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Alternative Water Supplies for Arid Areas

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Abstract

Water is an essential component of growth and life; unfortunately, many countries face growing challenges in providing safe water. This has created a need for alternatives in the ways water can be treated, saved, or reused. In this paper, four alternative water supplies are reviewed: desalination, grey water reuse, harvesting of rainwater, and harvesting of stormwater. These alternatives are examined in terms of their advantages and disadvantages, the waste by-products, other pollution that can be produced by them, and how to handle each one. To accomplish this, brief information about each alternative, what technologies are used for water treatment, and the advantages and disadvantages for each technology are provided.

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Introduction

Water is a principal source of growth and life; it is the center of economic and social development in communities. Water plays a key role in preserving health, managing the environment, growing food, producing energy, and creating jobs (The World Bank, 2018). More than three-quarters of the earth's surface is covered by water; the vast majority (about 97.5%), however, of this water is saline (Danoun, 2007). Freshwater represents only 2.5% of the total water on the earth, which includes water in lakes, groundwater, and rivers (Shatat & Riffat, 2012). Despite the importance of water, many places around the world, like Africa and the Middle East, are suffering from severe freshwater shortages due to climate change, excessive use of water, rapid population growth, wasted water, and increased agricultural and industrial activities (Shatat & Riffat, 2012; Schleifer, 2017). People in some areas must even walk long distances to get safe and sufficient water to maintain their lives. Therefore, one of the challenges facing communities in the present century is having access to water that is safe and free from pollutants (Pichel, Vivar & Fuentes, 2019).

Today, around 2.1 billion people worldwide lack secure access to safely managed drinking water services; of these people, 844 million do not have even a primary drinking water service (The World Bank, 2018). According to the World Health Organization (WHO), approximately 361,000 children under five years old die annually from diarrheal infections; these are a result of several factors, the most important of which is the lack of access to safe water (WHO, 2017b). Contaminated water leads to other diseases as well, such as cholera and typhoid (WHO, 2017a). This water shortage is a major problem that needs to be resolved at the state and individual levels. It is very important that communities cooperate in providing water for human, environmental, and economic needs especially since the need for water will continue to increase in the coming years: from now until 2050, the need for water is expected to increase by 400% from manufacturing and by 130% from household use (Guppy & Anderson, 2017).

Over the past few years, great effort has been taken to make progress in providing safe drinking water to a large number of people. Because of the increasing pressure on freshwater resources, water shortages and their costs have increased in many places worldwide (Allen, Christian-Smith, & Palaniappan, 2010). Considerable efforts have been made to address the problems and to identify new ways to meet water needs. Despite these efforts, millions of people still lack access to improved water (Guppy & Anderson, 2017). One of the essential solutions to meet the lack of access to safe water is to implement and use alternative water supplies. Alternative water supplies are sustainable sources of water that do not come directly from surface water or groundwater. They include seawater desalination, rainwater, stormwater, and grey water.

The use of these alternative water supplies has rapidly increased worldwide in recent years in many potable and non-potable applications, such as irrigation, with many benefits for the individual and society (WHO, 2007). Benefits include reducing reliance on rivers and wells, reducing water bills from water distribution systems, and saving the costs of wastewater treatment facilities. These supplies must be used scientifically; otherwise, there may be undesirable outcomes from their use. For example, unsuccessfully treated wastewater used for agriculture resulted in 75% of children aged 8-12 years in those areas suffering from gastroenteritis compared to 13% in areas utilizing freshwater (Guppy & Anderson, 2017).

One of the most important alternative supplies to obtain clean water for human usage is desalination (Ahmed & Anwar, 2012). Desalination is the removal of salt and other minerals from water to make it suitable for human consumption and use in industry and agriculture. Saudi Arabia and the United States are the highest producers of desalinated water (Ahmed & Anwar, 2012); however, the growing demand for fresh water has raised global interest in the desalination of seawater as an attractive solution to the freshwater crisis because of the abundance of salt water (Wenten, Ariono, Purwasasmita & Khoirudin, 2016). Additionally, the improvement of desalination technologies has led to an increase in the benefits since reverse osmosis (RO) processes have resulted in the production of fresh water at lower costs and energy needs than thermal-based processes (Wenten et al., 2016). In spite of the great benefits offered by desalination plants, there are still some issues that have caused serious concern in several communities. For example, the concentrated discharge of the waste product of the desalination process, brine, has a great impact on the growth of marine organisms (Ahmed & Anwar, 2012).

Since nearly 80% of the world's wastewater is released to nature without reuse or treatment, another effort is to increase the efficiency of water usage and to expand the efficiency of alternative water sources that were previously considered unusable (Schleifer, 2017). Grey water, also defined as wastewater, is used water from washing machines, cleaning, sinks, and bathtubs, as well as uncontaminated water from toilets. This type of water supply is different from black water; black water is the wastewater from toilets that contain feces and urine, which is also called sewage (Allen et al., 2010). Black water contains disease-causing bacteria harmful to human health (Environment Protection Authority South Australia (EPASA), 2017a). Similarly, grey water contains some substances that can affect human health and the environment, such as oils, bacteria, and chemicals (EPASA, 2017b); however, this kind of water generally has lower levels of contaminants and a higher potential for reuse (Allen et al., 2010).

Additional alternative water supplies include rainwater harvesting and stormwater harvesting, which aim to save water to use when needed. These methods look alike as they both come from the rainfalls; however, there is a difference. Stormwater is the water on the land from precipitation such as rain runoff and surface water runoff, which is when rain falls on ground surface areas (driveways, lawns, roads, and parks); stormwater may also include snowmelt and drainage when rain falls on the rooftops of houses and moves out through gutters into drains (Department of Environment and Conservation NSW, 2006; California Urban Water Agencies (CUWA), 2016; National Academies of Sciences, Engineering, and Medicine, 2016). Since population growth, urbanization, and increased construction of residential, commercial, or industrial structures have led to an increase in impervious surfaces, an increased flow of water via runoff carries waste and pollutants to rivers and lakes. The collection and utilization of stormwater can thus prevent flooding, reduce the pollutants in bodies of water, and increase development in those areas while also providing a new source of water in arid countries that suffer from shortages.

Rainwater, on the other hand, refers only to the rain that falls on the roof of a home or other structure and can be stored in a tank before contacting the ground. The quantity and quality of rainwater varies due to geographical location (Buntat et al., 2015). It can be used directly from tanks without the need for a treatment process, but is often used for non-potable purposes. Rainwater harvesting is generally clean and free of contaminants if collected and stored carefully; however, it may be polluted by environmental factors and become unsuitable for potable purposes. For example, rainwater harvesting from the roofs may contain some contaminants, such as bird droppings, and should therefore be treated prior to use for drinking (Buntat et al., 2015).

The purpose of this study is to discuss the advantages and disadvantages of alternative water supplies, what kind of waste byproducts or other pollutants result from these methods, and the different ways to address these issues. The study will also discuss the best alternative water supply that can be used in an arid country.

Literature Review

The most important alternative water supplies are desalination, grey water, rainwater harvesting, and stormwater harvesting. Such alternatives have been used for several decades in many places around the world. For instance, the desalination process has been used for over almost fifty years in Scotland (Shatat & Riffat, 2012). Several factors have led to the spread of these alternatives: the lack of sufficient water, economic benefits, and prevention of environmental problems.

Desalination

Seawater desalination plays a significant role in solving the water shortage problem in many regions in the world. There are many water sources used in a desalination plant, including seawater, brackish water, and wastewater (Ihsan Ullah, Rasul, & Khan, 2013). The most significant source is from seawater desalination at approximately 67% of production, followed by brackish water at 19%, river water at 8%, and finally wastewater at 6% (Ihsan Ullah et al., 2013). According to Shatat and Riffat (2012), the WHO limits the permissible salinity in drinking water up to 500 ppm and in specific cases up to 1,000 ppm. Most of the water on the earth has a salinity up to 10,000 ppm, while seawater usually has a salinity from 35,000 to 45,000 ppm (Shatat & Riffat, 2012). Desalination plants purify salt water and convert it from high salinity water not suitable for drinking to fresh water suitable for drinking and use in several other purposes. This process is critical to the economic and social development of countries with a shortage of fresh water, such as in the Middle East.

Desalination is a process whereby the water is divided into two parts: fresh water, which is suitable for human consumption, and brine concentrate, which has a higher salinity concentration than the original feed water (Shatat & Riffat, 2012). In 2012, the total desalinated water worldwide was 71.9 million cubic meters per day (Ihsan Ullah et al., 2013). Water desalination technology has been introduced for several decades and has contributed well to the provision of water. With new developments in technology, desalination has contributed to providing a large amount of secure water and the process has expanded to many places around the world. Cost is one of the main obstacles (WHO, 2007). The cost of this technology has remained alarming until the present time, but has become tolerable given the alternative—the lack of water (WHO, 2007).

