on the efficacy of *in situ* RWH practices in sub-Saharan Africa, and found that these systems have an overall positive effect on infiltration, groundwater recharge, biomass production and soil water storage.

Figure 2.6 Man-made *demi-lunes* created in an agricultural field (Vohland and Barry, 2009).

Green roofs and urban farming do not actually infiltrate rainwater; however, they can reduce stormwater runoff. The heat island problem common in large cities can also be mitigated by the creation of vegetated green roofs, and some food can be produced in addition to the formation of a new community gathering space. A new paradigm of concave-type green roofs as part of the water–energy–food nexus is recognised, and has received several international awards.

3 WATER REUSE AND DESALINATION

3.1 WATER REUSE

Reusing water enhances potential for conserving existing freshwater resources, many of which are being used beyond sustainable levels. Additionally, water reuse could be a more reliable source than pumped surface and groundwater in some areas, as it is less sensitive to drought conditions and increased demand. Not only does this help to ensure the quantity of water in lakes, rivers and aquifers, but direct water reuse prevents the deterioration of water quality since the act of discharging wastewater into the environment can lead to the accumulation of persistent chemicals in water, flora and fauna.

3.1.1 POTABLE WATER REUSE

Recycling water for potable reuse is becoming increasingly popular. An important consideration in these uses is that the risk of illness from contamination be extremely low. All plants designed to reuse water – either directly or indirectly – should have additional redundancies in place to minimise the risk of distributing contaminants of concern (Rietveld *et al.*, 2011).

Indirect potable reuse (IPR) is the treatment of reclaimed water to drinking standards after it has been discharged into a surface or groundwater reservoir (Figure 3.1). Wastewater may undergo either advanced or basic treatment before reaching the environment, but thorough purification must occur before it is added to the community supply. The idea behind IPR is that discharging water into the environment first creates a buffer, as the processes of dispersion, infiltration and nutrient uptake by plants remove some unwanted contaminants (Leverenz *et al.*, 2011). It is commonly used around the world, and exists both in a planned and in an unplanned (*de facto*) capacity.

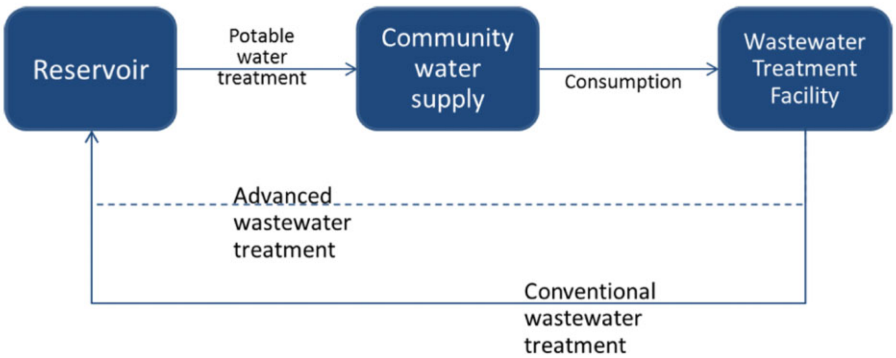

Figure 3.1 The pathway of water in IPR, which can use either conventional or advanced wastewater treatment processes (based on Raucher and Tchobanoglous, 2014).

IPR can produce high-quality drinking water and is an important resource option globally, but Leverenz *et al.* (2011) suggest that direct potable reuse (DPR) may be preferable, as fewer steps in the treatment process can save costs and energy, as well as reduce discharge of wastes to the environment. DPR involves treating reclaimed water to drinking standards and directly blending it with the potable water supply. In DPR, an engineered storage buffer (ESB) can be used in place of the environmental buffer used in IPR, but is not mandatory (Figure 3.2). Also, IPR may not be an option in all areas, as some communities do not have sufficient groundwater or surface water resources to behave as environmental buffers (Raucher and Tchobanoglous, 2014).

DPR of reclaimed water is often viewed as a promising resource option for the future. It reduces the strain on existing surface and groundwater sources and eliminates the need for a separate distribution system, which is necessary when reclaiming water for non-potable uses. DPR was first implemented in 1969 in Windhoek, Namibia (see section 6.6), and even at that time provided a safe drinking water supply (Drewes and Khan, 2015). Owing to the continual improvement of water treatment technology, it is possible to reduce the concentrations of harmful contaminants in water down to minute quantities that do not threaten human health. DPR may also be less expensive, less energy intensive and less complicated to implement than other water resource options because of the ability to reuse water locally rather than transporting it long distances (Leverenz *et al.*, 2011).

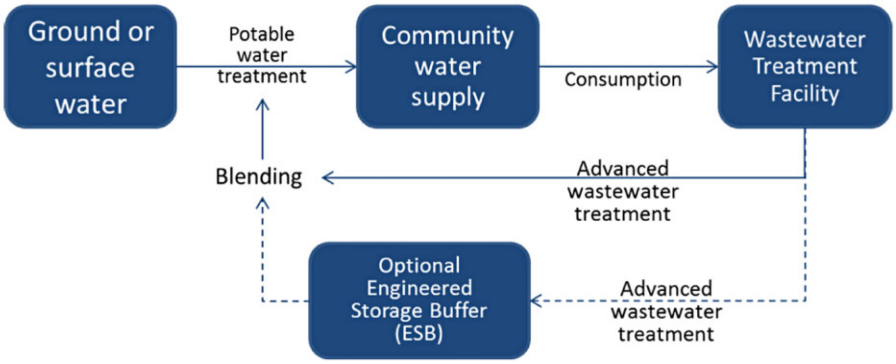

Figure 3.2 The pathway of water in DPR, which can operate without an ESB (based on Raucher and Tchobanoglous, 2014).

Whether potable reuse is direct or indirect, there are a few key elements of every water reuse project that must be incorporated into its design (Figure 3.3; Drewes and Khan, 2015).

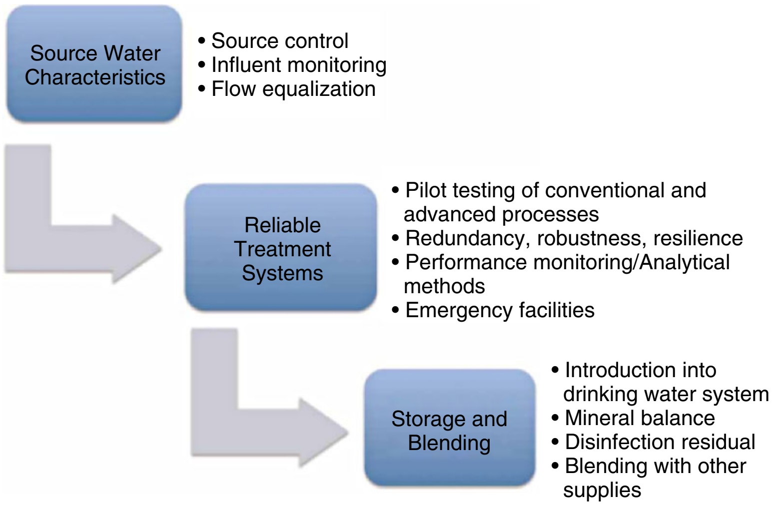

Figure 3.3 Key considerations in the planning and implementation of potable water reuse schemes (reprinted from *Journal of Water Reuse and Desalination* 5 (1), 1–7 (2015) with permission from the copyright holders, IWA Publishing).

Firstly, source water can vary widely its biological, chemical and mineral components, which is why it is important to know what kind of effluent is being discharged and how it is regulated. Full knowledge of source water quality is key in deciding on appropriate treatment methods, and therefore comprehensive water quality monitoring should be performed. More robust system reliability can be ensured by creating redundancy with multiple barriers, enabling the removal of a wide variety of contaminants and designing response plans to effectively mitigate system failures. After treatment, water must be stored or blended with other water supplies before distribution; making sure that quality is maintained until it reaches the consumer (Drewes and Khan, 2015).

One prominent challenge in water reuse – particularly potable reuse – lies in community acceptance; many people are inherently averse to drinking or using reclaimed water. Brown and Davies (2007) conducted a study assessing the community receptivity to water reuse in a region of Sydney, Australia, and found that peoples' aversion to water reuse increased as uses became more personal. Table 3.1 shows that the acceptance of rainwater for almost all practices is higher than that of greywater, with only 2% accepting treated greywater for drinking. Given that the study was performed in Australia – where issues of water scarcity are inherently well known – acceptance of water reuse practices may be even lower in countries with more abundant water supplies. Water professionals are making efforts to change the public's perception of reused water. As Louis van Vuuren of the National Institute of Water Research South Africa said, "Water should not be judged by its history, but by its quality" (Roux, 2013).

Use	Filtered rainwater	Treated recycled greywater
Drinking	28%	2%
Cooking	32%	3%
Showering	59%	13%
Washing clothes	69%	31%
Washing car	85%	77%
Rushing toilet	85%	87%
Watering garden	94%	95%

Table 3.1 Percentage of study participants who would be open to using either filtered rainwater or treated recycled greywater for several different end uses (reprinted from *Water Science & Technology* 55 (4), 283–290 (2007) with permission from the copyright holders, IWA Publishing).

3.1.2 NON-POTABLE REUSE

Non-potable reuse is an important application of reclaimed water, as it can substitute potable water, providing the same global supply. Potential uses of non-potable reclaimed water include agricultural irrigation, industrial processes, street washing, toilet flushing and landscaping. Diversifying non-potable water reuse practices and improving system efficiency may be key factors in conserving freshwater and meeting demand (Kalavrouziotis *et al.*, 2015).

3.1.2.1 Agriculture and Landscape Irrigation

One of the primary non-potable uses for reclaimed water is in agriculture. Reclaimed water may even improve agricultural productivity owing to the high nutrient content, and reducing costs spent on fertiliser while still producing a high crop yield. Carr *et al.* (2011) performed a case study on three different research sites in Jordan, in which recycled water was used for crop irrigation. The plant-beneficial nutrients that water was tested for were potassium, phosphate, sulphate and magnesium, and barley was the test crop being grown at each research site (Figure 3.4).

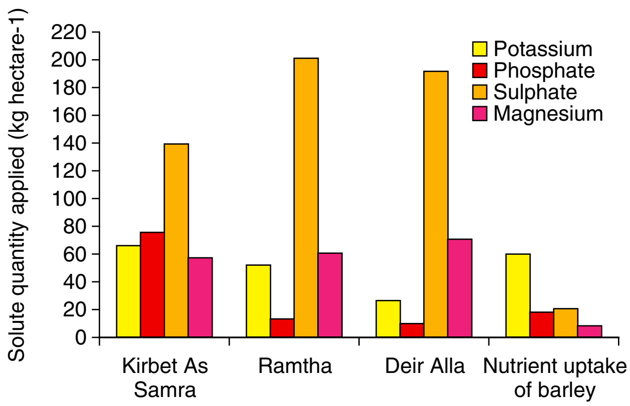

Figure 3.4 Quantity of each plant beneficial nutrient applied to three study fields – Kirbet As Samra (direct), Ramtha (direct) and Deit Alla (indirect) – compared with the average quantity of each nutrient that can be taken up by barley (reprinted from *Water Science & Technology* 63 (1), 10–15 (2011) with permission from the copyright holders, IWA Publishing).

The authors established that the nutrients found in reclaimed water were generally sufficient to meet the needs of farmers, sometimes with supplementary fertiliser needed. This allowed both the conservation of limited freshwater resources, as well as a reduction in fertiliser needs, allowing farmers to reduce costs. Carr *et al.* (2011) state that with the continual application of reclaimed water to agricultural fields, the potassium and phosphate content of soils can be enhanced, leading to increased productivity. However, excessive quantities of sulphate and magnesium in soils can reduce agricultural productivity; therefore these nutrients should be monitored carefully. An important condition is that farmers be well educated about the nutrient content of their irrigation water, so that they know how much – if any – fertiliser to apply to crops, thus maximising the benefits associated with reusing water for irrigation. Findings by the World Bank (2015) suggested that Bolivian farmers had a broad understanding of issues related to water reuse for agricultural irrigation, and consequently wished to take part in community efforts to increase agricultural water reuse.

Greywater can also be used for irrigation, but, like wastewater, it must undergo some treatment to remove oil, grease, surfactants and other compounds before it is applied to crops. This is because the use of raw greywater for irrigation can drastically change the soil properties, increasing the hydrophobicity of soil particles and eventually making the soil unfit for agricultural activities (Travis *et al*., 2010).

Reclaimed water also has potential uses in landscape irrigation, including parks, cemeteries, golf courses and other non-agricultural spaces. This helps to curb the excessive use of potable water for non-drinking purposes, especially in summertime. This water also generally does not need to undergo disinfection, therefore reducing energy requirements (Haering *et al*., 2009).

3.1.2.2 Industrial Use

Reclaimed water has extensive uses in industry because water quality guidelines tend to be less strict and the need for potable water is reduced or eliminated. Industrial processes that utilise reclaimed water include evaporative cooling, boiler feed, washing and mixing (Chartered Institution of Water and Environmental Management, 2012).

An example in which this has been implemented is the Gippsland Water Factory (GWF) in Australia, which treats domestic wastewater as well as that of a nearby pulp and paper mill. The facility uses primary sedimentation, anaerobic reactors, nutrient removal by activated sludge and reverse osmosis (RO). The GWF creates a drought-resistant water supply for industrial customers, and reduces the quantity/increases the quality of effluent discharged to the nearby regional outfall system (ROS) (Daigger *et al*., 2013).

Another good example of industrial water reuse is in Terneuzen, The Netherlands. The DOW Chemical manufacturing plant uses an integrated membrane system (IMS), consisting of continuous microfiltration and two-stages of RO. As a result, high-quality reclaimed water is produced using significantly less energy and fewer chemicals than would be used to desalinate seawater to the same quality (Rietveld *et al*., 2011).

An alternative method of reusing water in a mainly industrial setting is *cascading*, in which effluent from one industrial user is pumped directly to another; provided the effluent quality of the first user is higher than the mandated influent quality of the second. Thoren *et al*. (2012) performed a study looking at how water reuse potential could be maximised in Vancouver, Canada. Using water quality guidelines, influent and effluent volume and location of plants, they assessed three different scenarios to see which provided the greatest opportunity for water reuse at the lowest cost and energy expenditure. Since the guidelines in place require this water to be processed before it can be reused, cascading is not a cost- or energy-efficient reuse option unless satellite water reclamation facilities are situated in the centre of industrial areas to treat effluent from multiple users before it is reallocated. Expanding networks to include not only industrial users but also commercial, institutional and multi-family residential users would further increase the efficiency of the system and the quantity of water saved (Thoren *et al*., 2012). However, this type of scheme takes a decentralised approach to water reuse, which may not be in line with the goals of all decision-makers, who may display reluctance due to perceived risks and instead favour centralisation, which is more common in developed countries (Domènech, 2011).

3.1.3 GREYWATER REUSE

Both greywater and blackwater can be reclaimed for further use. However, since their compositions can vary dramatically, the treatment processes used must vary as well. Greywater can be defined as any water used in homes or office buildings excluding that which contains faecal matter. The main pollutants of concern in greywater are chemical contaminants from detergents, personal care products, bleaches and dyes. However, microbial contaminants are also a concern. While greywater has fewer microorganisms than does blackwater, the concentrations of heavy metals, nutrients and chemicals are often similar (Warner, 2006).

One challenge in treating greywater is the high variance in composition by source. Greywater collected from a kitchen sink or dishwasher may contain grease and animal fats, while water collected from a washing machine often contains tiny, non-biodegradable fibres from clothing. For this reason, it is vital to filter greywater first to remove fibres, cellulose and grease, and to change filters regularly to prevent clogging. Misinformation to homeowners can also become an issue, as monitoring and maintaining on-site greywater treatment systems is often left up to the owner, who may or may not have full understanding of the risks involved. If a system malfunctions or water is used for incorrect purposes, the consequences can be severe (Warner, 2006).

An example of how greywater can be integrated into a more complex system is the proposed "Green Village" at the Delft University of Technology, which aims to be an autarkic system through the use of efficient technology, greywater reuse and RWH (Figure 3.5). Built from 30 recycled shipping containers made into office spaces, dormitories, bathrooms, a lunchroom and a laboratory, the project stresses decentralisation and a "fit-for-purpose" water supply. Drinking water in the Green Village will come from 100% recycled sources: 53% from recycled greywater and 47% from rainwater. Greywater will be

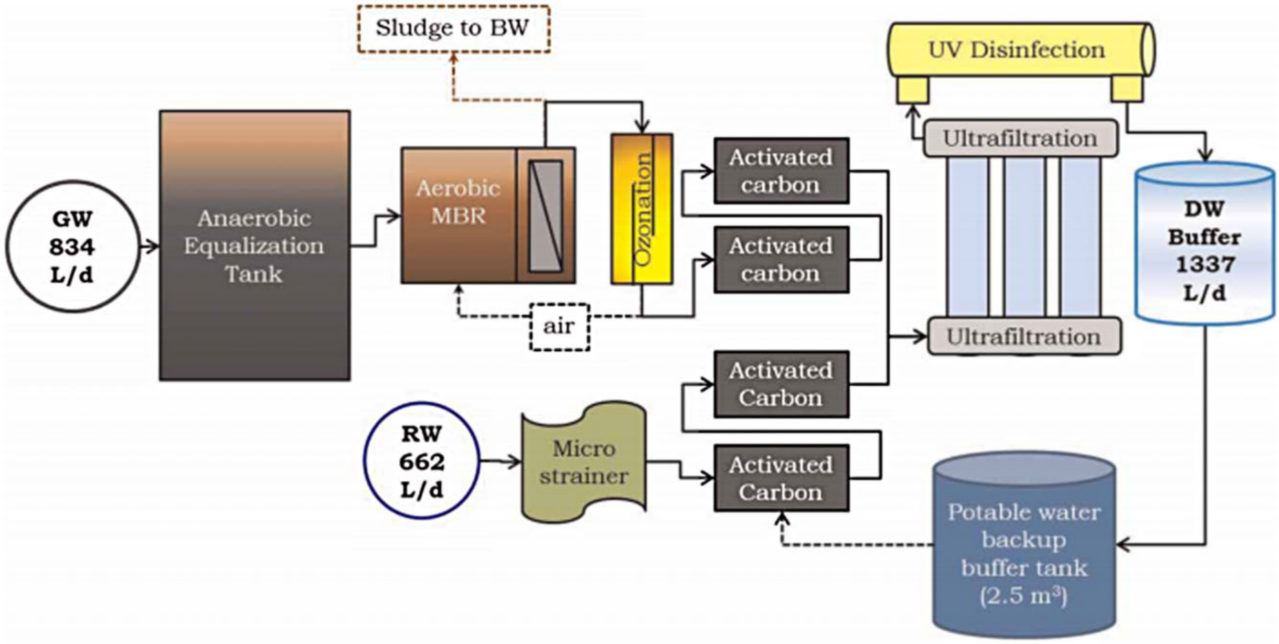

Figure 3.5 Treatment processes to be used in proposed Green Village at the Delft University of Technology (reprinted from *Journal of Water Reuse and Desalination* 4 (3), pp 154–163 (2014) with permission from the copyright holders, IWA Publishing).

subject to a triple barrier of ultrafiltration (UF), UV disinfection and ozonation, while rainwater will only be subject to UF and UV (van der Hoek *et al*., 2014).

