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Technology review and data analysis for cost assessment of water treatment systems

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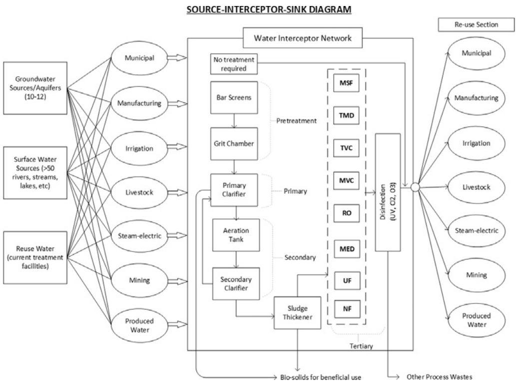
HIGHLIGHTS

- Capital, operating and unit product cost comparison for treatment technologies
- Cost data compiled from over 100 research articles, white papers, technical reports
- Network representation of water distribution and treatment followed by reuse options
- Membrane techniques more suitable than thermal due to lower cost and energy demands
- Integration or coupling strategies can lower cost based on conventional techniques.

GRAPHICAL ABSTRACT



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ABSTRACT

A wide variety of water sources, treatment methods, and recycling options have created a myriad of water management options. For modeling of sustainable water treatment options, computationally efficient models may be required. This paper provides a comprehensive and comparative review of the water management systems and the associated economic, environmental, and performance metrics. The water management systems are represented as a network of sources, users, technologies, recycling options, and quality of water. Special attention is given to desalination systems. The two main technology categories currently used for desalination are thermal (e.g., Multistage Flash “MSF”, Multi-Effect Distillation “MED”, and Mechanical Vapor Compression “MVC”) and membrane (e.g., seawater reverse osmosis “SWRO”, brackish water reverse osmosis “BWRO”). The cost assessment includes a capital cost comparison (for which regression analysis has been used to account for the nonlinear nature of the capacity-cost curves), an operating cost comparison, which includes energy requirements, labor costs, chemicals used, maintenance and repair costs, membrane replacement costs and a unit product cost ($/m^3) breakdown, which combines the capital and operating costs. Numerous data were collected for the cost of desalination systems. Statistical methods were then used to analyze these collected data to establish deeper understanding of the relationship to capital cost, operating cost, capacity, constraints due to treatment method capabilities, requirements of the users. The paper also briefly discusses other cost considerations such as the water intake and distribution costs. The environmental impacts (concentrate disposal and CO_2 footprint) have also been compared for the various technologies considered. Some integration strategies such as use of hybrid systems, cogeneration plants and use of renewable energy have shown reductions in cost associated due to

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energy consumption and thereby, reducing the unit product cost. Finally, the paper provides a selection guide suitable for various situations with consideration of the different factors affecting cost, environmental impact and energy demands.

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1. Introduction

The need for clean water is a growing demand for many parts of the world. Growing population trends in major cities have placed an incredible amount of stress on the natural water resources, while inadequate methods to provide the water have caused severe deficiencies. Water is used for various purposes such as drinking and irrigation, where the water sources need to be treated, in most cases, before it can be used for any beneficial purposes. When clean freshwater sources are not available, seawater has been used and desalination technologies have dominated the market for rendering the water usable. Hence, desalination has emerged as one of the major options for providing fresh water. The need for desalination continues to grow, with the global cumulative capacity (contracted as of June 2017) reaching 99.8 million m^3/d, a growth of almost 25 million m^3/d since 2010 (IDA (International Desalination Association) and GWI (Global Water Intelligence), 2017). The growing capacity is both a result of technological advancements making water treatment and desalination competitive with conventional freshwater supply and growing public and governmental awareness of the depleting water resources and a need for a sustainable approach. Technical developments in the recent years for the major desalination methods have been summarized by Reddy and Ghaffour (2007), Blank et al. (2007), Wade (2001), El-Halwagi (2007), Elsayed et al. (2014), and Semiat (2000). Desalination can also be performed on several wastewater sources, and increased public acceptance of wastewater reuse for potable purposes after proper treatment has played a vital role in the development of the desalination industry (Coxon et al., 2016).

Treatment costs have gone down significantly over the last few decades due to the reduced energy consumptions, enhanced materials used for construction and improved membrane life (in case of membrane processes). Seawater desalination costs were quoted around \$0.64–0.8/m^3 (mid-1990s values) for a large sized plant in the 1990s (Glueckstern, 1991) and have decreased to around \$0.50/m^3 for such large-scale RO plants in the current decade (Kiang and Young, 2003). These costs are expected to reduce further, with an estimated reduction in energy use by 20% in the next five years and up to 60% in the next 20 years (Voutchkov, 2016).

This paper aims to compile a body of review literature that will aid in the development of water networks that connect the supply chain, reuse, and/or recycle of water systems. A framework for total water use and disposal cycle is taken for demonstration purposes here. The network design is unique in the aspects of simultaneous mass and property integration, where not only the quantity of water distribution to various users is considered, but also the quality requirement of each user is matched through an optimization framework. This matching is required particularly when the wastewater streams need to be treated for reuse. A process synthesis methodology is intended for the water network, where for given qualities and quantities of water, the treatment, reuse, and disposal strategies will be ascertained. Capital and operating costs and their ability to treat and render usable water are reconciled in this paper so that it can be readily used for process design and for systems level analysis of water. Additionally, the type and quantity of energy needed for each treatment strategy, along with the environmental impacts across the system is quantified.

In this paper, all of this information is compiled from over 100 research articles, white papers, technical reports etc. and standardized for unit production of water. Then, statistical methods are used to analyze these collected data to establish deeper understanding of the relationship to capital cost, operating cost, capacity, constraints due to treatment method capabilities, and requirements of the users. These are documented in this paper through graphs and equations, which can be used for ranges of required water volumes to be treated. The contents of this paper are different from the already published reviews in the way that this paper presents a technical and economic outlook to the reader that is essential and comprehensive for optimal process selection and presents cost values that have been obtained through an extensive data collection and statistical analysis. It also paves road for formation of optimization frameworks for macroscopic water network systems (cities, regions, etc.).

2. Methodology

Fig. 1 shows the general flowchart of the decision-making process for the choice of a suitable technology. This diagram forms the basis of the workflow to be followed when water of a certain quality is required. We start with the pre-treatment steps such as bar screens, skimming, etc. (refer Section 2.5.1) followed by primary and secondary treatment (refer Section 2.5.2) with aerobic and anaerobic choices. This is followed by a selection of tertiary treatment (if required) on the basis of the salinity of the incoming stream through thermal or membrane processes (refer Section 2.5.3) or sometimes both (refer Section 5.2.2). A post-treatment step (refer Section 2.5.4) usually follows, resulting in a stream that should meet end user quality requirements. The process selection also depends on some other factors as discussed in Section 5.1.

In the following sections, a generalized diagram of the water network representation is described followed by detailed description and quantification of each node of the network.

2.1. Water network representation

Fig. 2 shows a generalized representation of water distribution and treatment followed by reuse options. This diagram is divided into five parts: water sources, water users, wastewater characterization, interceptor network design (treatment facility), and re-distribution to users. This framework is based on the generalized mass integration framework (El-Halwagi et al., 1996; Gabriel and El-Halwagi, 2005; Nápoles-Rivera et al., 2015; Sotelo-Pichardo et al., 2014; Jiménez-Gutiérrez et al., 2014). The methodology provides a holistic approach to track species and streams through the identification of sources, sinks, and interception devices that can treat water to match the desired quality. Water user groups retrieve water from groundwater or surface water sources. The wastewater generated by these users is intercepted by the treatment network to undergo a series of treatment options for obtaining the final quality of end-use or disposal. After treatment, water can be reintroduced into the supply system, thereby reducing the reliance on natural sources and improving drought resilience for the future. The selection and sequence of steps within the water interceptor network are dependent on the feed and product quality requirements. The conceptual treatment pathway can be any combination of the various processes, but the optimal choice will depend on a set of criteria for cost and/or quality.

