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Costs for water supply, treatment, end-use and reclamation

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ABSTRACT

The paper reviews the cost of different water supply and water treatment options around the world. The cost of supplying ground water is found to be proportional to the lift. The relationship between cost and volume of water treated by specific treatment options is assessed. Vehicular transportation of water is found to be very costly compared to wastewater treatment and compared to conventional water treatment and supply. Efforts have been made to differentiate the cost of water with respect to its application in various sectors. The capital cost of infrastructure required to extract, treat, supply, and reclaim water is also studied. Finally, the effects of precipitation, geographic aspects, population, financial, regulatory laws, and social attributes of a specific region are considered as they affect the cost of water. Global use of water in agriculture and the costs of agricultural irrigation are studied. Pressurized irrigation systems are costlier compared to flood or surface irrigation systems.

Keywords: Costs; Energy; Pumping; Treatment; Desalination; Reuse; Transport

1. Introduction

Water is a finite resource and necessary for life. It is ubiquitous, and it has a number of important physical characteristics that affect its use. In the form of water vapor, it is the third most abundant atmospheric gas, after nitrogen and oxygen, respectively [1]. Water has a very high latent heat of vaporization, which accounts for the enormous energy cost to distill it [2]. Water is considered as a universal solvent and therefore, dissolves and absorbs numerous materials with which it comes in contact [1]. This property accounts for the high cost to treat water.

The Water Atlas reports a volume of 1,386 million Gm^3 of water on Earth, which consist of 97.5% saline water and 2.5% fresh water [3]. Out of 35 million Gm^3 of fresh water on Earth, approximately 30.5% is available for human use. This amounts to 10.5 million Gm^3 water as ground water and 0.13 million Gm^3 in lakes, soil, wetlands, etc. [3]. Annually 0.5 million Gm^3 of seawater evaporates and about 120,000 Gm^3 of water precipitates on land. Evapotranspiration consumes about 70,000 Gm^3. The net precipitation over land results in ground water recharge and surface water run-off and a significantly smaller amount of ground water recharge (about 2,200 Gm^3). The water distribution on Earth is variable and location specific [4]. The increase in population, socioeconomic trends of urbanization, globalization, and industrialization affects the purity and quantity of the water in available water resources [1,5].

Water is characterized in many ways as a precious resource, "blue gold," "the oil of the twenty-first century," etc. [1]. Water has a vital role in any country's

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macroeconomic equation. The UN defines water stress when the local water availability falls below 1,700 m^3/person-year and is illustrated in Fig. 1 [6,7]. The annual domestic water withdrawals of 50 countries with gross domestic product (GDP) less than US$8,000 were below 24 m^3/person [8]. The USA, with a per capita GDP of US$45,800, withdrew almost 800 m^3/person annually [8].

Further, the water consumption in China is approximately 6,859 m^3/person-year [9]. The Hai River basin in China has a very low per capita water resource of less than 400m^3/person-year [9,10]. This number is below the severe Falkenmark water scarcity level of less than 500 m^3/person-year as shown in Fig. 1 [8]. Therefore, available Falkenmark indicator values (m^3/person-year) of all nations hide the details of scarcity at a local level. Water accounts for about 2.3% of GDP in China [11,12]; 56% of this cost is due to the scarcity of water and the rest is due to water pollution [11]. These estimates do not include the cost of ecological impacts due to the depletion of quantity or quality of water [11]. Africa alone lost 5% of its GDP due to lack of access to drinking water and sanitation [13]. Thus, the local demand for water at a location transforms the nature of water scarcity to a socioeconomic one.

Human activities when imported to certain geographic locations without the consideration of its natural ability to host such activities can lead to huge financial as well as resource expenditure [7]. The water scarcity issue has led countries to scavenge for water outside their boundaries. Water is being imported using vehicular transport, pipeline, waterways, and transboundary aquifer pumping as well as in the form of virtual water (water content in traded goods) [3].

The availability of fresh water for human use was mapped by the International Water Management Institute (IWMI) as shown in Fig. 2 [14]. From a climatic perspective, irregularities in spatial distribution of precipitation divide the globe into water scarce and abundant regions. The abundant water locations around the globe with less than 25% water withdrawals were grouped by IWMI as regions of little or no water scarcity. Water resource development exceeded sustainable limits in some parts of the world. If more than two-thirds of the available water was withdrawn in a location, this was accounted as physical water scarcity [14]. The locations with more than 60% withdrawals were labeled as approaching physical water scarcity [14].

Apart from physical and economic scarcity, politically constructed scarcity is also visible at many locations. Approximately 260 river systems flow across national boundaries around the world and other 13 river systems are shared by more than five nations [3,5]. Water therefore has been a cause of conflict and thus caused water availability imbalance at various locations. Approximately 61% of all water conflicts

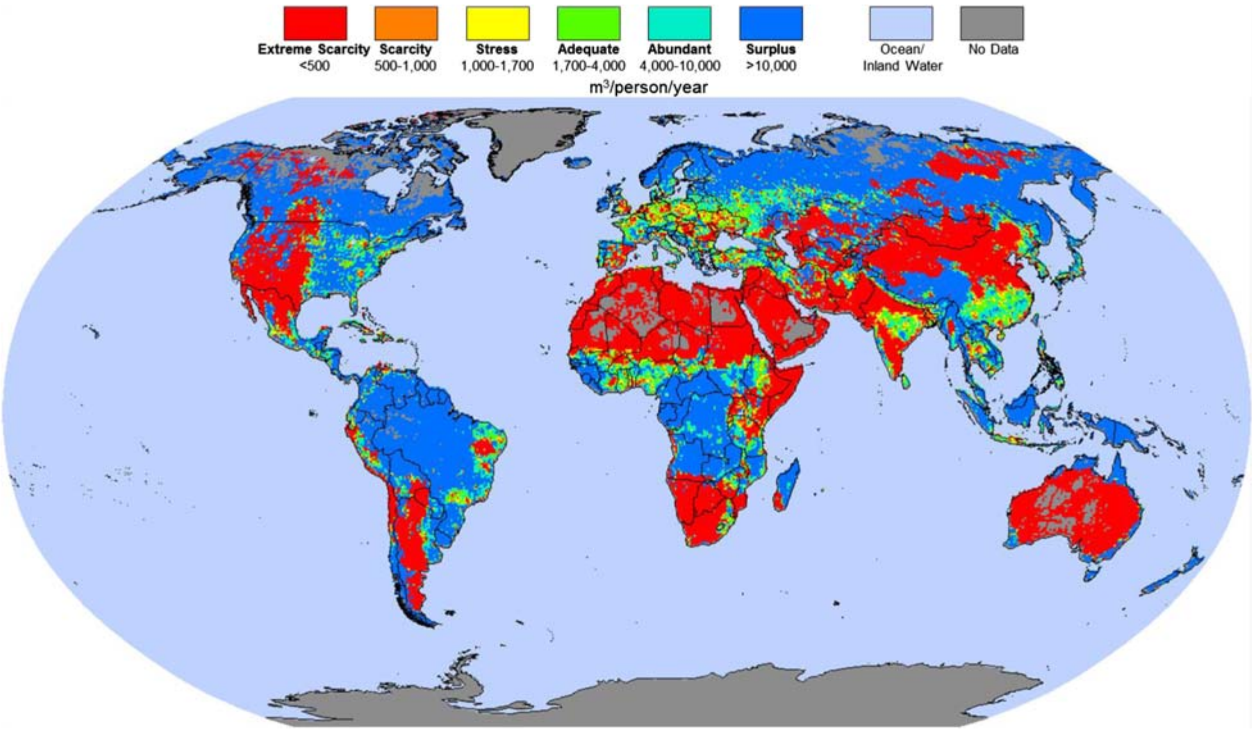


Fig. 1. Subnational level water scaricty picture of the world in 2005 [6].