The Green Village will utilise low water consumption appliances – including vacuum flush toilets requiring about 1 L per flush – and blackwater will be treated by an upflow anaerobic sludge bioreactor (UASB) to produce biogas, before being diverted to a vertical flow constructed wetland for secondary treatment (van der Hoek *et al*., 2014). It also aims to integrate various methods and principles of sustainable water management into one design. By limiting water consumption through water-saving devices, treating greywater and rainwater for drinking and other uses, and producing energy through anaerobic digestion of waste, the village can have an autarkic water supply and have a relatively small energy footprint. Van der Hoek *et al.* (2014) indicate that the addition of wind or solar energy would create an autarkic energy supply as well, but these aspects have not yet been incorporated into the project design.

There are an increasing number of regulations making a certain degree of reuse mandatory, particularly in very water-scarce countries. This can be seen in India, where the National Environmental Policy states that, as of 2006, all new buildings meeting a specific set of criteria must include a water recycling plant to help supplement the water supply. On top of this, smaller buildings are offered property tax credits to implement water reuse, even though it is not required by law (Barringer, 2014).

3.2 DESALINATION AND SALINE WATER USE

Desalination is thought to be able to either greatly reduce or completely eliminate water scarcity issues in arid and semi-arid regions (El Saliby *et al*., 2009). Coastal areas or those lying above saline groundwater reserves often have limited freshwater options, so making desalination technologies viable and accessible in these regions could help a high proportion of the global population to meet their water needs. Unfortunately, conventional desalination technologies generally still carry high costs in terms of money, energy and environmental damage, including greenhouse gas emissions, disruption of marine life in construction phases and at plant intake points, and the discharge of chemical-containing saline brine that poses risks to marine ecosystems (Lattemann and Höpner, 2008; Baten and Stummeyer, 2013). However, the process of desalination has become more sustainable and cost-effective over time, and new and emerging desalination methods may have the potential to increase the sustainability of the process further. Some experts even state that it is becoming possible to desalinate seawater using less than 2.0 kWh per cubic metre, a novel development (Macharg, 2011).

3.2.1 REVERSE OSMOSIS (RO)

In 2013, the total global desalination capacity was dominated by RO, which accounted for 59% of capacity (Ng *et al.*, 2013), and this market share is continually growing, as is the energy efficiency of RO technology (Baten and Stummeyer, 2013). Macedonio *et al.* (2012) list RO technology as the most promising among membrane techniques because it removes smaller contaminants – including some pharmaceutical compounds – and carries a smaller carbon footprint than many other desalination technologies. Its drawbacks lie in the large number of joints and connections in the process, the need for additional pre-treatment and post-treatment stages to ensure adequate system performance, and the removal of certain minerals that may actually be desired in drinking water (Macedonio *et al.*, 2012). Mogheir *et al.* (2013) suggest that improving the pre-treatment process using nanofiltration (NF) could both improve water recovery rates and prolong the life of RO membranes by reducing scaling and fouling.

RO plants discharge brine that is 100% more saline than the influent concentration, but is the same temperature as seawater. This is in contrast to multiple-effect distillation (MED) and multi-stage flash (MSF) desalination plants, which discharge brine about 15% more saline than seawater, but 5°C to 10°C warmer. Of these two factors, increased temperature has greater negative impacts on marine ecosystems. Therefore, despite the high salinity of RO discharge, it is more environmentally sound (Al-Karaghouli and Kazmerski, 2013).

RO desalination is also described as being more cost-effective than thermal desalination methods by several experts. Wittholz *et al.* (2008) completed a cost comparison of the most common desalination methods, including MSF, MED and RO, and both the capital costs and operating costs of the RO technologies were lower (Figure 3.6), which bodes well for the implementation of desalination in lower-income countries.

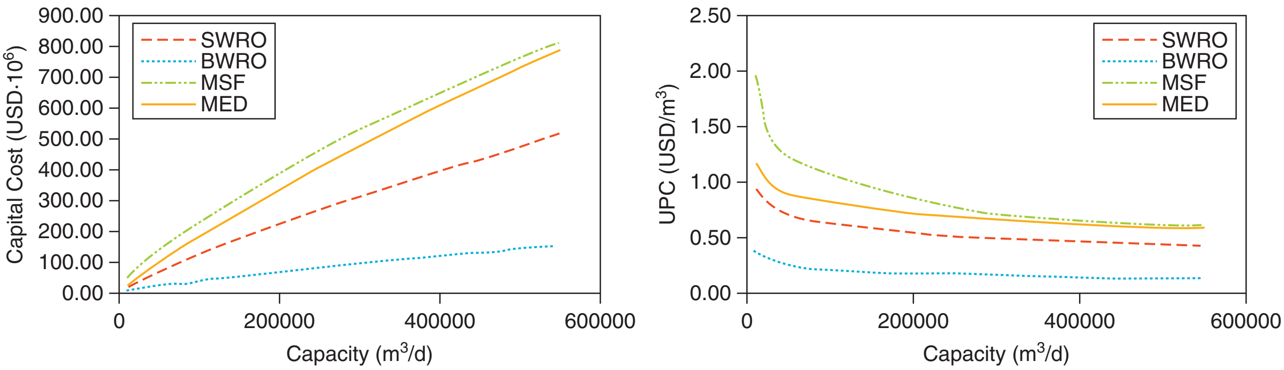

Figure 3.6 Capital and per unit costs of desalinating water by four different methods (Wittholz *et al.*, 2008).

3.2.2 OTHER NON-THERMAL DESALINATION

Although RO is currently the most widely used non-thermal desalination technology – as well as the most commercially viable – many other promising non-thermal methods exist.

Ghyselbrecht *et al.* (2013) report that electrodialysis (ED) technology is becoming increasingly popular owing to its ability to recover ions in the process, and according to Turek (2003), ED can be as cost-effective as RO. However, the cost of ED is directly proportional to the feed water salinity, so it may be infeasible for salt water above a certain concentration.

Membrane distillation (MD) harnesses low temperature heat sources (renewables or waste heat), using minimal chemical treatment and electrical energy. Several types of MD exist, including direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), air gap membrane distillation, and finally, vacuum membrane distillation (VMD), which tends to have a higher flux rate and lower susceptibility to fouling than other types of MD (Ramezanianpour and Sivakumar, 2015).

With the use of VMD technology, low temperature thermal energy is supplied in the first stage of the process, followed by several stages of evaporation and condensation (Mendez, 2012). VMD has removal efficiencies of close 100% for all major parameters of concern, and remains effective with increasing feed water salinity methods (Ramezanianpour and Sivakumar, 2015).

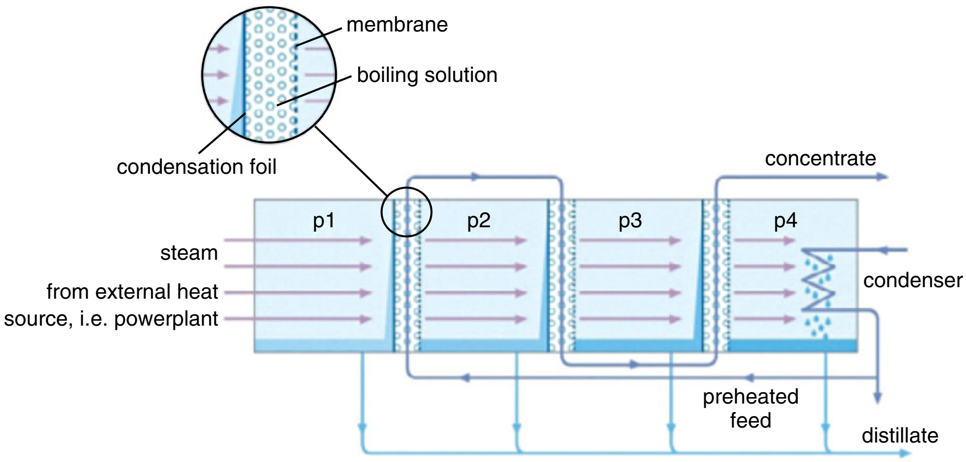

Figure 3.7 Aquaver MD desalination unit (Mendez, 2012).

Mendez (2012) states that VMD (Figure 3.7) is a low maintenance technology, and is prone to minimal scaling and fouling, resulting from low temperature heat utilisation and hydrophobic membranes. This type of technology may be especially important in off-grid locations where conventional energy and reliable freshwater sources are not accessible. The application of low temperature heat provides an opportunity to couple the technology with waste heat rejection streams or renewable energy, increasing its sustainability (Kempton *et al*., 2010).

Another form of non-thermal desalination is forward osmosis (FO), which uses a highly concentrated solution to draw feed water through a membrane. Since the technology uses osmotic pressure instead of hydraulic pressure – as is used in RO – it requires less energy. Membranes are also subject to less scaling and fouling than in RO, especially combined with microfiltration (MF) pre-treatment (Venketeswari *et al*., 2014).

There is evidence that coupling different membrane processes may produce a higher-quality end product, while reducing or eliminating effluent brine (Macedonio *et al*., 2012). Given the promising aspects of both VMD and FO technologies, Li *et al.* (2014) tested the efficacy of a combined FO/VMD system on highly saline shale gas drilling flow-back fluid. Using the two mechanisms consecutively – first FO with a KCl draw solution, then VMD – water recovery rates of 90% efficiency were achieved, minimal scaling and fouling occurred, and the resultant discharge had a quality resembling bottled water, despite the initial poor quality of the feed water (Li *et al*., 2014).

3.2.3 THERMAL DESALINATION

Even though thermal techniques tend to be more energy intensive, with higher costs and greater environmental footprints than non-thermal methods, they are still widely used; mainly in MENA countries (Macedonio *et al*., 2012). However, an increasing number of studies demonstrate the benefits of cogeneration or polygeneration by combining thermal desalination with energy generation as a way to reduce energy use, cost and by-product waste. According to Gude *et al*. (2010), when a MSF desalination plant is connected to a power plant, the specific energy required to produce freshwater is significantly lower. This was demonstrated in Kuwait, where a stand-alone MSF plant used 290 kJ/kg of energy to produce freshwater, compared with 160 kJ/kg when connected to an energy generation plant.

Similarly, Maraver *et al.* (2012) released a study assessing the viability of a polygeneration configuration to create three useful end products: energy from biomass, desalination and cooling. The proposed system has three main subsystems: an organic Rankine cycle (ORC) engine, a MED plant and a lithium bromide-water simple effect (LBSE) absorption chiller. The system is ideal for isolated areas in which freshwater availability is poor, but algae, energy crops or residual biomass can be found easily, such as islands. The authors deemed this it to have a high fuel energy savings ratio (FESR) and predicted that the resultant cost savings could equal installation costs in 4–20 years depending on the type of biomass used.

Hybrid desalination methods combine both thermal and non-thermal processes, and generally include RO desalination combined with MSF or MED. The most common and feasible setup is a RO-MSF plant, which requires lower monetary and energy inputs and achieves higher water recovery rates than each process individually, owing to coupling of both thermal and electrical energy sources. RO can be easily integrated into existing MSF plants, reducing the need for large capital investments (Gude *et al*., 2010). According to Karagiannis and Soldatos (2008), MSF seawater desalination plants can reduce costs by up to 15% by incorporating RO, and many studies have found the combination of thermal and non-thermal desalination methods to improve performance, cost effectiveness and water recovery rates.

3.2.4 SALINE WATER USE

Saline water can also be used directly – usually for toilet flushing – without the need for desalination. An example of this is in use in Hong Kong, where extreme freshwater scarcity has led to the implementation of a dual water supply, which uses freshwater for potable uses and seawater for toilet flushing. According to Leung *et al.* (2012), this dual system has been in place since the 1950s, serves 80% of Hong Kong's inhabitants and has resulted in a 20% reduction in total water demand. Seawater is treated with chlorine to prevent microbial growth in the pipe system, distribution pipes are lined with cement mortar, and long-lasting polyethylene pipes are used indoors. Seawater's lack of discernible colour or odour makes it widely accepted by residents and tourists in Hong Kong. The one prominent issue with this system is that the saline concentration of the effluent drastically limits water reuse options.

Saltwater is also being used in Qatar for evaporative cooling and humidification in greenhouses. This allows the crops' freshwater requirements to be minimised, but supports high yields and reduces the need to desalinate water, thus minimising the carbon footprint of the whole project (Sahara Forest Project, no date).

3.2.5 DEVELOPMENT ON LOW-ENERGY DESALINATION

In all forms of desalination, expenditure on energy – either thermal or electrical – makes up more than half of the total operating budget, and the majority of desalination plants worldwide use fossil fuels to meet their needs (Baten and Stummeyer, 2013). This not only leads to high volumes of greenhouse gases being emitted, but as fossil fuels become scarcer, their increasing prices may make desalination prohibitively expensive. Therefore, the future sustainability of desalination will be influenced by the ability to increase efficiency in the processes, harness renewable energy sources (Baten and Stummeyer, 2013) and/or recover energy, which can be recaptured from high-pressure pumps (Macharg, 2011).

Renewable energy can be a controversial topic because many of these sources – such as solar photovoltaic (PV), concentrated solar power (CSP) and wind – have fluctuating availability (von Medeazza, 2004). Also, depending on the technology, renewable energy-powered desalination can be significantly more expensive than where conventional fuel sources are used (Table 3.2). However, these costs tend to decrease with time and technological innovation, and the environmental benefits provide an incentive to use renewable energy regardless of cost (Gude *et al.*, 2010).

Water type	Desalination system powered by (112 3 renewable energy source
Freshwater	Tankers to remote areas
Brackish water	Conventional energy + RO. HD
Brackish water	Photovoltaic energy + RO
Brackish water	Photovoltaic energy + ED
Brackish water	Wind + RO
Brackish water	Wind + ED
Brackish water	Geothermal + MED
Seawater	Conventional energy + RO, ED, MSF, MED, VC
Seawater	Photovoltaic energy + RO
Seawater	Wind + RO
Seawater	Wind + VC
Seawater	Solar thermal + MED
Seawater	Geothermal + MED

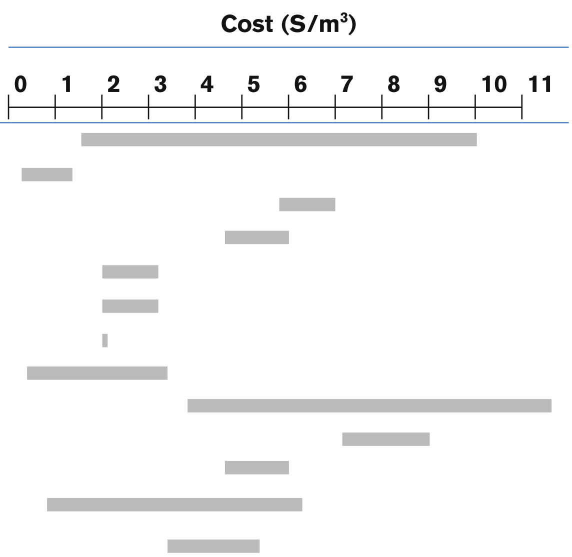

Table 3.2 Cost comparison (in US dollars) of various desalination methods coupled with either conventional or renewable energy (Gude *et al.*, 2010).

Solar stills may be ideal for remote areas with extreme water scarcity and limited access to electricity, since they have been in use for many decades and are simple to construct, although these may not be viable on a larger scale. Solar multi-effect humidification (MEH) units have greater capacity and are still relatively simple. The largest operation using this technology has been functioning in Dubai, UAE since 2008, and consists of a 156 m^2 plant (Al-Karaghouli and Kazmerski, 2013).

There also exist several viable systems that couple renewable energy with conventional desalination processes, such as PV-powered RO or ED desalination. Although they require minimal energy to function, they are relatively high-cost options; most accessible to wealthy countries. Wind power can be coupled with RO or mechanical vapour-compression (MVC) technology, and works well in remote areas, but must either have a control system in place to smooth out fluctuations in wind patterns, a backup battery, or additional freshwater storage capacity (Al-Karaghouli and Kazmerski, 2013). Park *et al.* (2012) state that the development and application of better energy buffering methods has the potential to improve the viability of renewable energy membrane technology, and provide more reliable water supplies in areas where connecting to an energy grid is infeasible.

4 DEMAND MANAGEMENT AND WATER LOSS REDUCTION

In conventional water management scenarios, the usual response to increased water demand – driven by population and income growth – has typically been to increase groundwater and/or surface water extraction rates. This has resulted in environmental degradation and the overuse of several freshwater resources. Controlling demand so that less water is used is a more sustainable option, and consequently, many municipalities and utilities use methods for achieving this result (Table 4.1), such as economic incentives, water-saving technologies, metering, awareness campaigns and leak reduction. In general, demand management either incentivises the conservation of water resources or provides ways to use less water without altering lifestyle. Measures that control demand tend to be less expensive, less energy intensive and carry smaller environmental footprints than AWR technologies that actually augment supply (Grant, 2006). This section will explore ways in which this is possible.

Level of intervention	Mechanism
Policy	Utility credits for implementing stormwater management, RWH, water reuse and other best practices for water cycle management
	Financial incentives, tax exemption and other advantages offered on water-saving appliances and/or use of AWR
	Certifications offered on eco-efficient homes and buildings (water/energy management)
	Amendment of building codes to include conservation/demand management measures
	Availability of free water efficiency/use diagnoses for homes and businesses
	Implementation and enforcement of regulations on water use and withdrawal
	Publication of technical documents on best water-demand management practices, made available to public
Supplier	Installation of meters throughout entire distribution network or for selected users
	Appropriate volumetric pricing structure to ensure fairness and full cost recovery
	Implementation of efficient tools and methodologies for leak detection and repair
	Training and education for staff on demand management
	Public education and awareness campaigns
	Application of operational efficiency measures
Consumer	Installation of water-saving devices
	Participation in water conservation-related education programmes and workshops
	Increased awareness of water use habits
	Regular monitoring and system assessment to detect leaks and/or other damages
	Timely repair of leaks and damaged devices and plumbing
	Conservative and responsible outdoor water use, particularly in summer months
	Substitution of low or non-water using practices in place of water intensive practices where possible
	Use of AWR where possible

Table 4.1 Demand management strategies for varying levels of intervention.

4.1 ECONOMIC INCENTIVES

There are a few ways in which economic incentives can be used to reduce water demand and which are generally quite effective. They include raising water prices towards full cost pricing, offering rebates on water bills for installing certain water management best practices or offering direct rebates on water-saving appliances (Biswas *et al.*, 2009). Many places in the world still have subsidised public water supplies, where the true cost of production is not reflected in the price paid by consumers. This leads to the gradual dilapidation of infrastructure due to lack of revenue, and incentivises wastage (European Environment Agency, 2013). In general, higher water prices tend to correspond to lower usage rates and vice versa (Figure 4.1). Also, higher prices do not tend to influence demand for drinking water, but excessive uses such as car washing and filling swimming pools are decreased (European Environment Agency, 2013). Therefore, re-evaluating municipal water pricing structures may be one of the first steps in managing a country's water demand.