Thermal desalination and membrane desalination are two of the main types of water desalination technologies used around the world (Shatat & Riffat, 2012). Alternative technologies exist, yet are not generally used. Membrane technology features the use of a special filter to produce desalinated water, while thermal technology includes boiling, evaporation, and the subsequent condensation. Membrane desalination includes reverse osmosis (RO), membrane distillation, and electrodialysis; the common technologies of thermal desalination are multi-effect distillation (MED), multi-stage flash evaporation (MSF), vapor-compression evaporation (VC), and solar water desalination (Shatat & Riffat, 2012).

Thermal technology is one of the oldest methods used to convert seawater and brackish water into fresh water (Shatat & Riffat, 2012). It works by heating the water until evaporation, condenses the vapor, and then leaves the salt separate (Shatat & Riffat, 2012). One of the processes of thermal desalination is multi-stage flash evaporation (MSF). This process produces about 64% of desalinated water around the world (Thimmaraju et al., 2018). MSF is the process by which feed water (e.g., seawater) is heated in a vessel until it reaches a certain temperature less than the saturation boiling temperature. The heated saline water flows within a series of vessels, in sequence, where the lower ambient pressure makes the water boil quickly and vaporize (Shatat & Riffat, 2012). Just a small percentage of this water changes into water vapor. The percentage of vapor depends mostly on the pressure.

The boiling continues until the water cools and evaporation stops; the vapor is then converted into fresh water by condensation (Thimmaraju et al., 2018).

Most MSF plants are located in the Middle East where energy resources are plentiful and inexpensive (Shatat & Riffat, 2012). Building and operating these plants are relatively simple processes, yet stainless steel must be used to prevent corrosion (Thimmaraju et al., 2018). There are no moving parts and only a few pieces of connection tubing, which increases efficiency and enhances the quantity of water produced (Shatat & Riffat, 2012). However, even if these plants are easy to build and operate, their permits in some countries such as the United States are often fraught with complications. Additionally, MSF works at a very high temperature (about 115°C). This may cause problems when salt, such as calcium sulphate, creates thermal and mechanical problems, such as a blockage of the tube, and raises the cost of construction and operation (Thimmaraju et al., 2018).

A second process of thermal desalination technology is multi-effect distillation (MED). MED produces 3.5% of the desalinated water around the world (Shatat & Riffat, 2012). The most prominent characteristics of this process are high heat efficiency and the high quality of distilled water (Shatat & Riffat, 2012). MED uses a similar process to MSF, but with decreased ambient pressure rather than extreme temperatures (Thimmaraju et al., 2018). In the MED process, a series of evaporator effects expose the water to gradually lower pressures. As pressure declines successively, the water heats at lower temperatures, and then the water vapor of the first vessel works as the heating medium for the second vessel and so on. If the number of vessels increases, the performance ratio increases as well (Thimmaraju et al., 2018). The evaporated water is collected and condensed during boiling. Because the water quality of the feed water is not crucial, it does not need pre-treatment and can avoid additional costs (Thimmaraju et al., 2018). The efficiency of the performance in MED plants is also higher than in MSF plants, which means that they are more effective in terms of the cost of producing fresh water and heat transfer (Shatat & Riffat, 2012). Lastly, the MED process is designed to operate at a low temperature of around 70°C; this reduces the possible corrosion of tubing (Thimmaraju et al., 2018).

Another process of thermal desalination is vapor compression evaporation (VC). This process operates either by itself or in combination with another process such as MED (Krishna, n.d.). In VC, the heat for evaporating the feed water comes from the compression of vapor (Thimmaraju et al., 2018). Two devices are used, a mechanical compressor and a steam jet, to condense the water vapor to make enough heat to evaporate the feed water (Shatat & Riffat, 2012). VC units are built in a diversity of configurations to improve the heat needed to evaporate the feed water (Shatat & Riffat, 2012). VC is usually built with a capacity of 3,000 m^3/day so it is simple to use in many facilities, such as hotels and resorts, where fresh water is not readily available (Shatat & Riffat, 2012). The temperature for operation is also low (below 70°C), which simplifies its energy requirements and helps lower the probability of pipe corrosion (Shatat & Riffat, 2012).

The last thermal process is solar desalination. Solar desalination is generally used on a smaller scale and in dry places where fresh water is not readily available (Thimmaraju et al., 2018). As the name implies, solar desalination relies on the sun to provide heat energy to evaporate the water from salt water. The resulting water vapor is condensed onto a pure glass or plastic covering, and that fresh water is then collected in a condensate basin. The remaining water and salt should be disposed off suitably (Thimmaraju et al., 2018). Several difficulties restrict the use of this process on a large scale. One of these difficulties is the vulnerability to weather-related damage (Buros, 2000). Solar desalination also needs a large solar collection area to produce a substantial amount of desalinated water (Buros, 2000). This difficulty lies in its proximity to the cities where land is scarce and expensive. Although thermal energy could be free, additional energy is required to pump water into and from the facility. Moreover, there is often a need to repair the glass or vapor leaks in the stills (Buros, 2000).

In addition to thermal technology, membrane technology is also capable of desalination. Membrane technology was originally limited to municipal water treatments, such as water desalination and microfiltration, but it has been expanded to include, for example, beverage purification due to the development of new types of membranes (Thimmaraju et al., 2018). This technology uses a comparatively permeable membrane to transfer water or salt and make two zones of varying concentrations to generate fresh water (Shatat & Riffat, 2012). Membrane technology has several processes, reverse osmosis (RO), membrane distillation, and electrodialysis; the main difference between them lies in the size of the ions and suspended particles that are kept or allowed to pass through the membranes (Shatat & Riffat, 2012).

Reverse osmosis is a relatively new process and has been successful in the desalination of salt water (Shatat & Riffat, 2012). The RO process uses pressure as a driving power to push saline water through a semi-permeable membrane into a brine stream and product water stream (Thimmaraju et al., 2018). Osmosis is a simple phenomenon where water moves through a semi-permeable membrane from a low salt concentration to a more concentrated solution. When pressure is employed to the solution with the higher salt concentration, the water will pass in a reverse direction within the semi-permeable membrane and leave the salt behind (Krishna, n.d.). Currently, the largest desalination plants that use RO are located in the Middle East region (Shatat & Riffat, 2012). The RO desalination plants at Al Jubail and Yanbu in Saudi Arabia have capacities of 24 and 33.8 million gallons per day, respectively (Shatat & Riffat, 2012). RO is also currently used for desalination in the United States (Krishna, n.d.).

Water desalination plants using RO are made up of four basic systems: pre-treatment, high-pressure pumping, the membrane system, and post-treatment (Krishna, n.d.). The pre-treatment system is of great importance in the RO process because it protects the high-pressure pumps and the surfaces of the membranes from fouling (Shatat & Riffat, 2012). At this stage, the salty water is treated to remove suspended solids and debris. Next, a high-pressure pump provides enough pressure to enable water to pass through the membrane as the membrane restricts the crossing of the dissolved salts and allows the water to pass. The concentrated brine water is then discharged into the sea. As for the membrane system (RO modules), it must be strong enough to withstand the pressure. In principal, the membrane system is semi-permeable because it permits a high degree of water permeability, but provides an impermeable barrier to salts. Finally, in the post-treatment system, water usually settles; this stage may include pH adjustment and the removal of dissolved gases such as hydrogen sulphide (Shatat & Riffat, 2012).

The advantage of RO is that the problem of material corrosion is much lower than MSF and MED processes due to the surrounding temperature conditions (Thimmaraju et al., 2018). Also, developments over the past years have helped reduce RO operating costs (Shatat & Riffat, 2012). Conversely, RO needs a large amount of feed water to produce a small quantity of safe water; for example, 40-90 gallons of water produces only five gallons of usable water (Thimmaraju et al., 2018). Additionally, the precipitation of salts on the membrane is a common problem in RO, but it is less than with MSF (Shatat & Riffat, 2012).

Another membrane technology is electrodialysis (ED); this is a voltage-driven process where an electrical potential is used to separate salts using a membrane and leave fresh water behind (Krishna, n.d.). ED uses a direct current in which the ions flow through ion selective membranes to the oppositely charged electrodes (Thimmaraju et al., 2018). The polarity of the electrodes is generally reversed as the dissolved salts form into ions and these ions leave towards electrodes with an opposite electric charge (Thimmaraju et al., 2018; Krishna, n.d.). Proper membranes allow passage of selective ions, either anions or cations. ED technology has several advantages: it can produce a large amount of fresh water with less brine solution, the energy usage is equivalent to the salts separated, it is better than RO in the treatment of feed water containing high levels of suspended solids, and the usage of chemicals during the pre-treatment phase is low (Shatat & Riffat, 2012). While it is possible to treat water containing a concentration higher than 30 g/l of dissolved solids, it is not economically feasible (Shatat & Riffat, 2012).