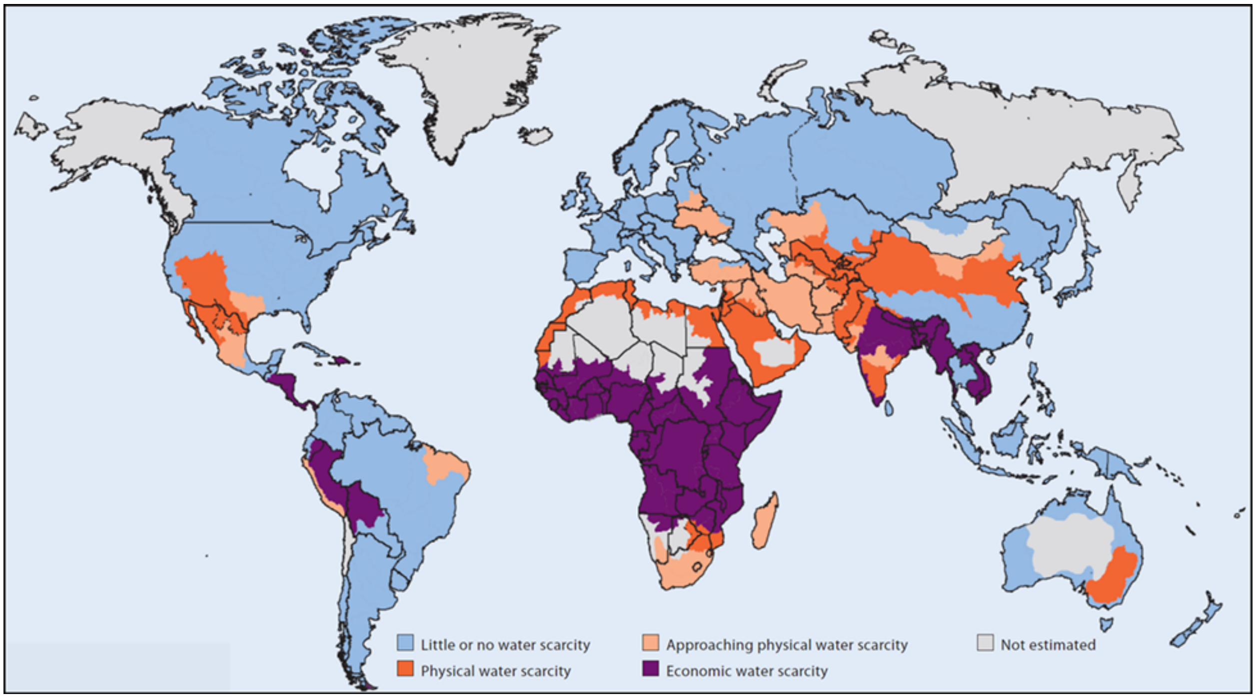


Fig. 2. Map of water availability [14]. Source: UNEP/GRID-Arendal (2008).

were over the quantity of water shared between nations, while the other major aspect influencing water conflicts has been infrastructure [3]. It was observed that water also cemented friendship between some nations. For example, the Mekong treaty brought together Thailand, Cambodia, Vietnam, and Laos [3].

In spite of having some of the highest levels of precipitation, the north-eastern part of India, Bangladesh, and Myanmar were grouped under economically water scarce locations of the world [8]. Similarly, Brazil with the highest surface water availability (Amazon basin has 16% of global run-off) suffers from economic scarcity with communities earning less than a dollar a day [7]. The lack of acceptable quality and sufficient quantity of water is a major factor in poverty, food insecurity, health, economic development, and geopolitical conflicts [1]. A study by the United Nations demonstrated that the water use per every dollar of gross domestic product in many developing nations has declined during the last couple of decades [15]. Some of these nations include India, Egypt, China, Morocco, and Cyprus. This decline is dominant in all developed nations across the globe due to their better water resource management and development. However, the water use to GDP ratio increased in Iraq, Iran, Saudi Arabia, and Libya [15]. This may be due to production of water through high energy and cost intensive processes such as desalination.

Annually more than 1.8 million diseases related to water consumption and malnutrition are reported from parts of East Africa, Central Africa as well as West Africa [8]. These locations are also categorized as economically water scarce locations with less than a quarter of available water withdrawn for human activities [14]. The economically poor have the lowest access to water and are mostly agrarian [15]. They are likely to be more vulnerable to varying climatic and socioeconomic conditions [15]. Infrastructural and financial stress at household and municipal levels of these regions impeded water resource development [8]. The World Health Organization (WHO) in 2002 reported that nine out of ten child deaths and 54.2 million disability adjusted life years were lost mainly due to shortage of potable water [16]. Thus, the link of water resources to water uses influences the socioeconomic characteristics of people. The various uses of that water drive development and urbanization create both positive and negative impacts. The negative impacts such as water pollution, water overdraft, and climatic change, etc. are the issues which should be alleviated by careful consideration and proper action.

1.1. Water pollution and treatment: Why and how?

Other than human activities, nature itself loads water with many minerals which must be removed if the water is to be suitable for human use. Geological and biological contaminants are major and diffuse sources of water contamination. Leaching of inorganics (arsenic, fluorine, etc.) and cyanotoxins (microcystins, geosmin, etc.), for example, cause health problems. Other diffuse sources include agriculture, spills, combustion, etc. [13]. A common material associated with mining of coal, iron, and copper is sulfide. Sulfide ions in contact with water will form sulfuric acid. It is estimated that approximately 20,000 km of river and 700 million square meters of lakes are polluted by acidic waters from these point sources [13]. Similarly, lead poisoning in Asian rivers is 20 times more than rivers in Organization for Economic Co-operation and Development (OECD) nations [3]. Some industrialized nations still use age-old lead pipes to supply water to residences. Further, arsenic leaching is a major issue in Bangladesh, Nepal, and some parts of India [17]. It was found that the unit cost of arsenic removal is very high compared to unit costs for water pumping as well as conventional treatment methods [17].

Wastewater in cities is polluted by point sources such as bioactive pharmaceuticals, endocrine disruptors, and persistent organic pollutants in industrial effluent [13]. Pharmaceuticals are changing the chemistry of animal bodies as well as introducing toxins into their water habitats [18]. For example, some fish in the River Seine in France experienced hormonal changes and have become feminine [18,19]. In water-scarce areas of China, the cost of pollution-induced water scarcity is in the range of 1–3% of local GDP [12]. Further the local government does not have adequate finances to run the treatment facilities, which indicates an imminent increase in cost and energy requirements for treatment [12]. More than half of the rivers in north China do not even meet the lowest national water standards due to pollution and therefore are unsuitable for agriculture [19]. Less than half of cities in China have water or wastewater treatment facilities [12]. The situation is not much better in neighboring India, where only 10% of wastewater generated from the municipal, industrial, and agricultural sectors is treated before being dumped into water bodies [20]. The 90% of sewage is directly dumped into more than 14 major freshwater rivers and other freshwater water bodies [20]. Due to the emergence of new contaminants with technological advancement, increasing levels of contamination, and changing treatment scenarios, the historical cost estimates of water treatment cannot be blindly updated to current day figures. This is a primary challenge in economic studies on water treatment.

Waterborne pathogens from feces-contaminated water are point sources responsible for the death of more than three million children annually [13,19]. The reduction in exposure of children to pathogen-infected water may provide them long healthy lives and improve their educational prospects [19]. Several subsidized piped water supply and microbial filtration schemes have been recently implemented in many economically developing nations under the auspices of the UN, World Bank, and other NGOs [16]. The economically poor in developing nations have a willingness to pay the significant cost for piped or point of use water provision [16,19] This determination to pay for drinking water is significantly driven by education, family size, children of small ages, women, financial status, and access to medical facilities [16,19].

A recent US survey on environmental problems revealed that 59% of Americans are concerned about pollution of potable water [21]. Other major concerns of the American public included pollution of freshwater sources and soil and water contamination by toxic substances [21]. This trend has seen a decrease with access to safe drinking water nearing 100% in the USA and other industrialized nations [19]. This has been possible with the setting of regulatory standards for providing water [19].