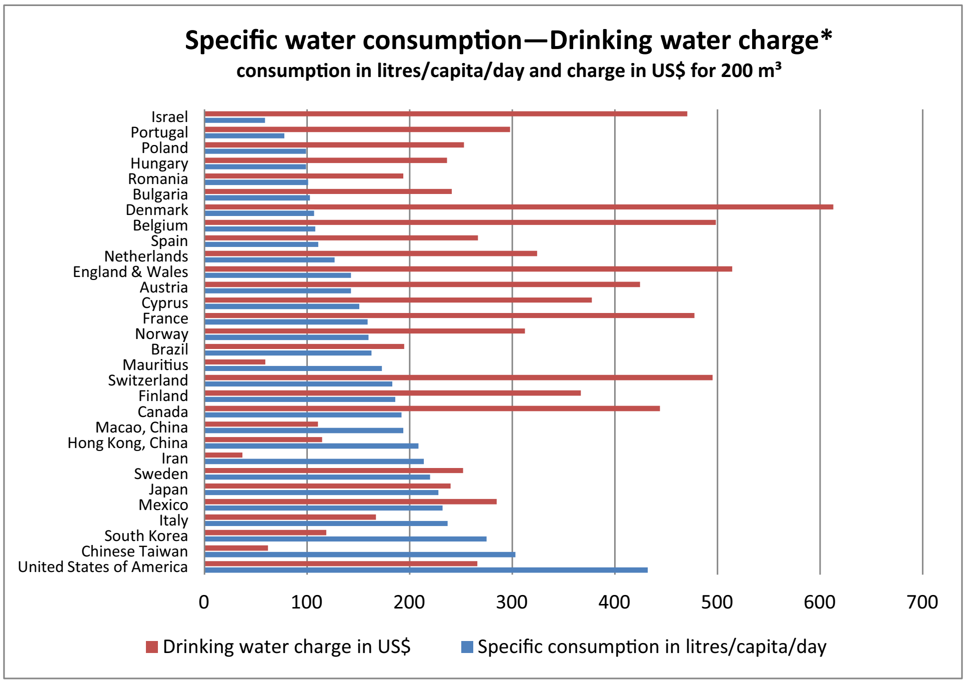

Figure 4.1 Comparison of water pricing versus consumption in select countries (International Water Association, 2014).

An important consideration when looking to create a more equitable pricing scheme is the type of fee structure, of which many exist. Households may use between one third and one half less water when they are metered and charged by volume rather than by a flat fee, regardless of the actual prices (Brandes *et al*., 2010; European Environment Agency, 2013). However, not all volumetric pricing schemes are created equal, and they can lead to different outcomes. Different types of variable charge pricing structure are summarised in Table 4.2.

Structure	Description	Comment
Uniform rate	Price per unit is constant as consumption increases	Targets all users equally; simple to calculate bill
Inclining block rate	Price increases in steps as consumption increases	Targets high volume users; requires more complex calculating for billing
Declining block rate	Price decreases in steps as consumption increases	Charges low volume users the highest rate; typically used where utilities want to provide large industry with a lower cost of service
Excess use rate	Price is significantly higher for any consumption above an established threshold	Can be used to target high consumption during peak periods; more effective with frequent (e.g., bi-monthly) meter reading
Seasonal surcharges	Price is higher during peak periods (i.e., summer)	Targets seasonal peak demand; tied to the higher marginal costs of water experienced during peak periods
Zonal rates	Users pay for the actual cost of supplying water to their connection	Discourages difficult-to-serve, spatially diffused connections
Scarcity rates	Price per unit increases as available water supply decreases (e.g., during drought)	Sends strong price signal during periods of low water availability; an alternative to outdoor watering restrictions
Lifeline block	A first block of water is provided at low or no cost beyond the fixed charge to ensure everyone has a minimum amount of water to meet basic water needs	Used to address equity issues and ensure that all consumers' basic water needs are met

Table 4.2 Existing types of volumetric water use fee structure (adapted from Brandes *et al*., 2010).

Inclining block structures tend to discourage excessive wastage and unnecessary water uses such as lawn watering and car washing, but some argue that it is unfair to large families and goes against the UN declaration of water as a basic human right, which is why lifeline block structures have been implemented in some areas (Brandes *et al*., 2010). However, at this point, there still does not seem to be any one single fee structure that can satisfy all consumers.

Molinos-Senante (2014) proposes a dynamic pricing structure combining an inclining block rate (IBR) with additional peak-load pricing (PLP) to conserve water resources in the seasons when water is most scarce, prevent excessive use in the tourism sector and obtain full recovery of all costs incurred in the acquisition, treatment and distribution of water services. The author felt that, in addition to meeting the stated goals, the dual pricing system could create more equitable distribution of costs among users and reduce consumption in the tourism sector.

A similar incentive programme was implemented in central California, where inclining block pricing structures were applied to an irrigation district to reduce consumption, as well as saline interflow to the San Joaquin River. Crop-specific pricing tiers were set on the basis of past data of average irrigation depth, and information was made readily available to farmers. The programme was effective in reducing irrigation depth, and in general, support of the pricing structure was high from those involved, suggesting that farmers do respond to economic incentives (Wicheins, 2006).

Colorado Springs Utilities (CSU) in the United States took a similar approach by introducing an inclining block rate structure with price increases every five years (Figure 4.2). They also offered rebates for implementing conservation measures and invested in public education; aiding in the acceptance of fee increases. Included in this were media campaigns, community meetings and call centres to answer questions or complaints. With the combination of these factors, the programme reduced consumption by an average of 13%, despite population growth, and was generally accepted by the public (Water Research Foundation, 2015).

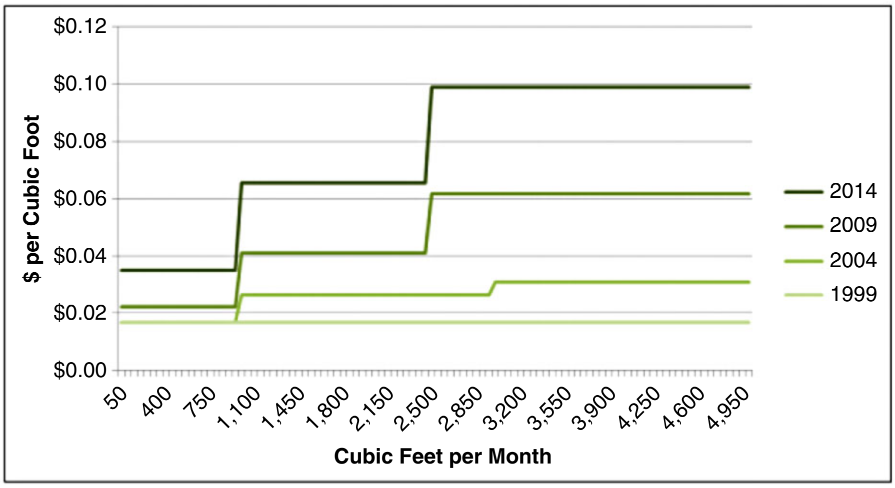

Figure 4.2 Colorado Springs Utilities (CSU) inclining block rate structure and fee increases (Water Research Foundation, 2015).

4.2 WATER-SAVING TECHNOLOGIES

Water-saving technologies can be installed at multiple scales, from households to large commercial and industrial buildings, and include low flow toilets, faucets and shower heads, and water-efficient washing machines and dishwashers, etc. The idea behind implementing these technologies is to allow users to consume less water without altering their lifestyles.

The city of Albuquerque in the United States implemented a rebate programme for water-saving appliances and practices, which helped to significantly reduce water demand in conjunction with small price increases and an awareness campaign. After implementation of the rebate programme – between 1996 and 2009 – total water demand decreased by 16% (Price *et al*., 2014). Furthermore, Price *et al.* (2014) were able to determine which water-saving device had the biggest marginal impact on consumption (Table 4.3): low-flow toilets had the greatest effect, followed by efficient washing machines and dishwashers.

Change in water use (AWU) due to low-flow device.					
Rebate	**AWU (%)**	**AWU (Gal/Dav)**	**Single device AWU (Gal/Dav)**	**Rebate value ($)**	**Device lifespan (vrs)**
LFT 1	–12.86	–37.98	–37 98	200	25
LFT2	–14.78	–46.87	–8.89 (LFT2-LFT1)	400	25
LFT3	–14.78	–60.36	–13.49 (LFT3-LFT2)	600	25
SH/LFT1	–16.26	–46.69	–8.71 (SH/LFT 1-LFT 1)	210	10
WM	–3.32	–30 43	–30.43	100	12
DW	–4.87	–17.84	–17 84	50	10
XS (100 ft^2)	–0.84	–3.08	–3.08	75	25

Table 4.3 Change in water use due to specific water-saving devices, including low-flow toilets (LFT), water-efficient showerheads (SH), washing machines (WM) and dishwashers (DW), and xeriscaping (XS) (Price *et al.*, 2014).

Water saving methods and technologies also have extensive applications in agriculture, and may include water-saving irrigation, limited irrigation and dryland cultivation. Respectively, these methods use less water while achieving the same or higher yield; induce deficits in the soil-water balance during non-critical growth periods, and then irrigate during essential stages; and rely on the efficient capture and usage of rainwater in areas beyond existing irrigation networks (Deng *et al.*, 2006).

Specific methods of improving water use efficiency (WUE) include selective irrigation to restrict watering to critical stages of plant growth, crop rotation, intercropping, application of animal manures to enhance soil fertility, or mulching, which decreases soil evaporation and evapotranspiration, as well as increases in grain yield and WUE. The application of chemical fertilisers has been shown to double grain yields and therefore WUE, although this can cause chemical loading to water bodies via runoff (Deng *et al.*, 2006; Tischbein *et al.*, 2013).

A paper by Deng *et al.* (2006) examined the best water-saving irrigation methods, many of which used harvested rainwater. Among these are root-zone drip irrigation and under-mulch irrigation. To illustrate, traditional practices such as furrow and border methods use water at a rate greater than 7,000 m^3 per hectare, whereas drip irrigation uses just over 3,000 m^3 of water per hectare, while achieving the same or similar yields.

There also exists a variety of smart sensing technologies to limit the use of water for gardening and irrigation in particular. Some of these technologies include the following.

- WaterSense irrigation controllers: devices that use local weather forecasts to determine when and how much to water plants (United States Environmental Protection Agency, 2015).
- Soil moisture sensors: sensors placed in the soil to measure the soil water content and control the irrigation system accordingly (United States Environmental Protection Agency, 2015).
- Rain sensors and shutoff devices: these devices sense when it is raining and shut off irrigation systems (United States Environmental Protection Agency, 2015).

4.3 WATER LOSS REDUCTION

Water losses can occur at every stage of the water cycle; extraction, treatment, distribution and usage, and comprise real and apparent losses. The former includes leaks and pipe bursts, while the latter includes unauthorised consumption and customer metering inaccuracies. These, in conjunction with authorised, unbilled consumption make up non-revenue water (NRW) (Trow and Farley, 2006), the global annual volume of which is conservatively estimated at 50 billion m^3 (Liemberger, 2009).

If utilities can reduce NRW through identification and appropriate billing, the cost savings are potentially huge, allowing utilities to greatly increase their income to cover the additional repair, replacement and monitoring costs. This also reduces the need to invest in additional infrastructure or technologies for augmenting the water supply because the existing supply will be able to satisfy more of the present and future demands (United States Environmental Protection Agency, 2013).

Water loss reduction can often be the least expensive and most effective method of ensuring the adequacy of the water supply. For example, in the 1980s, UK utility North West Water invested over 200 million pounds in a project to augment supply, only to experience a mere 2% increase in available water. However, by controlling their leakage – which accounted for 35–40% of the total water in the network – they were able to greatly increase the supply of available water with minimal spending (Waldron, 2001). This section will explore the best practices for ensuring that water loss is kept to a minimum.

Leak management has two main types, active and passive (reactive). Passive leakage management occurs in response to incidents such as pipes bursting or drops in pressure. Active management includes leakage monitoring and regular surveying of the whole distribution system. The active method is preferable, as it results in fewer losses, but sometimes resources do not allow for this kind of strategy. When assessing a system's water losses, a water balance should be conducted to indicate how much water is being lost and where it comes from. Table 4.4 shows the components of a water balance, including water losses and NRW. However, methods for carrying out a water balance vary in different countries, making international comparisons difficult (Trow and Farley, 2006).

<table>
<tr><td rowspan="4">System input volume (corrected for known errors)</td><td rowspan="2">Authorised consumption</td><td>Billed authorised consumption</td><td>Billed metered consumption (including water exported)
Billed un-metered consumption</td><td>Revenue water</td></tr>
<tr><td>Unbilled authorised consumption</td><td>Unbilled metered consumption
Unbilled un-metered consumption</td><td rowspan="3">Non-Revenue Water (NRW)</td></tr>
<tr><td rowspan="2">Water losses</td><td>Apparent losses</td><td>Unauthorised consumption
Customer metering inaccuracies</td></tr>
<tr><td>Real losses</td><td>Leakage on transmission and/or distribution mains
Leakage and overflows at utility's storage tanks
Leakage on serv ice connections up to point of customer metering</td></tr>
</table>

Table 4.4 Components of a water balance (Trow and Farley, 2006).

To solve this problem, IWA developed a performance indicator (PI) called the infrastructure leakage index (ILI), to allow international comparisons of real losses. The ILI uses several parameters, including the condition of the facility's infrastructure, leakage, and pressure management and leak repair programmes (Trow and Farley, 2006). To calculate ILI, the current annual real losses are divided by the unavoidable annual real losses (UARL), which is the smallest amount of water that can be lost from an efficient, well-maintained system. The adoption of the ILI by utilities around the world is an indicator both for its accuracy and applicability as an international standard. An ILI value lower than 2 means that the current real losses are less than twice the unavoidable losses; systems with such ILI values are generally considered to be a very efficient (Delgado, 2008).

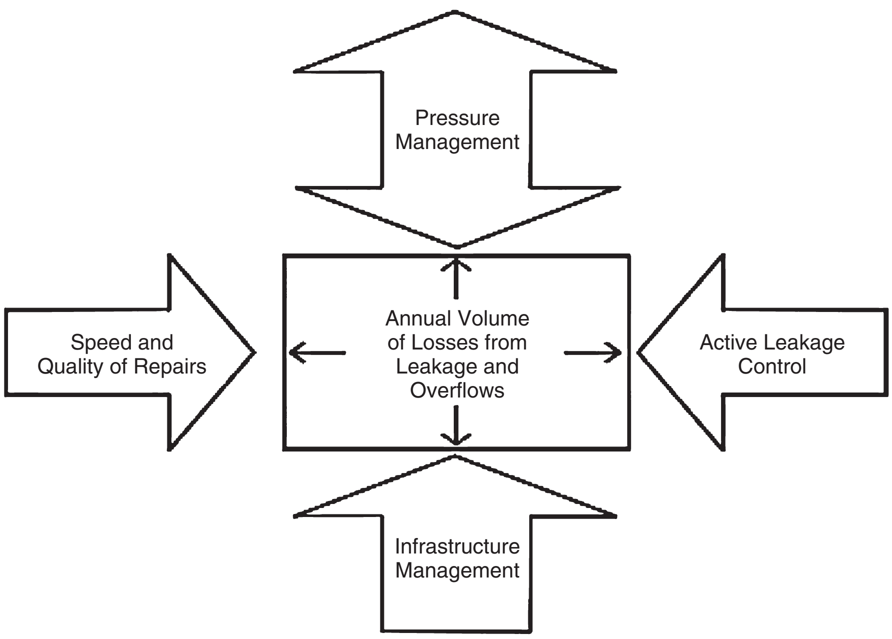

Figure 4.3 Four pillars of leakage management (Trow and Farley, 2004).

IWA also developed four main pillars of leakage management (Figure 4.3). The pillars include pressure management, speed and quality of repairs, infrastructure management and active leakage control, each of which have diminishing marginal returns in reducing the volume of losses and leakage (Trow and Farley, 2004).

Perhaps the most important of these four pillars is pressure management, as more water can be quickly saved through this method than any other. Controlling pressure in distribution systems can be extremely efficient at reducing leakage, and do so at a low cost; most pressure management programmes have payback periods of less than two years. Types of pressure control include flow-modulated control, time-control and fixed-outlet control, and the best method to use is dependent on the supply system in question and the funds available. A strong example of large scale water loss reduction with pressure management is the Khayelitsha installation in South Africa, the implementation of which resulted in annual water savings of 9 million m^3; a 40% decrease in average daily flow (7th World Water Forum, 2015).

It should be noted that direct comparisons cannot always be made between percentages of water loss reduction. Consumption of water can vary enormously owing to the weather, making a percentage leakage rate appear to double or half during extensive periods of rain or droughts. Water supply systems carry inherent differences in size, demand and complexity; two utilities expressing the same percent reduction in losses may have had varying levels of success. Therefore, care must be taken when using percentages for such comparisons, and it is wise to also have an alternative figure to compare, such as litres per property per hour, litres per length of water mains, and ideally showing the ILI value.

The existence of water losses can be proved with a combination of smart metering, district metering and bulk metering systems. Integrating these data allows utilities to quantify leakage with relative accuracy and analyse night flow rates to improve water loss reduction strategies. Loureiro *et al.* (2014) achieved this by using select district metered areas (DMAs) as case studies and collecting hourly customer data from meters, then using algorithms to determine which components were apparent losses, assuming that real losses stayed fairly constant. They were also able to detect pipe bursts and illegal water use this way (Figure 4.4). Using the collected data to improve their understanding, the authors were able to make targeted efforts to reduce losses by an average of 10% in the studied DMAs.

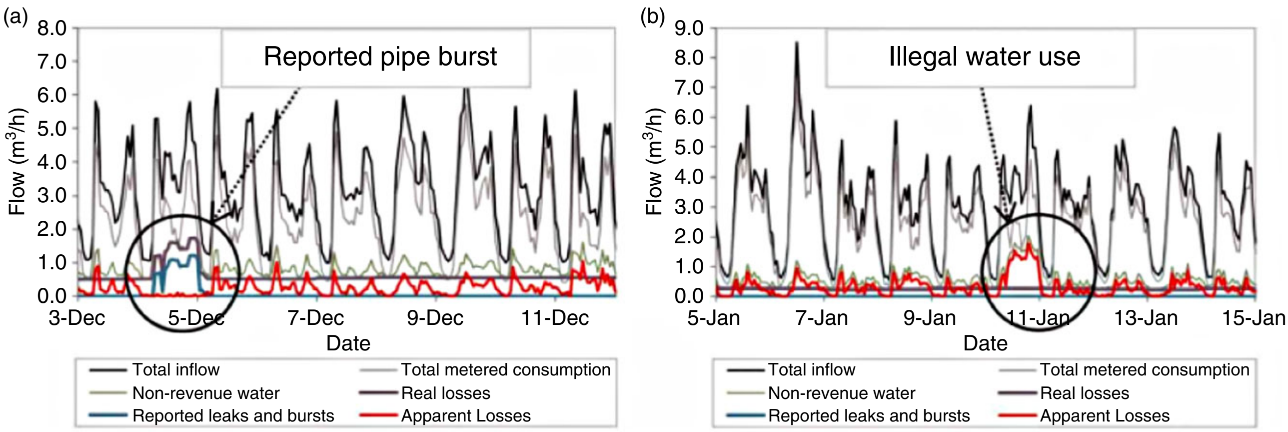

Figure 4.4 Flow profiles of a chosen DMA, modelled to detect illegal water use and pipe bursts (reprinted from *Water Science & Technology: Water Supply* 14 (4), 618–625 (2014) with permission from the copyright holders, IWA Publishing).

