Rev Environ Sci Biotechnol (2017) 16:591–609
DOI 10.1007/s11157-017-9449-7

MINI REVIEW

Desalination and water reuse to address global water scarcity

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Published online: 28 October 2017

Abstract The act of ensuring freshwater is considered the most essential and basic need for humanity. Although the planet is water-rich in some terms, the freshwater sources available for human consumption and beneficial uses are very limited. Excess population growth, industrial development coupled with improving living standards have caused an unprecedented need for freshwater all over the world. Regions once rich in water resources are struggling to meet the ever increasing demands in recent years. In addition, climate change and unsustainable management practices have led to a situation called "drought" in many regions. Water supplies in drought conditions can be addressed by taking two major approaches related to management and technology development. The management approaches include demand mitigation and supply enhancement. Demand mitigation can be done by implementing water conservation practices, and by enforcing a mechanism to influence user-responsible behavior through higher water fares and other billing routes. Supply enhancement can be achieved by utilizing the methods available for water reclamation, reuse and recycle including rain harvesting. This paper provides a critical insight of the causes for drought and the issues caused by persistent drought conditions followed by discussion of management and technological approaches required to maintain adequate water resources around the world. Challenges and opportunities involved in implementation of desalination and water reuse technologies in addressing global water scarcity are discussed in detail with case studies

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Keywords Drought · Water scarcity · Water reuse · Recycle · Ground water · Sustainability · Energy · Pollution · Water supplies · Desalination · Aquifer storage · Dams · Rain harvesting · Public education · Outreach

1 Introduction

Water is an abundant and most essential commodity, often regarded as basic and free right (Yarlagadda et al. 2011). Although water is one of the most abundant resources of the earth which covers three quarters of the earth's surface, about 97% of this volume is saline, and only 3% is fresh water, suitable for humans, plants, and animals. Of this fraction, nearly 2.5% is blocked in polar ice caps, glaciers and atmosphere, leaving about 0.5% of water accessible to human needs in the form of river water and groundwater (Gude and Nirmalakhandan 2009). However, due to various reasons related to population growth and increasing living standards and changing climate, these water sources are dwindling at a faster rate than they can be naturally replenished. Most of the world population still depends on groundwater which is available in finite reserves and others along coastal areas depend on seawater as a source of water supply. In addition, many communities around the world face water supply challenges due to increasing demand, persistent drought, resource depletion and impairment of surface water and of groundwater sources, and dependence on single sources of water supply.

About 30% of the people living around the world lack clean water sources for basic sanitation needs and 60–70% of the global population will live in the regions with conditions of absolute water scarcity or severe water stress (Macedonio et al. 2012). Water scarcity related to either physical unavailability or economic unaffordability (see Fig. 1) has become a common phenomenon in many geographical regions (Rijsberman 2006). Physical water scarcity refers to inadequate water resources to meet the present demands. Economic water scarcity indicates the lack of mechanisms to acquire access to available water sources in the region. This type of scarcity is due to human, institutional, political influences and financial capital limitations. However, economic water scarcity is mostly associated with unaffordability to obtain clean water. Many countries including the U.S., Middle Eastern and North African countries (MENA region) and southeastern European countries, Southern India, Pakistan, Mongolia, Afghanistan, Kazakhstan, Turkmenistan, Uzbekistan, Tajikistan and western Australia are facing physical water scarcity. Economic water scarcity is experienced in Central and Latin America including Caribbean region, South and Central Africa, North India, some parts of China and some other Asian countries. There is little or no water scarcity in the North American countries like Canada, and most of the South American countries including some of the north European countries.

Several indices are available for indicating water scarcity and water stress levels with ongoing discussions on their definitions and usefulness (Damkjaer and Taylor 2017). A summary of indices are shown in Table 1 (Rijsberman 2006; Chenoweth 2008).

Many of the drought affected communities have access to brackish groundwater and seawater which

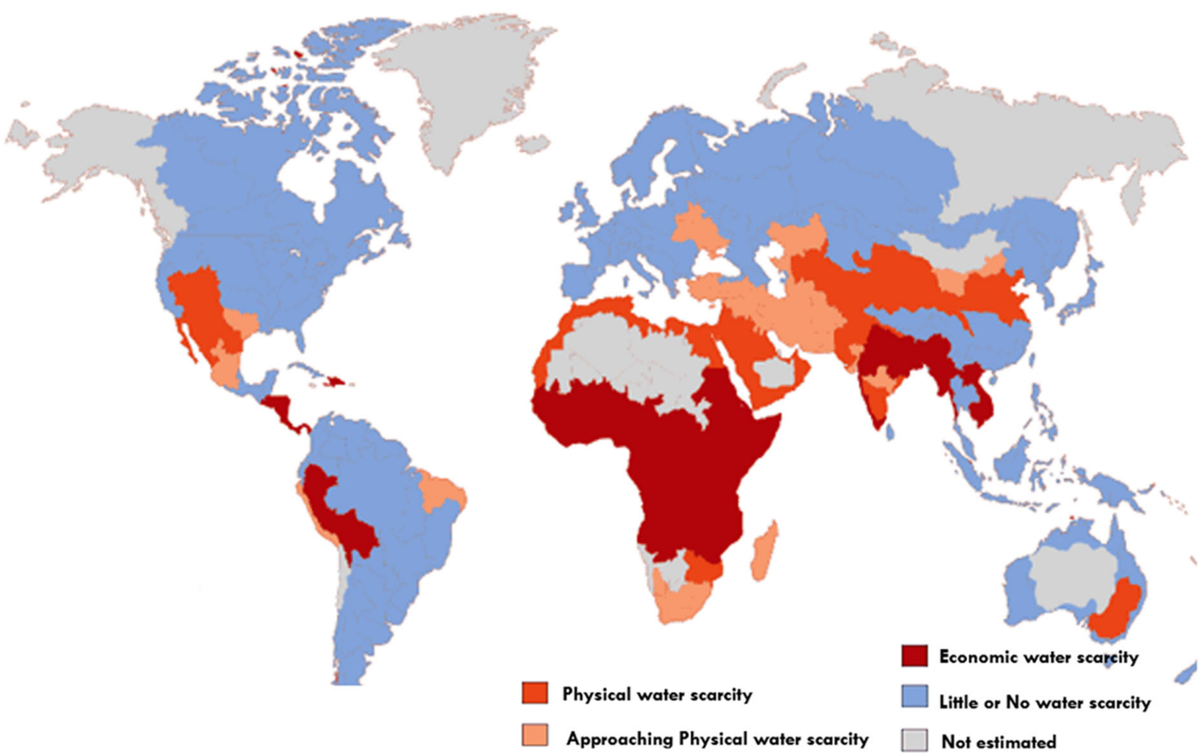

Fig. 1 Different types of water scarcity around the world (FEW Resources. Org)

Table 1 Summary of water stress index (WSI) thresholds

Category	Inverted WSI (people/flow units)[a]	Contemporary WSI threshold (m^3 $capita^{-1}$ $year^{-1}$)
No stress	< 600	> 1700
Water scarcity	600–1000	1700–1000
Water stress	1000–2000	1000–500
Absolute water stress	> 2000	< 500

[a]A flow unit in the column for Inverted WSI is equal to 10^6 m^3. To get contemporary WSI, one flow unit must be divided by the number of people competing for this water

make them suitable for desalination. Other approaches such as water reuse and recycling help address the water shortage problem, but treatment technologies are not quite affordable. Even if affordable, many engineering, operational, regulatory and social challenges need to be overcome (see Fig. 2). The purpose of this article is to (1) discuss various causes for water scarcity, (2) discuss the water quality issues in water-scarce regions, (3) present options for sustainable water supply alternatives, (4) discuss management and technological approaches for implementing these alternatives, and finally (5) provide insights for future directions and challenges and opportunities involved in sustainable water supplies based on desalination and water reuse technological platforms.