Application of this schematic to a region such as a city or state requires detailed knowledge on the quantity and quality of water as well as the spatial offset between the source and the sinks. Transportation (distribution) costs are often incurred. In order to achieve an optimum water distribution network design, it is imperative to make the

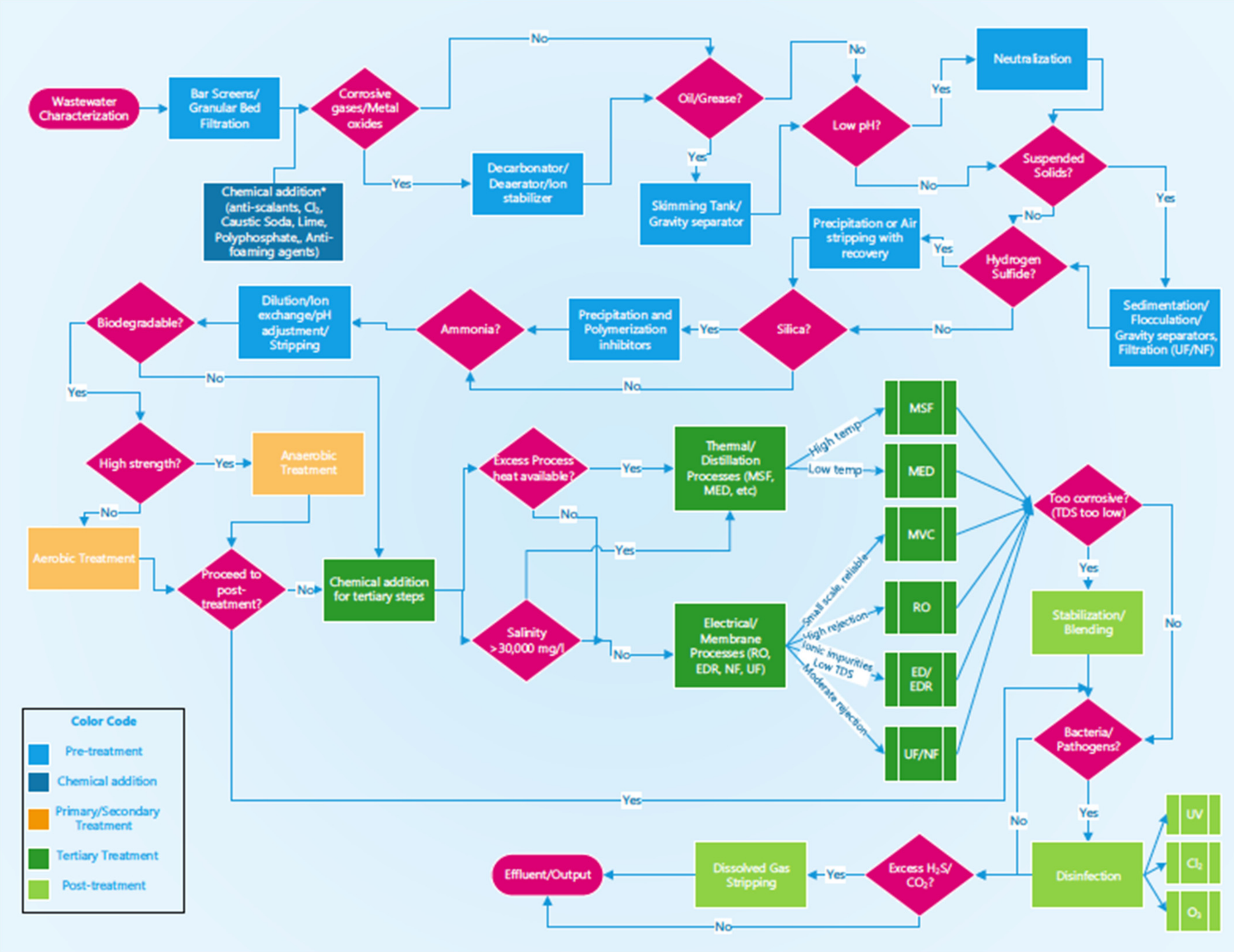

Fig. 1. Flowchart for the screening and selection of water treatment processes.

right judgment at each step in the model. In the next sections, we have discussed the steps involved in detail.

2.2. Water sources

2.2.1. Groundwater

Groundwater (aquifers) is part of the precipitated or run-off water that seeps down through the soil and gets stored in between the rock particles. It accounted for almost 22% (79,300 million gallons per day) of the total national water use in 2010 (The USGS Water Science School, 2018). Rising populations and increased demands have depleted the groundwater sources and could significantly impact the crop production in United States as most agricultural lands (~60%) rely on groundwater. Several states have set up conservation districts (Texas State Soil and Water Conservation Board, 2018) to monitor aquifer levels and develop locally driven solutions to conserve groundwater.

2.2.2. Surface water

Surface water corresponds to water in the rivers, lakes, streams, creeks and reservoirs. Almost 78% (275,000 million gallons per day) of the total national water use in 2010 came from surface waters (The USGS Water Science School, 2018). Majority of the public use (municipal), irrigation and industrial water supply can be credited to the surface waters. Thermo-electric power industry is a major user group for surface waters, accounting for almost 50.4% of the total fresh surface water use. This water is usually returned to the surface source after proper treatment based on NPDES (National Pollutant Discharge Elimination System) guidelines presented by the US EPA under the Clean Water Act of 1972 (United States Environmental Protection Agency (US EPA), 2018).

2.2.3. Reuse- and sea-waters

Reuse water refers to wastewater that can be treated for beneficial purposes, which ensures longevity of the existing sources and makes them more reliable. Reuse amounts are very low compared to the groundwater and surface water sources. However, with recent advances in water treatment techniques and improving public knowledge of the benefits of reuse, potable and non-potable reuse is predicted to increase (United States Environmental Protection Agency (US EPA), 2018).

Seawater is a source of water for many countries which do not have significant surface and groundwater resources. Seawater is characterized by higher salinity (>35,000 ppm) and requires treatment before it can be used for the purpose of any traditional use. The key ions in seawater are chloride, sodium, sulfate, magnesium, calcium, potassium, bicarbonate, bromide, and strontium.

2.3. Water use

Water users are categorized in multiple ways. United States Geological Survey (USGS) (2018) lists 8 (public supply, domestic, irrigation,