A promising technology for monitoring and reducing real losses in water distribution systems is the implementation of automatic meter reading for service pipes, which automatically collects consumption data and transfers it to a central database, eliminating the need to manually check meters, which can be time-consuming and lead to more wastage. automatic meter reading may also allow for more accurate detection of leaks that may not otherwise have been found, as well as precise estimations of leakage from night-time flows. The common practice of estimating night-time leakage has been the subject of criticism, with some experts stating that it lacks accuracy. The provision of hard data and accurate minimum night flow (MNF) values to utilities is invaluable in calculating losses, detecting leaks and creating greater efficiency in systems (Waldron, 2007).

In a study by Mun *et al.* (2008), a comprehensive water loss management strategy was implemented in Korea, in a city with high rates of water loss due to poor management, old, dilapidated pipes, and a revenue water ratio of only 55%. The main methods adopted to reduce water loss were the following:

1. introduction of a block zoning system;
2. pipe rehabilitation/replacement;
3. pressure control.

The zoning system – in which the whole service area is divided in large blocks, then again into medium and smaller blocks – helps to make the system easier to monitor and maintain. Each block is monitored for pressure as well as water quality and quantity, and leaks can be more easily identified and repaired. It also provides an additional element of control in emergencies, as problem locations can be isolated. The second method used in the management strategy was pipe rehabilitation and replacement. 50 km of pipe, as well as all water meters and valves were replaced owing to leaks, blockage or corrosion.

The third and most critical element of the Korean case study was pressure control, in which valves were installed according to the range of initial pressure to have maximal efficacy. Mun *et al.* (2008) isolated the effects of pressure control, and found that this step alone led to a 25% decrease in water production and a 10% increase in the revenue water ratio. Figure 4.5 shows the effect of the entire programme over a 2-year period on the revenue water ratio, which increased from 55% to 70% between 2004 and 2006.

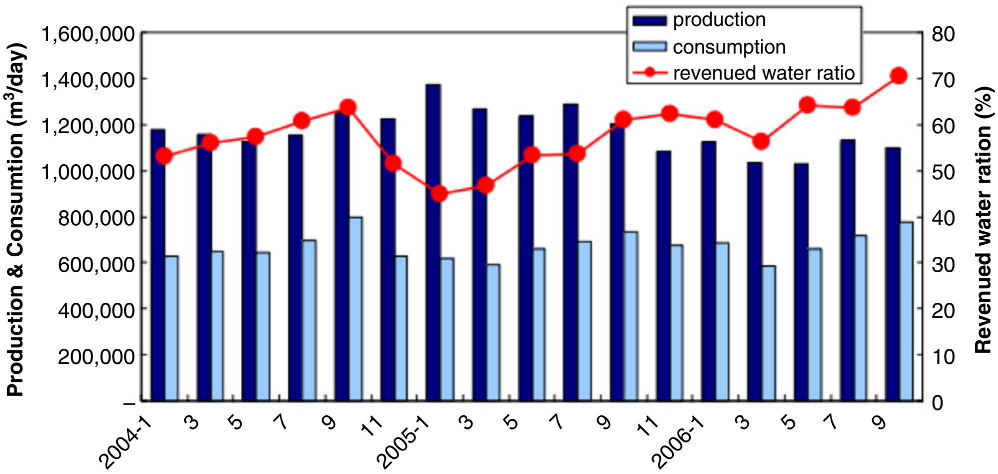

Figure 4.5 Production, consumption and revenue water ratio in the study location of Mun *et al.* (2008) from the beginning of 2004 to the end of 2006 (reprinted from *Water Practice & Technology* 3 (2), 1–7 (2008) with permission from the copyright holders, IWA Publishing).

It is important to consider socio-economic factors when creating strategies, as low- and middle-income countries account for about 70% of total water losses worldwide. According to Liemberger (2009), South and Southeast Asia have some of the highest rates of water loss in the world. In India especially, most water utilities experience intermittent supply, sometimes for only 3–5 hours every few days. Even with this lack of continuous supply, water loss rates are extremely high owing to poor maintenance and degraded infrastructure. Therefore, even if supply were to become continuous, NRW would be so high that the total supply would not be improved.

Another factor at play is the type of water loss taking place and in what proportion. Some utilities have higher volumes of unbilled commercial losses due to corruption, theft or poor metering, than physical losses due to leakage, and vice versa. Water loss reduction strategies should include investment in infrastructure repair and maintenance, as well as meter installation and incentives to reduce theft and unbilled consumption. There also exists a lack of data on water losses, especially in developing countries, and therefore data collection should be the first course of action in developing a management strategy (Liemberger, 2009).

Unfortunately, methods of reducing water losses can be very expensive, sometimes prohibitively so. It is not uncommon for governments and utilities to invest minimally in ageing infrastructure: a short-sighted approach that leads to greater costs in the future. A prominent example of this is Montreal, Canada, which loses 40% of water in the supply system every year because of dilapidated infrastructure. A third of the city's water pipes have already reached the end of their useful lifespan, and the other two-thirds are predicted to reach this point within the next 20 years (Fraser Institute, 2010). Despite the poor state of Montreal's water system, the city has yet to implement the steps necessary to change it because of the **4 billion Canadian dollar investment** that would be required to upgrade infrastructure (Fraser Institute, 2010). Further exacerbating the issue is the lack of installed meters and the flat fee pricing structure, subsequently creating a lack of revenue for water utilities. Implementing pricing structures that accurately reflect the cost of production may be a step in the right direction in terms of reducing water losses, but would probably be met with disapproval from residents who have grown accustomed to paying the current rates.

In general, water-loss reduction strategies must

- be tailored to the specific location of the water supply system;
- be well integrated into surrounding systems;
- be forward-thinking with a willingness to invest in long-term sustainability;
- take into account the economic, social, political and environmental factors of an area.

By taking these steps, more holistic and effective water-loss reduction strategies can be achieved (Schouten and Halim, 2010).

4.4 OPERATIONAL EFFICIENCY

Operational efficiency refers to the output to input ratio of water treatment processes, and an important pillar of water management is the development of strategies or technologies that will enhance this efficiency. This can include implementing technologies that emit fewer waste products, forming partnerships to create economies of scale or a greater range of expertise, and improving supervisory control and data acquisition of water supply systems. One way of ensuring better operational efficiency is the use of proper cleaning and maintenance of treatment systems. Too frequent cleaning can result in unnecessary wastage, whereas infrequent cleaning results in poor performance and clogging. Monitoring effluent turbidity or hydraulic head loss and then cleaning when necessary allows systems to perform optimally without wasting resources on over-cleaning. Air scour systems and air/water backwash systems are both efficient technologies for cleaning filtration systems (United States Environmental Protection Agency, 2013).

Operational efficiency can also be enhanced through improved storage capacity. Issues often arise because of discrepancies in water needs between seasons, for example, periods of highest rainfall also tend to be periods with the least water demand, and vice versa. With conventional above-ground storage methods such as tanks and reservoirs, overflow, contamination and diminished quality over time are potential problems. Aquifer storage and recovery (ASR) – in which treated water is introduced to aquifers for storage until later use – is a way of overcoming this while maintaining the water table, reducing the risk of contamination and ensuring adequate water supply in times of high demand or supply interruption (Niazi *et al.*, 2014). ASR especially improves operational efficiency for desalination and water reuse because it allows for steady energy use, removing the need for large variations that can result in wastage (Ghaffour *et al.*, 2013).

4.5 EDUCATION AND AWARENESS

Education and awareness of environmental and water scarcity issues can be powerful tools in reducing water demand. Examples of this include school-level water conservation programmes, radio and TV messages and information in mail-outs, workshops or newspaper advertisements. This is a mechanism that, even if it does not create permanent demand reductions on its own, can be incorporated fairly easily into any demand management strategy with very little downside.

Fielding *et al.* (2013) performed an experimental study to test the effects of various education-based interventions on household water demand in Australia. The average daily water use for all groups decreased during and immediately after the intervention period. Unfortunately, all groups returned to pre-intervention levels of water use by 12 months after the interventions ceased, suggesting a need for additional measures. Fan *et al.* (2014) also state that if users do not have accurate perceptions of their own water use, education campaigns and other demand management strategies may be less effective, and therefore awareness campaigns that allow consumers to realise their own consumption patterns are likely to be more successful.

Water metering is an indirect demand management tool that may help to enhance awareness of water use. Water meters allow the existence of leaks to be proved, and enable utilities to implement per unit, volumetric pricing structures, which incentivise more conservative water use (see section 4.1). Finally, when a consumer can see how much water is being used, the increased awareness may promote more sustainable consumption patterns (Beal *et al.*, 2011). Studies have shown that the installation of water meters leads to water savings of between 10 and 30%, and can be as high as 50% (Biswas *et al.*, 2009).

4.6 COMBINED DEMAND MANAGEMENT SOLUTIONS

Some demand management mechanisms are stronger than others, and additional benefits can generally be accrued by combining several strategies in one jurisdictional area. Table 4.5 compares the demand management strategies of various locations, and the average reductions in water demand that were achieved.

Location	Pricing	Metering	Water saving devices/ methods	Water loss reduction	Education & awareness	Legislation	Average Reduction	Study
Canada	●	●					43%	Brandes *et al.* (2010)
New Mexico, USA			●				16%	Price *et al.* (2014)
China			●				56%	Deng *et al.* (2006)
South Africa		●	●	●	●		~42%	Buckle (2004)
India		●	●		●		8-20%	Biswas *et al.* (2009)
Australia					●		6-15%	Fielding *et al.* (2013)
Colorado, USA	●		●		●	●	13%	Water Research Foundation (2015)
Portugal		●		●			10%	Loureiro *et al.* (2014)
South Korea				●			25%	Mun *et al.* (2008)
Guelph, Canada	●		●		●		18%	City of Guelph (2013)
Windhoek, Namibia	●		●		●	●	35%	Sharma and Vairavamoorthy (2009)

Table 4.5 Comparison of different demand management case studies and their associated water use reduction.

Some other examples of countries which manage demand effectively are the following.

- Singapore, whose NRW expressed as percentage of system input volume is less than 10%. They use economic incentives, comprehensive education programmes and conservation measures to reduce demand for water resources (Sharma and Vairavamoorthy, 2009).
- The UK, whose leak reduction programmes managed to reduce leakage by close to 30% between 1994 and 2009. Also, promotion of water-saving household devices, along with awareness campaigns, has kept per capita consumption relatively low (Sharma and Vairavamoorthy, 2009).
- South Africa, whose active leakage control programme and retrofitting of public and domestic buildings has reduced water demand (Sharma and Vairavamoorthy, 2009).
- France, where the province of Brittany used education campaigns, letters to residents, leakage monitoring and water-saving devices to control water demand both in public and in private systems, achieving water savings of between 14 and 79%, depending on the user (Sharma and Vairavamoorthy, 2009).

Unfortunately, developing countries are generally less well suited to benefit from demand management strategies because of lower income, dilapidated infrastructure, reduced elasticity of demand for water and lower institutional capacity.

An important concept in the integration of demand management solutions is that of different orders of scarcity. The first of these is physical scarcity, in which there is physically not enough freshwater to meet the needs of the population. Second-order scarcity refers to scenarios in which the water supply is not physically scarce, but contamination, poor management or inefficient use makes a significant quantity of the resource unusable; this is technological or institutional scarcity. Third-order scarcity refers to the social, political and cultural dimensions of water scarcity; the perceived abundance of water leading to overuse or habitual high-consumption lifestyles. Just as these three orders of scarcity are different, so too are their potential policy responses, listed in Table 4.6 (Wolfe and Brooks, 2003).

Order of scarcity	Dominant discipline	Responses
First	Engineering	Supply-side projects (dams, pipelines, canals, wells, desalination)
Second	Economics	Demand-side management; water as an economic good; technical fixes
Third	Social sciences within biophysical limitations	New options and reallocation, technological change, 'water-soft' paths

Table 4.6 Overview of the three orders of scarcity, the dominant disciplines applicable to them and their response options (adapted from Wolfe and Brooks, 2003).

The goal of third-order scarcity responses is to shift societal norms away from high consumption lifestyles and make conservation practices standard. This reallocation of resources in favour of conservation is called a 'water soft path', the implementation of which is becoming more popular in resources management. These practices can be difficult to implement, but naturally curb demand and increase the sustainability of water use, and should be integrated with policies addressing first- or second-order scarcity where needed (Wolfe and Brooks, 2003).

5 TOWARDS RELIABLE AND SUSTAINABLE WATER SUPPLY SYSTEMS

There is a growing need for reliable and resilient water supplies that use the highest efficiency use of alternative and conventional water sources in conjunction with minimised energy use.

In financial sectors, a "portfolio" management concept is used, which aims to mitigate risk by spreading it between several different resource options (Paydar and Qureshi, 2012). In the case of water management, a similar concept of the "portfolio" approach could be considered, which means utilising water from a variety of different sources – some of which should be hydrologically independent – to create a more robust supply. A comprehensive understanding of both hydrological and economic concepts is crucial when using this kind of approach. Portfolio-based water management projects should aim not only to effectively manage the water supply but also to increase environmental sustainability, use energy efficiently and yield social benefits.

The portfolio approach bears some resemblance to integrated water resources management (IWRM), but the two are not one and the same. IWRM covers a broader form of water management that "promotes the coordinated development and management of water, land and related resources to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership, 2012). While this may include using a portfolio approach, it is not mandatory, as IWRM plans may focus on a single water source within the scope of its main principles.

Regardless of whether or not approaches to water management are categorised under portfolio management or IWRM, they should aim to create more reliable and sustainable water supply systems.

5.1 CONSIDERATIONS AND EXAMPLES

Each potential AWR carries challenges, and with those challenges, possible solutions (Figure 5.1). It should be noted that lakes, rivers, reservoirs and groundwater can also be treated as "alternative" water resources, but Figure 5.1 aims to summarise the resource options discussed in Chapters 2–4. Water trading/transfers may also be necessary in some parts of the world, particularly in the case of droughts, disasters or other extreme events, but these are not included in the scope of this paper. There are many more potential problems and solutions inherent in AWR than are depicted in Figure 5.1, but, to simplify the visual representation, only more prevalent concerns were included.

The presence of these challenges inherent in each water supply option makes diversifying water supplies even more crucial. Combining multiple options creates redundancies in the system, reducing the risk of having insufficient freshwater supplies or issues of public health.

The monetary and energy costs of all possibilities should also be considered, to assess the feasibility of certain options against the available funds and energy sources; then a varied portfolio can be built out of these options. Table 5.1 provides a generalised comparison of the average monetary and energy costs of several water resource options used worldwide. Figure 5.2 depicts a visual representation of the same information.

China and other Asian countries have begun using AWR in an integrated approach, and have seen improvements in socio-economic conditions, environmental health and water scarcity factors. Wang *et al.* (2014) modelled three potential future scenarios for the Tongzhou district in China – business-as-usual, planning-oriented and sustainable development – to predict their effects on local industry, GDP and water scarcity. The first two scenarios used only groundwater and surface water to meet demand, whereas the sustainable development scenario met half of its demand with reclaimed water and incorporated water transfers as well. Under the business-as-usual scenario, the total water demand in 2020 was predicted to be about 366 million m^3, while in the sustainable development scenario it was 375 million m^3. However, even though this scenario's total water demand was slightly higher, it met almost half of its demand with reclaimed water, and experienced the greatest GDP increases due to a strengthened tertiary sector, and more efficient water use in the primary sector.

California is a prominent example of a water portfolio that is currently being expanded to respond to scarcity. In 2015, California implemented mandatory usage cuts of 25% below 2013 levels to utilities after voluntary reduction targets in 2014 were not met (Bluefield Research, 2015). As of the end of 2014, 45 regions in the state had implemented comprehensive integrated water resources management (IWRM) plans, with more planned (California Department of Water Resources, 2015). In January 2015, over US$850 million was allocated to planned and current water reuse and desalination projects to shift demand away from surface and groundwater supplies. While reuse and desalination have been slow to take hold in California because of high costs and community opposition, drought pressure has increased the market potential and public acceptance of both sources (Bluefield Research, 2015).

Figure 5.1 Simple 'mind map' depicting AWR options (blue), some general challenges (green) associated with each category and potential solutions (purple).

Resource option	Average Electrical energy equivalent per m³	Average Cost per m³	Source(s)
Surface water	~0.36 kWh (Worldwide)	US$0.0003–0.40 (Asia)	Gude *et al.* (2010); Zhu *et al.* (N.D.)
Groundwater	0.14–0.24 kWh (Worldwide)	US$0.05–0.07 (Asia)	Gude *et al.* (2010); Zhu *et al.* (N.D.)
Brackish water RO	1.22–1.62 kWh (North America)	US$0.26–1.05 (North America, Europe)	Gude *et al.* (2010); Raucher and Tchobanoglous (2014); Karagiannis and Soldato (2008)
Seawater RO	2.0–4.5 kWh (Worldwide)	US$0.75–1.89 (North America)	Gude *et al.* (2010); WateReuse Association (2012); Raucher and Tchobanoglous (2014); Cornejo *et al.* (2014); Macharg (2011)
MSF desalination	13.5–25 kWh (Worldwide)	US$0.80–2.00 (Australia)	Gude *et al.* (2010); Wittholz *et al.* (2008); Cornejo *et al.* (2014)
Potable euse	0.84–0.92 kWh (North America)	US$0.66–1.62 (North America, Africa)	Raucher and Tchobanoglous (2014); Lahnsteiner and Lempert (2007)
Non-potable reuse	0.27–0.42 kWh (North America)	US$0.25–1.59 (North America)	Raucher and Tchobanoglous (2014)
Rainwater harvesting	0–0.1 kWh (Worldwide)	US$0–0.20 (Vietnam, Tanzania)	Kim *et al.* (under review)

Table 5.1 Comparison of the average per unit costs and energy requirements of acquiring groundwater, surface water and several AWR options.