2 Causes for water scarcity and relevant issues

Causes of water scarcity are related to drought, overuse, anthropogenic pollution, physical distance and political and social stress. Deep understanding of the causes and issues related to water scarcity is the first step towards developing sustainable water supply alternatives for these regions.

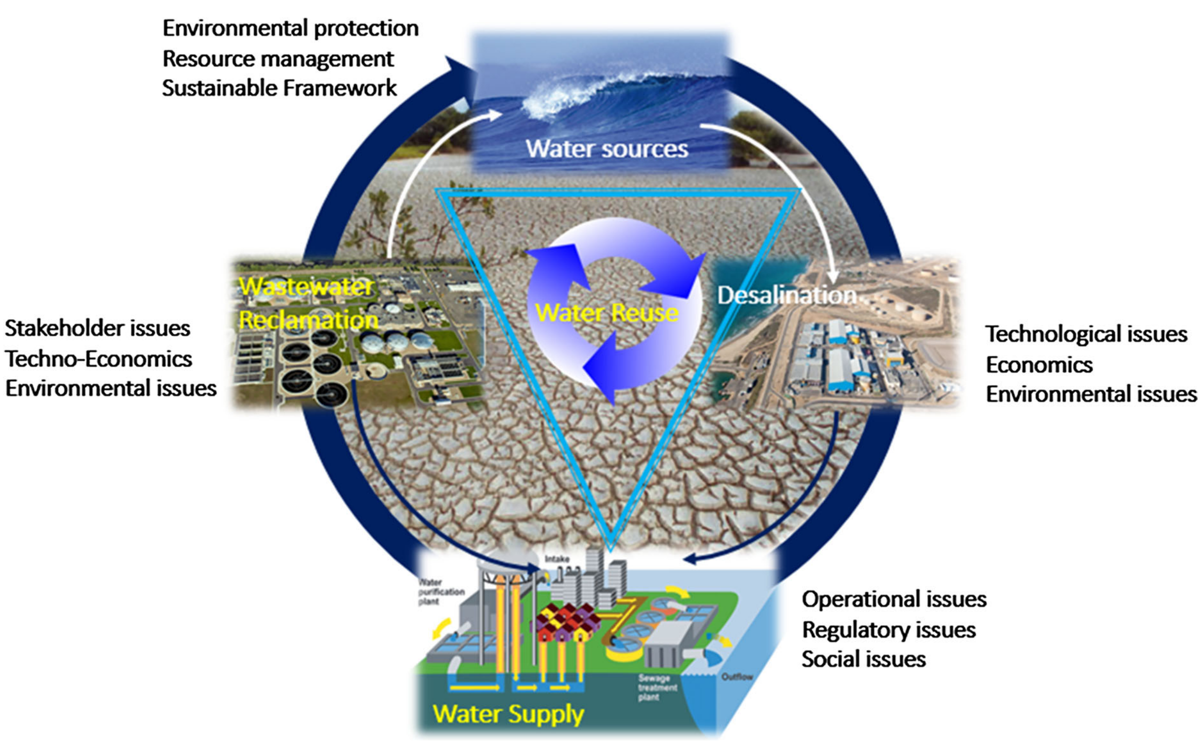

Fig. 2 Desalination and water reuse for sustainable water supplies—challenges and opportunities

2.1 Water scarcity due to drought

Drought can be occasional, temporary or perpetual which can have detrimental effects on the society and local water sources (Iglesias et al. 2007). Occasional droughts can be recovered from excess precipitation. Temporary drought usually occurs on annual basis which may also be recovered in successive years. Perpetual droughts are related to those areas which desertified over long period of time due to climate change, overuse and poor management practices. It has been noted that some regions of the world have experienced historical droughts in recent years. For example, the California's drought has increased over the past decades due to climate change and global hydrological patterns. Australia has experienced so called millennium drought.

Although considered a water-rich country, United States has some disparities in its water source availability. In addition, populations in many regions have increased between 100 and 400% within the four decades. For example, the population of Texas has doubled in this period while the populations in Florida, Arizona and Nevada have increased by 175, 275 and 450% respectively (U.S. Census 2010; NRC 2012). The Southwest region of the country is arid and drought-prone while other parts of the country are reasonably well-sourced. The water demands for domestic and commercial/industrial uses, in the United States are expected to rise by 60.56 billion m^3 per year by the year 2020 (Cohen 2007). For instance, the gross water demands including domestic and agricultural need have already increased by 1.23 109 m^3 per year in California. Adding to this, a majority of the nation's future population growth is anticipated to take place in Florida, Texas and California which are already facing severe water supply–demand issues.

One of the highly populated and driest continents in the world is Australia (Australian Government National Water Commission 2005). Its water supply sources continue to face risks due to climate change with continuous low precipitation events coupled with forest fires and floods. Drought conditions have persisted in this continent for over the past 15 years (Hall et al. 2011) and several studies have addressed various options and issues of managing the drought (Egan 2009). This continuing drought trend has led to the recent installation of a number of new desalination plants in Australia (El Saliby et al. 2009).

2.2 Water scarcity due to overuse and anthropogenic pollution

Population growth, urbanization and economic development in many regions of the world have caused overuse of water (Kumar and Singh 2001). Population growth alone stimulates the need for additional water resources for meeting the basic necessities of water for food production and hygiene and commodities. Some other causes for overuse are related to industrial processing of water due to high living standards which give rise to use of electronic devices and tourism where luxurious use of freshwater is a necessity. In some regions of the world, there is a situation called "Artificial shortage of surface water" which is caused by the excess withdrawals than the actual need (Slavikova et al. 2016). This happens due to poor water demand management. As the excess withdrawal becomes a norm, this leads to a situation where the availability of surface water declines, additional costs may be incurred to provide these excess volumes. Environmental pollution due to human activities such as domestic sewage, effluents originating from agricultural, concentrated animal feed (CAF) operations for dairy and meat production, illicit discharge of construction and industrial wastewaters and other pollutants originating from storm water, heavy floods, and recreational activities (Dokulil et al. 2000).

2.3 Water scarcity due to physical and political barriers

In some cases, water resources may be available in adequate quantities but at a distance that cannot be economically reachable (Molden 2007). This is particularly true for rural communities in underdeveloped countries. This can be named as a physical barrier. This also relates to geographical barriers across the nations that will not permit transport of water. The political barrier relates to those conflicts arising from the political interests between the water-rich and water-scarce regions.