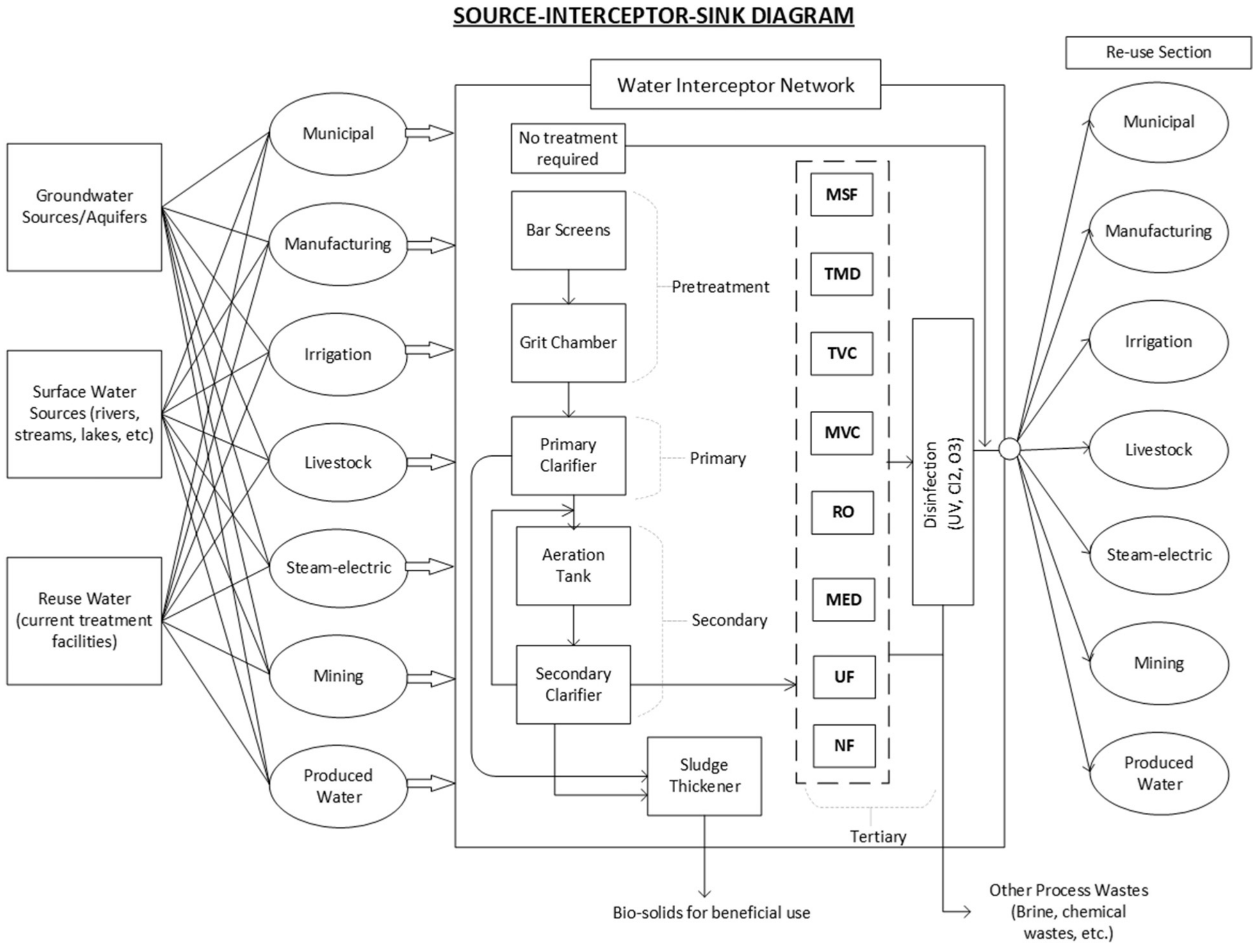

Fig. 2. Source-interceptor-sink diagram for treatment and management of wastewaters.

thermoelectric power, industrial, mining, livestock and aquaculture). The Texas Water Development Board (TWDB) (2017) gives 6 (municipal, industrial, irrigation, steam-electric power, mining and livestock) major categories. For the purpose of this paper, we will focus on the 6 categories from TWDB and will include a seventh category for fracking water (oil and gas production). Each water user group derives its water from groundwater, surface water or treated water sources. The usage pattern varies geographically across the country depending on the availability and the demand. For example, surface waters contribute around 79% for fracking activities in Marcellus Shale basin and range around 48% for Barnett Shale, Texas (Mittal, 2011). Fig. 3 shows the average contribution of ground and surface water sources in the water that was used for each water user group in 2010 in the US (The USGS Water Science School, 2018; Mittal, 2011).

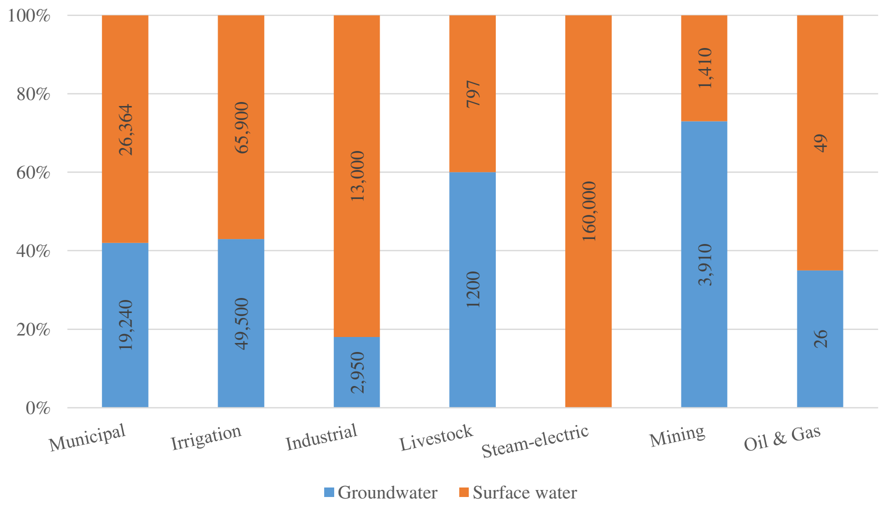

Fig. 3. Total water use in 2010 across different sectors (The USGS Water Science School, 2018; Mittal, 2011) (in mgd).

2.4. Wastewater characterization

It is important to characterize the wastewater source to ensure proper treatment as technologies vary according to concentration and type of contaminants. The most common characterization factors are based on total suspended solids (TSS), total dissolved solids (TDS), pH, temperature, alkalinity, oil and grease content, toxic ions, ammonia and others. The quality varies spatially, temporally and according to the user from whom it is generated. This review provides a brief description of the characteristics according to the user as this will help in determining the treatment method. The typical range of qualities for each use sector is compiled in Table 1.

2.4.1. Municipal

Municipal wastewater sources can be divided into residential and non-residential (offices, public places, restaurants, businesses, etc.). Residential wastewater is further categorized into grey water (water from everywhere except toilets) and blackwater (water from toilets) (National Small Flows Clearinghouse, 1997). Some of the non-residential wastewaters may carry additional substances such as blood, fats and cleaning agents resulting from meat processing facilities, photographic chemicals (silver halides, ammonium thiosulfate (hypo)), soaps, dyes, caustic compounds, and cleaning. These require additional treatment steps and should be dealt on a case by case basis (Gross, 2005). Typical range of BOD values for municipal wastewaters is from 100 to 400 mg/l depending on the strength of the wastewater. The total nitrogen (TKN) range from 20 to 85 mg/l and the total phosphorus values usually range from 6 to 23 mg/l. Refer Supporting information (Table S1) for more details.

2.4.2. Manufacturing/industrial

Wastewaters generated from the industrial sector can be divided into two categories: inorganic wastewater (water containing inorganic or mineral substances in dissolved or suspended form) and organic wastewater (from industries using organic chemicals for reactions such as pharmaceuticals, textile, breweries, leather, etc.) (Hanchang, n.d.). Several industries discharge toxic metals such as cadmium, mercury and lead. Quantities vary widely according to the type and in between industries (Munter, 2003).

2.4.3. Mining

The main pollutants in discharges from mining activities are dissolved minerals from aquiferous rock strata, metals, acids and salts. Wastewater from mines can be divided into four categories: mine water (seepage from excavated underground area), process wastewater (processing of products), surface runoff (during storms or rains) and sewage (from domestic facilities within the mining area) (Dharmappa et al., 1995). The quality of wastewater is dependent on the type of the mining industry. Metals such as Cadmium, chromium, nickel, iron, lead, mercury may be found in effluents from coal or metalliferous mining industry. Radioactive substances may be present in effluents from uranium mining (Dharmappa et al., 2002).

2.4.4. Produced and flowback water

Naturally occurring rocks in subsurface formations contain water that gets permeated along with oil or gas or a combination of them. Produced water is the water from oil and gas underground formations that comes to the surface during extraction activities (Lira-Barragán et al., 2016; Elsayed et al., 2015a,b). It may also include water injected during fracturing operations in the form of high pressure steam. The characteristics of produced water depend on whether natural gas, shale gas, crude oil or coal bed methane is being produced (Veil et al., 2004). These waters generally contain high amounts of hydrocarbons (oil and greases), dissolved solids, inorganic and toxic compounds and naturally occurring radioactive materials (NORMs) (Produced Water Society, 2017).

2.5. Treatment methods

Treatment methods are required to purify wastewaters, to mitigate its environmental impact before disposal and/or to reuse for potable or non-potable purposes. It is also important to treat wastewater for numerous environmental and human health regulations. Heavy metals are carcinogenic and can severely harm human circulatory and respiratory health. Release of nutrient-rich wastewaters to water bodies can cause eutrophication, a condition where excess growth of algae and plant growth causes oxygen depletion of the water body thus harming marine life (Hespanhol and Helmer, 1997).