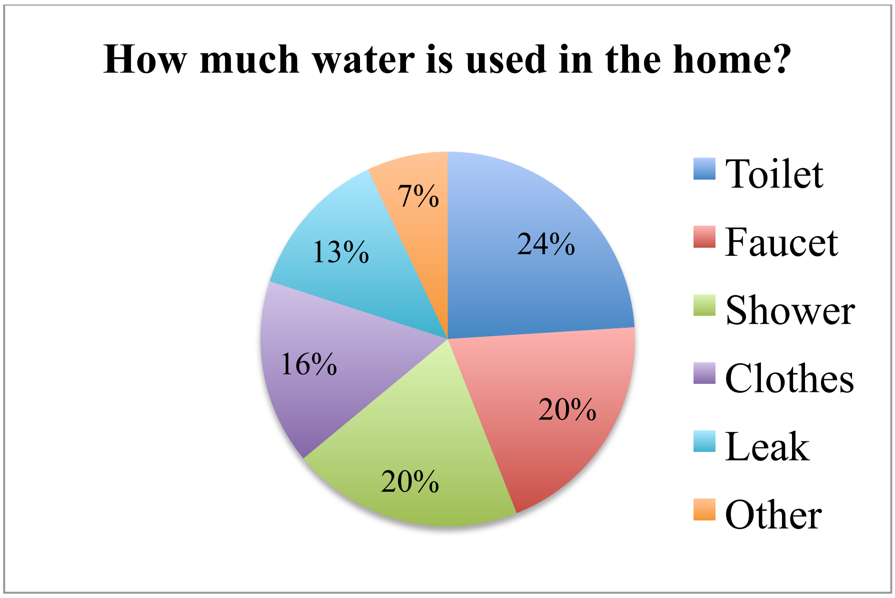
The final membrane process is membrane distillation (MD) technology. This is based on both thermal and membrane technologies so membranes and distillation are used in the process of evaporation (Thimmaraju et al., 2018). MD is a segregation process where the micro-porous hydrophobic membrane divides two aquatic solutions at different temperatures (Thimmaraju et al., 2018). Different temperatures create a difference in the vapor pressure that results in the transfer of vapor produced through the membrane to the condensation surface (Shatat & Riffat, 2012). MD technology is based on the use of hydrophobic membranes which are permeable only to vapor as the resulting vapor is condensed to produce fresh water. This process is remarkably simple and only needs a low operating temperature to run; it requires less operating pressure than pressure-driven membrane methods and reduced space for vapor compared to conventional distillation (Shatat & Riffat, 2012). MD does, though, require more space than other membrane processes, consumes energy at roughly the same consumption rates of MSF, and is limited in use because it needs feed water free from organic pollutants (Shatat & Riffat, 2012).

In general, desalination has numerous benefits in many areas. The developments of technology and multiple options as explained above have contributed to the widespread deployment and use of plants in arid areas around the world. Despite its benefits, there are many issues related to desalination plants that may cause harmful damage to the environment and people. Some plants may be uneconomical in places even though they are close to the coast where seawater is plentiful. One reason is, for example, the lack of fossil fuels and an inadequate electricity supply (Shatat & Riffat, 2012). Since desalination plants need a high capacity of energy to produce potable water, many stations operate on fossil fuels that produce large amounts of greenhouse gas (GHG) emissions. Some plants also are expensive in terms of construction, maintenance, and operation. Lastly, some plants may cause noise pollution (Ahmed & Anwar, 2012).

Grey Water

Another alternative water supply is grey water. People need water not only to drink, but for many non-potable applications in which grey water can be used instead, such as lawn irrigation, landscaping, toilet flushing, window washing, laundry, extinguishing, and car washing. According to DeOreo, Mayer, Dziegielewski, and Kiefer (2016), toilet flushing is the highest indoor use of water in single-family houses—approximately 24% of total indoor water use—followed by faucets 20%, showers 20%, washing clothes 16%, leaks 13%, and other reasons 7% (see Figure 1). Grey water ranges from 50% to 80% of the wastewater quantity generated by households (Albalawneh & Chang, 2015; Philp et al., 2008). Typical contaminants found in grey water are food particles, microorganisms, oil, and salts (P. Murthy, B. Murthy, & Kavya, 2016b). Grey water may also be contaminated by organic matter, heavy metals, and suspended solids (Albalawneh & Chang, 2015). The properties of grey water vary greatly from one source to another based on social behavior, lifestyle, and water availability (P. Murthy et al., 2016b).

Figure 1



Average indoor household water use (DeOreo et al., 2016).

The use of grey water locally is a great asset for people who do not have systems to provide safe water to their homes (Allen et al., 2010). Grey water can also be allowed to leak to the ground to feed groundwater and thus reduce the amount of wastewater that needs to be treated (Allen et al., 2010). In many countries, potable water is delivered through certain pipelines to homes; this water is used, collected through certain pipelines, and sent to treatment plants. In this type of system, high-treated water is used in all applications in and around the house. This water is used only once and then enters the wastewater treatment plants again. In some places, treated water is directly disposed of into the environment, bodies of water, or the ocean. This kind of system wastes money, energy, and water by not using the treated water again. The use of gray water can reduce the need for clean water by saving the energy from not using the water again.

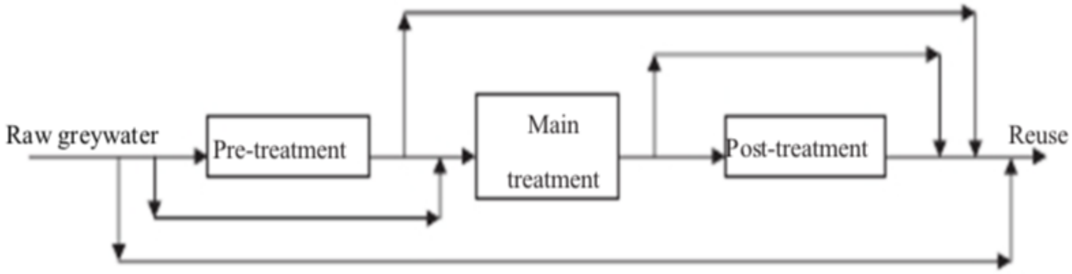
Grey water systems vary from simple, low-cost devices to systems that require complex processing including sedimentation tanks, filters, bioreactors, and disinfection (Allen et al., 2010). Some systems can reuse grey water immediately without treatment or storage. These systems redirect grey water into toilet tanks for flushing or to outdoor irrigation; they usually include filtration to capture some impurities, such as fat and hair, and may have disinfectants, such as chlorine tablets, to kill bacteria. Simple grey water systems are available in many commercial shops in countries such as the United States and are priced at $100-500 (Allen et al., 2010). Some can be built and stored individually, while others are more complicated and can remove hair, salt, blood, and bacteria. Certain systems might also contain bi-directional valves; opening and closing this valve allows the grey water to be directed to sewer pipes or reused according to the required volume.

Grey water is not malodorous upon immediate use, but it consumes oxygen quickly and becomes anaerobic when collected. Untreated grey water can turn septic if left untreated in less than 24 hours (EPASA, 2017b). Once septic, grey water forms a sludge and has a foul smell similar to sewage (WHO, 2006). The most appropriate and simplistic method of treatment is to introduce freshly generated grey water directly (WHO, 2006). Treatment of grey water varies greatly, and therefore the cost and energy required for grey water systems vary; costs usually run high if treatment levels are higher (Allen et al., 2010). Techniques rely on reuse options, grey water characteristics, technology performance, and costs (Ghunmi, Zeeman, Fayyad, & Lier, 2011).

The proper treatment of grey water as a type of alternative water source is of great importance as it will provide water not only for irrigation or different recreational venues, but also for homes. The treatment aims to meet re-use standards and overcome the aesthetic and health problems caused by pathogens and organic matter (Albalawneh & Chang, 2015; Ghunmi et al., 2011). Reusing untreated grey water though poses several health risks to humans and the environment. Therefore, grey water needs to be treated to a higher standard to ensure that the risks will not occur before reuse (Ghunmi et al., 2011). Most countries use the same standards as wastewater treatment, but others have established special standards for treating grey water, such as Australia and Jordan (Albalawneh & Chang, 2015). Grey water treatment can be classified based on biological, chemical, and/or physical processes (Albalawneh & Chang, 2015; Allen et al., 2010; Ghunmi et al., 2011; P. Murthy et al., 2016b). Most processing units rely on physical and biological treatment processes (Friedler et al. 2005). The physical and chemical treatments can include reverse osmosis, absorption, and adsorption; while biological treatments use membrane bioreactors, sunlight, and aeration (Oteng-Peprah, Acheampong, & deVries, 2018).