Depreciation in health, financial status, employment, etc. forces society to ponder options such as water policy formation, resource management, and international water agreements. These options again are influenced by economic, environment, technology, climate, cultural aspects, etc.

1.2. Regulations and cost

The value of water will become clearer by investigating the links between global population, its distribution, its health, local socioeconomic status, and water use. While investigating these parameters, one may confess that deriving the value of water can be ambiguous but instructive.

As early as 300 BC, water was regulated and a cost for its protection had been envisaged [22]. During that period, Kautilya's classic treatise on polity, "Arthashastra," put down regulations on the use and management of water [23]. Some of these regulations are revisited in the following lines: "Every ten households should have a well and water should be supplied to travelers for free" [22]; "Farmers irrigating their fields shall pay 20% of their produce as water rate" [22]; Referring to cleanliness, people responsible for water ponding on the streets shall be fined a quarter "pana" (unit of money in the Kingdom of Chandragupta who reigned from *c.* 321–*c.* 297); "Cities' administrative officials will hold daily inspection of water reservoirs" [22]; and "For wastewater regulations every household should be equipped by a water channel sufficiently sloped and long enough and there shall be free passage of water otherwise a fine of 12 'pana' will be imposed" [22].

In early days, water was free of cost and provided to people as a mark of hospitality [5,22]. Water was revered for its cleansing nature and its purifying capabilities (and it was provided a public health service) in all religions [5]. In the present world, with ever increasing population, the limited availability of water is slowly becoming a reality.

The 1850s marked the first era of water treatment, which saw control of pathogenic microbes by chlorination preceded by slow sand filtration to remove suspended particles being practiced in England [24]. In 1887, the first national study on water pollution was conducted by Ellen Swallow Richards of the Massachusetts Institute of Technology, Cambridge, USA [25]. Less than two decades later, the US Public Health Service set the first federal regulatory standards for the quality of drinking water in 1914 [26]. These standards applied only to drinking water systems in ships and trains and considered only contaminants capable of causing communicable diseases [26]. During the 1950s, the WHO worked toward establishing water regulations. In 1958, the WHO published the first International Standards for Drinking Water (ISDW). ISDW became a reference in developing drinking water standards for different countries. In 1962, the US Public Health Service standards regulated 28 water contaminants and were the most comprehensive federal drinking water standards in existence before the Safe Drinking Water Act [SDWA] of 1974. In the meanwhile, the Environmental Protection Agency [EPA] was established in 1970 [26]. ISDW standards were used until the WHO Guidelines for Drinking-Water Quality (GDWQ) was written in 1984 [27]. By 2004, more than 90 contaminants were regulated by the SDWA [28].

The WHO estimates that US$11.3 billion is to be spent to meet the UN Millennium Development Goal (MGD) of halving the population deprived of water and sanitation [29]. Providing water treatment would consume another US$2 billion. Additionally, the global water supply would cost in the range US$ 30–102 billion [29]. This is a cautious estimate of range by the UN since much of the cost will depend on technology and costs are location specific [29]. One of the major objectives of this article is, therefore, to discuss the influence of technology on the cost of water distribution and treatment.

The costs for providing clean water are staggeringly large. This expense has been due to growing demand, overdrafts in agriculture, and mismanagement of water [30]. A remedy for this problem is pricing water to reflect the costs of pumping, treating, distribution, and recycling. As such, an objective of this paper is to perform a cost-based life cycle analysis of pumping, treatment, distribution, and recycling of water.

1.3. Water industry: cost for somebody is revenue for others

Water is the third largest global industry (≈US $400 billion) after natural gas/oil exploration and electricity generation [1]. There are several private organizations as well as governments in the water business [1,4,5,18]. Some of the major drivers of the water industry are contained within trends of urbanization, industrialization, and globalization, and they include local socioeconomic development, population density, climatic change, water rights, cultural pricing of water as well as rural–urban differences [1,8,18].

Influence of fiscal constraints, desire to reduce cost, improvement in technical efficiency, political affiliation, strength of industry interests, and the specific ideology of governance are some of the major reasons for the privatization of water [31,32]. Water distribution is one of the two major processes that consumes and impacts local government expenditures [32]. The first-ever audit of India's water pollution was undertaken in 2011, which revealed negligence of regulations for water resources management, over exploitation of ground and surface water, lack of government funding, and degradation of water due to urbanization [20,33]. Recently, water supply services for Delhi, India, were proposed to be privatized by the government of India [34]. Privatization can reduce cost in large metropolitan and urban areas neglecting treatment efficiency [32]. Water distribution is characterized by high transportation cost of water and therefore less likely to be privatized [32,35]. Local governments will have difficulty in generating revenue from the privatization of water delivery services [32].

The financial ability of the water industry to comply with stringent regulations has created mounting public concern over water quality in industrialized nations [4]. All water quality issues are to only be addressed by water treatment methods. The water industry should have a working knowledge of all treatment techniques, latest trends, and alternatives in treatment technology, economics, sustainability issues, and regulation to provide water at a considerable cost.

The present challenge of the water industry is to predict location-specific economic shifts resulting from increased water prices and to find ways to minimize it. In a recent report, the World Bank insisted on providing incentives for the adoption of water saving technologies and behaviors [11]. It also contended that the price of water should reflect its local scarcity value [11]. The social impact of this price for water needs to be addressed by establishing socioeconomic measures at the local levels.

This paper will provide a global review of the cost of technologies for water production and management. It will also compare the cost of different technologies on the basis of size, quality requirements, and energy expense. The variation in price of water to the consumer with respect to location as well as means of production will also be studied. The cost of irrigation is also analyzed as a function of irrigation technique, area, system, and volume of water used. All the costs reported in this paper are in US dollars unless otherwise stated.

2. Water life cycle: cost assessment

Fig. 3 illustrates the water life cycle based on the structure laid out in a previous study by the authors [2]. The cost analysis will begin with cost for extraction of water from ground and surface sources. Extracted water will normally require treatment for the removal of dissolved solids and suspended microbial impurities. In some cases, advanced treatment is needed to remove organic compounds, dissolved ions, or absorbed gases. The treatment cost will vary with methodology, chemicals involved, quantity of water, and quality of influent water.

Treated water is used in different ways by various customers in the residential, commercial, industrial, and agricultural sectors. Heating water is a major component of energy and cost consumption in residential, commercial, and industrial sectors. For example, residential water heating consumed about 23% natural gas consumption in the US residential sector and almost 8% the residential electricity consumption. This accounts to about 12% of total US residential energy costs [36]. The cost of heating water will also vary with the type of fuel used. For example, fuel wood is the least expensive energy source and the most dominant household energy source in Nigeria [37].

Human activities on water at the end use stage in the water cycle will pollute the water [2]. Treatment of this polluted water becomes necessary before reuse or discharge to the environment. This treatment would require substantial amounts of energy and cost. Fig. 3 disaggregates each component in the cycle to illustrate some of the processes or components possible within each stage [2]. The economics of water will take into consideration the physical resource, which