There are a variety of treatment steps available, and combinations of these steps are required for desired separation. An informed decision is required to match the wastewater quality and quantity to the product specification. Treatment can be broadly classified into thermal and membrane processes. Each has its own sequence of pretreatment and post treatment options.

2.5.1. Pre-treatment

Pre-treatment depends on the wastewater feed and the subsequent desalination stage of the process such that the constituents do not impair the performance and to reduce the burden of treatment on the desalination stage. Pretreatment is required to prevent corrosion of heat

Table 1

Typical wastewater characteristics (Bay Area Regional Desalination Project, 2007; Borsani and Rebagliati, 2005; Ettouney, 2004; Chang, 2008; Pankratz, n.d.; Watereuse Association Desalination Committee, 2011a,b; Voutchkov, 2004; Organization of American States, n.d.; Plappally and Lienhard, 2012; Lee et al., 2017; Liu and Zheng, 2002; Kally, 1993; Lattemann and Hopner, 2008; Younos, 2005; Mahi, 2001; Mickley, 2001; Luis et al., 2009).

Technology	TDS (mg/l)	TSS (mg/l)	BOD_5 (mg/l)	pH	Toxic metals (mg/l) (✓ = present but data unavailable or inconsistent)			
Municipal					Hg	Pb	Cr	Cu
Weak	250–500	190	100–150	6–9	1	30	15	40
Moderate	500–650	300	200–250	6–9	2	65	25	70
Strong	>850	450	350–400	6–9	3	80	40	100
Industrial					Hg	Pb	Cr	Cd
Pulp & paper	NA[a]	75–300	1400–1700	<7	✓	✓	✓	✓
Textile	NA	200–3000	1000–2000	8–12	–	–	✓	–
Pharmaceutic	NA	675–9320	200–6000	4–9	–	✓	–	✓
Petroleum	NA	130–600	100–500	2–6	–	✓	✓	✓
Produced water					Na	Ba	Sr	Ca
Oil & gas	1000–400,000	1.2–1000	Negligible	6–9	<150,000	<850	<6250	<74,000
Carbon bed methane	300–40,000	NA	Negligible	7–8.6	~465	~1.6	0.1–1.9	5.9–57
Mining	500–6500	10–100	<5	5–7	✓	✓	✓	✓

[a] Data not available.

Table 2
Pre-treatment for various concerns in thermal and membrane processes (Wesley Eckenfelder et al., 2009; Morin, 2010, 1993; Watson et al., 2003).

Concern		Alleviation measure
Equipment corrosion	Corrosive gases	Decarbonator and deaerator followed by an oxygen scavenger such as sodium bisulfite
	Low pH	Removal of CO2 gas by decarbonators; neutralization
Scaling and Membrane Fouling	CaSO4, BaSO4	Addition of synthetic anti-scalants or polyphosphate, lower temperature or use NF (nanofiltration)
	CaCO3 or Mg (OH)2	Use HCl/H2SO4 to lower pH along with anti-scalants and installing a decarbonator
	Metal oxides (Fe^{3+}, Mn^{3+})	Deaerator/anaerobic conditions, metal ion stabilizer
	Biological	Disinfectants and biocides, BAC filters
Erosion due to TSS		Sedimentation, logooning, floatation, Filtration (UF), gravity separation, cyclone separators
Oil and grease		Skimming tank or gravity separator
Heavy metals		Precipitation or ion exchange
Marine growth		Adding chlorine (periodic high dosage as shock)
Alkalinity or acidity		Neutralization
Silica		Precipitation and polymerization inhibitors
Hydrogen sulfide		Prevent oxidation to colloidal sulfur, precipitation or air stripping with recovery
Ammonia		Dilution, ion exchange, pH adjustment, stripping

Table 3
Differences between aerobic and anaerobic biological treatment (Mittal, 2011; Wesley Eckenfelder et al., 2009; Peters and Cadena, 1988; Office of Groundwater and Drinking Water, Environmental Protection Agency (EPA), 2009).

Parameter	Aerobic treatment	Anaerobic treatment
Application	Low to medium COD (<1000 mg/l) and difficult to biodegrade e.g. municipal and refinery wastewater	Medium to high COD (>1000 mg/l) and easy to biodegrade e.g. food and beverage containing water
Degree of treatment	High	Moderate
Footprint	Relatively large	Relatively low/compact
Startup time	2 to 4 weeks	2 to 4 months
Capital cost	High; much more sensitive at high influent BOD values	Low with payback; not so sensitive at high influent BOD values
Reaction kinetic	Relatively fast	Relatively slow
Energy demands	High	Low
Advantages	Low maintenance Less odor issues Relatively safer	Low sludge generation Biogas production (methane)
Disadvantages	Volatile emissions High sludge yield	Potential odor issues Low to moderate stability
Examples of technologies	Activated sludge (cyclic or conventional), MBR, aerated lagoons, fixed file processes e.g. trickling filter	CSTR/digester, upflow anaerobic sludge blanket (UASB), ultra high rate fluidized bed reactors e.g. EGSBTM, ICTM, etc.

exchanger and tubing surfaces, membrane fouling due to metal oxides, biological growth etc. as these are the prevalent concerns facing water purification. Common pretreatment methods used for these issues are given in Table 2.

The main objectives of pre-treatment in thermal processes are to control scaling and corrosion of water treatment equipment. For membrane processes, the main objectives are to control membrane fouling due to biological activity, metal oxides, colloids, particulate, minerals and silica precipitation. Various disinfectants and biocides are used to restrict membrane fouling. For example, use of BAC (Biological Activated Carbon) has been quite effective in minimizing biofilm formation (Mingo, 2017). Most scaling compounds have higher solubility in concentrates than in feed solution (increasing ionic strength increases the solubility product constant, K_{sp}). Once the RO system rejects the ions in the concentrate, the possibility of scaling is reduced (Wesley Eckenfelder et al., 2009). RO processes require higher levels of feed purity than thermal processes due to the strict thresholds (Morin, 2010).

2.5.2. Primary and secondary treatment

When wastewater contains soluble organic impurities, biological treatment becomes an integral part of the treatment plant. The primary treatment is mostly physical involving the use of primary clarifier to remove suspended impurities. The secondary treatment constitutes biological treatment through a reactor and secondary clarifier arrangement. The biological treatment is mainly categorized into aerobic and anaerobic types. Table 3 briefly discusses the differences between the two types.

Several alternatives exist for both aerobic and anaerobic treatment types; the technology choice depends on the feed wastewater, reliability desired, ability to utilize the generated biogas and other site specific and waste disposal factors (Mittal, 2011). Tertiary treatment may also be required depending on the desired product quality.

2.5.3. Tertiary treatment

Tertiary treatment can be categorized into thermal and membrane processes. The most common thermal processes are: Multi-Stage Flash (MSF), Multiple Effect Distillation (MED) and Vapor Compression Distillation (VC). Membrane processes generally used include Seawater Reverse Osmosis (SWRO), Brackish Water Reverse Osmosis (BWRO), Microfiltration (MF), Nanofiltration (NF), Ultrafiltration (UF), Electrodialysis (ED) and Thermal Membrane Distillation (TMD).

Thermal processes work on the principle that dissolved salts (non-volatile) remain in solution as the water is evaporated. The leftover solution, after several rounds of recycling, is concentrated and ultimately disposed. Membrane processes use membranes in various configurations to reject dissolved salts from the wastewater. RO uses dynamic pressure to reject salts whereas ED uses electrical power to induce ion-selective permeation leaving dilute water solution behind. NF is used to partly remove heavy salts from water. UF is another method that removes bacteria and viruses. MF is used to discard suspended particles and viruses (Semiat, 2000).

All these processes differ in their capital investments and operating costs (energy usage, labor, chemicals, etc.) and the process selection depends on the process objectives and constraints and is case specific. A detailed cost analysis for the various desalting processes has been presented in the following sections.

2.5.4. Post-treatment

Post-treatment is done to refine the water after desalting processes and to make it suitable for the different user groups. The level of post-treatment depends on the desalting process preceding it and the quality of water required by the user groups. Some of the post-treatment methods include stabilization, dissolved gas stripping, blending and disinfection (UV, Cl_2, O_3) (Watson et al., 2003).