Three different treatment steps can be used to treat grey water depending on the required quality of the effluent: pre-treatment, main treatment, and post-treatment (see Figure 2; Albalawneh & Chang, 2015; Ghunmi et al., 2011). Several types of treatment processes (i.e., physical, biological, or chemical) can be used in each step. These steps are used for many purposes. For example, the pre-treatment step (screens and filters) are used to decrease the amount of grease and particles to avoid clogging the subsequent treatment, while the post-treatment (disinfection) is used to meet the microbiological requirements (Albalawneh & Chang, 2015). Filtration and sedimentation are commonly used as a pre-treatment step before biological and chemical treatments or as a post-treatment step before disinfection (Albalawneh & Chang, 2015). Filtering methods for pre-treatment include sand bed filtration, gravel filtration, screen meshes, and metal filters (Boyjoo, Pareek, & Ang, 2013; Oteng-Peprah et al., 2018). Although filtration is necessary, relying on its use in grey water as a sole treatment is not enough because it does not guarantee a sufficient reduction of organic matter and nutrients (Albalawneh & Chang, 2015; Ghunmi et al., 2011). In general, the smaller the porosity of the filters, the better the effluent character is; consequently, poor filters have a low impact on removing contaminants present in grey water (Boyjoo et al., 2013).

Figure 2



Grey water recycling and treatment: possible steps (Ghunmi et al., 2011).

Types of chemical processing of grey water include electrocoagulation, adsorption, coagulation, advanced oxidation processes (AOPs) such as ozonation, and others (Boyjoo et al., 2013). These systems are effective in treating light grey water and may include laundry grey water (Albalawneh & Chang, 2015). Chemical treatment processes can diminish the turbidity in grey water and organic substance better than physical treatment processes (Albalawneh & Chang, 2015). They can decrease these amounts to a specific degree, but not enough to meet the non-potable reuse standards (Albalawneh & Chang, 2015; Boyjoo et al., 2013).

In contrast, the biological treatment process may involve membrane bioreactors, rotating biological contactors, fluidized bed reactors, and others (Albalawneh & Chang, 2015). Biological treatment is typically preceded by several steps, such as a filtration step to remove sludge or biosolids and a disinfection step for the removal of microorganisms (Boyjoo et al., 2013). Most organic matter is removed during the biological treatment process; odor problems are avoided as well, which makes storing the resulting grey water for an extended period more likely (Albalawneh & Chang, 2015).

The main obstacle to the reuse of grey water is that some people perceive it as unhealthy or unsafe (Brown & Davies 2007). Nonetheless, studies have revealed that a high proportion of the public accepts the reuse of grey water in several specific activities (Allen et al., 2010). For example, some rural populations in the Kingdom of Jordan who suffer from water shortages accept the reuse of treated grey water for irrigation; they are willing to learn more about grey water treatment methods in order to operate grey water systems for irrigation purposes (Al-Mashaqbeh, Ghrair, & Megdal, 2012). Allen et al. (2010) reviewed different techniques used for the treatment of grey water system; the advantages and disadvantages of these techniques are shown in Table 1.

Table 1

Treatment technique	Description	Advantages	Disadvantages
Disinfection	Chlorine, ozone, or ultraviolet light can all be used to disinfect grey water.	* Highly effective in killing bacteria if properly designed and operated. * Low operator skill requirement.	* Chlorine and ozone can create toxic by-products. * Ozone and ultraviolet can be adversely affected by variations in organic content of grey water.
Activated carbon filter	Activated carbon has been treated with oxygen to open up millions of tiny pores between the carbon atoms. This results in highly porous surfaces with areas of 300- 2,000 square meters per gram. These filters thus are widely used to adsorb odorous or colored substances from gases or liquids.	* Simple operation. * Activated carbon is particularly good at trapping organic chemicals, as well as inorganic compounds like chlorine.	* High capital cost. * Many other chemicals are not attracted to carbon at all such as sodium and nitrates. This means that an activated carbon filter will only remove certain impurities. It also means that, once all of the bonding sites are filled, an activated carbon filter stops working.
Sand filter	Beds of sand or in some cases coarse bark or mulch which trap and adsorb contaminants as grey water flows through.	* Simple operation. * Low maintenance. * Low operation costs.	* High capital cost. * Reduces pathogens but does not eliminate them. * Subject to clogging and flooding if overloaded.

Aerobic biological treatment	Air is bubbled to transfer oxygen from the air into the grey water. Bacteria present consume the dissolved oxygen and digest the organic contaminants, reducing the concentration of contaminants.	* High degree of operations flexibility to accommodate grey water of varying qualities and quantities. * Allows treated water to be stored indefinitely.	* High capital cost. * High operating cost. * Complex operational requirements. * Does not remove all pathogens.
Membrane bioreactor	Uses aerobic biological treatment and filtration together to encourage consumption of organic contaminants and filtration of all pathogens.	* Highly effective if designed and operated properly. * High degree of operations flexibility to accommodate grey water of varying qualities and quantities. * Allows treated water to be stored indefinitely.	* High capital cost. * High operating cost. * Complex operational requirements.

"Common grey water treatment technologies" (Allen et al., 2010).

Rainwater Harvesting

An alternative water source that is seen less negatively is rainwater. Rainwater has significant value for its purity and softness—its pH is approximately neutral and it is free from natural contaminants, disinfection by-products, salts, and minerals (Texas Water Development Board (TWDB), 2005). According to the United States Environmental Protection Agency (USEPA) (2013), rainwater harvesting has been divided into negative systems (referred to as rainwater harvesting systems in this thesis) and active systems (referred to as stormwater harvesting systems in this thesis).

Rainwater harvesting can be defined as the collection, storage, and use of rainwater for a number of different purposes including drinking, vehicle washing, irrigation, toilet flushing, showering, and recharge of groundwater (TWDB, 2005). Rainwater harvesting has existed since about 2000 BCE (USEPA, 2013; TWDB, 2005). Researchers have shown interest in this program in recent years to meet the increasing demand for water, reduce the energy used to desalinate or treat water, maintain the ecosystem, and decrease stormwater runoff volumes and associated pollutants (Hassan, 2016; Lani, Yusop, & Syafiuddin, 2018; USEPA, 2013). Rainwater harvesting often has a higher quality than groundwater because groundwater contains many contaminants, including soil, oil residues from the roadway, fertilizer from gardens, organic materials, and the like.

Rainwater harvesting systems range from complex to simple systems through which the rainwater can be discharged from smooth surfaces to planted landscape areas. The most complex systems consist of catchment surfaces, gutters, pipes for water conversion, tanks for storage, pumps, and treatments for potable water use. A building's owner is usually responsible for the operation and utilization of rainwater harvesting, not local authorities (Philp et al., 2008). Rainwater harvesting systems influence water quality as some pollutants from storage tanks or catchment surfaces may affect it. With adequate care of the system and with minimal treatment, rainwater can be used as potable water (TWDB, 2005).

The process of rainwater treatment varies according to its final purpose. If the goal is to use the rainwater for anything other than drinking either by human or animals that end up being consumed by human beings, then rainwater may not need to be treated; the presence of leaf screens on gutters and a roof washer is sufficient (TWDB, 2005). Often, drinking water is taken from treated water while rainwater used for non-potable purposes is taken directly from the collection water tank (Lani et al., 2018; Martin, Buchberger, & Chakraborty, 2015). The cost of water treatments, distribution systems, and maintenance is usually high, so the use of rainwater harvesting for non-potable purposes will save energy, reduce the amount of water needed for usual use, and reduce greenhouse gas emissions (Martin et al., 2015).

An excellent example of harvesting rainwater is the Storage and Reliability Estimation Tool (SARET) that was created to estimate the reliability of using harvested rainwater for irrigating gardens, topping off air conditioners, and flushing toilets at several residential buildings in New York City (Basinger, Montalto, & Lall, 2010). The SARET uses a nonparametric stochastic generator to mimic rainfall in the city. The researchers found that New York City backyard gardens can be watered and air conditioning units provided with water harvested from local roofs with a reliability of more than 80% and 90%, respectively; however, for toilet flushing, the reliability of using harvested rain as a source of water was as low as 7-40% (Basinger, Montalto, & Lall, 2010).

If the purposes of rainwater harvesting are to drink or prepare food, then proper treatment is necessary to remove sediment and pathogens. Rainwater can contain fecal coliforms, lead, and turbidity above the limit regulated by the WHO according to a study on the quality of rainwater collected from rooftops in Malaysia (see Table 2; Lani et al., 2018). A simple treatment needs to be done to overcome those parameters and to maximize the benefits of the rainwater harvesting system.

Table 2

Parameter	Galvanized Iron Roof	Concrete Roof	WHO Standardization
pH	6.4-6.6	6.8-6.9	6.5-8.5
Turbidity (NTU)	10-22	25	5
Total solids (mg/L)	64-119	116-204	-
Suspended solid (mg/L)	52-91	95-153	-
Dissolved solid (mg/L)	13-28	23-47	-
Zinc (mg/L)	2.94-4.97	0.05-1.93	5
Lead (mg/L)	1.45-2.54	1.02-2.71	0.05
Fecal coliforms (MPN/100 mL)	0-8	0-13	0
Total coliforms (MPN/100 mL)	25-63	41-75	0

"Summary of roof rainwater quality for different roof types in Malaysia" (Lani et al., 2018).