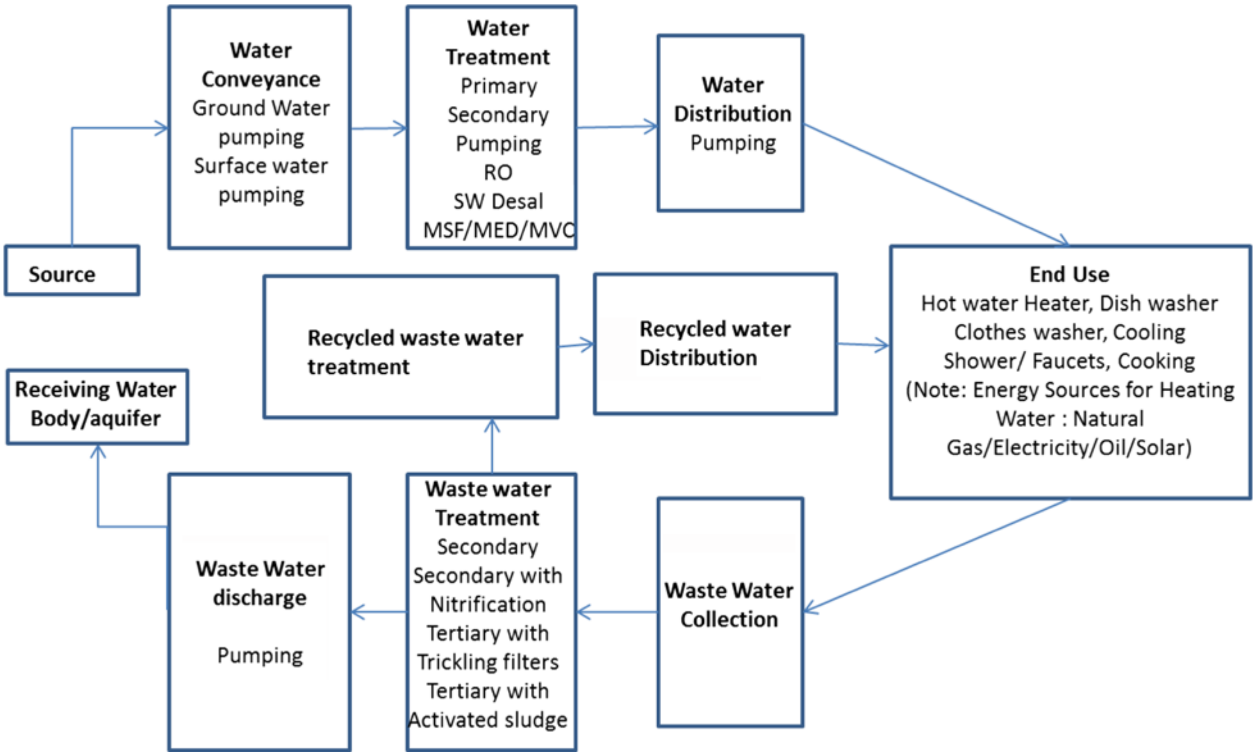


Fig. 3. Stages of the water life cycle through the municipal sector [2].

includes precipitation, rivers, lakes, and aquifers; the water users, which include farmers, households, power generation, and industry; the pumping and treatment infrastructure; and the water rights, regulations, and quotas [38]. Water allocation is performed based on its profitability by a private producer of water [39]. Considering the water life cycle, the cost of water depends upon volume of water, point of use, level of treatment, supply reliability, and energy costs [40]. The cost of water in this article refers to costs associated with conveyance, treatment, distribution, end use related activities, recycling, and discharge.

2.1. Ground water supply

Ground water is used to provide approximately half of the global drinking water supplies though it accounts for only 20% of the annual global water withdrawals [41,42]. Cost of ground water pumping is a function of pump efficiency, lift, and cost of the type of energy expended [43]. Globally ground water pumping costs are in the range $\$0.01/m^3$–$\$0.20/m^3$ [44]. Fig. 4 reports ground water pumping electricity costs of water in the USA [2,45]. The pump is assumed to be 100% efficient in this case. The average cost of electricity in the USA in 2011 is assumed to be $0.13/kWh for the calculation of data for Fig. 4 [46]. The horizontal axis of Fig. 4 denotes lift. The cost of ground water pumping will increase with the depth of the water level [44]. Global ground water depletion, therefore, will increase pumping costs [47].

The costs of pumping will increase as the efficiency of the pump decreases [43]. There is a regular deterioration with time in the efficiency of large water pumps. The deterioration in efficiency of split casing water pumps over a period of 40 years is shown in Fig. 5. The data enumerated in Fig. 5 are collected from 300 split case pumping units [48]. The overall efficiency of a pump is a product of its mechanical efficiency, efficiency of the motor, and efficiency of any variable frequency drives associated with the system [49]. This decrease in efficiency can be used to calculate operation or running costs over time [48]. The product of density, volume of the water, and the head against which the water is pumped gives the water power. The water power applied by the pump for a specific time at a specific overall efficiency of the pump provides the total energy consumed. Energy consumed can be multiplied with the price of energy to find the cost of pumping.

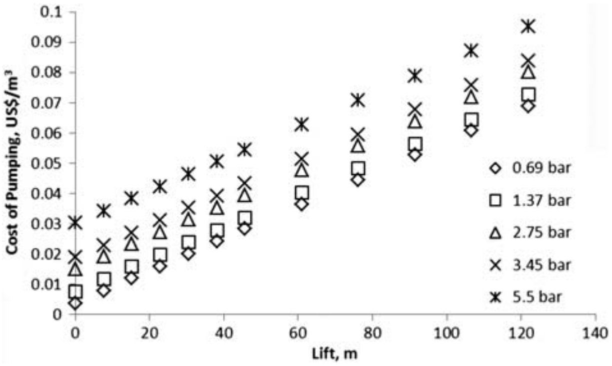


Fig. 4. Ground water pumping cost at different discharge pressures.

2.2. Surface water supply

Water produced from ground water aquifers as well as surface water bodies have been transported over long distance using various surface water supply options. Libya's great manmade pipeline project gets its water from the Nubian aquifer system and distributes annually 2 Gm^3 at a cost of $0.25 per cubic meter [50]. The ground and surface water extraction costs in Western countries and Australia are similar and are tabulated in Table 1 [51].

The capital and production cost of water supply using pipelines is linearly dependent on distance of

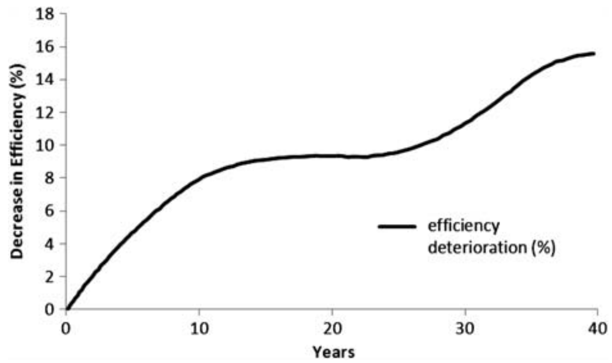


Fig. 5. Average rate of decrease in efficiency of the split casing pumps with age [48].

Table 1
Ground and surface waters extraction costs in Australia, Europe, and the USA [51]

Location	Process	Cost ($\$/m^3$)
Europe and USA	Ground/surface water production [no distribution cost]	0.40–0.75
Western Australia	Ground or Surface water production with distribution	0.45–0.61

transfer and its volumetric capacity [52]. Zhou and Tol (2005) derived multiparameter linear regression equations relating capital and production cost of water supply to distance of transfer and capacity of the transfer pipelines. Zhou and Tol (2005) also cautioned on the use of these equations for a rough or preliminary estimate of most likely ranges of capital and production costs. Fig. 6 illustrates that with increase in length of the pipe, the investment, production, as well as operation and maintenance costs increases.

The prices for water at a location are affected by different factors. Some of these aspects include quantity, distance of water transport, terrain, infrastructural costs of utilities and age, maintenance costs, economic status, and operation costs. Table 2 illustrates the variation of cost with change in quantity and distance through which water is supplied to Perth, Australia. With increase in volume of water transported there is a decrease in the cost of supply. Other similar studies in Australia reviewed in Table 3 also confirm this trend.

The cost of imported water supplied by the State Water Project, Colorado River Aqueduct in California ranges from a minimum of $0.12/m^3$ to a maximum of $0.46/m^3$ [40]. The other major example is the most expensive water transfer project in the USA: the Central Arizona Project. It has a 539 km long aqueduct with a capacity of 18.5x10^6 m^3 between Lake Havasu and Central and Southern Arizona. The cost of water supply was ascertained to be $0.052/m^3$ [54]. The cost of pumping equal amounts of groundwater is much lower than the cost of water transport through the 539 km long aqueduct [54].