Stabilization is done to make the water less aggressive or corrosive by adding some minerals (lime, caustic soda, sodium bicarbonate) or chemical additives. In some cases, blending the water with brackish feed water is a more attractive solution because it brings down costs. Excess CO2 or H2S are generally removed by dissolved gas stripping in a packed tower. Restricting H2S concentration is important because it may oxidize downstream to form colloidal sulfur (Peters and Cadena, 1988).

Disinfection is done to make product water free of viruses, pathogens, especially those introduced during the blending process. Some common ways include chlorine application, ozonation, use of UV, chlorine dioxide and monochloramine. Some disinfection by-products (DBPs) may form in the distribution system (Watson et al., 2003).

Table 4
Average disinfection costs ($\$/m^3$) (Tran et al., 2016).

Disinfection Method	Cost ($\$/m^3$)
UV	0.018
Cl_2	0.021
O_3	0.035

These DBPs (trihalomethanes, haloacetic acids) should be treated before release as they are regulated by US EPA's National Primary Drinking Water Standards (Office of Groundwater and Drinking Water, Environmental Protection Agency (EPA), 2009). Typical disinfection costs per m^3 of water are presented in Table 4:

3. Data driven treatment cost analysis for water

The two types of costs involved in the treatment of water are capital and operational costs. The section below discusses these costs in some detail, enlisting the major contributors for each technology type. Followed by this, we perform a rigorous data collection for costs in each category. The data is obtained from various sources, and we wanted an insight using data-driven approaches for the costs. Regression analysis for cost-capacity correlation identification is used on the collected data.

We start with data collected from various sources for technologies and the costs represent a wide variety of information. For any meaningful analysis, and for further use in a model, a correlation is sought between cost and capacity. For any given technology, the capital costs (CAPEX) and operating costs (OPEX) are nonlinear functions of the capacity. The degrees of nonlinearity and types of correlations are unique for each technology. To find appropriate correlation for each technology, we ensure that each has been represented by suitable correlation with high coefficient of determination (R^2 values).

The cost-capacity correlation of different technologies can be used to find the cost associated with a particular capacity for any given technology. Thus, we can compare between different methods and identify the most cost-efficient technology for processing a certain amount of water. Due to the nonlinear nature of the correlation, treatment capacities within a certain range are more cost effective and crossing the threshold may increase the cost in a nonlinear or exponential way. In such cases, it may be economical to use parallel processing units. The analysis is conducted on Matlab®.

4. Results

4.1. Capital costs

Capital expense (CAPEX) include land, equipment, installation, etc. up to the commissioning of the facility. Direct capital costs include the investment for desalination equipment, piping, valves, water intake structure, site preparation, concentrate discharge systems, auxiliary equipment such as water storage, emergency response systems, engineering etc. Indirect capital costs include freight and insurance (~5%), contractor's overhead (~15% of the dollar size of the project), legal, fiscal and administrative fees. Construction and equipment costs constitute the majority of the costs for both thermal and membrane desalination systems (Marseille CMI, 2016).

Empirical relations for relating cost to capacity have been developed by various researchers through nonlinear regression of plant data with reasonable R^2 values. In this work, we have used a power law to correlate processing capacity with capital cost. The relationship is as follows:

$$Capital\ Cost = m \times Capacity^c$$

Wittholz et al. (Wittholz et al., 2008) reviewed cost data for 331 desalination plants spanning the period from 1970 to 2005 for the major desalination techniques and used a logarithmic correlation. Zhou and Tol (2005) analyzed unit product cost data for 442 MSF and 2514 RO facilities and looked into impact caused by the quality of feed water, location, year, etc. McGivney and Kawamura (2008) details construction and capital investment curves for a variety of pre-treatment and advanced water treatment techniques. The cost data was adjusted to present values by using Chemical Engineering Plant Cost Index (CEPCI) values published by the Chemical Engineering Journal.

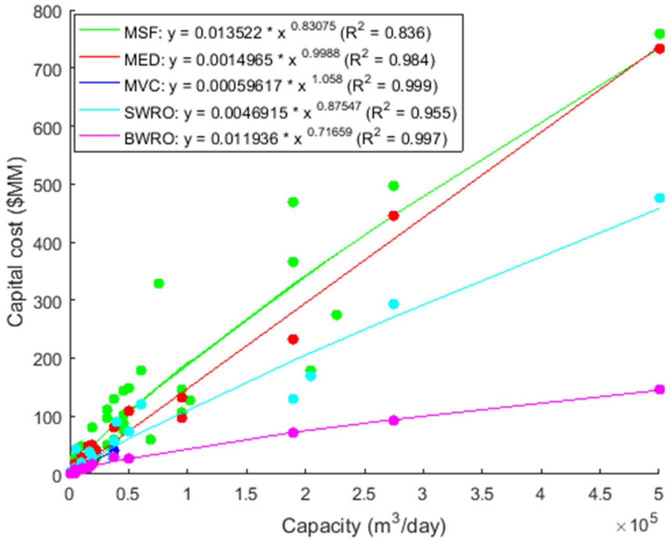

Fig. 4. Cost correlations of major desalination technology as a function of capacity.

Fig. 4 plots the correlations and shows the growing difference in capital cost requirements for membrane and thermal treatment systems as one increases the capacity.

4.1.1. Capital cost per unit product ($\$/m^3$)

Table 5 shows the capital cost per m^3 of unit product (treated water) for four capacities, ranging from 3785 m^3/d (1 mgd) to 189,250 m^3/d (50 mgd). For MSF and MED, only the unit cost at a performance ration of 12 has been shown. The performance ratio (PR) is defined as pounds of water produced per pound of steam (roughly equivalent to 1000 BTU). The higher the PR, lower the steam consumption.

4.2. Operating costs

Operational expenses (OPEX) (also known as operating costs) include labor, energy costs (thermal and electrical), chemicals, insurance, maintenance and spare parts (or membrane) replacement and some indirect costs. These costs are proportional to the quantity of water treated. Indirect costs also referred to as manufacturing overhead and may include repairs and maintenance, electricity for the production facility and equipment, salaries and wages for indirect manufacturing personnel. For thermal processes, energy represents the major cost component (66%) with labor (9%), indirect costs (10%), maintenance (7%) and chemicals (4%) representing the other major cost heads. For membrane processes, the energy demand is lower (41%) than the

Table 5
Capital cost contribution to the unit product cost ($\$/m^3$).

Technology	Capital cost ($\$/m^3$)			
	3785 m^3/d	18,925 m^3/d	37,850 m^3/d	189,250 m^3/d
MSF (PR = 12)	1.110	0.766	0.454	0.294
MED (PR = 12)	0.381	0.275	0.219	0.125
MVC	0.090	–	0.126	–
SWRO	0.305	0.220	0.175	0.100
BWRO	0.122	0.100	0.073	0.041

Table 6
Electrical energy required for the desalination processes.

Technology	Capacity (m^3/day)	Unit electrical energy (kWh/m^3)	Cost per m^3 (\$/m^3)	References
MSF	5000–500,000	3–4	0.18–0.24	3, 4, 58–66
MED	10,000–500,000	2–2.7	0.12–0.16	4, 59–62, 65–68
MVC	500–30,000	7–10	0.42–0.6	58–60
SWRO	250–500,000	4–6	0.24–0.36	4, 60–63, 68–73
BWRO	20–200,000	1.8–2.8	0.11–0.17	60–62, 65, 74

Table 7
Quality and cost contribution of thermal energy required for MSF and MED. [a, b] – 46, 47 [c] – 4, 47, 60–65; [d] – 58, 60, 62, 65, 67.

Technology	Zone of operation (T)	Cost of steam (Steam Systems Best Practices: Knowing the Cost of Steam, 2011) (\$/1000 lb)	Unit thermal energy (MJ/m^3)	Cost per m^3 (\$/m^3)	Remarks
MSF	190–235 °F [a]	3.16	190–290 [c]	0.58	Scaling issues at higher temperatures
MED	~160 °F [b]	3.07	120–257 [d]	0.56	Maximum temperatures can go up to 250–260 °F

Table 8
Chemicals used and cost contributions to OPEX (Reddy and Ghaffour, 2007; Wade, 2001; Watson et al., 2003; Matz and Fisher, 1981; Borsani and Rebagliati, 2005; Ettouney, 2004).