There are several methods to treat rainwater: slow sand filtration, disinfection, ozonation, membrane filtration, and adsorption (Lani et al., 2018). The rainwater treatment should be selected based on the cost-effectiveness and efficiency of the method to treat certain contaminants. Most of these treatment processes have been reviewed and briefly explained in the previous pages. In regards to ozone treatment (oxidation), the process of ozonation does not need the addition of chemicals or energy for heating (Buntat et al., 2015). Ozone (O_3) is created from oxygen (O_2) and returns to oxygen after treatment; it is an unstable gas at the temperature and pressure in ambient water (Philp et al., 2008). With the proper concentration, ozone can eliminate a wide variety of microbiological (viruses and bacteria such as E. coli), inorganic, organic, taste, and odor problems (Buntat et al., 2015; Philp et al., 2008). The ozonation process is environmentally friendly because there is no need to add chemicals during treatment; additionally, ozone is 15 times stronger than chlorine, which ensures the safety of water for use after treatment because it destroys spores, enzymes, bacteria, and microbes on contact (Buntat et al., 2015). Nonetheless, ozone requires filtration to remove suspended solids (Buntat et al., 2015); it can be costly and toxic, as well as form harmful by-products such as aldehydes (Philp et al., 2008).

Stormwater Harvesting

The last alternative water supply examined in this thesis is stormwater. When rain falls in the natural environment, it is absorbed by plants or soaks into the groundwater, which can be easily used by digging wells. However, in urban areas, large quantities of plants are removed and covered with impervious surfaces such as buildings, parking lots, and roads. When the water runs on these surfaces, it carries waste and other contaminants that eventually drain into bays, dams, or other sources of water (CUWA, 2016). Stormwater harvesting is of great importance in the provision of water, sustainable development, and the prevention of flooding and pollution (CUWA, 2016; National Academies of Sciences, Engineering, and Medicine, 2016; Philp et al., 2008). Harvested stormwater is usually used in activities such as irrigation or in different industries (Philp et al., 2008).

Stormwater should be captured and utilized through an appropriate infrastructure to obtain safe water that can be reused for several purposes (Philp et al., 2008). Stormwater harvesting systems or schemes are considerably different between projects, but most include collection, storage, treatment, distribution, and end use (Department of Environment and Conservation NSW, 2006; Philp et al., 2008). The arrangement of these components varies depending on the ultimate purpose of use or according to the design of the individual system (Philp et al., 2008). Stormwater is collected from general urban runoff, creeks, stormwater drains, or ponds into storage for harvesting (Department of Environment and Conservation NSW, 2006). The collected stormwater is temporarily stored in above ground or underground tanks, aquifers, or dams to balance supply and demand. Each type of storage has advantages and disadvantages (See Table 3).

Table 3

Storage type	**Potential advantages**	**Potential disadvantages**
Open storages	• Low capital and maintenance cost	• Public safety • Mosquito-breeding potential • Higher potential for eutrophication • Aesthetic issues with fluctuating water levels
Above-ground tanks	• Moderate capital and maintenance costs • No public safety issues	• Aesthetic issues
Underground tanks	• No visual issues • No public safety issues	• Higher capital cost • Higher maintenance costs
Aquifer	• Little space required • Cost effective • Prevents saltwater intrusions to aquifer	• Requires suitable geology • Potential to pollute groundwater unless pre-treated

Comparison of stormwater storage types (Philp et al., 2008).

Stormwater storage is an important part of effective use schemes (Philp et al., 2008). The storage can be on-line, built on the creek or drain, or off-line, built some distance from the drain or creek (Department of Environment and Conservation NSW, 2006). As for stormwater treatment, options include screening, filtration, disinfection, adsorption, and coagulation. The level of treatment depends on the ultimate purpose of water use and catchment characteristics that affect the type and level of contaminants. For example, filtration and disinfection are enough for industrial use (Philp et al., 2008). After storage and/or treatment, the treated stormwater is distributed to the area of use. There are several factors affecting the distribution process: the spatial scale of the distribution area, such as a park or playground to thousands of housing units, the final use density, and the presence of fire fighting requirements within the stormwater distribution range.

The last component is the use of the harvested stormwater. As mentioned, the previous elements are operated depending on the use of the water. If the harvested stormwater is for non-potable purposes, then the treatment process does not need to be as intense as it would be for potable purposes. Stormwater harvesting and reuse as an alternative method of water supply may face several difficulties: construction activity, percentage of impervious surfaces, spatial and temporal variations, and interactions of collection surface, waste disposal and sanitation practice, population density, soil type, and climate change (Philp et al., 2008). The cost of stormwater harvesting systems in terms of water collection, storage, treatment, and distribution is also an obstacle for many countries to take advantage of this water supply (CUWA, 2016).

Through this literature review, many alternative water supplies have been identified; the most important are the desalination of seawater or brackish water, grey water, rainwater harvesting, and stormwater harvesting. The objective of this thesis is to identify the advantages and disadvantages of each type, what kind of pollutions and waste by-products are generated from those alternatives, and the options to handle them. In order to achieve that, the alternative water supplies have been discussed in several ways such as how they work and the processes used to treat them. The thesis also discusses the best alternative water supply that can apply to an arid country.

Methods

The contents of this thesis discuss alternative water supplies for arid areas to provide water to meet water shortages. Four types of essential alternative water supplies are examined in terms of their advantages and disadvantages: the desalination of seawater or brackish water, grey water, rainwater harvesting, and stormwater harvesting. Additionally, this thesis explores the pollution and waste by-products that result from these alternatives, and the suitable ways to deal with these issues. To accomplish this task, important information about these alternatives is obtained from extensive research on relevant sources including how they work and what processes are used for treatment so that these alternative supplies might be used for potable and non-potable purposes. After understanding the topic in all its aspects, the data are then analyzed and the advantages and disadvantages are compared to assess how the alternate water supplies might apply to areas where water is hard to get. Based on this analysis, the possible ways to avoid waste and other pollutants are also be identified. The sources used in this thesis include peer-reviewed journal articles, published books, government reports, and other scholarly informational sources.

Results and findings

Desalination is a process to convert saline water into potable water by removing salts and other solids from seawater or brackish water. There are important advantages of desalination. First, desalination can provide a great amount of potable water to areas that suffer from a shortage of fresh water (Darre & Toor, 2018). Indeed, this is the main purpose of building desalination plants in dry places. For example, the Yanbu desalination plant located in Saudi Arabia can produce 33.8 million gallons per day (MGD) (Shatat & Riffat, 2012). These plants are also easily built and operated. Second, the quality of the treated water is high. Desalination plants usually produce desalinated water with a high level of purification using MSF and other processes (Shatat & Riffat, 2012). Therefore, it is possible to rely on desalinated water for drinking and other purposes. Additionally, the desalination process decreases the pressure on conventional water sources within the area, which helps preserve some water sources such as groundwater. Lastly, some desalination processes have the potential to produce a large amount of fresh water compared to a small amount of brine, such as the electrodialysis process.

Although seawater desalination plants can produce a large quantity of potable water in many places around the world, there are some drawbacks. First, the construction and operation of desalination plants are expensive and depend on several factors. For example, the proximity of the plant to the ocean or to the source of power reduces the length of the pipeline, which reduces the cost; however, the reverse is also true. Additionally, the operation of some desalination plants usually requires a significant amount of energy (Thimmaraju et al., 2018). This is one of the most critical disadvantages since energy is expensive and can produce huge amounts of greenhouse gas emissions (Ahmed & Anwar, 2012). Other water treatment technologies are more energy efficient. Water also has to be pumped uphill to the plant, which may require considerable power. Lastly, permit requirements to build a desalination facility can be challenging in some places, such as, for example, Carlsbad, California.

There are also adverse environmental impacts from desalination plants: discharged brine, air pollution (e.g., greenhouse gas), thermal pollution, and noise pollution (Tularam & Ilahee, 2007; Danoun, 2007; Dawoud & Al Mulla, 2012). Regardless of the method or process used in the desalination plant, the impact can extend to the environment surrounding these plants depending on several factors: the location of the desalination plants, the process used in the desalination plant, and the site of the inlet and outlet (Danoun, 2007). Although many desalination plants have been built in many countries around the world, there is little research on the impact of their discharge (Ahmed & Anwar, 2012; Roberts, Johnston, & Knott, 2010).

To start, desalination plants may produce noise pollution (Danoun, 2007; Younos, 2005). Noise pollution may occur from some of these plants due to high-pressure pumps and energy recovery turbines (Danoun, 2007). The location of desalination plants should not be close to residential areas, schools, or public places. Noise pollution can lead to several risks to human health including hearing loss, sleep disruption, and loss of productivity; hearing loss is the most common of these problems (USEPA, 2018).

The location of a desalination plant should be carefully selected before starting construction to prevent noise pollution (Tularam & Ilahee, 2007). The site must be away from residential and other important areas, such as schools or universities. The site should also be away from coastal recreational areas to prevent noise pollution for visitors and to not restrict recreational activities such as fishing and boating around the inlet or outlet areas. These considerations should also extend to maintaining the architectural and visual beauty in those areas. If the plants are close to residential or other public areas, some measures should be applied to reduce the noise pollution resulting from those plants, such as using canopies or acoustical planning (Younos, 2005). In addition, workers near the sources of the noise pollution should isolate the source of the noise, reduce their time of exposure, and, if necessary, use hearing protection.