Water scarcity causes lack of access to clean drinking water required for basic sanitation (water needs for bathing, cooking and cleaning) and hygiene. This results in use of available impaired waters which causes development of new diseases and other issues public health issues. Many children and infants loose lives due to consumption of unclean water. Regions facing drought and water scarcity often have limited production of essential crops and meat. This causes hunger and impacts the morality of the people in these regions. Prosperity and well-being is affected severely leaving populations in poverty. Poverty and the drive for ensuring reliable supplies of food will cause internal and external conflicts. On the other hand, poverty and lack of basic sanitation will lead to lack of education. This causes the communities lacking education are not necessarily knowledgeable in managing the local, limited water supplies. They need education to understand the value of water and to manage this precious source in an equitable and beneficial manner.

3 Water quality in drought areas

3.1 Groundwater quality

Lack of surface waters to meet the water demands due to persistent population growth and urbanization drive the worldwide population to access groundwater sources. These resources are finite and deplete with continued activity called as "mining" for our increasing demands. Figure 3 shows the regions in the USA where groundwater depletion is highly pronounced. In some regions, though they were originally water-rich, the depletion rates are very high (Konikow 2013). This is usually associated with increased withdrawals for irrigation as in the case of Mississippi. In some cases, it is compounded by the water needs due to excessive population growth, for example the water crisis in Central valley of California.

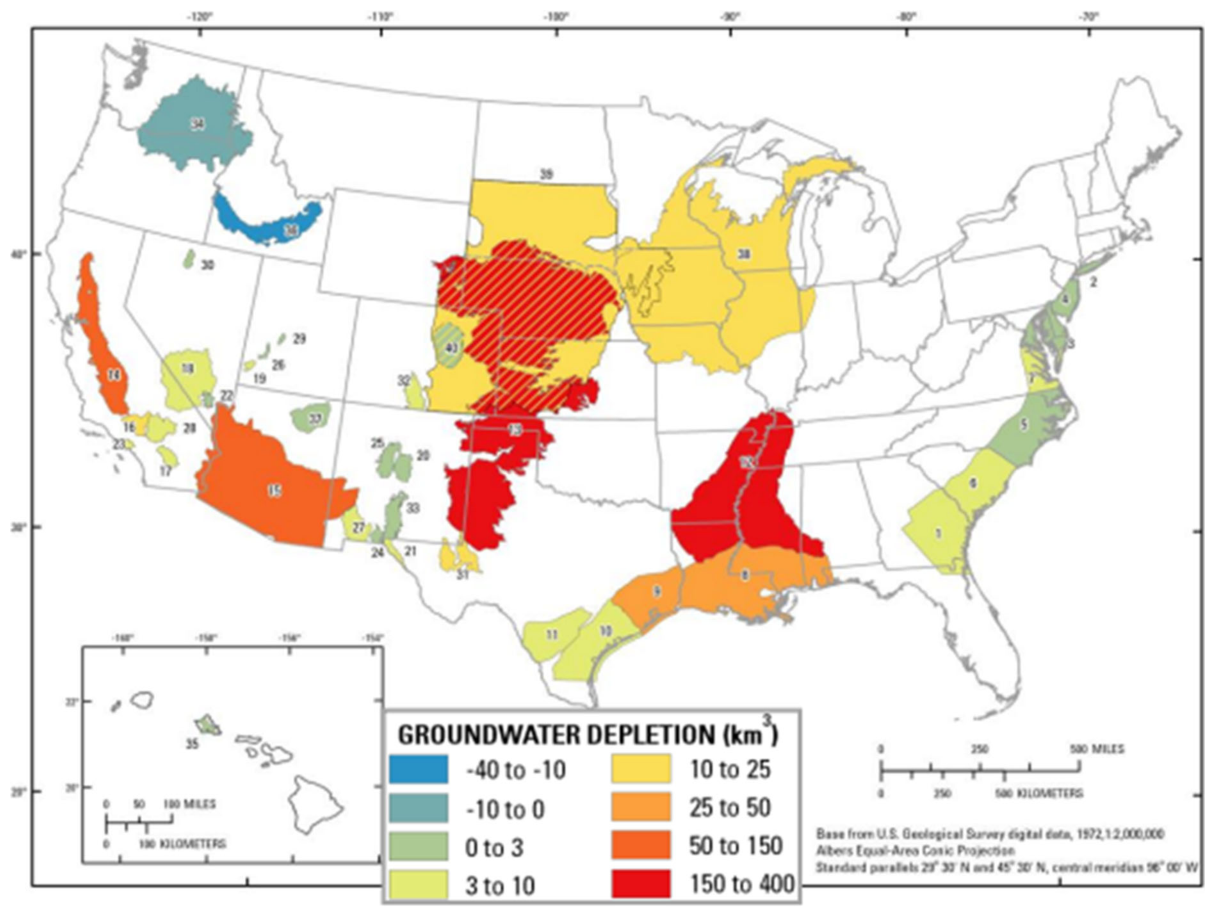

Fig. 3 Groundwater depletion in the United States between 1900 and 2008. (Konikow 2013, USGS)

As the quantity declines in many groundwater reserves, the quality of the source becomes unsuitable for many purposes due to other undesired groundwater chemistry that could take place when soil and water coexist. In addition, ground water sources are impaired either by the naturally occurring hazardous substances such as uranium, fluoride and arsenic (Yarlagadda et al. 2011). In some cases, the impairment is caused by illicit discharges by industrial sectors. Often, these ground waters also contain high dissolved solids leading to their categorization as brackish waters. Traditional treatment techniques are not adequate to remove the dissolved solids. As an example, about 60–70% of ground water sources in the US are highly saline. About 75% of ground water in New Mexico is too saline (10,000–35,000 ppm) for most beneficial uses and the remaining 25% of the ground water contains dissolved concentrations of lower than 2000 mg/L causing many treatment and supply management issues.

3.2 Brackish groundwater

Many groundwater sources around the world are not suitable for direct use. These sources are highly saline which require additional treatment for removing salts to produce potable water or water suitable for other non-potable uses (Mohsen and Al-Jayyousi 1999, Yarlagadda et al. 2011). Similar to many parts of the world, some regions of the United States, especially southwestern part is in critical need of potable water supplies. As mentioned earlier, extreme population growth and industrial development coupled with unsustainable practices have resulted in unmanageable water demands. As shown in Fig. 4a, some of the highly populated cities are located in water-scarce regions. In addition, about 50% of the population is concentrated in coastal regions where access to freshwater is an issue (Fig. 4b). Other regions that are in desperate need for freshwater are the inland communities which are committed to agriculture and irrigation as shown in Fig. 4c. It can be noted that groundwater sources in many of these regions contain high dissolved solids concentrations which render them unsuitable for most potable uses including irrigation. Non-traditional technologies such as membrane and thermal desalination processes should be considered to treat these water sources.