Supplying 10^8 m^3 water using a 100 km long pipeline would cost approximately $0.05–0.06/m^3$, which is illustrated in Fig. 4, equates to the cost of lifting water through 100 m [55]. A fivefold increase in the quantity of water transported through a 100 km distance would cost $0.02/m^3$ [55]. Table 3 summarizes the variation of capital investment and water delivery charges in Australia with change in flow rate. The increase in capital cost due to size of the pipes can be recovered in the long term with low operating or delivery costs. These systems have much lower capacity than the California projects previously mentioned.

The variation of pumping uphill and flow due to gravity are other aspects that can influence the variation in the cost of water. An example for the cost analysis of these two aspects was derived from the water conveyance program in Jamaica and is illustrated in Table 4 [56]. Energy is expended to lift water, while water flow due to gravity is a way to recover energy [2]. The cost of pumps and connected infrastructure may be the major factor influencing cost for pumped water transfer systems. There is also significant influence of the mode of transport on the cost of water

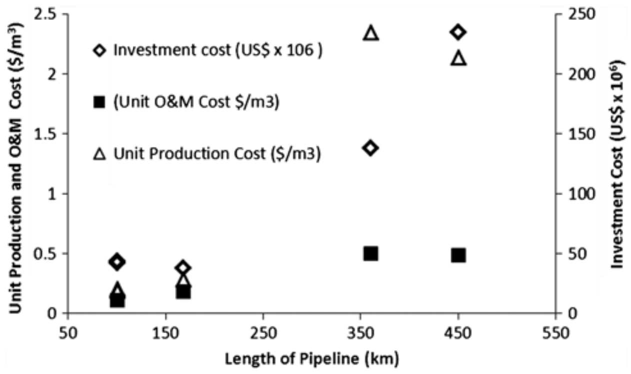


Fig. 6. Cost of long-distance piping projects in Egypt carrying treated Nile water [52].

Table 2
Unit cost and amount of water supplied to Perth in Australia [53]

Length, km	Volume (10^8 m^3)	Unit Cost (US$/m^3)
1,960	3	5.77
1,960	4	4.92
1,840	3	5.35
1,840	4	4.53
2,100	3	6.02
2,100	4	5.12

Table 3
Variation of capital and delivery cost as a function of change in flow rate [53]

Flow rate (m^3/d)	Capital Cost (10^6 $)	Delivery cost ($/m^3)
4,540	75–107	6.47–9.41
22,700	236–289	4.02–7.74
45,400	375–492	3.53–5.88

Table 4
Capital cost estimates for pumped and gravity flow water conveyance system [56]

Flow characteristic	Capacity (m^3/d)	Distance (km)	Diameter of pipeline (m)	Capital cost ($ × 10^6)
Pumped	45,400	6.5	0.76	30
Gravity	104,000	30.6	0.96	15

supplied. Piping or tunneling water is costlier than canal-based water transfer [55]. Pipelines are preferred over canal-based water transport to reduce water lost due to water percolation through the soil and seepage [52].

Other than Libya's great man-made pipeline project, this section also assesses “Medusa® Bags” large plastic bags of capacity 1.75×10^6 m^3 for transporting European water to Libya through sea. The projected cost of this supply technology was approximately \$0.17/m^3 in 2004 [50]. Similarly, water bags [cucumber bags] of capacity 10,000 m^3 were also used in 1998 to supply spring water from Alanis Turkey to Guzelyurt in Turkish controlled Cyprus through the Mediterranean Sea. It was projected that if the capacity of the bags was increased to 20,000 m^3 then the cost of water was estimated to be US \$0.5/m^3. The other major project in Turkey is an underwater (78 km) pipeline water transport from Dragon River to Guzelyurt, Cyprus which is able to provide 75×10^6 m^3 of water at a cost range of \$0.25–0.34/m^3 [57]. Shipping water by sea to Israel from Turkey was estimated to cost \$0.70–0.80/m^3 and price of the water shipped was to be sold at \$0.13–0.18/m^3. This would mean that cost of water would be around a \$1.00/m^3 in Israel [58].

The Australian Government recently discussed the use of water bags to transport 2×10^8 m^3 annually to meet its water supply needs among other water supply options [59]. Another mode of bulk transport of water is performed by using 300,000 ton tanker over a distance of 2,500 km from Kimberly to Perth in Australia. The cost of this mode of transport in 2002 was \$5.30/m^3 of water [53]. This was lower than Kimberly pipeline project cost of \$6.10/m^3 of water. The Kimberly aqueduct pumped water through 175 km from an elevation of 75 m at Lake Argyle to an elevation of 425 m using three water pumps. The discounted selling price of this water to consumers was in the range \$2.48–\$2.99/m^3 [53]. The comparison of cost and energy for these water supply options was performed by Australia and is shown in Fig. 7 below. The unit cost of water supplied using canal, tanker, water bag, and pipeline was found to be costlier than desalination [59].

Similar studies on different water supply options for Asia were performed recently. It has been proposed to convey 28×10^6 m^3 of water from Sistan River in Iran to Zahidan city, Iran through 200 km long channels with a pumping head of 1,800 m which is estimated to cost \$0.58/m^3 [60].

The 10th Chinese five-year plan (2001–2005) proposed an initiation of the South-North Water Transfer Project to reduce water scarcity and improve water quality in North China Plain [61]. Three major routes of water transfer were proposed. They were the central route, the eastern route and the western route. The central route is proposed to transfer 13 billion m^3 of water across the Huanghe [9]. It serves domestic and industrial water uses in Beijing, Tianjin, and some cities in Hebei, Henan, and Hubei provinces [61]. The central route has a capital investment of 10 billion US dollars and runs 1,242 km [62]. Gravity helps water flow through the central route and the canal is also appended with a 142 km branch to Tianjin on the east [62,63]. The eastern route takes water from the lower reach of the Yangtze River to the north along the Beijing–Hangzhou Grand Canal [64]. The water is pumped through 1,156 km [62]. The eastern route has a 740 km branch to north of Huanghe [62]. The water from the Yangtze River will be lifted 65 m high to the Yellow River from there water will flow to the north by gravity across the Hai basin to Tianjin [63]. This route is projected to transfer 14.8 Gm^3/year [65]. From this, 4.5 Gm^3 of water will be transferred to the north of Huanghe [65]. The capital investment for the eastern route is around 8–10 billion US dollars [62].

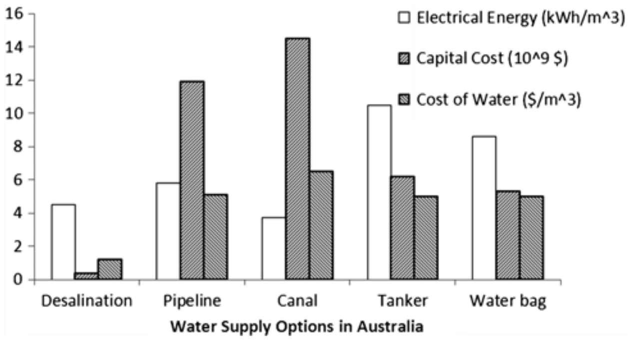


Fig. 7. A comparative cost analysis of various water supply options in Australia [59].

In summary, the transfer of approximately 32 billion cubic meters of water from Yangtze River to water scare north China will cost \$0.1–0.16/m^3. This canal transfer has a length of 1,150 km supplying water at a head of 65 m [66]. Chennai, India, is a location with an anthropogenic water scarcity, which derives from interstate water sharing conflicts, intra-societal problems, socioeconomic problems, and the fact that more than a third of its population are living in the slums [7]. The cost analysis of the various water supply options in Chennai are shown in Fig. 8.

Thirty-nine percent of total annual water supply of 304 million cubic meters for Chennai is provided by ground water resources such as domestic bore wells and coastal aquifers [7]. The present annual water demand is assumed to be about 530 million cubic

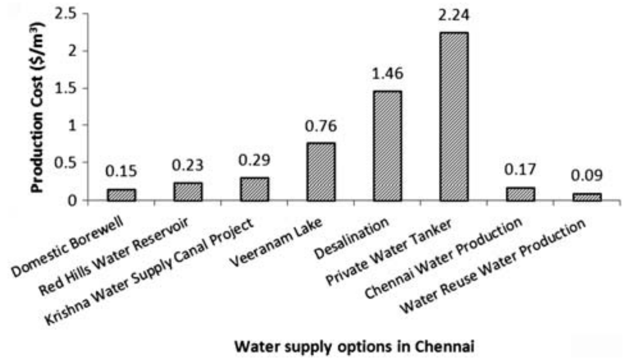


Fig. 8. Cost analysis of water supply options in Chennai, India [7].