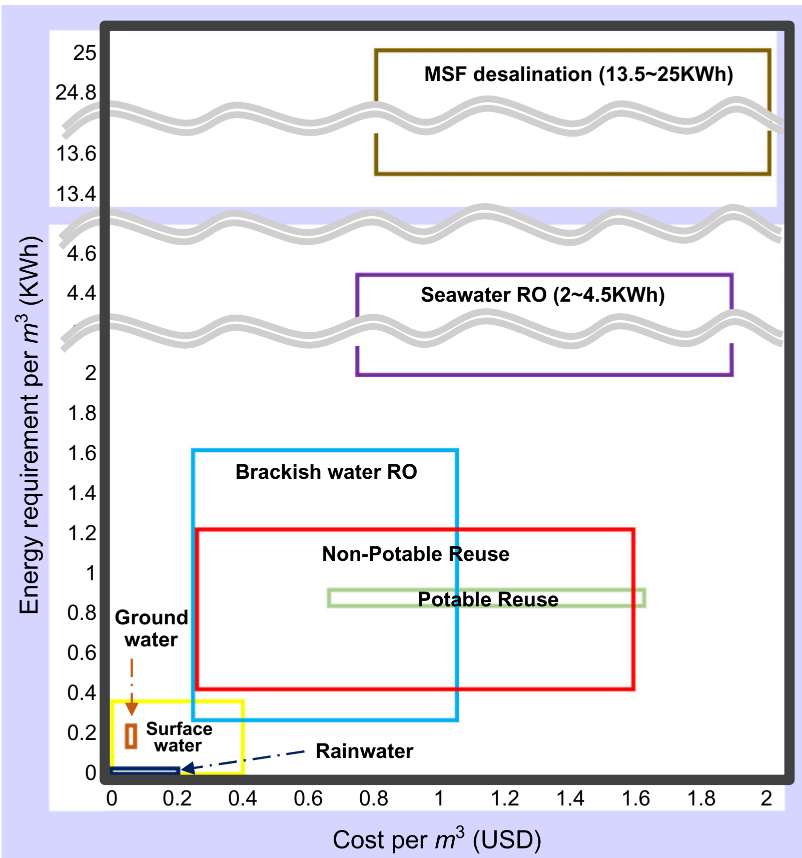

Figure 5.2 Unit cost and energy consumption for various AWR (provided by Mooyoung Han).

5.2 INFLUENCING FACTORS IN WATER SUPPLY SYSTEMS

To create integrated solutions to issues of water scarcity and resource use, all relevant factors must be taken into account, including environmental, social, economic and political/institutional aspects. A central goal of sustainable water management is to reduce the likelihood of scarcity, so it must include day-to-day water use provisions, as well as contingency planning for droughts.

5.2.1 ENVIRONMENTAL FACTORS

Environmental aspects influencing water portfolio decisions may be difficult to identify, quantify and manage. Factors such as greenhouse gas emissions, effluent discharge, ecosystem fragility, biodiversity, water pollution, salinisation of aquifers and many other related issues must be considered.

To ensure that minimal environmental damage occurs, a comprehensive environmental impact assessment (EIA) must be completed to assess all possible locations, scales and technologies, taking into account water demand and environmental factors. With this information, parties can determine the operational procedures that will best alleviate the relevant region-specific water concerns. Projects must also be performed with proper accounting of the energy requirements to see how these fall in with national (or international) commitments to energy and emissions production, or other environmental agreements, as well as a thorough understanding and integration of the water–energy nexus (Schreiner *et al.*, 2014).

5.2.2 SOCIAL FACTORS

Social factors affecting water use may be overlooked in favour of economic factors, but they are extremely important. First and foremost, decision makers must remember that clean water is a basic human right, as designated by the United Nations, and this cannot be ignored (United Nations, 2014). All efforts must be made to make water for drinking and sanitation available to all people. The ethical dimensions of water management extend also to the role of women, who in many countries are the main users of domestic water, are more susceptible to waterborne diseases than men, and must fetch water for their households (United Nations, 2005). In regions where women are more heavily affected by water management decisions, their opinions, ideas and welfare should be of central focus.

Another important dimension of the social factors of water portfolios is the existence of social norms affecting local behaviour. In many developed countries, the “myth of abundance” – which leads people to believe that there exist more than sufficient natural resources to satisfy human needs – is deeply rooted in the prevailing mind set, reducing the likelihood that the majority of people will engage in certain conservation behaviours. Societies in which children have been raised to understand that water is a scarce resource that must be conserved are more likely to have low per capita water demands and to respond to demand management strategies. These attitudes also have a significant effect on whether or not water reuse can be implemented, since without public acceptance, such projects are unlikely to be successful. However, these attitudes are unlikely to change quickly, and may take time to be effective.

5.2.3 ECONOMIC FACTORS

Economic factors are often a strong consideration for decision-makers when managing the water supply, as finances can be a highly limiting factor, particularly in the early stages of a project, when potential economic benefits have not yet been accrued. Therefore, these factors may often determine whether a project can be implemented.

Before a project can be implemented, a comprehensive cost–benefit analysis (CBA) must be completed. The CBA must take into account both the capital and operational costs of the development, the potential economic benefits such as job creation, environmental improvement, reductions in water acquisition costs from other sources, and a strategic life-cycle assessment (LCA) of the proposed project against other potential water supply options (Schreiner *et al.*, 2014). Perhaps the most difficult aspect of assessing the costs and benefits of water supply projects is the act of environmental valuation, which can be highly subjective. Valuing ecosystem services and recreational uses of the environment often require indirect valuation methods and discounting on future values, and may not take into account positive and negative externalities. Therefore, these calculations must be done carefully, and assign appropriate value to natural environmental entities.

5.2.4 POLITICAL/INSTITUTIONAL FACTORS

Good governance and policy strongly support the implementation of good water management, but legal and institutional constraints to portfolio management must be addressed. Legislative processes may be lengthy, with multiple steps involved, which can inhibit approval of AWR-based projects. These projects can also fail because of stringent guidelines regarding water reuse or other similar processes. Therefore, when choosing water supply options, the local guidelines must be kept in mind so that time and funds are not wasted on projects that will probably be rejected.

From a government's point of view, agencies should aim for processes and legislations that support long-term sustainability, build capacity for future growth and encourage engagement of a wide range of stakeholders. By taking into account the needs and values of all interested parties, governments can aid in the creation of more holistic water portfolios while simultaneously gaining support from the public.

The development of relevant policy incentives to ensure the integrity, sustainability and regulatory compliance of all phases of project implementation is crucial (Schreiner *et al*., 2014). As has been mentioned earlier in this Compendium, people respond to monetary incentives, and if individuals or groups are motivated to comply with health and safety guidelines and use environmentally friendly practices, the safety and reliability of water portfolios can be safeguarded.

6 SHOWCASE OF AWR TECHNOLOGY

6.1 HONG KONG INTERNATIONAL AIRPORT

Hong Kong International Airport (HKIA) – assessed in a paper by Leung *et al*. (2012) – successfully implemented a triple water supply (TWS) system that includes a freshwater supply for potable uses, a seawater supply to be used in toilet flushing and air conditioning, an irrigation system using reclaimed greywater, and separate collection systems for greywater and black water (Figure 6.1). The HKIA uses approximately 9,000 m^3 per day of freshwater for use in food services, aircraft washing, and bathroom sinks. Of this, approximately 4,000 m^3 is reclaimed as greywater and used for garden irrigation surrounding the airport.

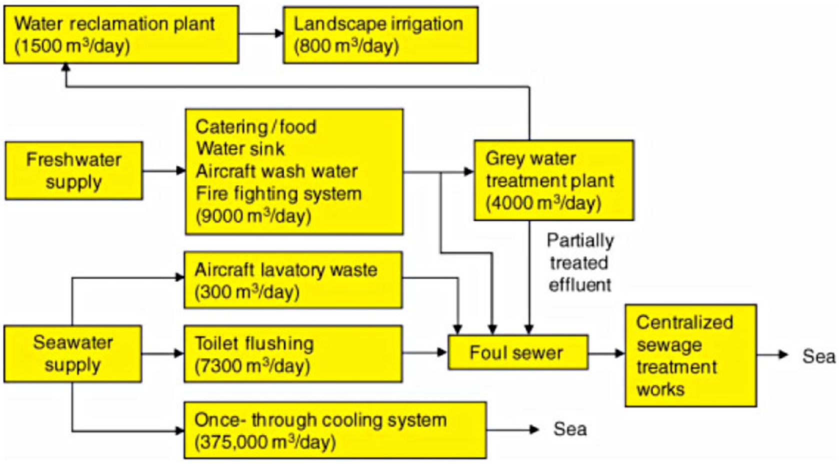

Figure 6.1 HKIA triple water supply (TWS) system (reprinted from *Water Science & Technology* 65 (3), 410–417 (2012) with permission from the copyright holders, IWA Publishing).

Through the implementation of the TWS system, the HKIA has been able to reduce their water demand by 52%. Of this, 41% is from flushing toilets with seawater, 4% is from greywater reuse, and the other 7% is attained by planting drought-tolerant grasses and thus minimising irrigation needs (Leung *et al*., 2012). The system also provides benefits in the form of energy savings, mostly because of the minimal treatment needed to use seawater for toilet flushing as opposed to greywater. Table 6.1 shows the estimated energy, cost and emissions associated with treating seawater, freshwater and reclaimed water for their respective end uses. According to the study of Leung *et al*. (2012), substituting seawater for reclaimed water can save US$240,000, 1,600 tonnes of CO_2 emissions and 2,800 MWh of electricity per annum.

	seawater for toilet flushing[a]	Freshwater 1 supply[b]	Reclaimed water[c]
Energy consumption (kWh/m^3)	0.013–0.025	0.05	0.2–1
Comparison based on Airport Isle 7,600 m^3/day: Island's TWS system with flushingseawater flow of 7,600m^3/day:			
Electricity cost[d] (US$ thousand/ year)	3.1–6.0	12	48–240
Energy consumption (MWh/year)	36–69	140	560–2,800
CO^2 emission[e] (tonne/year)	21–40	80	320–1,600

Table 6.1 Energy consumption, electricity cost and emissions associated with treating three types of water for their desired end uses (reprinted from *Water Science & Technology* 65 (3), 410–417 (2012) with permission from the copyright holders, IWA Publishing).

The reduced treatment costs are not the only monetary benefits associated with the TWS system. Although the capital cost of implementing the system was about US$70 million – including treatment plants, upgraded distribution systems, seawater cooling and toilet flushing systems – savings per year has averaged US$3.8 million, reducing the payback period to less than 20 years. Included in these cost savings are the reductions in electricity costs, freshwater purchased, and sewage and trade effluent charges (Leung *et al*., 2012).

Although some issues with the TWS system were encountered early on – particularly with respect to seawater toilet flushing – the replacement of uPVC pipes with polyethylene piping, upgrading the material used for the flushing valves and changing the shape of the toilet bowls to make them more conducive to cleaning and maintenance made the system function more optimally (Leung *et al*., 2012). Owing to the success of the TWS system at HKIA, similar systems may be feasible for implementation around the world, particularly in low-income and freshwater-scarce countries where seawater desalination is prohibitively expensive.

6.2 PERTH, AUSTRALIA: RO DESALINATION

Australia has a long history of desalination, with its first plant being built in 1903 to treat saline groundwater in the country's gold fields, and its popularity rising between the 1960s and 1980s (El Saliby *et al*., 2009). Between 2006 and 2013, six large-scale desalination plants were built in Australia in response to prolonged periods of drought and increasing water demands (Bosman, 2014).

The Perth Seawater Desalination Plant (PSDP) in the state of Western Australia is one example of a large-scale drinking water desalination plant (Table 6.2), which was finished in 2006, producing 144 ML per day of freshwater (El Saliby *et al*., 2009). Its energy efficiency is exemplary, as it consumes only 3.29 kWh per m^3 thanks to an energy recovery rate of about 30% (Kempton *et al*., 2010). Before the implementation of the project, an environmental impact assessment was performed to determine the effects that the plant would have on marine organisms, emissions, public health and safety risks, noise, surrounding vegetation and Aboriginal cultural values. After the extensive study was completed, the proposed plant was deemed environmentally sound, and shortly after its opening it was recognised as the world standard for that type of plant, as it is the largest desalination plant in the world powered by renewable energy (El Saliby *et al*., 2009).

Indicator	**Key data**
Plant type	SWRO
Capacity	140,000 m^3/d
Design expansion capacity	250,000 m3/d
Seawater temperature	16–24°C
Salinity	35.000–37.000 mg/L
Environmental monitoring required	TDS, temperature, DO, sediment habitat
Process energy requirement	4–6–kW/m^3
Contract types	Design and build, operate and maintain
Contract period	25 years
Anticipated water cost	AU SSI.17/m^3
Project cost	AUSS387 M
Renewable energy	Wind farm via grid

Table 6.2 Key operating data for Perth Seawater Desalination Plant (PSDP) (El Saliby *et al*., 2009).

Figure 6.2 shows a schematic of the desalination process at the PSDP, whereby it pumps pre-treated seawater through a series of filters, adds an anti-scalant before it is pumped at high pressure through RO membranes and then performs post-treatment before it is directed to a nearby reservoir.

Australia as a whole has diversified its water portfolio a great deal, actively using demand management techniques such as education, metering, water-saving devices, low-impact development (LID) and pricing that – to varying degrees – reflects the cost of production. It has also shifted away from groundwater sources, and increasingly uses surface water, RWH and reuse technology, as well as desalination, while actively recharging aquifers (Mollenkopf, 2014). In fact, the capacity of desalination and water reuse as a proportion of total water demand has been steadily increasing (Figure 6.3). In 2013, the number of water recycling plants in Australia was 165, with a total capacity of 467 GL, and the number of desalination plants was 82, with a total capacity of 751 GL (Radcliffe, 2015).

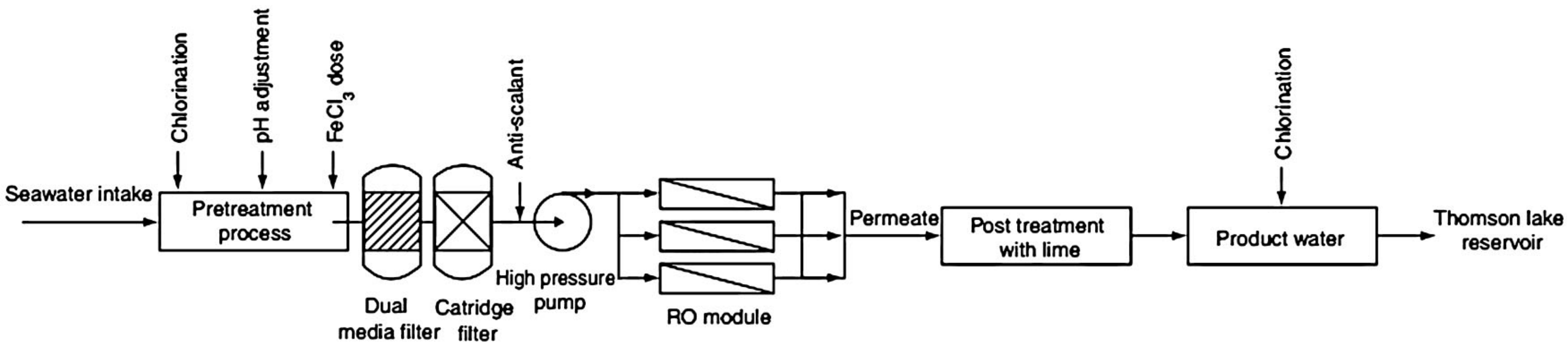

Figure 6.2 PSDP treatment process, from seawater intake to discharge into storage reservoir (El Saliby *et al.*, 2009).

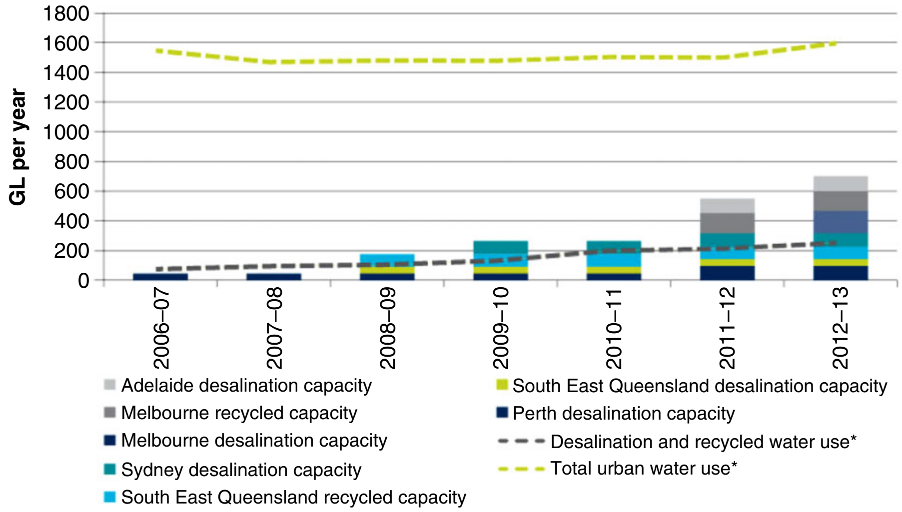

Figure 6.3 Total desalination and water reuse capacity in five major urban areas in Australia from 2006 to 2013, compared with the total urban water use in these areas (National Water Commission, 2014).

6.3 HYBRID CONSTRUCTED WETLANDS, CHINA

Constructed wetlands (CWs) have become a popular natural method of treating wastewater and stormwater, as well as creating riparian buffer zones and enhancing the aesthetic value of an area. They are also low-cost in both energy and monetary terms, making them feasible in both developed and developing countries. An innovative hybrid form of CW has been successfully implemented in southern China, a general schematic of which is depicted in Figure 6.4. This CW was designed to have a small size, making it ideal for southern China, where land prices can be exorbitantly high. The hybrid system consists of a vertical-baffled flow wetland (VBFW) and a horizontal subsurface flow wetland (HSFW), as well as natural aeration ditches (NADs) to enhance the dissolved oxygen content of the discharged water, and an optional internal circulation (IC) system (Zhai *et al*., 2011).

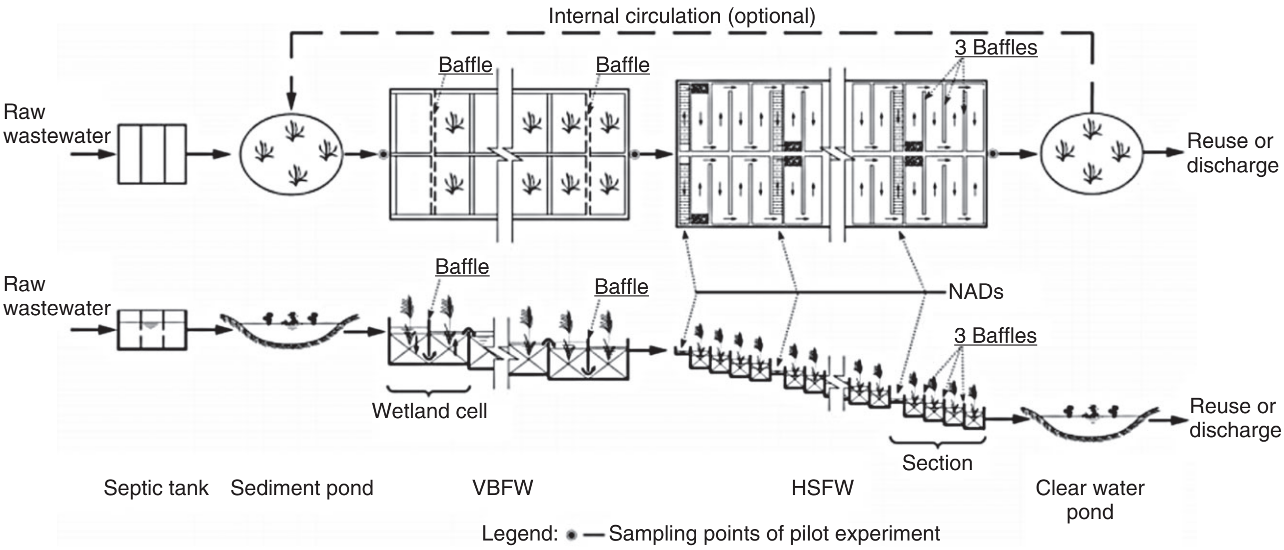

Figure 6.4 Hybrid constructed wetland schematic, overhead (top) and cross-sectional (bottom) view (reprinted from *Water Science & Technology* 64 (11), 410–417 (2011) with permission from the copyright holders, IWA Publishing).