Some desalination plants around the world also produce several air pollutants due to the intensive energy use with non-renewable fossil fuels (Dawoud & Al Mulla, 2012; Tularam & Ilahee, 2007). These air pollutants include greenhouse gas emissions, nitrogen dioxide, sulphur dioxide, and carbon monoxide (Ahmed & Anwar, 2012; Dawoud & Al Mulla, 2012; Younos, 2005). Greenhouse gas emissions, in particular, represent a major environmental problem due to their potential impact on climate change. The other ambient air pollutants lead to many health risks that may result in premature death. According to the World Health Organization (WHO) (2019), about 4.2 million premature deaths worldwide are linked to ambient air pollution, mainly from lung cancer, heart disease, stroke, and acute respiratory infections in children. The WHO (2019) states that there is substantial evidence for the public to be concerned with certain pollutants, including nitrogen dioxide, particulate matter, sulphur dioxide, and ozone.

The primary step to prevent and control air pollution from desalination plants is to reduce fossil fuel combustion. Renewable energy, such as solar or wind power, can replace fossil fuels. Relying on renewable energy has many benefits to public health since it does not emit air pollution (Union of Concerned Scientists, 2017). Many countries are looking to run desalination plants with these resources with the added benefit of lower operating costs (Darre & Toor, 2018). Lower sulfur-containing fuel can also help reduce the level of sulfur dioxide produced by fossil fuels (MJ Bradley & Associates, 2005).

Another way in which air pollution can be reduced is the use of air pollution control equipment. Air pollution control equipment can trap pollutants before they can escape into the atmosphere; for example, scrubbers and oxidizers (catalytic). Scrubbers (wet or dry) can control some pollutants such as sulfur dioxide (MJ Bradley & Associates, 2005). Oxidizers can control some pollutants such as carbon monoxide (CO), but the disadvantage of this equipment is that carbon dioxide is generated through the process of oxidation (MJ Bradley & Associates, 2005). Many factors should be considered when selecting proper air pollution control equipment such as the cost, chemistry of pollutant to be controlled, and disposal of potential waste.

Desalination's most significant environmental problem is brine—a concentrated saline solution (sodium chloride) produced from the process of treatment after the separation of potable water that contains a high percentage of salts and dissolved minerals. In desalination, a large amount of feed water is withdrawn from the sea or ocean to be treated and converted to potable water. Only part of this feed water is converted to potable water, depending on the efficiency of the process used, and the rest is considered brine. For example, in the reverse osmosis (RO) process, 50% of the water withdrawn from the ocean will be converted to potable water and the other 50% will be discharged brine (Danoun, 2007). For every one cubic meter of desalinated water, two cubic meters are produced as reject brine (Dawoud & Al Mulla, 2012). The discharge brine usually returns directly to the sea or ocean (Dawoud & Al Mulla, 2012). How much of this discharged brine is mixed and diffused in the seawater depends on the speed and direction of the wind and the speed and height of the wave (Danoun, 2007). The faster the dilution, the lower the impact on the quality of seawater.

Brine is a problematic byproduct of desalination because brine can change the salinity, alkalinity, and seawater temperature at the discharge site. This ability is because brine contains high amounts of concentrated salt and is alkaline due to the increase of the calcium carbonate and calcium sulfate; the brine is also at higher temperatures because of the high temperature used in desalination plants (Danoun, 2007). These factors can lead to significant changes in aquatic water, all of which can kill or harm marine organisms.

One of the adverse effects of brine discharge is salinity—a hypersaline layer in the seabed due to its high density (Roberts et al., 2010). Salinity has the potential to influence local marine habitats and activities, and affect their growth. Although the process of RO does not significantly change the temperature, the discharge of brine from this process increases the salinity by a factor of two (Ahmed & Anwar, 2012). According to Ahmed and Anwar (2012), some studies have found that there is a relationship between increases of salinity up to 50 ppt and the adverse effects on fish size and survival rate. High levels of salinity in the sea water can also decrease the levels of dissolved oxygen, which can suffocate plants and result in the hypoxia of aquatic organisms and animals (Ahmed & Anwar, 2012; Dawoud & Al Mulla, 2012).

The second adverse effect of brine discharge is alkalinity. Alkalinity can be defined as the number of equivalents of calcium carbonate in seawater (Danoun, 2007). Brine discharge increases the amount of calcium carbonate, calcium sulfate, and other elements in the seawater. The change of total alkalinity in seawater may then change the pH range of marine environments (Ahmed & Anwar, 2012). As stated by Ahmed and Anwar (2012), a few experiments may be conducted to quantify the change of the total alkalinity in seawater because of the brine discharge as well as the tolerance limit of marine life to it.

The final adverse effect of brine is the thermal pollution that can occur by increasing seawater temperatures (Ahmed & Anwar, 2012; Danoun, 2007). Several studies have indicated a relationship between temperature change in seawater and the response of marine flora and fauna to that alteration in temperature (Danoun, 2007; Roberts et al., 2010). The increase in temperature depends on the method used in the desalination plant. According to Danoun (2007), the sea temperature can increase 60% in an area close to brine discharge;

this means that seawater temperatures can rise dramatically from a range of 10°-25° C to 40°C.

The concerns about brine and the high use of desalination plants has led to the development of many ways in which the effects of brine discharge can be reduced; however, some new methods may be suitable only for different sites. These methods should be evaluated environmentally and economically before relying on any of them. The ways that can be used to reduce the effect of the brine include changing the place of disposal, treating the brine before discharge, and associating the desalination plant with other treatment plants.

Since discharged brine in seawater leads to increased salinity, alkalinity, and thermal pollution, changing the place of disposal by injecting brine through wells in limited and non-potable aquifer systems preserves marine life from damage (Ahmed & Anwar, 2012; Younos, 2005). It is essential to monitor wells close to the injection well to ensure that there is no leakage. Another solution is to dilute the brine solution by spreading it in shallow ponds until it evaporates gradually (Younos, 2005). The remaining solids left behind in the pond can be used in landfills or collected for reuse. There may be a need for solid linings or monitoring of nearby wells to make sure that these ponds do not pollute the surrounding soil or aquifers. The disadvantages of these methods are that they are land intensive and only suitable for small or medium sized plants.

Another solution is to treat the brine before discharging. This can be done by directing the brine solution to the existing sewage treatment plant before discharge (Ahmed & Anwar, 2012). The volume of the brine, the transport process, and the reaction of the brine solution to the wastewater should be considered here. The high range of dissolved solids in wastewater may be a significant concern for marine environments when the treated water is again released into seawater (Ahmed & Anwar, 2012).

Lastly, desalination plants can be co-located or associated with current treatment plants, such as a powerplant or salt works. These methods can be beneficial in decreasing the effect of brine. Desalination plants can be co-located with a thermocouple plant to weaken the brine with power-plant cooling water (Roberts et al., 2010). This method may be appropriate for large-scale plants that would limit the brine plume and decrease their impact to receiving water bodies (Roberts et al., 2010). Desalination plants can also be combined with solar salt works by directing the brine to salt works to produce salt with the purpose of achieving a zero discharge desalination plant (Ahmed & Anwar, 2012). By using this method, extra salt can be produced in the factories which results in additional income.

As with desalination, the reuse of grey water has many advantages, especially in arid areas, and disadvantages. One of the most important benefits of grey water reuse is the reduction of overall water demands (i.e., less reliance on fresh water). The proportion of grey water generated by a single house ranges between 50% and 80% (Albalawneh & Chang, 2015), so reuse of this additional resource will solve part of the growing demand for water. Other benefits include reductions in the amount of wastewater delivered to the sewage system, in the pollution of waterways, and in the energy used in desalination plants as demand for water will decrease. Additionally, the reuse of grey water can protect aquatic ecosystems due to the low desalination demand, replenish groundwater, contribute to a healthy water cycle (P. Murthy et al., 2016b), and respond to environmental responsibility for water conservation and reuse. An interesting benefit of using the grey water from dish washing for irrigation is an improvement in the soil. Naturally, such a system can also reduce water bills (P. Murthy et al., 2016b).

There are, however, disadvantages to using grey water. First, grey water should be used in a short period (24 hours or less) or else the nutrients will break down and consume oxygen, which causes sludge that produces a foul odor (P. Murthy et al., 2016b). Some components of grey water such as soap and biodegradable detergents may also cause a problem over time if this water is used for irrigation (Murthy et al., 2016b). Similarly, grey water may contain oils, fats, grease, hair, and others chemicals that will affect plants (Murthy et al., 2016b). The contaminants also cause concern about health standards and water quality. Additionally, water drainage systems must be separated from the source (i.e., grey water must have a particular discharge that differs from black water). Consequently, the installation of some grey water systems is expensive and some system parts and maintenance can be very costly as well.