Technology	Chemicals used	Cost contribution (\$/m^3)	% contribution to total OPEX
All	Chlorine, lime, caustic (50%), sulfuric acid (93%)	–	–
MSF & MED	Anti-foam, ferric chloride, corrosion inhibitor, polyphosphates	0.024–0.06	2.2%–4%
MVC	Sodium bisulfate, polyphosphate	0.02	1.7%–2.8%
SWRO	Sodium bisulfate, scale inhibitor	0.065–0.08	8%–10.5%
BWRO	Sodium bisulfate, scale inhibitor	0.045–0.064	10.9%–17.6%

thermal processes with labor (13%), chemicals (11%), indirect costs (8%) and membrane replacement (5%) making up the majority of the operating costs (Marseille CMI, 2016).

As prior discussed, the major contributors of operating cost are energy, labor, chemicals, maintenance and membrane replacement costs (for membrane processes). In this section, the costs for each of these will be detailed.

4.2.1. Energy costs

Comparison of energy use within the different desalination systems is important since it represents a large proportion of the operating costs especially for thermal systems. MSF and MED use thermal energy to run the evaporators and to power the process pumps. RO uses electrical energy for driving the high-pressure feed and process pumps. The energy usage also depends on the performance ratio and whether the plant is a single-purpose or a dual-purpose one (Wade, 1993).

For a particular technology, the variation with capacity was weak and thus not been considered (Watson et al., 2003). The quality (pressure and temperature zone), aside from the amount of thermal energy for MSF and MED, is also important to know when designing desalination systems (refer to Tables 6 and 7).

4.2.1.1. Cost contribution of electrical energy. The cost for electrical energy has been taken as \$0.06/kWh (Watson et al., 2003; Wilf and Klinko, 2001; Ettouney et al., 2002) and is location specific. Several desalination plants combine power generation with water treatment and have greatly reduced energy requirements through the utilization of waste heat from the power plants and providing even cheaper electrical energy.

4.2.1.2. Cost contribution of thermal energy. MSF requires steam at a pressure of 25.7 psia and usually operates at around 190–235 °F. MED operates at a lower temperature, around 160 °F and requires steam at even lower pressures of 6 psia. Table 7 details the cost contributions of thermal energy to the final product cost. At a performance ratio of 12, the amount of steam required comes out to be 0.183 klb/m^3.

4.2.2. Labor costs

Labor costs are mostly site specific and also depend on whether the plant is publicly or privately owned (Ettouney et al., 2002). The staffing is usually employed for regular maintenance and operations and thus depends on the type of technology being used; membrane systems require less personnel usually (Watson et al., 2003).

4.2.3. Chemicals

Chemicals are used for cleaning, pre-treating and post-treating water in desalination plants. These include chlorine, sulfuric acid, caustic soda, antifoam agents and anti-scalants such as polyphosphates, acids, polymers, etc. Chemical usage is independent of the capacity as well as the performance ratio. The cost for these depends strongly on the proximity to manufacturing facilities and the global market (Dharmappa et al., 1995). Tables 8 and 9 detail the chemical costs and the contribution to the unit product cost for various technologies.

4.2.4. Maintenance and repairs

The per capita cost for maintenance and repairs decreases with increase in capacity of size of the plant but it increases with increase in PR in thermal systems. It is usually considered to be around 1–3% of the capital costs (Watson et al., 2003).

4.2.5. Membrane replacement costs

The scale and extent of treatment determines the quality of membranes being used and their replacement rate. It also depends on operation efficiency (Ettouney et al., 2002). They range from 5% for plants with low-salinity feeds to around 20% for plants with high-salinity

Table 9
Dosing rates and costs for the 4 main chemicals used (Ettouney et al., 2002; Chang, 2008).

Chemical	Dosing rate (g/m^3)	Unit cost	Cost contribution (\$/m^3)
Sulfuric acid	24.2	\$87–94/ton	0.00232–0.0025
Chlorine	4	\$190–325/ton	0.0008–0.0014
Caustic soda	14	\$495–822.5/ton	0.0076–0.0126
Anti-scalants	5	\$1723.6/ton	0.0095

feeds. For moderately sized plants, typical replacement cost is around 1.3 ¢/m^3 of permeate for brackish and around 3.1–5.3 ¢/m^3 of permeate for seawater desalination.

4.3. Unit product cost

The unit product cost is the sum of the capital cost depreciated over the plant life and operating cost per m^3 water treated. Depreciation is usually taken as 20 yrs without salvage value. The amount of water treated can be expressed in terms of the plant capacity and plant availability. Plant availability is defined as the number of days in a year that the plant operates – usually taken as 90–95% (Watson et al., 2003; Nafeya et al., 2006), depending on the demand and intake ratios. This is to allow room for unforeseen delays and maintenance. For a particular plant capacity and desalination technology selection, unit product cost can be calculated as:

$$\mathrm{UPC}(\$/\mathrm{m}^3) = \frac{\left(\frac{\text{Capital cost }(\$)}{\text{Plant life(yrs)}}\right) + (\text{Annual operating cost}(\$))}{\text{Plant capacity}(\mathrm{m}^3/\mathrm{d}) \times \text{Plant availability}(\mathrm{d/yr})}$$

Similar calculations were done for other desalination technologies at varying capacities (see Table 10 and Supporting information Table S11).

Assumptions:

1. Capital cost increases as the performance ratio increases. This is because an increased performance ratio comes as a result of adding more effects in the case of MED or stages in the case of MSF, leading to decisions which lead to an increase in capital investment. The increase in per capita capital cost from the base case of PR = 8 is taken as 10% for systems with PR = 10 and 25% for PR =12.
2. Accurate predictions of cost cannot be guaranteed because of the quality of data. For example, some capital cost data may include land and other intake and/or distribution costs whereas others may not. An order of magnitude difference was observed for some cases. The errors may range from ±20% to ±30%.
3. When a particular cost head ranges from one value to the other, the lower of the two values is attributed to the one with more capacity (economy of scale).
4. If the data for an operating cost section could not be found, an approximation was made from the percentage breakdown discussed earlier.

4.4. Other cost considerations

4.4.1. Water intake systems

Water intake systems define the quality, design capacity and pretreatment process for the desalination plant. The distance of intake to the plant also directly affects the economics of the process. Careful consideration should be given to the design of intake systems so as to protect the downstream equipment as well as the upstream marine environments (Pankratz, n.d.). Poorly designed intakes can entrain small organisms from the water body that pass-through filters and/or impinge aquatic life onto the bar filter screen (Bay Area Regional Desalination Project, 2007; Watereuse Association Desalination Committee, 2011b).

Table 10
Summary of all cost heads and the unit product cost ($/m^3).

Technology	Capacity in m^3/d (mgd)			
	3785 (1)	18,925 (5)	37,850 (10)	189,250 (50)
MSF (PR = 12)	2.746	1.925	1.582	1.339
MED (PR = 12)	2.146	1.455	1.336	1.128
MVC	1.333	0.926	0.867	–
SWRO	1.401	0.893	0.820	0.716
BWRO	0.712	0.447	0.380	0.297

4.4.1.1. Surface water intake. Surface water intakes take water from lakes, rivers and other surface streams via Open, Pipe or Ranney collector intake types. The **open intake** consists of feed water pumps with coarse bar screens, open concrete screen intake chambers and some auxiliary equipment such as traveling water screens, velocity caps or passive screens to remove debris (Watereuse Association Desalination Committee, 2011b). **Pipe type** intakes are similar to the open intake systems but differ in water conveyance structure (Pankratz, n.d.). These use a pipeline laid from point of intake to the intake structure. Open and pipe systems are easy to construct and require lesser operation and capital inputs. **Ranney collector** consists of a caisson constructed from reinforced concrete and installed into the water table. It is used to extract water from an aquifer that has direct connection to a surface water body. The amount of water extracted (>25 mgd) and no colloidal material in the feed make this an attractive option as well (Morin, 2010).