The unique shapes and features included in the VBFW + HSFW wetland system allow it to make optimal use of the relatively small volume of the wetland bed, and to simplify its operation. Zhai *et al.* (2011) conducted a study indicating that the system is successful at treating effluent to meet water quality guidelines with minimal costs and energy requirements. On the basis of test results, the average removal efficiency of the CW system for COD, suspended solids, ammonia nitrogen (NH_4^+-N), total nitrogen and total phosphorus were around 84%, 95%, 72%, 65%, and 68%, respectively, exceeding the performance of either vertical or horizontal flow wetlands alone.

6.4 MADHYA PRADESH, INDIA

Most greywater reuse projects tend to be in urban and peri-urban areas of developed countries, and are less frequently explored in rural areas of developing countries (Godfrey *et al.*, 2010). However, given the relatively low pathogen content and high availability of greywater, it offers several advantages in these settings. Godfrey *et al.* (2010) examined a rural greywater reuse system, which was implemented in schools in the province of Madhya Pradesh, India, and by 2009 was operating in 300 schools and 1,500 households owing to its success. The system is relatively simple to construct and can be made with locally found materials. It consists of five steps to treat household greywater, including absorption, sedimentation, filtration, aeration and chlorination. A schematic of the system is shown in Figure 6.5. First, soap and hair are absorbed into the sponge filter before the water flows into a settling tank, where the sedimentation process allows most solids to be removed. Four filtration chambers follow the settling tank, which filter the water with progressively smaller gravel substrates (from 60 mm to coarse sand). The aeration stage occurs as water is aided by gravity through a step tank, and then it is stored in a clean water tank, where chlorine is applied twice per week.

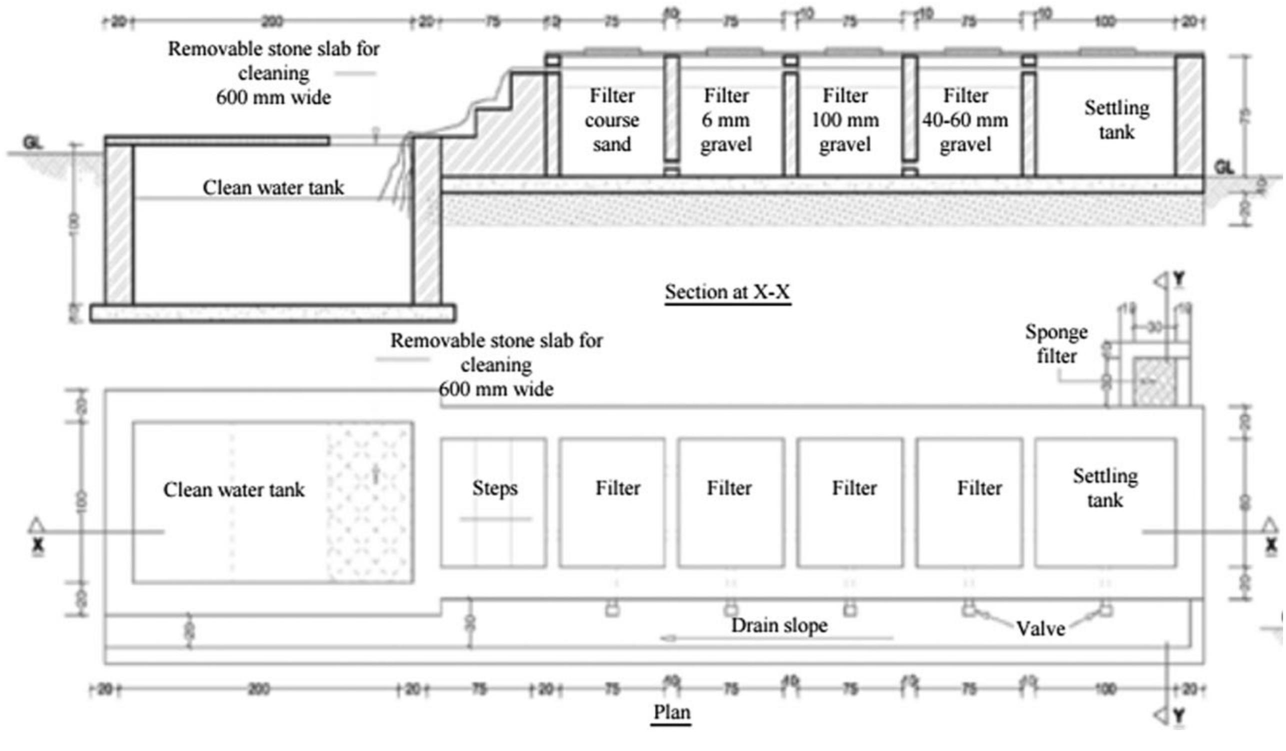

Figure 6.5 Cross-sectional (top) and overhead (bottom) view of greywater treatment system implemented in Madhya Pradesh, India (reprinted from *Water Science & Technology* 62 (6), 1296–1303 (2010) with permission from the copyright holders, IWA Publishing).

The treated water is used for toilet flushing and watering kitchen gardens, and users are educated to refrain from directly watering fruit and leafy greens with greywater, and to wash and/or cook vegetables well before eating. Godfrey *et al.* (2010) assessed the efficiency of the system by measuring five key parameters (TSS, turbidity, BOD, COD and faecal coliform) in both the influent and the effluent, to see how many contaminants had been removed in the process (Table 6.3). Results indicate that – although the effluent water does not meet potable standards – it is safe to use for non-potable uses. The authors also note that the system in question can be implemented at an affordable cost, thus making it optimal for low-income areas. Not only this, but it helps to alleviate sanitation issues, as more water is made available for toilet flushing.

Parameter	Influent	Effluent	Efficiency; % or log removal
Suspended solids, mg/L	190	120	37
Turbidity, NTU	142.5	80	44
BOD^5, mg/L	187,5	90	52
COD $(total)^t$ mg/L	529.5	248	53
Faecal coliform, log	4.2–54 Ulog/lOOmL	4–4.6 Ulog/100mL$^+$	0.2–0,3

Table 6.3 Efficiency of greywater treatment system, based on five key water quality indicators (reprinted from *Water Science & Technology* 62 (6), 1296–1303 (2010) with permission from the copyright holders, IWA Publishing).

6.5 TENORIO WASTEWATER TREATMENT PLANT, MEXICO

Tenorio Wastewater Treatment Plant (WWTP) in San Luis Potosi, Mexico, was the first treatment facility in Mexico to produce multi-quality recycled water for a variety of end uses. Given the arid climate of the region and over-pumping of the two main aquifers, freshwater is minimal, and it has resulted in untreated wastewater being used for agricultural irrigation. The Tenorio WWTP uses the recycled water for agriculture, industrial use (power plant), environmental enhancement and groundwater restoration. It has been successfully operating since 2006, saving over US$18 million for the connected power plant (Lazarova *et al*., 2014).

Tenorio WWTP treats 45% of the wastewater from the city of San Luis Potosi, and has a total capacity of 90,720 m^3 per day (Lazarova *et al*., 2014). The primary treatment step is applied to all incoming wastewater and includes initial screening, removal of grit and grease and primary clarification. After this step, more than half of the primary treated water is discharged to the Tenorio Reservoir – which was converted to a constructed wetland – to remove organic matter and faecal coliforms before the water is pumped for agricultural irrigation. The water that is not allocated to irrigation undergoes secondary treatment by activated sludge nitrogen removal, followed by tertiary treatment with sand filtration, lime, softening and chlorine disinfection to be used for cooling purposes in a nearby power plant (Lazarova *et al*., 2014). A schematic of the treatment process is shown in Figure 6.6.

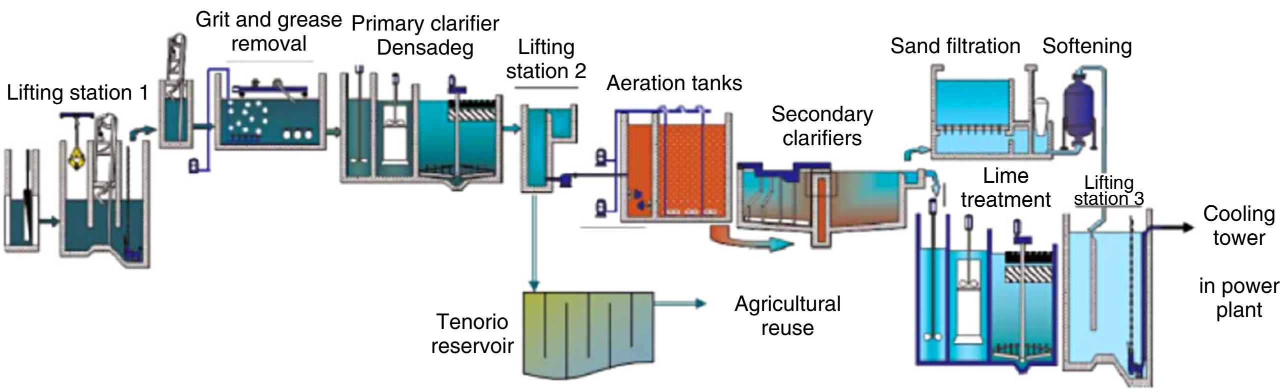

Figure 6.6 Schematic of Tenorio WWTP in San Luis Potosi, Mexico (reprinted from *Journal of Water Reuse and Desalination* 4 (1), 18–24 (2014) with permission from the copyright holders, IWA Publishing).

The Tenorio WWTP saves about 7.9 Mm^3 of potable water per annum, improves the quality of irrigation water and provides wildlife habitat through wetland restoration. The primary treatment process is effective in removing suspended solids down to a concentration of 82 mg/L – which is further improved to 28 mg/L after wetland treatment – while maintaining nutrient content to allow reduced fertiliser use in agriculture. In addition to this, disinfection of faecal coliforms is ensured with a 40 day residence time in the CW system. Salinity is also controlled to reduce the risk of damaging salt-sensitive crops (Lazarova *et al*., 2014).

An ecosystem monitoring programme was set up to evaluate environmental health in and around the Tenorio Reservoir since its modification to perform as a wetland. The study found that the presence of the wetland has enhanced biodiversity in the region by attracting a variety of migratory birds, as well as increasing the number of species of small mammals and flora (Lazarova *et al*., 2014). Finally, the project led to several social and economic benefits in the area, including a reduced incidence of gastrointestinal diseases from raw wastewater-irrigated plants, economic benefits for farmers and industry due to a more reliable alternative water supply, improved standards of living due to a cleaner environment, and conservation of groundwater resources (Lazarova *et al.*, 2014).

6.6 GOREANGAB RECLAMATION PLANT, WINDHOEK, NAMIBIA

The Goreangab Reclamation Plant (GRP) in Windhoek, Namibia, has been in operation since 1969, supplying drinking water through DPR. The plant successfully ensures suitable water quality with multiple barriers, including treatment, non-treatment and operational measures. The actual treatment process includes a combination of ultrafiltration (UF), activated carbon filtration and ozonation (see Figure 6.7).

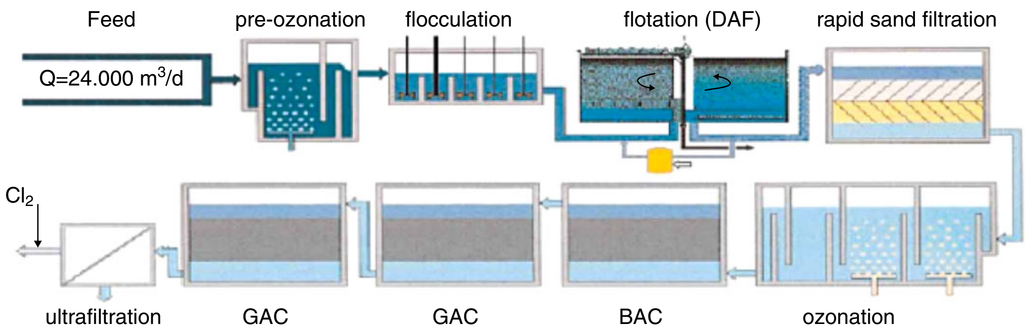

Figure 6.7 Technical schematic of Goreangab Reclamation Plant in Windhoek, Namibia (reprinted from *Journal of Water Reuse and Desalination* 5 (1), 64–71 (2015) with permission from the copyright holders, IWA Publishing).

Some of the non-treatment barriers include the following:

- diverting trade wastes to a different water treatment plant;
- monitoring at both the inlet and outlet points of the facility;
- constant monitoring of potable water quality;
- blending of reclaimed water with other potable water sources;
- active community engagement programme to improve public acceptance.

Along with the GRP's treatment processes – which ensure that between one and four barriers are in place for each identified water quality parameter – the above actions help to ensure that safe drinking water is obtained from the plant (Law *et al.*, 2015).

6.7 GUELPH, CANADA

The City of Guelph in Ontario, Canada, is a prominent example of a municipality using demand management strategies effectively. As a city that gets 100% of its drinking water from aquifers, the importance of conserving that finite resource is crucial. In 1998, the City began a Water Conservation and Efficiency Study, followed by implementation of a Water Supply Master Plan in 2004 (City of Guelph, 2009).

Included in the City's demand management mechanisms are (Great Lakes Commission, 2015) the following:

- rebates on water-efficient toilets and washing machines;
- *Blue Built Home* certification programme – based on the presence of efficient home fixtures;
- incentives for installing home greywater reuse or RWH systems;

- institutional, residential and industrial (ICI) audit and capacity buyback – pays users for retrofits that permanently reduce water consumption;
- free audits to assess home water and energy efficiency, plus free retrofits;
- free consultations to improve garden and landscape water use.

Toilet and washing machine rebates and the ICI capacity buyback alone resulted in over 400,000 m^3 of water savings in a 5-year period (City of Guelph, 2009).

Overall, Guelph's water conservation programmes have resulted in savings of around 10,000 m^3 per day, despite a 15,000 person population increase (Great Lakes Commission, 2015), making the per capita water use of the average Guelph resident nearly one-third lower than that of the average Canadian (City of Guelph, 2013). Not only is the City conserving freshwater, but their demand management programmes have resulted in financial benefits of close to six times the initial investment in avoided supply, capacity and wastewater costs (Table 6.4).

Activity Name	PV Cost ($)	PV Benefit ($)	NPV ($)
Royal Flush Toilet Rebate, SF	$1,676,300	$12,068,155	$10,391,855
Royal Flush Toilet Rebate, MF	$525.400	$2,534,944	$2,009,544
Royal Flush Toilet Rebate, IQ	$55,600	$441,405	$195,605
Smart Wash Washing Machine Rebate	$1,333,250	$4,506,374	$3,473.124
Blue Built Home - Bronze	$329.2S0	$545,125	$215,546
Blue Built Home - Silver	$15,900	$21,467	$5,587
Greywater Reuse Systems	$21,000	$3,157	$(17,843)
ICI Audit and Capacity Buyback Program	$967,395	$12,323,719	$11,356,324
Rainwater Harvesting System	$50,000	$7,264	$(42,736)
Healthy Landscape Visit	$368.970	$36,022	$(332,948)
Efficient Home Visit Surveys (GEL/NetZero City)	$229,505	$24,127	$(205,378)
Total	$5,572,800	$32,811,780	$27,238,980

Table 6.4 Present value of total costs and benefits of each City of Guelph demand management strategy (Great Lakes Commission, 2015).

By implementing a wide variety of demand management strategies, as well as encouraging small-scale acquisition of AWR through greywater reuse and RWH, the City of Guelph displays exemplary understanding of integrated water supply management.

6.8 BORA BORA, FRENCH POLYNESIA

The French Polynesian island of Bora Bora was experiencing increasing water shortages due to dwindling rainfall, increased development and a large tourism sector. Since the existing freshwater resources on the island were not sufficient to meet the needs of permanent residents plus the large influx of tourists, it was imperative that water reuse and desalination be implemented. Additionally, the lagoon ecosystems typical of French Polynesia are fragile, and the discharge of untreated water poses a serious risk to local flora and fauna, creating another incentive to reuse water. Bora Bora finally put a water recycling programme into place, but several constraints had to be addressed to ensure community acceptance of the programme (Lazarova *et al.*, 2012).

Two wastewater treatment plants have been implemented on the island, using UF to treat reclaimed water to European standards for bathing water (Table 6.5). The recycled water is stored in a covered reservoir after treatment, then chlorinated and pumped through a non-potable distribution network. In 2010, solar photovoltaic energy was applied to improve the overall energy efficiency of the programme. Desalination is also being utilised in Bora Bora, with three RO plants having been implemented since 2000 (Lazarova *et al.*, 2012).

According to Lazarova *et al.* (2012), the main approach to increasing public acceptance of water reuse in Bora Bora was community consultation, which included the following:

- public forums and interest groups;
- consulting interest groups and holding workshops;

Parameter	Raw sewage	Secondary effluent		Recycled water (UF permeate)	
		Measured	Consent	Measured	Guide value
COD (mg/L)	595 (270–837)	31 (21–65)	90	15 (4–34)	40
BOD^5 (mg/L)	349 (200–540)	7 (<5–22)	25	4 (1–6)	20
TSS (mg/L)	238 (125–275)	9.5 (4–19)	35	<5	20
N^{tot} (mg/L)	47 (30–70)	8.3 (2–18)	20	7.3 (2–17)	20
P^{tot} (mg/L)	6.8 (4.1–8.1)	2.5 (1.0–5.8)	–	1.9 (0.45–5.8)	–
E. coli/100 mL	ND	10^5–10^7	–	Non-detected	0/100 mL

[a]Average value and limit of variations (monthly composite samples, excluding *E. coli*. that was monitored in grab samples).

Table 6.5 Measurement of water quality indicators at several stages in the treatment process, from raw sewage to treated recycled water (reprinted from *Journal of Water Reuse and Desalination* 2 (1), 1–12 (2012) with permission from the copyright holders, IWA Publishing).

- education programmes indicating the safety of the reuse scheme, as well as the need for such a project given the water constraints;
- collaboration with media to market reclaimed water as a sustainable solution.

As a result of these public engagement initiatives, demand for reclaimed water in Bora Bora has increased, as has the number of end-users, which doubled after tertiary UF treatment was implemented. Recycled water is now used for boat-washing, landscape irrigation, fire protection, industrial uses, large-scale cleaning and other non-potable uses (Lazarova *et al*., 2012).