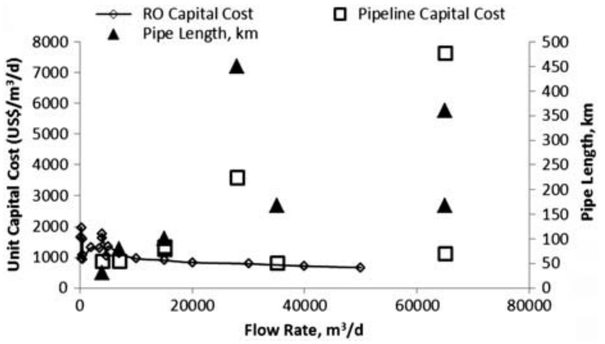


Fig. 9. Capital cost of reverse osmosis [RO] and pipelines systems in Asia as a function of flow rate [67].

meters [7]. It is observed that water management has also recently been given importance in south India due to looming water scarcity. The water harvesting and wastewater reuse potential is high due to relatively high precipitation [7]. Chennai's water harvesting reservoirs, such as the Redhills reservoir, provide about 200,000 m^3/d [7]. The Krishna water supply project supplies 130,000 m^3/d water to Chennai from the Kandaleru dam 175 kms away. Desalination of seawater has also been recently introduced as a part of the solution to this water scarcity problem [7].

The capital cost of RO is found to be very low as compared to pipeline water conveyance systems [67]. With distance, there is an equivalent increase in the cost incurred for conveying water. From Fig. 9, the capital cost of small desalination plants (less than 30,000 m^3) in Asia is found to be lower than the capital cost of pipeline transport of water to a distance of 100 km.

2.3. *Centralized conventional water treatment*

The basic centralized conventional water treatment systems consists of coagulation with rapid mixing followed by flocculation [using alum], settling, and filtration with disinfection by chlorine [24]. Fig. 10 lists all the processes in conventional centralized water treatment systems. Percent cost of unit operations in 37,800 m^3 and 387,000 m^3 treatment plants is shown in Fig. 10. It compares the difference in the expenditures of unit operation with change in treatment capacity. The larger plant had gravity sludge thickeners and filter press as opposed to sand drying beds used in plant with capacity 37,800 m^3/d. The use of chlorination decreases with an increase in size, but flocculants and coagulants are required in larger quantities [24]. This would increase expenses incurred on chemicals used in water treatment. About 17% of the cost shown in Fig. 10 for the 378,000 m^3/d treatment facility is for chemical use.

Increased size also requires more flocculating devices and clarifiers thus incurring additional capital cost [24]. The use of granular media gravity filters, which remove nonsettling flocs after coagulation and sedimentation, is the most important and expensive procedure. Cost of gravity filtration does not vary with the size of the treatment plant. It helps to remove all major impurities above the size range of 2–4 μm [68].

When the influent water quality is exceptionally good, several processes such as coagulation, sedimentation, etc. can be neglected. For example, sedimentation processes are neglected in direct filtration treatment [24]. This will reduce the cost (see Fig. 12). Inversely, the quality of the influent water determines the cost of chemical usage in a water treatment system. Thus, influent water quality is a major reason of variation in treatment costs. This is also supported by the results of Dearmont et al. [69] which state that approximately every 1% increase in turbidity increases the chemical cost by 0.27%.

The total process cost is approximately 55% of the total project cost for a treatment utility of 378,000 m^3 discussed in Fig. 10. In 2008, the total project cost for a centralized conventional treatment plant of this size in the USA is approximately US$136 million. The total project cost (35%) is assumed to arise from the engineering, legal, and administrative services. Conventional treatment plants in the USA spend almost 20% of the total project cost on electricity and control systems for the different processes [24]. While studying the project costs, it should be kept in mind that no two plants are alike and that construction is very site specific. Therefore, the costs involved should be studied independently [70,71]. The present day production cost of water is illustrated as a function of varying size of the conventional treatment plant in Fig. 11. These costs are comparable to the cost of water of

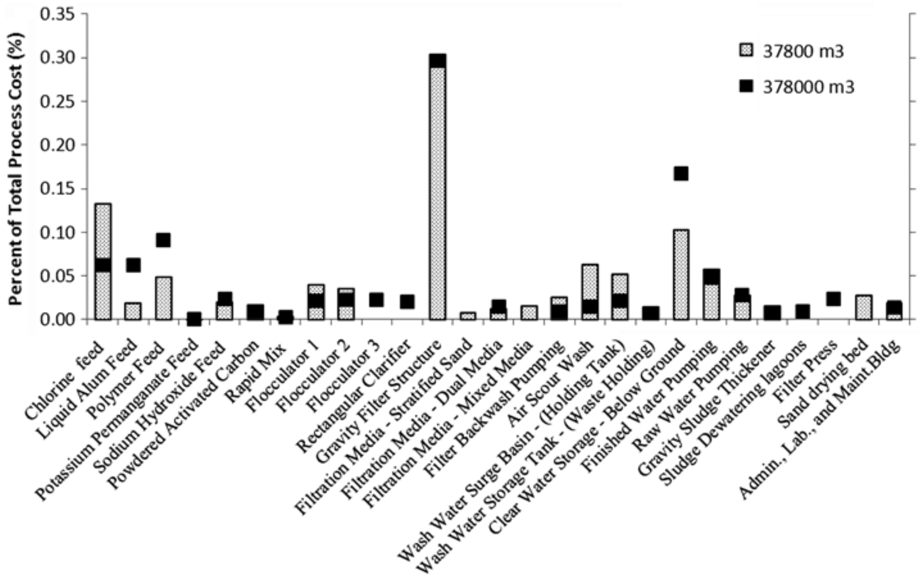


Fig. 10. Percent contribution of each unit operation toward the total process cost for a conventional water treatment plant [24].

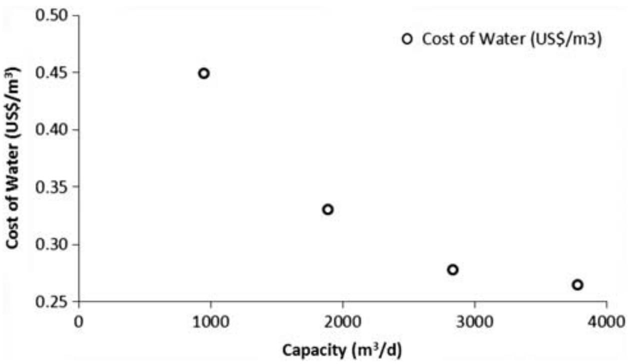


Fig. 11. Conventional treatment water production cost [70].

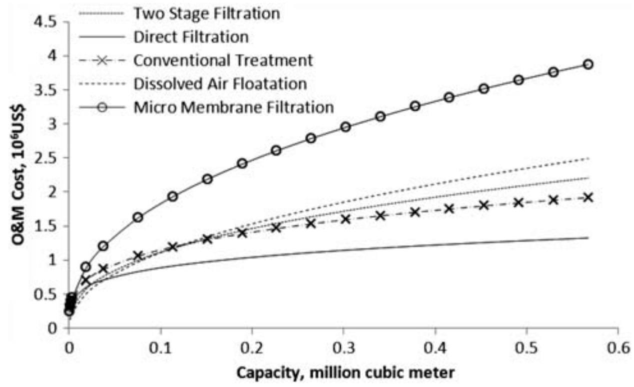


Fig. 12. Operation and maintenance cost (in 2008 US dollars) of water treatment systems [24].

$0.25/m^3$ [in 1995 US dollars] after conventional water treatment [72].