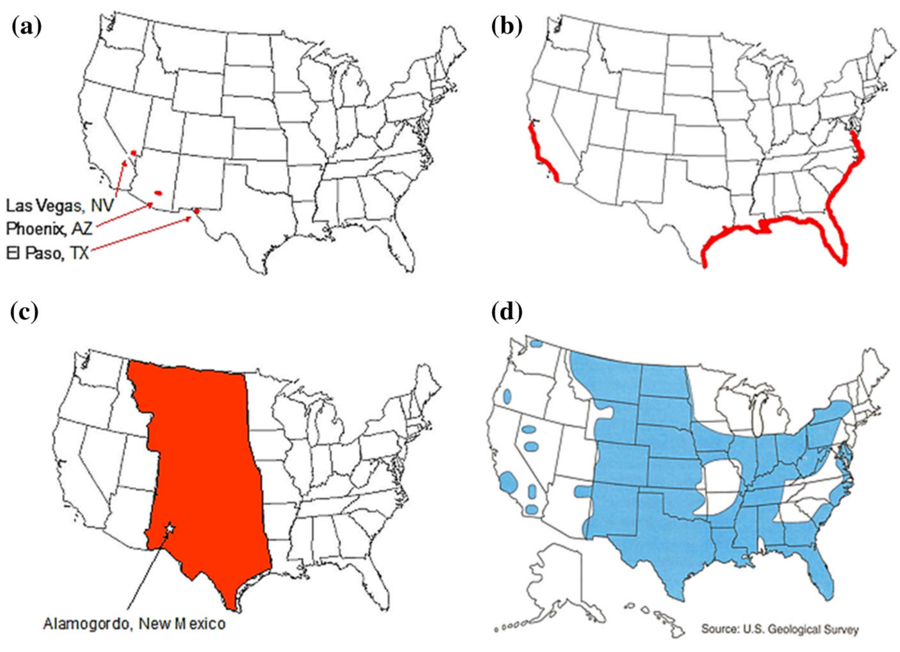

Fig. 4 Water-scarce regions and ground water quality in the USA: **a** major water-scarce, populated inland cities in USA; **b** highly populated coastal communities; **c** water-scarce inland rural communities due to excess irrigation needs; and **d** brackish water reserves in the USA

4 Solutions to water supply issues in drought areas

Water supply issues in drought areas can be addressed using different approaches. This is a multi-faceted problem which requires involvement from users, governing bodies, industrial partners, and research and development and regulatory agencies. Figure 5 shows the approaches that should be considered for a holistic management of the problem. The solution includes mitigation of current demands where possible with proper governance and supply enhancement to meet the demands by management and technological approaches.

4.1 Demand mitigation

Utilities could play an important role in controlling the water demand to a certain extent. Pricing and rate structures and non-price strategies which include public education, technological improvements and water restrictions. Conservation activities such as retrofitting water-saving fixtures in domestic applications, industrial production and other public amenities where water use is a must. Agricultural sector contributes to most of the water loss followed by power production industry. Water conservation practices in irrigation practices can make significant improvement in this aspect. About 30–75% of the water withdrawals are lost in power production, especially in cooling applications. Water losses due to evaporation can be reduced by considering other novel approaches such dry cooling and among others (Gude 2015a).

Water is often considered abundant natural source available freely in abundance. This is a misperception that many of the communities carry across generations. Water should be realized as a precious and dwindling commodity to ensure its availability for future generations to come. This can only be achieved by enforcing appropriate water pricing dependent on the socioeconomics of a community. This will enable improve user behavior in terms of responsible use and concern for its protection and management. This approach requires active involvement of public, administrators and industrial partners. Public education and outreach is a key to achieve success. The main drawback is that the progress can be slow as it depends on the user psychology, preparation levels and willingness to protect the valuable resource.

Demand mitigation approaches do not solve the supply problem directly but they can establish a system in which water supply options can become more feasible and affordable. The above mentioned approaches will not provide solutions to those problems that are severely affected by climate change and other demographic changes in a local community of interest.

4.2 Supply enhancement

Water supplies can be enhanced following management and technological approaches. Water management approaches include immediate or near-future construction activities or those intended for long-term sustainability. Short term and immediate approaches involve water transfer acts across the regions. The

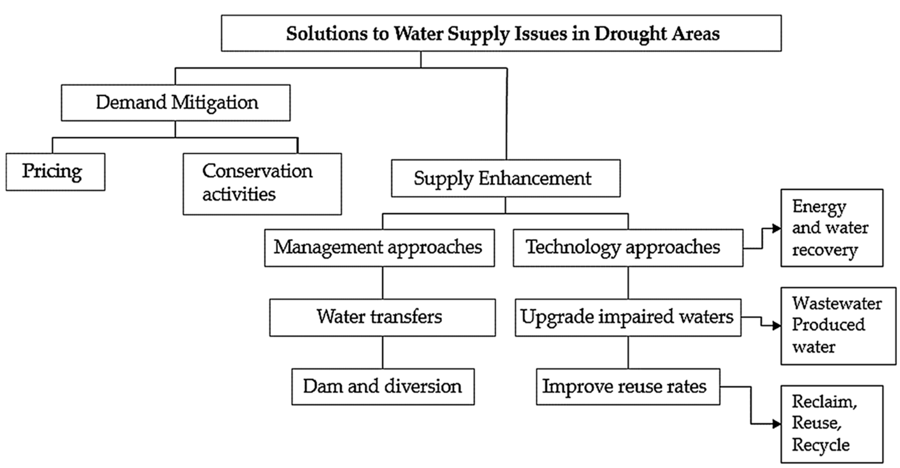

Fig. 5 Solutions to holistic management of water supply issues in drought areas

main mechanisms in which water supply enhancement can be done is by: intercepting (rain harvesting), diverting (water diversions), storing (dams and reservoirs) and transferring water (transport water among basins or regions). The following paragraphs discuss the.

4.2.1 Water transport

Water management can be done by considering transport of water from water-rich region to a water-scarce region if affordable water costs can be achieved through this mean. For example, many countries such as Singapore, USA and other European countries already practice this approach as a water supply alternative (Gude 2016a). International transfer and inter-state transfer is possible depending on the situation. The main drawback with this option is that this arrangement may create some political stress and economic dependence on water-rich countries. Construction of dams and water flow diversion can be considered as other feasible approaches when dealing with the surface water sources with seasonal and geographical changes.

4.2.2 Technology development

Technological approaches include innovation in the present technology based on scientific discovery and practical feasibility. Many technologies are available that produce high quality and safe drinking water or water suitable for other beneficial uses. Technological approaches depend on the type of source water as well as the purpose of the end product. Surface and ground water sources with less than 3000 mg/L total dissolved solids (TDS) can be treated with conventional technologies such as coagulation. Flocculation, lime-softening and sedimentation and filtration processes. Membrane technologies can also be used to remove the TDS effectively. Ground waters and seawaters having TDS higher than 3000 mg/L should be treated using membrane or thermal desalination technologies.