In addition to community consultation processes, pricing mechanisms were put into place, consisting of fixed and volumetric costs chosen to reflect the willingness-to-pay of consumers. Bora Bora put in place a two-part pricing structure with a declining block rate with lower per unit prices than potable water. Large end-users and tourism-related businesses helped to increase public acceptance of reused water by providing funding to the reuse industry, which helped to keep costs low for small consumers (Lazarova *et al*., 2012).

As a result of Bora Bora's expanded water portfolio, freshwater resources are being conserved, the lagoon environment is being protected, businesses are reaping economic benefits, and the community as a whole is adopting and accepting more sustainable practices. In addition to the facilities already in place, Bora Bora would like to extend the operation to include a more widespread network of fire protection infrastructure and a UF/RO membrane facility for the production of potable water (Lazarova *et al*., 2012).

6.9 KOGARAH, SYDNEY, AUSTRALIA

A successful example of a dual RWH and stormwater collection system is being used in the town square of Kogarah, a suburb of Sydney, Australia, a depiction of which is shown in Figure 6.8. Stormwater runoff first flows through a gross pollutant trap (GPT) to remove larger particles and litter, before being collected in a storage tank for "dirty" water. It is stored there until it is ready to be used for irrigation of green spaces in surrounding courtyards, which act as bio-filters and remove some of the finer pollutants. It is collected once again after it has percolated through the bio-filter and stored in a "clean" water tank, located adjacent to the dirty water tank (Chanan *et al*., 2010).

Also collected in the clean water tank is rainwater from rooftops. This water is used for toilet flushing and car washing, as well as to top up other tanks when water levels are low. Eighty-five per cent of precipitation that falls on the square is used in the area through the described system. It is estimated that between the reuse of rainwater and stormwater, approximately 7,920 kL of potable water are saved annually (Chanan *et al*., 2010).

To treat stormwater from the larger catchment area, a 9,500 m^2 constructed wetland was also implemented in Kogarah, which – in combination with a GPT – treats 95% of stormwater runoff in the catchment. Stormwater enters the wetland at one end where the 2 m depth allows sediments and heavy metals to settle and remain undisturbed; then flows through a shallow section in the middle where macrophytes are present to aid in nutrient filtration; and finally, the breakdown of bacteria is aided in a final, deeper section by sunlight and wind. After the entire process is completed, an outlet pipe carries the treated stormwater to Oatley Bay, a popular recreation area. The construction of this wetland has drastically improved

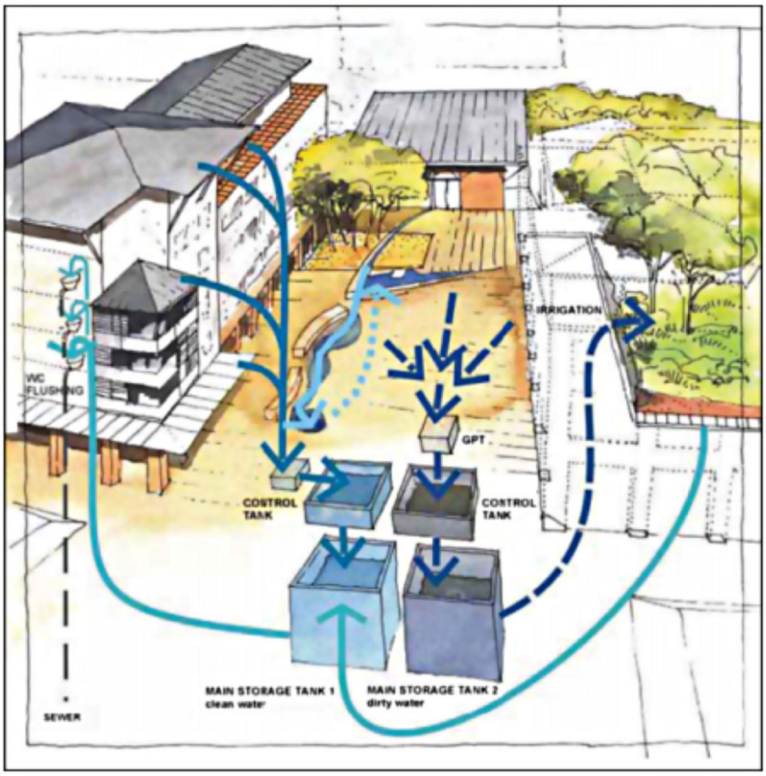

Figure 6.8 Flows through Kogarah RW/SW harvesting system. Included components are "clean" water for toilet flushing (light blue), rooftop-harvested rainwater (medium blue) and stormwater (dark blue) (reprinted from *Water Science & Technology* 62 (12), 2854–2861 (2010) with permission from the copyright holders, IWA Publishing).

the quality of stormwater above pre-construction levels, which were previously very high in heavy metals and other pollutants (Chanan *et al*., 2010).

6.10 STAR CITY, SEOUL, SOUTH KOREA

In operation since 2007, Star City is a large real-estate development in a suburb of Seoul, South Korea, that is home to more than 1,300 apartments in four high-rise buildings. The development features an innovative RWH system that is used simultaneously for flood prevention, water conservation and emergency response purposes. The subject of worldwide acclaim, its success has resulted in other cities across South Korea implementing systems of similar design. Han and Mun (2011) collected 2 years of operational data from Star City to assess water and energy savings, water quality and runoff control.

A schematic of the Star City RWH system is depicted in Figure 6.9. The total roof catchment area is 6,200 m^2 of rooftop and 45,000 m^2 of terrace, and the storage capacity is 3,000 m^3 of water stored in three 1,000 m^3 tanks. Two of the three tanks store rainwater collected from rooftops as well as the ground; this water is used for garden irrigation, and is then recycled and stored for further use. The third tank holds treated, emergency tap water. The issue of this tank's water quality deteriorating over time is addressed by pumping half of its volume into one of the rainwater tanks at regular intervals and replenishing it with a fresh supply. Screens and filters are present at tank inlets to maintain quality, and calm inlets and floating suction devices are used to avoid re-suspending sediments (Han and Mun, 2011).

Upon analysis of the system, Han and Mun (2011) found that it conserves a volume of approximately 26,000 m^3 per year of potable water, which is close to 50% of the total precipitation that falls over the area of the Star City complex. By recycling irrigation water as well as storing unused water from one month to the next, the system is able to maintain fairly consistent usage throughout the year. All water tested in the study had turbidity levels below the Korean Gray Water Standard (KGWS) ($<$1.5 NTU) and pH within the range specified (6–8.4) in the Korean Drinking Water Standard (KDWS).

Han and Mun also assessed the runoff control potential of the system, which is illustrated in Figure 6.10. The tank volume to catchment area ratio of the system is 5.8 m^3/100 m^2, meaning that in the event of a 50-year storm with a peak flow of

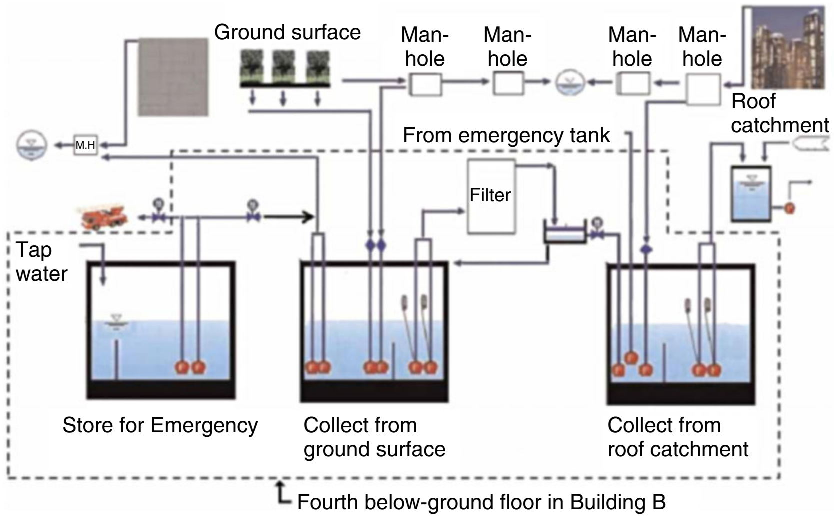

Figure 6.9 Star City, South Korea, RWH system schematic (reprinted from *Water Science & Technology* 63 (12), 2796–2801 (2011) with permission from the copyright holders, IWA Publishing).

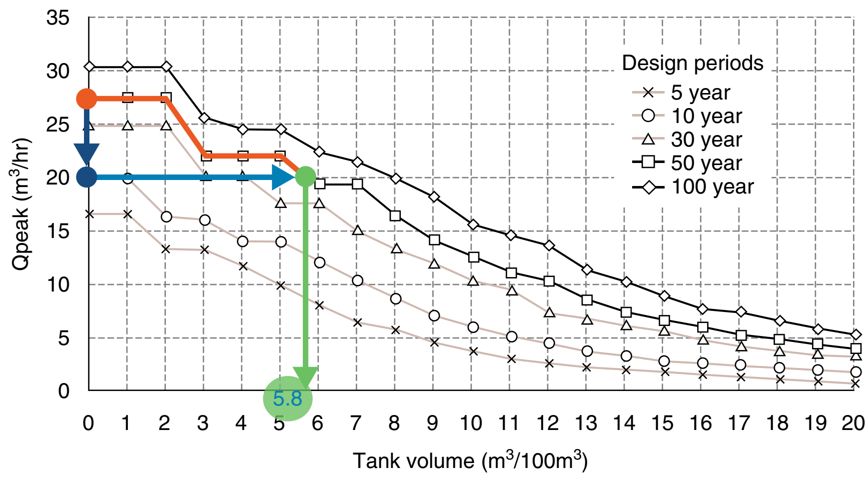

Figure 6.10 Runoff control potential for flood events from 5 to 100 years in magnitude, according to RWH tank volume (reprinted from *Water Science & Technology* 63 (12), 2796–2801 (2011) with permission from the copyright holders, IWA Publishing).

27 m^3/hour, the Star City tank could reduce the peak flow discharge to 20 m^3/hour, equivalent to a 10-year storm event. Star City is also estimated to save approximately 8.9 MWh of electricity every year, owing to the reduced need for the treatment and conveyance of potable water.

6.11 DECENTRALISED WATER REUSE WITH ZERO DISCHARGE, CHINA

A water reclamation and reuse system was designed and installed in Xi'an Siyuan University located in the southeast suburban area of Xi'an City, China. As shown in Figure 6.12, water supply in this university depended on groundwater wells with a capacity of 2,800 m^3 per day; which could meet the demand for potable uses for up to 35,000 students living in the campus, but was insufficient for covering all the non-potable consumption as projected in Table 6.6 (Wang *et al*., 2015).

After potable use, the collected used water is sent to the on-campus treatment station where a sophisticated process (Figure 6.11) is used for water reclamation by combining an anaerobic–anoxic–oxic (A^2O) unit with a membrane bioreactor (MBR) for the production of high-quality reclaimed water. To enlarge the source for water reclamation, the reclaimed water – after being used for toilet flushing – is also collected and added to the treatment station inflow. As a result, the potential of reclaimed water production becomes larger than the original groundwater source and every drop of used water is added

Water use	Specification	Quantity	Demand	Remarks
1 Toilet flushing	30 L/d/person	25,000–35,000 persons	750–1050 m^3/d	
2 Gardening	3 L/m^2/d	50,0000 m^2	1500 m^3/d	For 50 hectares green belt
3 Lake replenishment	20% daily replacement	50,000 m^3	1000 m^3	For lakes of 5,000 m^2 and 1 m depth
4 Lake water loss	20% of lake replenishment	1,000 m^3	200 m^3	Evaporation and other loss
5 Total			3,450–3,750 m^3/d 2,450–2,750 m^3/d	Including item 3 Excluding item 3

Table 6.6 Projection of non-potable water demands (Wang *et al.*, 2015).

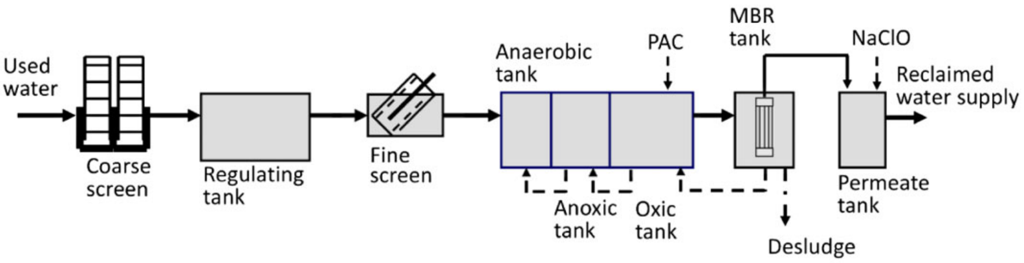

Figure 6.11 The used-water treatment and reclamation process (Hu *et al.*, 2013).

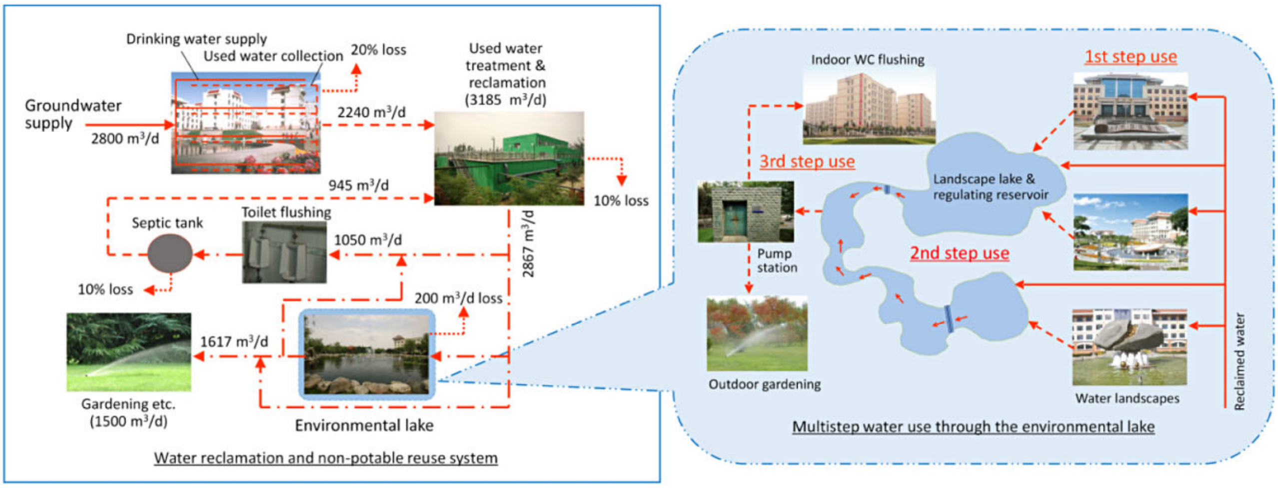

Figure 6.12 Configuration of the campus water reuse system (Wang *et al.*, 2015).

to the source for water reclamation, instead of being categorised as 'waste' to be discharged (Hu *et al.*, 2013; Wang *et al.*, 2015).

A noticeable feature of the system shown in Figure 6.12 is the introduction of a so-called 'environmental lake', which performs the functions of both water landscaping and storage. Multi-step water use has also been realised by supplying reclaimed water, firstly to a series of water landscapes before the lake, and then pumping water from the lake for outdoor gardening and indoor toilet flushing. Therefore, the hydraulic retention time of water in the lake is dynamically controlled at about 5–7 days without additional water consumption for its replenishment. A green campus has thus been completely nourished by sufficient reclaimed water through a zero discharge and efficient water reuse system (Wang *et al.*, 2015).

6.12 SCHOOL DRINKING WATER SUPPLY IN HANOI, VIETNAM

Cukhe Elementary School is located in Cukhe Village, in the southern part of Hanoi, Vietnam. The school has 300 students, 15 teachers and 3 buildings with relatively secure and suitable roofs. In the past, they have had to use expensive bottled water for drinking because of arsenic contamination in the local groundwater. In July 2014, a new approach was introduced and the Lotte Department Store donated money for a rainwater system as part of its corporate social responsibility (CSR) commitment. A team from Seoul National University (SNU) designed the system, which consists of a 180 m^2 roof catchment, gutter, first flush tank, two 6 m^3 rainwater holding tanks, and UV filters near the tap (Figure 6.13). Local people using locally sourced materials constructed the system, and following construction, both the residents and the donor company were satisfied with the outcome. Water level gauges and water meters were installed to monitor remaining water supplies and cumulative water consumption. About 6 m^3 rainwater can be saved from the RWH facilities per month, which means US$150 can be saved monthly as a result of not having to buy bottled water. This is equivalent of building another community-based RWH system every 2 years (US$3,600).

School	Area	Volume of Tank
Kindergarten	150 m^2	6,000L × 2 = 12,000L
Primary School	80 m^2	5,000L × 2 = 10,000L

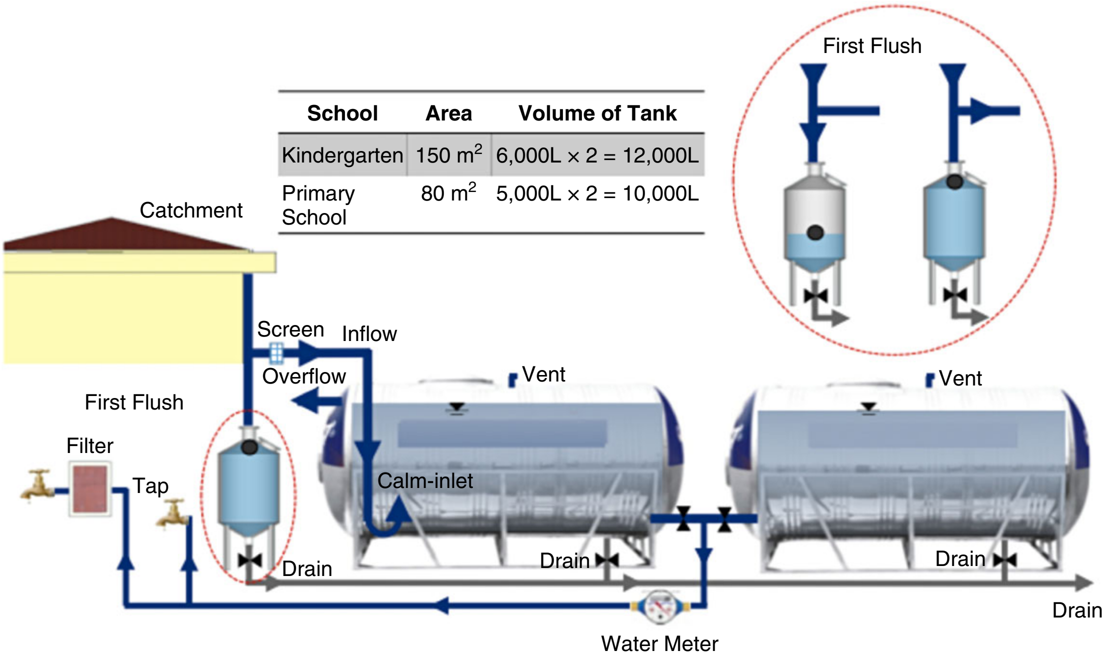

Figure 6.13 Rainwater tank at Cukhe Primary School, Vietnam (provided by Mooyoung Han).