The US EPA promulgated safe drinking water standards in order to provide water not only safe, but also of high quality. These standards include removal of microbes and other impurities, which regular conventional treatment cannot achieve. To achieve maximum removal of inorganic and organic chemicals, microbes, radionuclides, turbidity, and other impurities, advanced treatment measures are required. Some of these are dissolved air flotation process, UV disinfection process, and advanced membrane filtration process such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and various RO processes. The application of the membranes for water treatment is based on the size of their pores [68].

With the need of specific advancement in technology, the process costs also may increase. Fig. 12 illustrates the variation of operation and management (O&M) costs for different conventional and advanced water treatment options. The operating costs are dependent to a great degree on the energy requirement and chemical dosage. These costs are directly related to the quality of the raw water set by regulatory agencies, which are dictated by the plant hydraulic profile [24]. For example, energy costs in a conventional water treatment utility are 30–40% of the total operation costs, and it follows labor costs which consume approximately 35–45% [73]. The electricity costs (85%) are used for water pumping and the rest is for treatment [2,73]. This would mean that 15% of the total operating cost of conventional treatment is for procuring chemicals used in water treatment [73].

Further, O&M costs include fixed costs as well as variable costs. The fixed costs include labor and administrative costs. Variable costs include cost of chemicals, power, repair and replacement costs, and other support services to operate the process plant. In Fig. 12, direct filtration refers to conventional treatment of water without the use of sedimentation components. This is basically used with high quality of water without suspended solids [24]. The new cost that can again influence operating and capital cost of water treatment plants is climatic change. Other miscellaneous factors that significantly affect O&M costs include the policies of the owner and climate and the technology update costs [24]. A recent study revealed that implementation of water levies on production will generate revenue relative to the capital and operating costs incurred due to plant adaptation to climate [74].

3. Advanced treatment: membranes

Some of the selective passage pore size-based water purification processes are MF, electrodialysis (ED), UF, NF, and reverse osmosis (RO). The MF and UF are physical straining procedures used to remove suspended and particulate impurities.

Membranes with a pore size range of 0.7–7 μm are categorized as MF membranes [68]. A process cost analysis of a cross flow membrane filtration process is depicted in Fig. 13. From Fig. 13, it is found that the micro membrane unit is the costliest. The membrane contributes to 76% of the total process cost of a 37,800 m^3 micro membrane treatment plant [24]. With 10 times increase in plant size, the contribution of membrane unit increases by 8.5% toward the total process cost of the larger plant [24]. With increase in size the total process cost also would increase by approximately 15%. The calculated process and project cost of a 37,800 m^3 plant is approximately $ 26.3 million and $ 480.6 million. The project cost includes 74% construction cost and the rest is engineering, legal, and administrative costs [24]. The cost of MF-based water treatment is cheaper than conventional water treatment and is illustrated from the discussions above [24,75].

MF is operated at a feed pressure range of 0.3–2 bar pressure and is used to treat influent waters with moderate turbidity to produce drinking water [68,76]. MF is used as pretreatment for other advanced treatment processes. For example, MF is combined with sedimentation to purify water from the River Seine for drinking purposes and MF also removes colloids and suspended particles, which can cause fouling in RO membranes. Therefore, MF is a preferred pretreatment for seawater RO [75,77].

The UF is also used to treat mostly surface waters to produce potable water and is a process in the pore size range of 0.008–0.8 μm occurring in the pressure range of 0.5–4 bar [68,76]. Compared to MF, the UF removes smaller impurities from water, such as viruses and macromolecules. But still the permeate will have low-molecular-weight organic solutes and salts. The approximate ranges of percent contribution of capital cost, membrane replacement, energy, and labor toward the operation cost of an UF plant is 35–50%, 25–32%, 15–20%, and 10–18%, respectively [78]. Considering these contributions, a range of \$0.1–0.2/m^3 (in 1994 dollars) was quoted as operating costs for a unit of water produced [79].

The capital cost and operating cost analysis for UF plants of different capacities was performed recently by the Water Research Foundation in 2010 [80]. This analysis is depicted in Fig. 14. The maximum capital cost and annual O&M cost for the 37.8 m^3/d UF plant is about \$4,761.9/m^3 and \$1.12/m^3, respectively. An

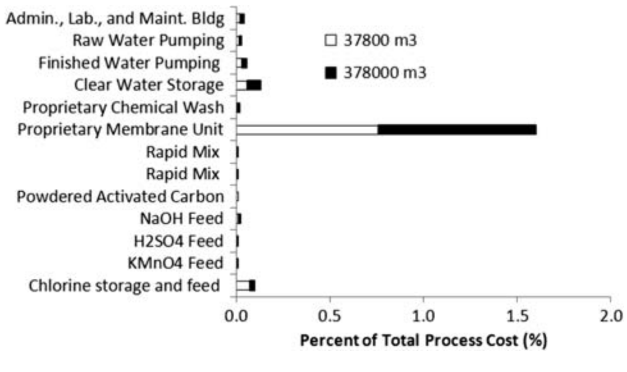


Fig. 13. Process cost analysis for a micro membrane treatment plant [24].

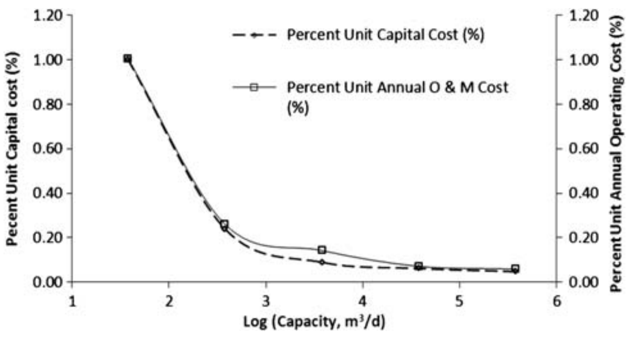


Fig. 14. Approximate cost of UF plant as a function of treatment capacity [80].

increase of UF plant size to 378 m^3/d results in more than 75% decrease in both capital and O&M costs, respectively. Fig. 14 also depicts a further decrease in plant expenses with increasing plant size but at a very slow rate. Similar to MF, UF is also used as a preferred pretreatment option for RO plants. The UF pretreatment also increases RO permeate flux by about 22% than compared to conventional water treatment [81]. The total cost of the RO desalination plant using UF pretreatment will be 2–7% lower than those using conventional water treatment [81,82].

The 45% of the membrane market in the USA and 30% and 25% of the membrane markets in Europe/Middle East and Asia/South America, respectively, are covered by MF and UF products [83]. The MF and UF products accounted for about one-third of the global membrane market in 2004 [83].

The ability to selectively reject dissolved ions and to reject low molecular weight compounds puts NF between RO (high rejection) and UF [passes all dissolved compounds]. Thus, NF can help to partially soften drinking water [76]. NF is a membrane process that occurs within the pore size range of 0.00–0.008 μm and pressure range of 5.5–8.3 bars [68]. It has a recovery rate in the range of 85–92% [76]. Cost of membrane systems is definitely varied and depends on energy consumption, capacity, influent and product water quality, design criteria, climate condition, infrastructure, etc.

The NF costs basically include capital and operational costs to produce water of a specific quality. The energy consumption, membrane, maintenance, chemical usage, and disposal of waste constitute the major costs for NF. In 1995, NF plants in Florida were found to expend an average of about 30% of its O&M cost on energy, another 30% on labor, 15% on chemicals, 10% on membrane replacement, and the rest on repair and maintenance [72]. The O&M costs of 3,780 m^3/d plants were in the range of $\$0.42–0.53/m^3$ and for 56,700 m^3/d plants the range was $\$0.11–0.14/m^3$ [72].