4.2.3 Energy efficiency and water recovery

As shown in Fig. 5, energy efficiency and water recovery are the two important factors in determining the feasibility of a desalination technology. Membrane technologies offer superior performance at lower specific energy consumption while thermal technologies require both thermal and electrical energy. In general, both technologies are energy-intensive and cost-prohibitive. However, the absolute necessity for water makes these technologies viable. In some regions where low-cost thermal energy is available as a result of power generation, thermal technologies are more feasible. The reason for utilization of thermal technologies is also often associated with high TDS seawater and seasonal fluctuations in temperatures. Energy recovery schemes have offered a less energy-intensive desalination option in both membrane and thermal technologies. Reuse and recycling is the fundamental principle followed in thermal technologies whereas the advent of energy recovery devices has made the membrane desalination a feasible option despite high capital and maintenance costs. More details on the energy recovery aspect are not within the scope of this chapter and hence not discussed here. However, readers are referred to other publications in this area (Gude 2011, 2015a, b)

4.2.4 Rain harvesting

Some drought regions face water scarcity not because of low precipitation levels, rather due to lack of methods for capturing the excess water during rainy events which is usually drained or lost to the environment. Rain harvesting has been practiced for centuries as a simple, proactive alternative to deal with the dry seasons. Rain harvesting can be done at very small to large scale applications depending on the water needs. Capturing the rain water itself can be done many ways (Sharma and Smakhtin 2006) which are in situ harvesting, cisterns/tamks/kunds, Khadin system, Nadis/tobas, check dams, and percolation tanks.

In-situ rainwater harvesting is practiced by developing field/contour bunding, ridging, and conservation furrows. Vegetative barriers or constructed micro-catchments are methods to capture the rain water in in situ conditions. Cisterns/tankas/kunds which are essentially underground storage tanks that collect rainwater runoff, are used most commonly for centuries and more commonly in arid regions of India, Pakistan, Sri Lanka, China and several other countries. Farming using rain water is well suited in deep soil plots surrounded by some sort of natural catchment zone. Nadis/tobas are excavated or embanked village ponds used for harvesting precipitation to mitigate drinking water scarcity. Pond water can be available over long periods after rain, depending upon the catchment characteristics and amount and intensity of rainfall (Sharma and Smakhtin 2006).

4.2.5 Water reclamation and reuse

Supply enhancement can be achieved by utilizing impaired waters such as treated secondary effluents (wastewater) for water reuse related to non-potable uses, and other impaired waters used in process cooling and heating applications and produced waters from shale gas production. As the conventional water supplies are diminishing and the need for water reuse is inevitable. Water reclamation and reuse allows for securing the longevity of available water resources for more critical needs while the recycled water can be used for non-potable uses.

Water reuse has been practiced for over 5000 years; however, during the last 100 years efforts have been made in many regions of the world, for the production of high quality reused water, following strict quality guidelines (Angelakis and Gikas 2014). Water reuse can be practiced at domestic (grey water–wastewater from clothes washers, bath tubs, showers and sinks) levels, and in municipal, industrial, and agricultural sectors. Grey water reuse is widely practiced in United States, Europe and many other countries in Middle East. Around 75% of wastewater is reused in the Middle Eastern countries. The quality of the product water for reuse depends on intended end use (WEF 2006). Kuwait and Qatar reuse more than 10% of total water supply (Madwar and Tarazi 2003) while reclaimed water reuse is well practiced in Australia (Dillon 2009).

4.2.6 Water reuse implementation

Water reclamation and reuse programs have been widely adopted across the world in view of the increasing demands for water supplies. However, the contribution from this approach still remains to be unsubstantial (Miller 2006). Including water reuse option in the water supply and management portfolio helps to realize the true value of the contribution from this approach. It can be instrumental in water policy development and its implementation which may lead to long-term sustainability (especially, availability) of these resources. However, including water reuse in the overall water supply and management portfolio can create many challenges rising from water governance, health risks, regulatory aspects, and public perception. Other requirements would be the need for developing innovative technologies, technology transfer, and novel applications and public education. Novel technologies are essential to remove the emerging contaminants such as endocrine disrupting chemicals and pharmaceutical and personal care products. In some regions, groundwater recharge or aquifer storage is considered a long-term sustainability approach.

4.2.7 Framework for water reuse implementation

Several options can be considered to make the water reuse and recycle programs to be effective (see Fig. 6). These options are: education and outreach, incentives, removing barriers, and mandates and regulations (GE 2015).

Education and Outreach may include programs that promote certification programs and recognition awards. Programs to disseminate the scientific information and general benefits and essential facts about the water reuse by education and outreach efforts. Educating the users on water withdrawal trends, consumption, discharge and reuse data can help create interest in water reuse implementation.

An incentive program including direct subsidies, reductions in payments to the government, payments for water reuse, adjusting pricing mechanisms, regulatory relief for recycled water users, government procurement of water recycling/reuse equipment and structuring of water rights to reduce the use of potable water can be beneficial in supporting the water reuse implementation.

Regulatory reliefs may include modification of local regulations depending on the application especially in terms of water quality standards, revising plumbing codes to allow dual piping, and monitoring permitting and inspection requirements for recycled water.

Creating mandatory requirements should consider utility planning and management to develop plans for recycled water, restricting potable water to human or food-related uses, and requiring the use of recycled water for agriculture and other non-potable uses and requiring water recovery systems.

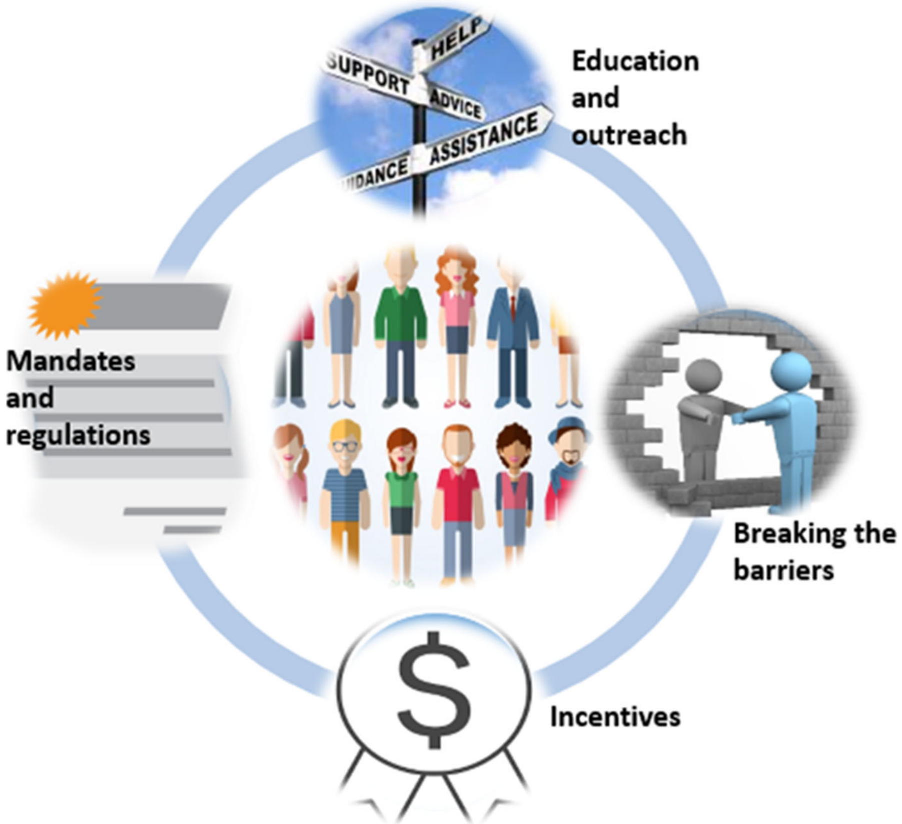

Fig. 6 Framework for water reuse implementation

5 Water reuse technologies

Various chemical and microbial contaminants should be removed to make the wastewater sources suitable for potable or non-potable uses. Advanced treatment using chemical and physical separation mechanisms is often considered as a treatment scheme. Numerous treatment options, including engineered and natural treatment processes are available to achieve this goal. Selection of a suitable treatment scheme depends on the specifics of water quality objectives intended for specific uses. Advanced treatment processes are also capable of removing emerging pathogens or contaminants such as endocrine disrupting chemicals and pharmaceutical and personal care products (Fast et al. 2017).