Another prominent issue in the area was insufficient rainfall data, as most rainfall data are collected in urban centres. Therefore, Cukhe Village did not have adequate rainfall data to make a precise RWH design. The solution was to install a simple rainfall gauge and work with a group of science students to maintain rainfall records via a website (Figure 6.14), which they can then use in future designs.

Figure 6.14 The rain gauge installed at Cukhe Primary School, Vietnam.

The lessons learned from this case study are threefold: the importance of building local residents' capacity to design, build, and operate RWH systems; the importance of involving industry through CSR activities as a win–win strategy; and the benefit of local data collection by students, which resulted in democratic design decisions that can be used as reference for future designs and operations.

7 KNOWLEDGE AND TECHNOLOGY GAPS

The following section and section 8 incorporate ideas and recommendations from experts in AWR-related fields. All the knowledge contained in these sections is that of the contacted professionals, unless a different source is cited. Individual contributors are listed in the document under "Key Contributors".

Despite many promising technologies emerging in AWR sectors, there still exist some prominent gaps in the present knowledge, practices and technology. Some examples of these gaps will be identified and explained in this section.

7.1 DATA COLLECTION AND INTEGRATION

Today, mathematical modelling has become fundamental for natural resources management, in particular for water resources. Governmental agencies rely on models to manage current conditions and forecast future strategies. However, gaps still exist – particularly in less developed countries – in which information are roughly collected and rarely made public in a complete form.

The lack of consistent data in the water sector can lead to poor understanding of the present conditions and effectiveness water management plans, a lack of trust from the public and difficulty complying with regulations. Free and open data, available to research institutes and citizens, help to clarify current water resources conditions and increase social awareness. Efforts must be made at the international level to develop a common network for data presentation and interpretation. Not only this, but social, economic, health and engineering data should be integrated under a common framework to make science-based and risk-based decisions. This type of framework currently does not exist, but is necessary for creating safer and more robust water supply systems.

7.2 FRAMEWORK FOR ASSESSING CASE-BY-CASE SCENARIOS ON THE BASIS OF ENVIRONMENTAL IMPACT AND COST-EFFECTIVENESS

Each water deficient situation needs an optimised solution, but a common solution for every case does not exist. The fundamental point is to find an optimal solution tailored to each individual scenario that compromises between social, economic and environmental objectives, while keeping in mind sustainable development goals.

There is a present lack of a comprehensive framework or guidance tool for selecting specific technologies and management strategies that can be adapted on a case-by-case basis. The creation of such a document is essential to making decisions that will be sustainable in the long-run. This is especially important in the AWR sector, where new technologies are constantly emerging and may not yet have undergone widespread implementation or had the opportunity to build a reputation. There is still considerable room for improving knowledge of cost and environmental solutions that are effective and reliable over time.

7.3 MORE EFFECTIVE AND RELIABLE WATER SOLUTIONS FOR ARID CLIMATES

The creation of safe and reliable water supplies in arid regions is still a great challenge around the world. Areas without sufficient ground and surface water to meet their needs may experience a reduced quality of life if they lack the capacity to obtain water from elsewhere or to harness AWR. More attention is needed in creating solutions that increase water availability where few options are available, and do so in a way that can be adjusted to fit the economic and environmental capabilities of the region in question. This may involve creating more effective water storage solutions, implementing high-efficiency water reuse schemes, utilising water-saving technology or substituting processes that use water for ones that do not.

This need also applies to regions in which dry season water needs cannot be met by water made available in the wet season. For example, problems still exist with managing collected rainwater effectively from the wet to dry seasons. Often there is still not adequate storage capacity to protect against significant dry season shortages. To mitigate these issues, a shift in consumption patterns must occur so that lower rates of utilisation occur in the dry season (Mwamila *et al.*, 2015).

The implementation of a dual water supply that uses rainwater for drinking and reclaimed water for non-potable uses would help to slow the rate of depletion of existing freshwater sources. Engineering simulations should be conducted for the optimal design of this kind of system (Nguyen and Han, 2014).

7.4 HIGH RATES OF WATER LOSS

A major problem affecting water utilities around the world is the huge amount of water being lost from water supply and distribution networks. A high level of water loss is a proxy indicator of a poorly run water utility reflecting huge volumes of water being lost through leaks or not being invoiced to the consumers, or both. The World Bank conservatively estimated that the water lost daily across the world through leakage in the distribution networks would be sufficient to serve nearly 200 million people. In addition, 30 million m^3 are delivered every day to customers, but are not invoiced because of pilferage, corruption, and poor metering (Kingdom *et al*., 2006).

Water loss reduction would have an immediate operational and financial benefit to the water utilities, and this should capture the attention of all concerned particularly local authorities and governments. Reducing water losses represents a cheap AWR, which can be provided at a much lower cost than other viable options. The continuously rising cost of producing, treating, transporting, storing and distributing water presents new opportunities for the creation of innovative strategies and technologies. Solutions must be provided to the problems of excessive leakage, inaccurate billing, network inefficiency, excessive energy use, etc.

7.5 LACK OF PUBLIC ACCEPTANCE OF RECLAIMED WATER

One of the major challenges related to the use of reclaimed water is how to overcome the psychological barrier associated with this type of use. Many technologies exist which can produce safe and reliable reclaimed water, but it still carries an inherent “yuck factor” which must be overcome before widespread implementation can be feasible. This barrier does not just exist in regards to potable use. The use of reclaimed water for bathing, laundry, car washing and even gardening can become problematic when users do not trust its safety or quality.

Overcoming this obstacle requires the use of awareness programmes targeted at educating the public on the safety and treatment processes of reclaimed water. Even with these kind of programmes, public acceptance can be slow, and therefore long-term strategies may need to be used. Safe and successful water reuse technologies should be made visible to enhance the trust and acceptance of communities.

7.6 SAFETY AND SUSTAINABILITY IN TRANSPORTATION

Transportation of water is critical to the functioning of all water supply systems. However, multiple issues can arise in transportation, particularly with regards to its safety and sustainability.

If alternative water sources are associated with different types of use (i.e. potable and non-potable) sharing the same space, the risk of cross connections is an issue, particularly because these are typically buried pipes. This risk of cross contamination may have severe consequences (e.g. public health). Colour codes for the pipes or similar solutions do not provide a high enough level of safety and other existing solutions bring added costs to construction and maintenance of the networks. There need to be as many networks as there are different water quality types, and these need to coexist with minimal cross connection risk. More creative, effective and cost-efficient solutions are needed.

Many experts in the water sector have also recognised that transporting water long distances may not be sustainable in the future. Firstly, the act of pumping water to another region usually requires a great deal of energy, and therefore can be cost-intensive and emissions-intensive. Further, relying on water being pumped from a distance may cause problems, particularly in the case of an emergency, natural disaster or significant water shortage. Plans should be made which take into account the possibility of unforeseen circumstances and incorporate appropriate contingency planning clauses.

8 RECOMMENDATIONS

8.1 AWR VISIBILITY

It is important to make AWR more visible within the fields of science, engineering, politics and business as well as with the general public. Spreading knowledge and understanding of new technologies will hopefully increase public acceptance and promote their use within water supply systems.

A good way to promote AWR is to present valuable case studies in which the desired goal(s) has been reached and a more sustainable water supply has been created. Scientists, technicians and citizens can use their respective work, knowledge and experience to improve the visibility of sustainable projects. Networks should be created between different sectors of society and a common space should be found in which to create a transparent and open framework for the development of AWR projects.

To build capacity and momentum, implementation may start small, such as with household-scale RWH or greywater reuse systems, focusing on the education and skill development of users. This is a bottom-up method of increasing awareness and understanding of AWR options, and making the general public more invested in creating sustainable water supplies.

In addition to increasing the visibility of AWR, the *rationale* behind its implementation should be well-known. AWR as an option for creating more sustainable water supplies would benefit from being more prominent in education, and the value of water in environmental, economic, cultural and social contexts may be taught to children from a young age to ensure that these principles are understood well in future generations.

8.2 TECHNOLOGICAL ADVANCEMENT

The development of advanced technologies for water management should be ongoing and highly valued. The water sector has seen much important technological advancement, which has allowed the provision of higher quality water at a lower cost and with less impact on the environment. However, these technologies can always be improved to make them more efficient, reliable, cost-effective and environmentally friendly.

For example, the use of renewable energy in water treatment is becoming increasingly popular, and improving the reliability and efficiency of these technologies could have large benefits for the water sector and the environment. Additionally, RWH has been around for centuries, but technological improvements continue to make it more able to effectively augment the water supply. Making these systems more automated, low-maintenance and user-friendly may help to promote widespread implementation of small-scale systems, which together can save vast amounts of potable water.

Water loss management is also a field in which technological advancement currently has and will continue to have a great impact on the efficiency of water supply systems. Some of the areas in which technology has been advancing and further work is currently being undertaken are water quality sensors, communication equipment, data management software, real-time supervisory control and data acquisition systems, remote control of equipment such as pumps and valves, automatic meter reading, etc. Broad areas in which continued development of technologies would enhance further improvement of water distribution networks include smart metering, water quality, energy efficiency, leakage management and data analysis. Although much of this knowledge is already available, applying it effectively and with proper foresight is important.

8.3 FRAMEWORK FOR AWR ASSESSMENT

There currently exist no clearly defined metrics for quantitatively measuring and comparing different AWR options. For example, it may be possible to measure the costs and benefits of two different desalination schemes, but how would one definitively choose between a water reuse scheme and one that uses demand management, taking into account the life-cycle costs, benefits and overall sustainability and resiliency of each system?

A comprehensive framework for benchmarking AWR technologies and strategies is needed. This framework will include tools for quantitatively and qualitatively assessing water management strategies. This will aid in the decision-making process and contribute to the development of a more reliable and sustainable water supply. The AWR Cluster could play a crucial role in the development of such a framework.

8.4 SYSTEM RECONFIGURATION

A paradigm shift should occur, with respect to the way urban water systems are designed. New systems would benefit from having enclosed water cycles with minimal freshwater supplied and minimal waste discharged (see example in Figure 8.1). To accomplish this, subsystems of urban water cycles (e.g., supply, sewerage, reuse and environment) should be harmonically integrated into a combined framework. In this framework, wastewater should be viewed as a resource, and natural or artificial water bodies should be an important part of these systems, to be replenished and used for water quantity regulation and water quality polishing (Wang *et al*., 2015).

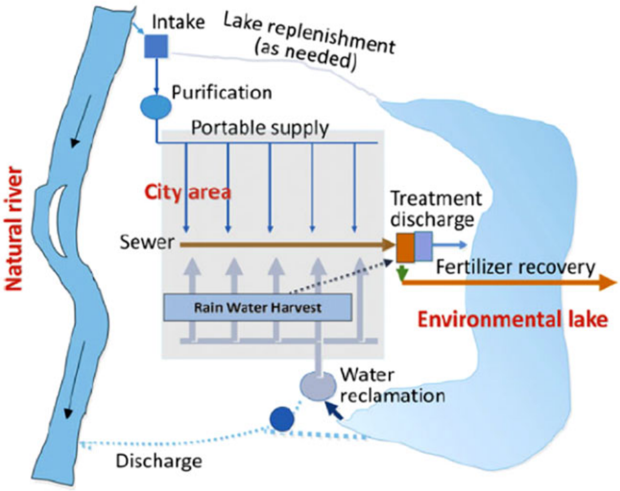

Figure 8.1 A cyclical urban water supply, in which resources are recovered to the furthest extent possible, discharge of waste is minimised and natural and artificial water bodies are used as buffers (Tambo *et al*., 2012).

In sustainable water systems, WWTPs should be conceived less as pollution control systems and more as residue valorisation systems. Many efforts are currently made to recover resources both in the water and in the sludge lines. Biogas production and valuable chemicals recovery are just some of main foci. These efforts share a common background: the direction through energy-efficient, socially acceptable and environmentally sound wastewater management systems. The reliability of these systems, as well as other kinds of water treatment systems, will increase as technology improves and regulatory frameworks adjust to the use of reclaimed water.

These cyclical systems would benefit from focusing on integrating features to serve multiple purposes. For example, a green roof with a rainwater collection function creates a community space, produces food, provides a cooling amenity for the building, mitigates flood risk and makes freshwater available for other uses; natural or man-made lakes create environmental buffers to aid in water treatment, create aesthetic value and may enhance biodiversity; water reuse augments the total water supply, decreases contaminants in the environment and creates opportunities for energy generation and the recovery of other resources. Systems should be evaluated in the framework of the water–energy nexus to ensure sustainability in both aspects.

Potential barriers to implementation of cyclical systems include water quality regulations, large investments of time, money and materials that may be necessary in reconfiguring an entire system, and societal opposition to using reclaimed water.

8.5 FIT-FOR-PURPOSE TREATMENT AND UTILISATION

Many end-uses for water do not necessitate the use of potable water. In many cities, the quantity of water that needs to be of drinkable quality comprises no more than half of the entire potable water quantity supplied, even in households. In water used for municipal, commercial, industrial and agricultural purposes, this percentage is much higher.

A smarter way to utilise water is to categorise the requirements for water quality into various grades and then to compare the requirements with the intrinsic qualities of the water from each alternative source. This method is fit-for-purpose source selection and fit-for-purpose water treatment. In this way, water use efficiency can be maximised, and energy consumption minimised.

For example, direct use of rainwater after only simple sedimentation processes is possible, as is currently being practised in many Australian houses and communities. Tertiary wastewater treatment may not be required when the treated effluent is used for agricultural irrigation, because residual suspended solids, organics, nutrients may not have negative impacts on crop growth; these constituents may even improve crop yield. Seawater can be directly used for toilet flushing, without the need for desalination, as is practiced in Hong Kong (section 6.1). Finally, multi-step reclaimed water use can be made possible to increase the efficiency of water utilisation and is currently being implemented in Mexico (section 6.5).

One possible challenge when implementing fit-for-purpose treatment is the presence of water quality regulations, which may restrict the use of water below a certain quality. Since standards and regulations can vary greatly by location, technological solutions for water reuse and their implementation plans must be tailored to local guidelines. Implementers may benefit from taking lessons from similar jurisdictions, and from creating systems that can be amended easily with small changes to technology and regulatory frameworks. To create fewer problems in the future, regulations may be made flexible enough to respond to rapidly evolving technology when possible. In another respect, regulations that are in place to improve resource efficiency may actually promote the use of fit-for-purpose treatment, rather than deter it (UN Water, 2015a).

8.6 DYNAMIC STRATEGIES

An important factor when creating water management strategies is the dynamic nature of the water sector. New challenges, concerns and contaminants are constantly emerging, and therefore the technology must be constantly improved to keep up with present conditions in supply networks. Regulations affecting water treatment and supply are also prone to changing, resulting in the need to update technology. Therefore, long-term, holistic and flexible strategies for improving water management schemes are generally better than one-time changes.

For example, frequently neglected in the design of interventions for water loss reduction is the dynamic nature of water losses and the interactions of its components. Many water-loss reduction strategies tend to focus on one part of the system, instead of the network as a whole. Efficiency of a water network at any moment is the combined result of its natural deterioration and the measures that have been put in place to combat this deterioration. If nothing is done, there will be an accelerated proliferation of leaks and occurrences of defective water meters, as well as the accumulation of out-of-date information in the customer and network databases. However, if short-term fixes are put in place and not maintained, the same result can occur. To sustain the gains of water loss efficiency, there should be a tendency to move away from short-term interventions towards multi-year investment plans, funded through the water utilities' water tariff structure, and operations should be refocused towards the desired outcome.

This gradual, dynamic approach is also preferable for building a reputation and gaining public trust. It is often more effective and sustainable to work slowly and make steady improvements to become first in class. To build up a good reputation, it is important to choose and implement safe and reliable technological solutions, and to utilise good communication, committed and capacitated personnel, and solid organisational procedures. Utilities should take care and ensure the safety of water with multiple barriers and redundancies, as one incident can destroy a good reputation built over years of hard work.

8.7 ENVIRONMENTAL PRIORITIES

Future technologies should be well manufactured, environmentally friendly and energy efficient. Sound engineering practices should be made a priority, with the aim to respect the environment. This includes consuming less energy – if they are consuming conventional energy resources (gasoline, coal, natural gas) – or directly using alternative energy resources (solar, hydro, wind, biomass, etc.). For example, desalination technologies can be highly energy consuming; heat must be used for water evaporation in thermal desalination, and electric energy is fundamental in pumping systems for RO. Harnessing the power of renewable, non-polluting energy sources would make desalination a more sustainable resource option. In the future, water professionals will be more aware of new sustainable technologies.

Important decisions regarding water and the environment should also be made with long-term sustainability in mind, rather than short-term goals or vested interests of politicians and business leaders. For example, governments may wish to strengthen their ties with particularly influential industries by making hasty decisions that may not be in the public's best interest in the long-run. This may include giving financial support to high polluting companies, or selecting infeasible projects as a result of lobbying that will be too expensive to maintain or even finish in the future. Companies may make decisions that are not sustainable in the long-run based on short-term profits.

Not only must decisions be made with the environment and sustainable resource use in mind, but regulators must have the willingness and the capacity to put in place high fines for non-compliance with poor practices. If fines are too low, industries may find it cheaper to pay rather than alter their practices. Fines and taxes should force a shift in the way companies view polluting.

9 CONCLUSIONS

Opportunities and needs for improvement are present in global water management strategies. The effects of climate change, population growth, over-consumption and pollution are taking a toll on our existing resources, and we need to adapt the way we think about and use water if we hope to create an effective, efficient, reliable and resilient supply for the future. All over the world, these changes are beginning to occur. The research, trends and case studies presented in this Compendium offer proof that AWR are increasingly becoming incorporated into water portfolios, and display the benefits of adopting such practices.

Existing solutions range in their costs, accessibility and energy efficiency. Most demand-management strategies tend to be relatively low cost, and since they aim to reduce water production, they actually reduce strain on water resources. RWH is an – almost – energy-neutral and low-cost practice that can be used almost anywhere that has sufficient precipitation. Other AWRs, such as reuse or desalination, are said to have near limitless quantities, but require energy in production and may be expensive or produce effluent that must be disposed of. Therefore, a comprehensive understanding of the water–energy nexus is needed in making decisions about AWR options, and integration of clean, renewable energy sources should be incorporated into projects as much as possible.

Whichever resource options are selected for a given scenario, it is essential to tailor them to the specific location in a holistic, integrated fashion. No one solution can be globally applicable, so it is up to water managers and political leaders – in consultation with relevant stakeholders – to select solutions that suit the region in question, work well in conjunction and take into account the social, economic, political/institutional, and environmental factors of the area. Doing so has the potential to create a safe and reliable water supply, while minimising unintended consequences on environmental systems and increasing the socio-economic well-being of the population.

Of course, water management sectors still have a long way to go before AWR-inclusive portfolios can be globally implemented. Significant gaps exist in related sectors, so better platforms must be created on which experts can collaborate to improve not only the robustness of the technology but also its accessibility and sustainability. Enhancing the visibility of successful AWR-centred projects through conferences, media outlets and documents such as this Compendium, the scientific community and the general public alike may not only grow to accept AWR practices, but demand them.

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