The third alternative water supply, harvesting rainwater, is an easy way to collect, store, and use water when needed. This method has many benefits. First, rainwater collection can reduce soil erosion and help reduce the occurrence of floods (Hassan, 2016; Lani et al., 2018). Rainwater systems are also less complex and are suitable for irrigation since the rainwater can be directed from the roof to farm directly. The total cost of installation and operation of rainwater harvesting is less than the water treatment and pumping system (Lani et al., 2018). Most rainwater storage systems are also easily maintained (Hassan, 2016). Overall, less energy is used (i.e., less use of desalinated water) and the wastage of water can be reduced (Hassan, 2016). As such, water bills are often decreased since the collected water can be used for many non-drinking purposes such as laundry and car washing.

Most importantly, though, rainwater can be used as potable water with minimal treatment and adequate collection and storage systems. Rainwater requires minimal treatment because it is sodium-free, which is beneficial for people with restricted sodium diets, and free of chemicals found in groundwater (TWDB, 2005). Similarly, rainwater is suitable for irrigation and contributes to the growth of healthy plants. A raindrop when falling from the cloud is one of the cleanest water sources (TWDB, 2005) as long as there is not acid rain, such as in industrial areas with considerable air pollution. Additionally, rainwater does not form mineral deposits because it is soft and so extends the life of the appliances.

While there are fewer disadvantages of rainwater harvesting than other methods, some still exist. The most obvious is that rainfall cannot typically be accurately predicted or that rain may fall in limited and/or varying quantities. Hence, harvesting rainwater should not be relied on alone to meet water needs in areas where access to safe water is difficult. Furthermore, rainwater storage facilities are limited. During heavy rains, storage facilities may not be able to retain all rainwater. Rainwater harvesting systems also require periodic maintenance as they may be exposed to the growth of algae and insects, and may become breeding grounds for mosquitoes if not preserved properly (TWDB, 2005). Leaks should be repaired and gutters cleaned regularly. This is important since some types of catchment surfaces may let in chemicals or animal droppings that can harm humans or plants (TWDB, 2005).

The final water alternative, stormwater harvesting, is used in many countries around the world. Like the others, this process has many advantages and disadvantages. Stormwater harvesting provides more water than harvesting rainwater and maintains a large amount of rainwater. This alternative also reduces pollution in bodies of water as it collects water from roads and other paved areas, as well as reduces the quantity of water sent to wastewater plants and the energy burnt and pollutants released from desalination plants (Department of Environment and Conservation NSW, 2006). As with rainwater, stormwater contributes to the conservation of aquatic ecosystems, as demand for water desalination will be reduced, and to the prevention of floods.

One major disadvantage of stormwater harvesting is cost (CUWA, 2016). The cost of access to water is higher than that of rainwater harvesting and the cost of building and operating facilities is high, but this cost is at least paid by local authorities or the owner of the plant. Storage facilities for stormwater can also be problematic as they occupy a large area, are attractive places for mosquito breeding, and pose a potentially high public safety risk (Philp et al., 2008). Lastly, stormwater may have higher pathogen levels than harvested rainwater (Philp et al., 2008).

The reuse of grey water or rainwater harvesting often does not produce waste by-products or other pollution because usually they do not need to be treated to high-quality standards if used for non-potable purposes (Eriksson, Srigirisetty, & Eilersen, 2010). However, if grey water, rainwater, or stormwater is treated, it produces two products: the treated water itself and the by-product, sludge. Approximately 99% is rejuvenated water, and the rest is waste by-products or sludge (Stehouwer, 2010). Sludge is produced after separation from treated water (Guyer, 2011). There is very little information about grey water, rainwater harvesting, or stormwater harvesting sludge components. However, the sludge, in general, may be produced from some wastewater treatment plants that include grey water and stormwater. This sludge usually contains organic matter, nutrients, microorganisms, and heavy metals (Eriksson et al., 2010).

Because of the unstable and decomposed nature of the sludge, raw sludge poses health and environmental hazards (Stehouwer, 2010). It should, therefore, be treated to reduce the pathogens that it contains and increase the content of solids; the most often used treatments are dewatering and anaerobic digestion. Several methods can be used in the process of dewatering such as air drying on sand beds and filtration (Guyer, 2011). This process contributes to increasing the content of solids and reducing pathogens (Guyer, 2011; Stehouwer, 2010). Anaerobic digestion is one of the most common ways to treat sludge. In this process, the sludge is retained in the absence of air for several days ranging from 15 days to two months at a temperature between 68°F and 131°F (Stehouwer, 2010). Anaerobic bacteria feed on the sludge and produce carbon dioxide and methane, the latter of which can be used as an energy source (Guyer, 2011). This process contributes to increasing the content of solids and reduces odors and pathogens as well (Stehouwer, 2010).

There are several ways in which the treated sludge can be handled: classified as biosolid, disposed of in a landfill, or incinerated (Stehouwer, 2010). Disposal of the sludge in a landfill is the simplest method (Stehouwer, 2010). There are some benefits of disposing sludge in a landfill; for example, it could be more economically feasible than other methods. However, there are some risks related to landfill disposal of the sludge as organic waste is subject to anaerobic decomposition in landfills, which results in methane that can be released into the atmosphere (Stehouwer, 2010). Methane is one of the greenhouse gases involved in global warming. This process may produce foul odors in the landfill as well.

Incinerating sludge is another method of treatment. Incineration reduces the sludge volume, destroys pathogens, and decomposes most of the organic chemicals (Stehouwer, 2010). One of the disadvantages of this process is ash formation, which contains most of the trace minerals in the sludge; these materials are often landfilled (Stehouwer, 2010). There are several other disadvantages to this process as it is one of the most expensive options. Incinerating sludge also produces carbon dioxide and other pollutants such as cadmium and lead.

The last method is to classify the treated sludge as a biosolid. Biosolids are organic matters very useful in improving soil quality and producing different crops; as such, the plant nutrients from sludge treatment can be reused. The commercial value of biosolids can be enhanced by subjecting them to composting, pasteurization, and heat drying, and then sold for agricultural and landscaping purposes (Stehouwer, 2010). There are also many other benefits of biosolids, especially for farmers, because the nutrients they contain can replace purchased inorganic fertilizers. According to Clarke and Smith (2011), the majority of the compounds in biosolids do not place human health at risk when the biosolids are recycled into agricultural land. Biosolids should be treated carefully and adequately; otherwise, the soil will receive the pollutants and pathogens in the biosolids, which will adversely affect human health, soil quality, water quality, and plant growth (Stehouwer, 2010).

Discussion

Climate change, increases in global population, and urbanization have resulted in severe water supply shortages and a rising crisis of access to freshwater (P. Murthy, B. Murthy, & Kavya, 2016a). The proposed alternative water sources (desalination, grey water, harvesting of rainwater, and harvesting of stormwater) are among the most important solutions to address this growing shortage, and they are effective methods for addressing water sustainability in the short and long term. The provision and reuse of alternative water resources are necessary in places where water is difficult to get and to ensure a healthy individual and environment. For instance, about 80 million cubic meters of potable water are produced every day from desalination technologies in 17,000 desalination plants across the world (Wali, 2014). Suffering from fresh water crisis, 70% of these plants are located in the Middle East (Wali, 2014).

The application of alternative water supplies in these arid and semi-arid areas thus appear to be successful steps that may be sufficient enough to solve the problem of the freshwater crisis. To apply these alternatives, however, certain factors need to be taken into account: the area's socioeconomic status (the ability to invest and apply any of these alternatives), geographical location (proximity to a sea to build desalination plants or ease of building a storage tank to harvest stormwater), the general weather (abundance or lack of rain water), the general population's acceptance of these alternatives, and the level of urgency for additional water.

As the water crisis in semi-arid and arid regions increases due to increased demand and low supply, the important question is what is the best water supply alternative. In fact, all four methods are essential and should be used wherever possible to take advantage of their benefits. For example, rainwater harvesting can be used even in places where fresh water is available while taking precautions, such as education about contaminants in rainwater storage tanks, to protect people and avoid risk. However, rainwater and stormwater harvesting are useful only for areas that receive a good amount of rainfall throughout the year. Therefore, it is dangerous to rely only on these two sources in arid and semi-arid areas as they may not be effective enough to solve the water crisis. In contrast, desalination technologies are reliable and efficient, frequently used on a larger scale, and are promising methods of providing water in arid and semi-arid areas, especially if the plants are near coastal areas (Oyoh, 2016; Zotalis, Dialynas, Mamassis, & Angelakis, 2014). As such, desalination is the best alternative for providing water in arid areas to solve the water crisis. Water-sharing agreements between countries are essential for landlocked areas. Coastal and landlocked areas should work together to share and develop water resources management among these countries.