Natural systems are considered in treatment schemes where the water quality objective is a potable water reuse. These involve "natural barriers" such as soil aquifer treatment, wetlands and other land application for soil infiltration to provide natural treatment of organic and nutrient compounds and microbial contaminants (Gude et al. 2013; Martinez-Guerra et al. 2015). This is achieved by providing a retention time suitable for natural attenuation of contaminants followed by blending with the water sources. Application of natural systems is subject to climate and hydrogeological conditions. These systems are not the preferred method currently due to lack of standardized guidelines for design and operation.

Engineered solutions are designed by taking the advantages of chemical, physical and characteristics of the contaminants in the water sources (Gude 2015a). Conventional sand filtration is commonly used to remove the suspended solids but membrane filtration processes such as microfiltration and ultrafiltration have become a more common practice in recent years. Chemical coagulation, precipitation, neutralization, oxidation, hydrolysis and other reactions are considered for organic contaminant removal. Trace organics including volatile contaminants can be removed using granulated organic carbon (GAC) filters and ion exchange columns. Nutrients and other microbial contaminants can be removed using natural systems such as wetlands, soil application, and air-stripping and reverse osmosis processes. Disinfection is performed using chlorination, and or ozonation, and or ultraviolet exposure (UV) depending on the specific objective of the water reuse application. Table 2 shows the different membrane technologies and their specific characteristics in water treatment and desalination applications (Baker 2000; Tsuru 2001; WEF 2006). Microfiltration and ultrafiltration are used in lieu of conventional sand filtration process due to higher efficiency and smaller footprint. Nanofiltration can be used to remove some specific contaminants at a molecular weight cutoff with much lower specific energy consumption compared to reverse osmosis. Salts and other dissolved and micro- or trace contaminants can be removed using reverse osmosis membrane filtration.

Some examples of water reuse applications in the United States are shown in Table 3. It can be noted that lime coagulation, clarification and media filtration are used in plants constructed in 1960s through 1990s. Membrane filters have become more dominant in the plants constructed after 1990s, mainly due to development of highly efficient membrane materials with lower energy consumption. Soil aquifer treatment is also used often in plants where the intended end use is the recharge of local water supply aquifers.

6 Desalination technologies

Dissolved solids present in saline water sources can be removed in a desalination process based on thermal evaporation or membrane separation principles. Desalination by thermal technologies involves boiling of seawater to evaporate freshwater from the saline water leaving the dissolved solids in the brine. The membrane processes function similar to mechanical filters where water molecules permeate through a semi-permeable membrane to produce permeate with low dissolved solids. Thermal processes are energy-demanding when compared with membrane processes mainly due to the latent heat required for evaporation of freshwater. However, membrane processes utilize electrical energy which is considered a premium form of energy.

Thermal desalination technologies include solar stills; multi-effect evaporation/distillation or boiling (MED/MEB); multi-stage flash distillation (MSF); thermal vapor compression (TVC) and mechanical vapor compression (MVC). Membrane processes include electrodialysis (ED), nanofiltration (NF) and reverse osmosis (RO). Other processes that involve a combination of the two principles in a single unit or in sequential steps to produce pure or potable water include membrane distillation (MD) and reverse osmosis combined with MSF or MED processes (Gude 2015b).

Table 2 General characteristics of membrane technologies for water treatment and desalination

Membrane type	Particle capture size	Typical contaminants removed	Typical operation pressure ranges	Key applications
Microfiltration	0.1–10 µm	suspended solids, bacteria, protozoa	0.1–2 bar (1–30 psi)	water treatment plants, pre-treatment in desalination plants, the preparation of sterile water for industries, such as pharmaceuticals, etc.
Ultrafiltration	ca. 0.003–0.1 µm	colloids, proteins, polysaccharides, most bacteria, viruses (partially)	1–5 bar (cross-flow) 0.2–0.3 bar (dead-end and submerged) (3–80 psi)	drinking water treatment, the pre-treatment process in desalination, and membrane bioreactors
Nanofiltration	ca. 0.001 µm	viruses, natural organic matter, multivalent ions (including hardness in water)	5–20 bar (70–220 psi)	treatment of fresh, process and wastewaters
Reverse osmosis	ca. 0.001 µm	almost all impurities, including monovalent ions	10–100 bar (800–1200 psi)	treatment of fresh, process and wastewaters, desalination of sea water

Table 3 Examples of water reuse plants and their operating schemes in the United States (National Research Council 2012)

Location	Type of indirect reuse	Project size MGD (10^3 m^3/d)	First installation year	Current status	Treatment technologies				
					Suspended solids	Organic compounds	Residual nutrients	Residual salts	Pathogens
Montebello Forebay, County Sanitation Districts of Los Angeles County, CA	Groundwater recharge via soilaquifer treatment	44 (165)	1962	Ongoing	Media filtration	Soil-aquifer treatment	Soil-aquifer treatment	None	Chlorination, soil-aquifer treatment
Water Factory 21, Orange County, CA	Groundwater recharge via seawater barrier	16 (60)	1976	Terminated 2004	Lime Clarification,	GAC filtration; Reverse osmosis; UV/AOP	Air stripping; reverse osmosis	Reverse osmosis	Lime clarification,; chlorination, UV
Upper Occoquan Service Authority, VA	Surface water augmentation	54 (204)	1978	Ongoing	Lime clarification, media filtration	GAC filtration	Ion exchange (optional)	None	Chlorination
Hueco Bolson Recharge Project, El Paso Water Utilities, TX	Groundwater recharge via direct injection	10 (38)	1985	Ongoing	Lime clarification, media filtration	Ozonation, GAC filtration	PAC augmented activated sludge system	None	Ozonation, chlorination
Clayton County Water Authority, GA	Surface water augmentation	18 (66)	1985	Ongoing	Land application system and wetlands	Land application system; wetlands	Land application system; wetlands	None	Chlorination, UV
West Basin Water Recycling Plant, CA	Groundwater recharge via direct injection	12.5 (47)	1993	Ongoing	Microfiltration	Reverse osmosis; UV/AOP	Reverse osmosis	Reverse osmosis	Microfiltration chloramination, UV
Gwinnett County, GA	Surface water augmentation	60 (227)	1999	Ongoing	Ultrafiltration	Pozonation; GAC filtration	Chem. Premoval	None	Ultrafiltration, Ozone
Scottsdale Water Campus, AZ	Groundwater recharge via direct injection	14 (53)	1999	Ongoing	Media filtration, microfiltration	Reverse osmosis	Reverse osmosis		Microfiltration Chlorination
Los Alimitos Barrier Water Replenishment District of So. CA	Groundwater recharge via direct injection	2.7 (10)	2005	Ongoing	Microfiltration	Reverse osmosis, UV	Reverse osmosis	Reverse osmosis	Microfiltration. UV