4.4.1.2. Sea water intake. Seawater intakes can be open ocean intakes (water is collected above seabed) or subsurface intakes (via beach wells, infiltration galleries, etc.). **Open ocean intakes** are similar to open intakes for surface water except that depending on the location of inlet structure, the intakes could be on-shore or off-shore and the pipelines could extend several hundred to thousands of meters into the ocean (Voutchkov, 2004). The water from open intakes usually requires more pre-treatment than subsurface waters. **Subsurface intakes** are naturally filtered typically through the ocean floor (Watereuse Association Desalination Committee, 2011b). Vertical beach wells, slant wells and infiltration galleries are examples of subsurface intake systems. Beach wells have proven economic for plants of capacity smaller than 4000 m^3/d whereas open ocean intakes prove economical at much higher capacities (Voutchkov, 2004).

4.4.1.3. Ground water intake. Ground water intake is usually through well-fields with a complex series of pumps and wells sunk into the ground water aquifer (Morin, 2010). Well-fields are designed so that there are no undue drawdown problems in the aquifer.

4.4.2. Transportation or distribution

Water conveyance can be done through tanker trucks, pipelines and aqueducts. Aqueducts are canals that are generally used to transport huge amounts of water and are more suited for slightly sloping or plain topographies. Tanker trucks are used to distribute water, usually locally, where pipelines and aqueducts are not convenient. Pipelines convey water either through gravity water or pumping. The diameter and material of pipes depends on the flow rate and the distance between source and destination (Organization of American States, n.d.). Pipelines are usually costlier than canal transport but it is preferred to avoid loss of water through percolation through soil (Plappally and Lienhard, 2012). Capital costs for pipeline supply systems include the cost of pipes (usually DCIP or Stainless steel), pump stations and establishment of distribution facilities (Lee et al., 2017). Maintenance operations include servicing pumps, inspecting for leaks, cracks and replacing electrical and moving components.

The cost for transport using pipelines is a function of the altitude (vertical transport) and distance (horizontal distance). Zhou and Tol (Zhou and Tol, 2005) estimate the cost for horizontal transport of 100 MCM water to be 6 cents per 100 km and that for vertical transport to be 5 cents per 100 m. For areas that are inland or are at a height or both, the cost of water transport may become dominant and can also exceed $1/m^3 such as in Mexico City, Mexico and Sana, Yemen (Zhou and Tol, 2005). Liu and Zheng (2002) estimate cost for canal transporting around 32 billion m^3/yr water for 1150 km and 65 m high at $0.10–0.16/m^3. Although, because of water percolation, only one-fifth water reaches the destination (Zhou and Tol, 2005). Capital costs for the construction of the project were estimated to be at $3.5 billion. Zhou and Tol also mention transportation costs through Kally's (1993) estimates for similar canal transport to be around $0.38/m^3.

4.5. Environmental considerations

4.5.1. Concentrate disposal

The by-product of desalination is a concentrated solution with a much higher TDS than the feed and other impurity concentrations and whose disposal affects the marine life and the environment. Salts and chemicals from pre-treatment and post-treatment steps used against bio-fouling, scaling, foaming, suspended solids and corrosion constitute the concentrate. With over 99% of the contaminants in the feed, the concentrate has 1.5–2 times the mineral content than the source water (Lattemann and Hopner, 2008).

The impact is decided by the concentrate's temperature, density and on the recovery ratio of the process. Higher the recovery ratio, more is the TDS in the concentrate and more is the damage done to marine environments (Mezher et al., 2011). Higher temperature reduces the dissolved oxygen levels (Al-Karaghouli and Kazmerski, 2013). The cone of initial dilution is the region near discharge where rapid and turbulent mixing tends to dilute discharge so that it ceases to rise or sink in the water column and spreads horizontally. When the density is high, the zone of initial dilution for a submerged buoyant discharge takes longer to get completed, impacting a much larger portion near the discharge port (Lattemann and Hopner, 2008). Around 48% of the desalination plants in the US use surface disposal method (Lattemann and Hopner, 2008).

A common practice is to dispose the concentrates to the front of the treatment plant. However, if the salinity or presence of chemical constituents is too high, it might cause the pre-treatment costs to increase and could also disrupt plant performance (Mickley, 2001). A potential application of the concentrate is in removal of greenhouse gases (GHGs) through the use of a combination of supported liquid membranes and ionic liquids (SLIMs) (Luis et al., 2009). The highly saline solution has high affinity towards SO_2, low volatility and high stability. Presence of NaOH (alkalinity) can further increase removal efficiency (Lee et al., 2006).

4.5.2. CO_2 footprint

The carbon footprint relies on the type of process as much as the energy efficiency and fuel used (Lienhard et al., 2016). Increased energy efficiency, using cleaner fuel and establishing minimum targets can help reduce CO_2 emissions (Office of Groundwater and Drinking Water, Environmental Protection Agency (EPA), 2009). Thermal processes generate more CO_2 per unit volume of water treated mainly because of the burning of fuel for thermal energy. Cornejo et al. (2014) studied >20 plants worldwide and compiled carbon emission data for them. Typical values for the carbon footprint are 5.5–25.0 kg CO_2/m^3 for MSF, 4.3–17.6 kg CO_2/m^3 for MED, and 0.4–4.0 kg CO_2/m^3 for SWRO (Global Clean Water Desalination Alliance, 2015; Lienhard et al., 2016; Cornejo et al., 2014; Liu et al., 2015).

5. Discussion

5.1. Process selection

The ultimate goal of this work is to determine a strategy for process synthesis and selection when certain targets related to water network is set. The major factors influencing selection of a particular process or treatment pathway are:

- **Feed water quality** (**salinity**, **hardness**, **pH**, **BOD**, **etc**.): Higher feed water salinities (>30,000 mg/l) are treated much more economically through distillation techniques. RO can be used for all ranges of salinity but higher TDS levels incur higher cost and membrane replacement rates. Feed with high turbidity, oil and grease content or suspended solids require a much more stringent pre-treatment. A high biological content, especially in the case of municipal wastewaters, may require a carefully designed activated sludge or membrane bioreactor setup (Watson et al., 2003).
  Feed temperature also plays an important role in the process selection decision. Thermal processes prefer lower feed temperature as the higher temperature difference between steam and feed water serves as a better driving force. On the other hand, RO processes prefer higher feed temperature as it increases the membrane flux.
- **Capacity** (**quantity**): Higher capacity generally brings the cost down for all processes via economy of scale. However, thermal processes become quite unfeasible at very low capacities (<5000 m^3/d). This is because the energy consumed per unit of water is lower at higher capacities.
- **Desired product quality**: Thermal processes bring the product salinity down to 0.5–25 mg/l whereas product from membrane processes generally ranges from 25 to 500 mg/l. As feed TDS increases, the recovery factor in RO systems (% of water recovered from feed as permeate) should be reduced for efficient membrane operation (Watson et al., 2003).
- **Energy availability**: Energy costs represent a huge chunk of the operational expenses for a desalination plant, especially for thermal processes. For single purpose plant arrangements, membrane processes and MVC are usually preferred over thermal processes. But for dual purpose plants where thermal energy can be provided in-house at cheaper rates than a single purpose plant, thermal processes are preferred. The added advantage in dual purpose plants is the lower CO2 emission due to lesser fuel consumption. Details on energy consumption can be referred from Tables 6 and 7.
- **Site location**: Proximity to certain chemicals used for pre-treatment or post-treatment can have an impact on the cost for the chemical and thus, on the treatment process itself. Thermal processes need to be located away from residential areas. However, RO systems can be integrated very easily in housing development areas (Watson et al., 2003). Thermal processes also require a larger land area for the setup than RO. Seawater RO requires more area than brackish desalination.
- **Environmental considerations**: Concentrates from RO have higher salinity and are much more ‘unstable’ than thermal processes. However, the concentrate from thermal process is 5–15 °C warmer than the ambient temperature. Areas that have strict environmental regulations regarding release of concentrates may have preference for one process over the other. Some polishing and blending may also be required prior to release.