Populations in arid and semi-arid areas need a sustainable and safe water supply. Desalination technologies are able to produce a large quantity of water through the conversion of brackish water or seawater. Since seawater covers a high percentage of the earth's surface, there is a lot of water that can be converted and used for different purposes. Unfortunately, one of the main obstacles to the construction and operation of desalination plants is the high cost. According to Zotalis et al. (2014), about 60% of the cost of operation and maintenance of desalination plants is on the use of energy. However, each desalination technology does not use the same amount of energy. Thus, the cost can be reduced by using technologies that consume less energy or by the use of brackish water instead of seawater (Zotalis et al., 2014). For example, reverse osmosis uses less energy than thermal-based processes, which decreases the cost of desalination and the cost of the water bill to the user.

Another alternative to the energy cost in desalination is renewable energy because it provides less costly energy in some desalination applications. The use of renewable energy has several other benefits as well since it prevents air pollution (e.g., from burning fossil fuels). Solar thermal energy, in certain arid tropical areas, is one kind of renewable energy used to produce thermal and electrical energy that is capable of operating desalination plants. Wind energy, another type of renewable energy, cannot provide thermal energy directly, but it can provide electricity to desalination plants (Oyoh, 2016). Wind energy is more competitive in windy arid or semi-arid areas as it is generally useful in areas where the wind speed is at least six meters per second (Oyoh, 2016). Together, solar and wind energy can provide energy for electrical-based technology plants using processes such as reverse osmosis.

Furthermore, with the advancement of science and technology, experts can devise new desalination technologies that contribute to the production of a significant amount of desalinated water without additional energy use. For example, MEDAD is a recent technology that is a combination of the conventional Multi-Effect Distillation (MED) and an Adsorption cycle (AD) (Shahzad, Thu, Kim, & Ng, 2015). This technology can work at a temperature lower than the operating temperature of conventional MED technology. According to Shahzad et al. (2015), the hybrid technology of MEDAD is capable of producing desalinated water as a result of the synergistic operation of MED and AD systems. The production of two to three times the amount of potable water created using the same amount of energy in conventional processes means that the environmental impacts (i.e., brine and air pollution) of this technology are fewer than in previous techniques.

Since many desalination technologies may produce pollution and waste by-products that may ultimately affect the environment and public health, these hazards should be appropriately considered and dealt with in order to minimize their impacts. The brine discharge should be treated either by desalinating it again or by sending it to wastewater treatment plants if possible. If the lands close to the desalination plants are available, they can be used as evaporation ponds. These evaporation ponds with agricultural applications and aquaculture can also be a viable economic option (Ahmed & Anwar, 2012). If the brine is discharged into these ponds, many aquatic organisms, such as brine shrimp and black bream, can be successfully raised (Ahmed & Anwar, 2012). High salinity plants can be irrigated near evaporation ponds by the brine to mitigate their harmful effects on the marine environment. The cost of land, lining, and the monitoring related to evaporation ponds can then be reduced by producing aquatic organisms, plants, and salts.

Lastly, choosing a desalination plant location is very important. The site should be a place with enough land available to build an evaporation pond or a place close to a wastewater treatment plant. It should also be away from residential areas to avoid noise and air pollution. Ultimately, the development of science and the innovation of new technologies and ideas are capable of reducing the environmental impact to zero. If desalination is used safely, there is the potential for no direct or indirect damage to the use of these processes on humans or the environment.

If there is little to no saltwater available, the reuse of grey water can be another effective solution to the water crisis in arid areas, especially noncoastal, arid places (P. Murthy et al., 2016a). The reuse of grey water is also an excellent alternative for water supply in arid and semi-arid areas due to its minimal environmental impacts (P. Murthy, 2016a). Unlike desalination plants, grey water does not produce pollution and waste by-products. The main drawback of grey water reuse is public perception. Unfortunately, some eco-friendly programs may not succeed because the end consumers do not accept them (Oteng-Peprah et al., 2018). Many questionnaires and interviews do indicate support for the reuse of grey water as an environmentally sustainable method, but the acceptance often is for specific uses only (i.e., non-potable purposes) (Oteng-Peprah et al., 2018). A comprehensive assessment of the grey water in the area where the grey water will be recycled should be conducted to determine the appropriate method of treatment. According to Ghunmi et al. (2011), in general, exclusively physical removal systems to treat grey water should be avoided; for efficient, simple, and affordable water treatment, a three-step system with anaerobic, aerobic and disinfection processes should be used. In order to effectively reuse grey water, extensive contributions and encouragement from experts in many disciplines are required (Oteng-Peprah et al., 2018).

The final two alternatives, rainwater harvesting and stormwater harvesting, are not as common as desalination and the reuse of grey water in arid and semiarid areas since the intensity of rainfall varies, but they are still important. In general, the use of rainwater harvesting reduces the load on water treatment facilities by almost half and reduces the demand for energy (Hassan, 2016; Martin et al., 2015). Directing excess rainwater to wells to recharge groundwater during the months of heavy rainfall thus leads to an increase in the aquifer that can be used when needed (Hassan, 2016). Since rainwater harvesting may contain some turbidities and microbiological agents (such as contamination of water collected by bird droppings), it should be treated before potable use (Buntat et al., 2015). The ozone treatment process has the potential to provide high-quality water through the removal of microbiological contaminations and odors and appears to be a reliable method that can be used for potable purposes (Buntat et al., 2015).

More valuable than rainwater is stormwater. Stormwater harvesting is essential in some arid places as it provides many social, economic and environmental benefits, including flood prevention, environmental enhancement, and water supply (Philp et al., 2008). Stormwater harvesting has several purposes: industrial uses, residential uses, irrigation of public areas, ornamental ponds, water features, and aquifer storage and recovery (Department of Environment and Conservation NSW, 2006). Aquifer storage and recovery is the process of injecting water into the aquifer during times when water is available, and then recovering and using the water at almost the same quantity when needed. This may lead to increased yields of the aquifers, but stormwater must be treated before injection to prevent blockage of the aquifer by particles and organic matter, or contamination by other pollutants (Department of Environment and Conservation NSW, 2006). In general, the cost of stormwater harvesting projects varies based on site-specific conditions, such as infrastructure requirements for collection, transport, processing, storage, and distribution of the collected water (CUWA, 2016). Thus, it is preferable to study such a project in each area separately in order to ensure its cost-effectiveness.

The advantages and disadvantages of several alternative water supplies that can be used to solve the water crisis in arid and semi-arid regions have been compared and contrasted in this thesis. In conclusion, all alternative water supplies are important, viable, and highly effective to solve an arid area's water supply. Of particular note is the desalination of sea or brackish water because of its promising technology that has contributed to solving the water crisis in many countries. Ultimately, the recommendation is to use environmentally friendly, renewable energy sources as they minimize negative environmental impacts from desalination and reduce associated pocessing costs. Further research is needed to improve membrane-based desalination technologies to become even more environmentally friendly.

Using grey water should also be applied and encouraged. It is one of the essential sustainable options to meet the increasing demand for water and to protect the environment from the wastewater treatment plant's impacts. It also contributes effectively to reducing water access cost. In addition, comprehensive studies are nedeed of the properties of grey water in each area separately (as mentioned previously) to identify their components and the appropriate treatment methods since the reuse of grey water in non-potable purposes, such as irrigation farms, without treatment or with improper treatment methods may lead to the accumulation of pollutants in the soil. Therefore, several studies should be conducted to know the effect of these pollutants on the soil and to identify the appropriate methods for treating grey water to minimize this effect.

Lastly, arid and semi-arid areas should invest in stormwater harvesting. The safety of stormwater storage must be maintained continually and kept outside urban areas if possible to ensure that they are free from contaminants. Rainwater harvesting should be encouraged, and its systems should be supported. People should also be educated about the importance of continuously cleaning up collection sites. The treatment services should be supported as well until the desired benefit is obtained.

Table 4

	Desalination Technology	**Grey Water Reuse**	**Rainwater Harvesting**	**Stormwater Harvesting**
Location	Close to coastal area	Close to the homes	Close to the homes	Prefered outside the urban areas
Capital costs	High, but paid by a central authority or facility owner	High if build a special infrastructure. However, low if reused in household	Low, but paid by homeowner	High, but paid by a central authority or facility owner
Costs of water used	Likely to be higher than other alternatives	Likely to be lower than desalination and stormwater harvesting	Likely to be lower than other alternatives	Likely to be higher than other alternatives – similar to desalination
Distribution costs	Likely to be higher, depends on the location of desalination plants	Likely to be lower than desalination and stormwater harvesting	Tanks located near use, with negligible distribution costs	Likely to be higher, depends on the location of the storage relative to the use
Pollution generation	- Air pollution - Noise pollution - Thermal pollution	- Soil pollution	- No pollution generation	- No pollution generation

Waste by-products generation	- Brine	- Sludge	- Sludge	- Sludge
Use	Often potable uses	Often non-potable uses	Often non-potable uses	Often potable uses
Energy	Often a large amount of energy is needed	Often less than desalination's energy is needed	Often less amount of energy is needed amongst alternatives	Often less than desalination's energy is needed
Yield	Enough water can be obtained	Large quantity of water can be provided	Depends on rainfall	Depends on rainfall

Summary of comparing and contrasting desalination, greywater reuse, rainwater harvesting, and stormwater harvesting

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