Table 3 continued

Location	Type of indirect reuse	Project size MGD (10^3 m^3/d)	First installation year	Current status	Treatment technologies				
					Suspended solids	Organic compounds	Residual nutrients	Residual salts	Pathogens
Arapahoe County/ Cottonwood, CO	Groundwater recharge via spreading operation	9 (34)	2009	Ongoing	Media filtration	Reverse osmosis, UV/ AOP	Reverse osmosis	Reverse osmosis	Chlorination
Permian Basin, Colorado River Municipal Water District, TX	Surface water augmentation	2.5 (9.4)	2012	Ongoing	Ultrafiltration	Reverse osmosis, UV-AOP	Reverse osmosis	Reverse osmosis	Chlorination

Recent statistics show that there are 18,426 desalination plants existing globally in June 2015 providing more than 86.8 million m^3 per day in over 150 countries supporting 300 million people (IDA 2017). Around 45% of this capacity is owned by the Middle East and North African (MENA) countries. Thermal desalination plants have been predominant between the years 1950 and 2000. However, membrane desalination plants have outnumbered in the past two decades reversing the situation with over 60% share (Gude 2016a, b) which is expected to be the trend in the future. The desalination plants are sourced by various water sources including seawater (60%), brackish water (21.5%), river water (8.3%), wastewater effluents (5.7%) and other water sources (4.5%) (Gude 2016a).

6.1 Energy requirements for desalination processes

Thermal and membrane desalination process operations demand for different forms of energy (Gude et al. 2010; Gude 2011). Both heat and electricity are provided in thermal desalination processes for evaporation and process flows respectively while membrane processes operate by high pressure pumps powered by electrical energy. The specific energy requirements for these processes (kWh/m^3) are shown in Table 4. The specific energy consumption for the MSF process is the highest followed by MED, VC and RO processes. Due to low energy consumption and inherent simplicity, RO process has become an attractive desalination alternative.

6.2 Energy recovery and integrated concepts

Thermal desalination technologies are generally considered energy-intensive and therefore cost-prohibitive. However, these technologies are more acceptable in regions where thermal energy sources can be accessed at low cost especially in oil-rich regions of Middle Eastern countries. Low temperature thermal desalination processes are considered energy-efficient (Gude and Nirmalakhandan 2008) which can also utilize waste heat sources such as reject heat from the domestic air-conditioning units, and heat harvested by solar collectors and photovoltaic thermal collectors (Gude et al. 2011a, b, 2012) Often thermal desalination technologies are co-located with power plants, the

Table 4 Equivalent electrical energy consumption for desalination processes (data taken from Gude 2016b)

Process	Steam energy (kWh/m^3)	Electrical energy (kWh/m^3)	Equivalent electrical energy (kWh/m^3)	Equivalent CO_2 emissions (kg CO_2/m^3)
MSF	7.5–11	2.5–3.5	10–14.5	0.09
MED	4–7	2	6–9	0.04
VC	–	7–15	7–15	0.051
SWRO	–	4–6 (with ER)	4–6 (with ER)	0.032
		7–13 (without ER)	7–13 (without ER)	
BWRO	–	0.5–2.5	0.5–2.5	
ED	–	0.7–2.5	0.7–2.5	0.038

waste steam from the condenser is utilized as a heat source for MSF or MED processes (El-Nashar 2001). In thermal desalination technologies energy recovery and recycling is done through successive stages. However, energy source utilization must be maximized. It should be noted that state-of-the-art power plants have a high energy efficiency of 35–40% whereas a cogeneration plant can achieve an energy efficiency of 75–80%. If the beneficial uses can be extended through heating and cooling applications in a configuration called "Poly generation", energy efficiencies as high as 90% can be reached.

Membrane desalination technologies are also considered energy-intensive because they utilize electrical energy which is a high quality energy. Energy recovery in membrane processes is a widely studied concept. Various types of energy recovery devices have been developed over the past few decades to minimize the specific energy consumption in membrane processes. Because minimum theoretical energy consumption cannot be achieved due to other constraints such as membrane scaling and biofouling, water recovery in multiple pass configurations can help reduce the specific energy consumption as well. For more information on this topic, the readers are suggested to refer to the contribution by the author (2011).

6.3 Role of desalination technologies

Combining water reuse and desalination schemes may help achieve supply enhancement (Gude et al. 2010). Membrane desalination/filtration processes can convert wastewater into high quality water suitable for various reuse applications. Membrane filtration processes have been widely used for water reuse (Madwar and Tarazi 2003). Micro- filtration (MF) and ultrafiltration (UF) have shown great potential for pathogen removal (Côté et al. 2004) and these have been the preferred pre-treatment processes for NF and RO. This treatment scheme allows for recovery of high quality potable water in water reclamation projects including aquifer recharge. The costs for water reclamation from treated effluents through membrane processes are significantly lower (50% lower) than seawater desalination. Water reclamation schemes carry several advantages such as higher recovery with higher flux rates at lower operating pressures (energy savings) with longer membrane life.

Reaching theoretical thermodynamic energy requirements for desalination technologies is an ongoing challenge. Many approaches based on energy and water recovery have been proposed (Gude 2011). Energy recovery schemes mostly include energy recovery devices based on Pelton turbine or pressure exchange recovery devices. Water recovery options include multiple pass and multiple stage configurations to maximize permeate recovery. Membrane technologies such as forward osmosis and nanocomposite membranes show the potential for wide application. Forward osmosis is a desired process to recover water from impaired sources such as wastewaters and other oil/gas-produced waters (Coday and Cath 2014).

6.4 Other considerations for desalination

The major drawback with the desalination technologies is one of the end products which is highly concentrated with salts called "brine" or "concentrate". Disposal and management of brine streams is an on-going issue for these facilities. Coastal desalination plants have the privilege of considering ocean discharge for brine disposal. However, inland desalination plants are faced with the dilemma of options that are usually not so environment-friendly. Evaporation, deep well injection, discharge to sewers, land application, and valuable chemical recovery through further processing are the available options, all of which are again energy- and cost-intensive. Environmental permits are another major hurdles that these facilities need to consider. Concentrate disposal into surface waters or sewers increase salt concentrations of existing water supplies whereas an impermeable barrier is required for evaporation and land application options.

7 Case studies for desalination and water reuse

7.1 Desalination—case studies

The need for desalination technologies and their implementation for alternative water supplies has been recognized in many parts of the world especially in arid regions including Middle Eastern and North African and Mediterranean countries. Recent developments and implementations of desalination plants around world including Australia, China, Kingdom of Saudi Arabia, Singapore, USA and several other Central American and Caribbean countries, and India were discussed in detail in previous reports (Gude 2016a, b). Readers are also referred to other contributions on this topic (Khawaji et al. 2008; Zotalis et al. 2014; Amy et al. 2017).

7.2 Water reuse—case studies

7.2.1 USA

A survey was conducted on the acceptance and perspectives of unplanned treated wastewater reuse in three metropolitan areas of Atlanta, GA, Philadelphia, PA, Phoenix, AZ with studies accounting for 421, 490, and 418 respondents respectively (Rice et al. 2016). It was found that the unplanned treated water reuse occurs at a higher rate than the expected in these cities. Moreover, 25% of the respondents perceive that unplanned water reuse occurs in their tap water and are ten times more willing to accept this unplanned reuse in their home tap.