5.2. Integration/coupling strategies

Several integration strategies can help in enhancing the process for the water network. Some of these strategies are summarized here.

5.2.1. Cogeneration

The heat required for desalination can either come from a boiler (single purpose) or from a power plant (dual purpose). Integrating power generation with desalination has several advantages. It has been reported that the steam for dual purpose plants comes at a much cheaper cost, has lower greenhouse gas emissions and results in lower product water costs (Morin, 1993; Watson et al., 2003; Mezher et al., 2011). The steam for desalination in a dual purpose plant can be taken from the power cycle steam turbine after electricity has been produced or it can be taken from back-pressure turbine exhaust. A heat recovery exchanger can also be used to generate new steam. It should be noted that the lower the pressure of steam required, the less will be the penalty for electricity generation (Morin, 1993). Dual purpose plants, however, face a practical issue of the power to water ratio not being constant and in times of high power requirements. An auxiliary boiler is required to provide steam in these circumstances which raises the specific energy consumption (Mezher et al., 2011). This issue can be effectively dealt with hybrid systems which are discussed in the next section.

5.2.2. Hybrid systems

Different thermal process technologies can be combined amongst themselves along with power generation systems to produce water at even lower costs and effectively utilize fuel energy and power generation to exploit the synergism resulting from water-energy nexus (Mukherjee et al., 2017; Bamufleh et al., 2017; Gabriel et al., 2016). A thermal technology is usually combined with a membrane process. They usually employ the same water intakes and discharges, pretreatment and post-treatment methods, thus saving on construction costs for individual processes. In times when power demands are low due to seasonal fluctuations, the idle electrical energy can be used to drive the RO system and the thermal energy from the heat recovery steam generator (HRSG) for MSF/MED system. Networks of multiple RO units along with energy recovery devices can be used (Khor et al., 2011; Zhu et al., 1997; El-Halwagi, 1992). Hybrid systems are very much effective in regions where the water and power demand fluctuates by varying the power-to-water ratio (Agashichev and El-Nashar, 2005). Another advantage is that the product water from both processes can be blended and a second pass through RO may not be required, improving the membrane life and reducing the unit product cost (Hamed, 2005). A third advantage is that the waste heat from MSF can preheat the feed for RO and that the concentrate from RO will be cooled down to acceptable temperatures so it can meet the discharge regulations (Ghaffour et al., 2013). The optimal ratio for outputs of RO and MSF/MED in hybrid plants has been reported to be around 1.5 to 3, with the peak ratio being about 2:1 (RO:MSF). The savings for a hybrid plant with the peak ratio and a capacity of 150,000 m^3/d would be around \$0.048/m^3 or \$2.4 million annually (Awerbuch, 2004).

A coupling scheme of a nuclear heating reactor plant with MED and VC resulted in water costs of about \$0.73/m^3 for a capacity of around 36,000 m^3/d and lower energy demands (Wu and Zhang, 2003). Hybrid NF-RO-MSF-crystallization systems offer significant improvement in performance, with water recovery factors as high as 77% and unit water costs as low as \$0.37/m^3 (Turek and Dydo, 2003). An optimization approach for integrating water desalination systems involving heat recovery aimed at reducing the desalination cost, energy consumption and overall greenhouse gas emissions has been presented by González-Bravo et al. (González-Bravo et al., 2017).

5.2.3. Use of renewable energy

Renewable energy forms (such as geothermal, wind, solar) can also be coupled to desalting technologies to do away with some of the fuel costs. Eltawil (Eltawil et al., 2009) details various combination strategies and estimated change in water costs for renewable energy system (RES)-desalination plants. Other studies such as those by Gude et al. (2010) and Al-Karaghouli and Kazmerski (2013) have also detailed costs for renewable energy powered desalination processes and described the energy source selection criteria. Reif and Alhalabi (2015) discuss the cost-effectiveness, energy efficiency, challenges faced and factors affecting the design and implementation of solar-thermal desalination systems.

5.3. Emerging technologies

Recent developments in membrane and thermal technologies have enhanced the performance as well as reduced costs. Advancements in membrane materials have taken down the electricity consumption from 26 kWh/m^3 in the 1980s to around 3–4 kWh/m^3 today (Chang et al., 2008). For thermal systems, changes in heat exchanger designs, heat reclamation techniques and combining thermal phase change with a membrane have also lowered energy requirements (Peñate and García-Rodríguez, 2012).

Several new technologies for treatment of wastewater and desalination have also been proposed, although not all of them will get commercialized and have widespread use. The emerging technologies can either be membrane-based, thermal-based or be an altogether alternative technology. In this section, we will briefly go through each of these categories.

5.3.1. Membrane-based technologies

Novel membranes such as nanocomposite, aquaporin or biometric, nanotube and graphene-based membranes have been introduced, although only nanocomposite membranes have been commercialized. Nanocomposite membranes have shown 20% lower specific energy requirements and have twice the amount of flux as compared to conventional RO membranes (NanoH2O, 2010). Other membrane processes such as semi-batch RO and forward osmosis (FO) have also been realized as practical alternatives to conventional RO systems. Forward Osmosis has an energy consumption of around 0.25–0.84 kWh/m^3 (Subramani et al., 2011). A combination of FO and RO has been found to increase flux and reduce specific energy consumptions (Choi et al., 2009) and also has lower fouling potential due to absence of transmembrane pressure (Subramani et al., 2011).

5.3.2. Thermal-based technologies

Development combining a membrane with thermal phase change include membrane distillation (MD) and pervaporation. Although MD has remained on a pilot scale and is yet to be commercially accepted, it has shown lower energy requirements (around 43 kWh/m^3 without waste heat integration), has an ability to reach 100% salt rejection and is very promising where excess waste heat is available. For purely thermal processes, humidification-dehumidification and adsorption desalination have been developed. Humidification-dehumidification has shown promise in remote applications where it can be combined with solar energy, although its specific energy consumption is high (Subramani and Jacangelo, 2015). Adsorption desalination is another technique that uses a highly porous silica gel and low energy waste heat or renewable energy source to power a sorption cycle. However, this technology is also in its developmental stage (Ng et al., 2013).

5.3.3. Other alternative technologies

Some other alternative technologies include ion concentration polarization, capacitive deionization, clathrate hydrates, microbial desalination cell. Although each of these technologies have their own drawbacks with regards to the implementation or operating robustness, all of them have one thing in common and that is their reduced energy consumption over conventional RO and thermal technologies. Microbial cell desalination which are based on transfer of ions from water in proportion to current generated by bacteria, in fact, requires no external electricity source but requires a carbon source (Subramani and Jacangelo, 2015).

6. Conclusions

This work has surveyed the main technologies for water treatment with special focus on desalination in the context of a macroscopic system that includes sources, interception units, and utilizing sinks. The overall treatment can be broken into four main parts: pre-treatment, primary and secondary, tertiary and post-treatment. Several options exist within each category and a concise description has been provided for each. Extensive review on the capital and operating costs showed the dependence of cost per m^3 of water produced on capacity and type of desalination technology. Capital cost versus size correlations were derived for the most common methods and a detailed breakdown of operating costs has been presented for a range of capacities. This review also went through environmental impacts of water treatment and a process selection guideline in brief. The selection of a certain treatment pathway depends on a variety of factors such as energy availability, site-specific constraints, feed water quality and quantity, desired product specifications, economics and environmental regulations.

The unit product cost was lowest for brackish water RO (\$0.3–0.7/m^3) followed by seawater RO (\$0.7–1.4/m^3) and then the thermal technologies mainly due to the lower energy consumption in RO and recent advances in membrane technology. There has been a shift towards RO in the past 10–15 years due to its multiple economic and environmental advantages over thermal methods. However, thermal techniques are still preferred in locations where excess waste heat or cheaper thermal energy can be derived such as in a cogeneration plant. Lastly, this study discussed some integration strategies in brief. Water-energy nexus was discussed as a promising option enhancing the overall efficiency of the system. Additionally, hybrid systems offer numerous advantages over conventional methods due to the increased flexibility and reduction in cost. Use of renewable energy for desalination provides attractive opportunities for the future, however, their use is limited as of now.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.363.

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