Most of the studies related to water reuse have been reported at large scale or large number of populations. Many small to medium inland and arid communities also battle with water reuse implementation issues. Indirect and direct potable reuse (IPR and DPR, respectively) are two supply management options considered often for recovering potable water from treated wastewater effluents in most of the cases (Herman et al. 2017). Planned indirect potable reuse schemes include an environmental buffer such as an aquifer or reservoir where high quality reclaimed water (from treated wastewater effluents) for a specified amount of time to be used after further treatment as possible drinking water source. In direct potable reuse scheme, an environmental buffer is not required but the reclaimed water goes through an advanced treatment process. The overall feasibility of different IPR and DPR schemes was evaluated in a recent study for medium sized arid and inland communities in USA (Herman et al. 2017). It was noted that the present worth for IPR with an aquifer as an environmental buffer is only slightly higher than for DPR with drinking water treatment; the present worth of both of these scenarios is higher than for DPR that does not include drinking water treatment due to the additional pumping and piping requirements. In addition, reverse osmosis for advanced treatment have significantly higher present worth values than ozone/biological activated carbon treatment. All reuse scenarios considered cost far less than purchased water.

7.2.2 UK (London)

A sewer mining scheme was evaluated in London, UK to disclose the challenges and opportunities for reclaimed non-potable water reuse in irrigation and toilet flushing applications. This study was performed around the site of London 2012 Olympic Park (Goodwin et al. 2017). Similar to the study on the three major metropolitan areas in USA, qualitative analysis of a survey from a large number of participants was performed. The analysis showed that formal and informal engagement activities centered on risk management can support the development of common understandings, build important inter-stakeholder relationships and help maintain trust. Non-potable reuse can contribute to the resilience of metropolitan area through infrastructure diversification, but its feasibility will depend on the willingness of stakeholders to participate and continually negotiate new risk management practices.

7.2.3 Australia

Australia has a long history of water reclamation for reuse and recycling applications both in the form of IPR and DPR. Several programs have been developed along with desalination schemes to combat the persistent drought and changing climate issues. A summary of water reuse implementation schemes is provided in Table 5.

7.2.4 MENA region

For Middle East and North African regions, groundwater appears to be the largest source (contributing to over 50% of total country withdrawals) especially in Bahrain, Iran, Jordan, Lebanon, Libya, Oman, Saudi Arabia, Tunisia, UAE, and Yemen (Siddiqi and Anadon 2011). In the Arabian Peninsula, it accounts for 84% of total water withdrawals, while desalination accounts for 8% of water supply. Agriculture is a dominant user of water in the MENA region. Wastewater generation in the region has increased significantly in recent years due to population growth, urbanization, and economic development and its productive use in agriculture has increased. There is limited information available on the extent of wastewater resources that could potentially be exploited in water scarce MENA region countries (Qadir et al. 2010).

In some cases, where desalination is a predominant technology, hybridization of thermal and membrane desalination technologies along with consideration of storage of additional desalinated water to allow for maximum production and stability in operation should be considered. Aquifer storage and recovery is suggested as an alternative for managing the water demand and increased reuse of treated wastewater could bring an integrated approach to water resources management (Ghaffour et al. 2013).

7.2.5 Greece

Based on a pilot scale study conducted in Athens, Greece, some preliminary conclusions were derived on sewer mining (water reclamation and reuse) that it provides a feasible alternative reuse option but relies on mature treatment technologies and presents an opportunity for small and medium enterprises. The study also suggests that sewer mining concept can become a reality only when small and medium size industrial stakeholders become active players in the water market, securing environmental, social and economic benefits.

8 Concluding remarks

The world's population is expected to grow creating enormous demands for water supplies. Other effects related to climate change also need to be addressed in pursuit of sustaining the water supplies. As discussed in this paper, both management and technological approaches should be considered and given equal importance. Because the combined benefits from the

Table 5 Locations, process schemes and applications of water reuse in Australia (Makropoulos et al. 2017; McFallan and Logan 2008)

Location	Technology	Capacity use	Cost
Flemington Racecourse Melbourne, Australia	Dual membrane, UV	100 m^3/d Irrigation	Estimated unit capital cost 0.42 $/$m^3$, operational cost 0.43 $/$m^3$, prices 2006
Darling Quarter, Sydney's CBD Australia	Moving bed, biofilm reactor, RO, UV	170 m^3/d toilet flushing, irrigation, cooling towers	unit capital cost 2.2 $/$m^3$ operational cost 2.1 $/$m^3$, prices 2011
Riverside Rocks Park, Sydney, Australia	Reed beds, UV	360 m^3/d Irrigation estimated	unit capital cost 0.49 $/$m^3$, prices 2006
Pennant Hills, North Sydney, Australia	MBR, UV	1000 m^3/d Golf field irrigation estimated	unit capital cost 0.49 $/$m^3$, prices 2008
Sydney Olympic Park	SBR, nutrient	2191 m^3/d Toilet flushing, irrigation	cost 1.05 $/$m^3$, prices 2009 (90% the price of potable)

two distinct approaches could be complementary in numerous ways.

It can be emphasized that desalination and water reuse technologies become the frontiers showing tremendous potential for efficient utilization of impaired and saline water sources. However, energy and cost related issues should be addressed with innovative, energy-efficient and cost-effective technologies that are socially acceptable and environment friendly.

Several novel desalination technologies have been developed in recent years both in thermal and membrane based separation processes. Efforts should be continued to minimize the energy demand and maximize the resource utilization which may be possible when hybridization, tri-generation (water, power and heat combination) and poly-generation (multiple processes sharing common source of energy and water sources) schemes are considered in the water-energy sectors.

Water reclamation, recycle and reuse should be considered as a primary alternative to demand mitigation. Suitable technologies should be developed for this approach. Improving water conservation practices can be the first step in demand mitigation. Sustainable water management practices should be explained to the farmers and other industrial users to reduce the water withdrawals and consumption. Improving sewage system as well as supporting clean water initiatives will help both ensure healthy surface waters which in turn can serve as safe reserves and sources for freshwater supplies.

Water reuse implementation issues vary from size to size. Decentralized and small communities face different sets of problems when compared to medium and large size communities. Economics and perceived benefits are not encouraging at small community levels whereas complex regulatory and implementation issues arise for medium and large size communities.

Public education about the value of water and adverse effects of water impairment and water scarcity will help implement some of the management strategies for demand mitigation. Governance and financing the clean water ad environment initiatives can aid to implement a long-term sustainable freshwater supply system in drought influenced regions. However, there are limited data available on the effectiveness of publication education and outreach programs in improving the water conservation and reuse. More comprehensive studies involving quantitative and qualitative analysis are required to determine whether how and what educational programs are more effective in promoting the water conservation ethic.

Acknowledgements This research was partially supported by the Grant, SU 836130 from the United States Environmental Protection Agency and research grants from the United States Geological Survey, and New Mexico Water Resources Research Institute. The author appreciates the support received from the Office of Research and Economic Development (ORED), Bagley College of Engineering (BCoE), and the Department of Civil and Environmental Engineering (CEE) at Mississippi State University.

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