Membrane cost is expressed as a power law function of membrane area [78]. Pumping cost can also be expressed as a power law function of a variable representing the product of pump flow rate and pressure head [79,84]. An operating cost of $0.26/m^3$ for a 100,000 m^3/d NF plant with a power requirement of 0.54 kWh/m^3 was recorded for surface water treatment of the Tagus River originating in Spain and flowing through Portugal to the Atlantic Ocean [84]. Groenflo et al. [85] predicted the operation costs of 20,000 m^3/d NF treatment for ground water with high hardness ($Ca^{2+} \approx 115$ mg/L and $Mg^{2+} \approx 12$ mg/L) and a dissolved organic carbon content of 2.9 mg/L. As illustrated in Fig. 15, deduction of capital expenses or amortization is the most expensive parameter influencing NF operation costs [85]. Energy cost, concentrate disposal, and membrane replacement cost followed the trend as shown in Fig. 15 and contributed 22, 16, and 10% toward the total operating cost of $\$0.28/m^3$ (1 € = US \$1.23) [85]. Further, the cost of chemicals was about 2% of the NF plant's operating cost. From the above discussions, energy, brine disposal, and membrane replacement are found to be the major aspects influencing NF plant treatment costs irrespective of size.

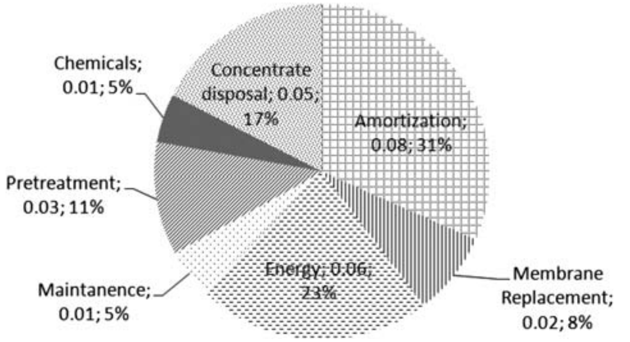


Fig. 15. Operating costs (in $\$/m^3$) and percentage contributions (%) of different parameters toward NF water treatment costs [84].

RO is the pressurized passage of water across a membrane working against the osmotic pressure and rejecting the dissolved constituents present in water. These nonporous permeable membranes typically operate at pressure ranges of 35–100 bars. RO membranes contain no pores and water passage through them is based on influent water dissolution on their surfaces followed by diffusion through them to the other side [75].

Water costs for RO systems are dictated by water quality, energy consumption to overcome osmotic pressure, plant size, and energy source as well as use of membranes [88,89]. From Table 5, the increase of RO costs with increase in total dissolved salts in the feed waters is confirmed. The Metropolitan Water District (MWD) and Inland Empire plants in California are brackish water plants, while Ashkelon, Israel, and Tampa Bay, Florida are seawater RO plants. Electricity cost contributes about 23–44% of the total operating costs of a RO plant [89,90]. Fig. 16 shows a general percentage split of cost of an RO plant [91]. The general cost range of membranes is about 5–14% of the RO operation cost. From the above discussions on the membrane cost for MF, UF, NF, and RO plants, the common aspect is that their contributions to the corresponding plant operation cost was almost equal. Recently, the American Water Works Association

Table 5
Capital and operating costs of different brackish and seawater RO plants [86,87]

Parameters	MWD Plant, CA	Ashkelon Plant, Israel	Inland Empire	Tampa Bay
TDS (mg/L)	500	40,700	800–1,000	26,000
Permeate (m^3/d)	700,300	330,000	27,000	95,000
Capital cost (\$/m^3)	0.057	0.311	0.29	0.37
Operation cost (\$/m^3)	0.139	0.214	0.33	0.47

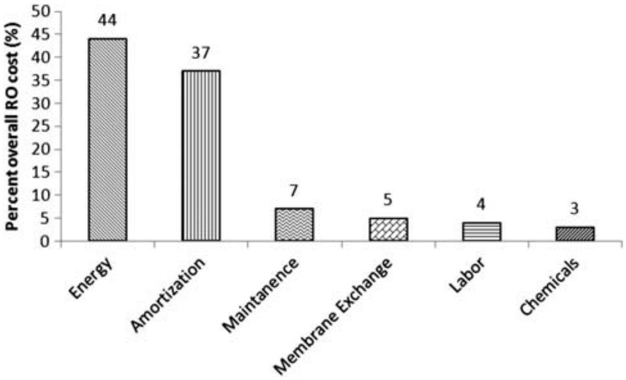


Fig. 16. Approximate percent contribution of basic common parameters toward the RO project costs [91].

Table 6
RO costs for ground, surface, and seawater treatment [94]

	Ground water	Surface water	Mediterranean Seawater
Salinity	1,000 ppm	–	38,000–40,500 mg/L
Turbidity (NTU)		15	
Size (m^3/d)	100,000	100,000	5,000
Operating costs			
Energy cost (%)	38	48	77
Chemicals cost (%)	35	35	11
Filter cost (%)	5	2	2
Membrane costs (%)	22	15	10
Production costs			
Operating cost (%)	57	54	61
Amortization (%)	43	46	39

(AWWA) predicted that membrane cost is not likely to drop in the near future [92,93].

From Fig. 16 and Table 6, the major observation is that energy consumption makes the RO water costly. It also confirms the increase in fraction of operating cost with decreasing water quality with a corresponding shift in the fraction of capital cost.

Energy should be recovered from the high-pressure brine to make RO cost effective. Energy recovery devices such as the energy recovery booster pump, Pelton wheel, turbocharger, etc. recover the energy present in the brine, and divert it back to pressurize the inflow to the membranes [88]. A recent study on energy recovery using ERI PX brand energy recovery booster pump (ERBP) was performed on a 100 m^3/d SWRO plants in Bodrum, Turkey. The comparative study of the cost and energy between a system with and without energy recovery revealed 54% decrease in electricity use and cost of desalinated water [95]. The cost of desalinated water for RO systems using ERBP recovery devices was about \$0.57/m^3 [95]. RO systems operating with the help of turbine systems are comparatively less costly with desalinated water costing approximately \$0.43/m^3 [88]. The other common membrane processes available to perform desalination is ED. It has an energy intensity of 0.5–1.8 kWh/m^3 and is primarily used for brackish water treatment and costs are about \$ 0.60/m^3 [2,96]. This technology has not seen much development in the last decade and contributes 4% toward global desalination capacity [89].

The major aim in some of the above paragraphs was to enumerate the cost of desalination classified under single-phase processes. Another major category of desalination comprises phase change processes or thermal processes. This category contributes to approximately 37% percentage of the global desalination

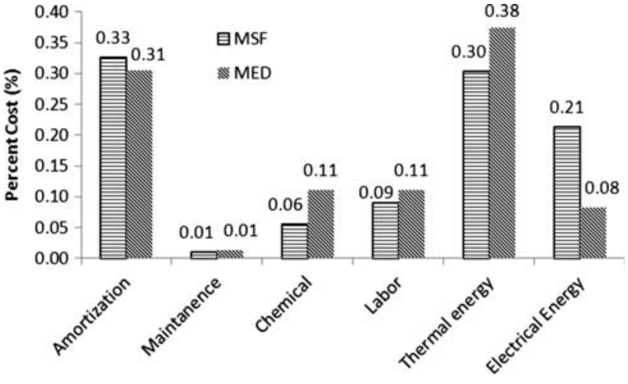


Fig. 17. General breakdown of cost expenses for a (100,000 m^3/d) MSF and MED plant, respectively [87,97].

Table 7
Representative energy and cost of desalinated water for thermal process plants irrespective of their size [2,96,98]

Thermal Processes				
Multi Stage Flash		Multiple Effect Distillation		Mechanical Vapor compression
Electrical Energy for pumping (kWh/m^3)	Thermal Energy (Equiv. Electrical Energy)	Electrical Energy for pumping (kWh/m^3)	Thermal Energy (Equiv. Electrical Energy)	Electrical Energy (kWh/m^3)
4.0–5.0	78 (10–20)	1.0–1.5	69 (3)	8.0–17.0
Cost of water ($/m^3)		Cost of water ($/m^3)		Cost of water ($/m^3)
0.89–1.50		0.70–1.0		2.2–3.8 (larger than MSF and MED due to small size)

production capacity. This includes 27% contribution by multi-stage flash (MSF) desalination process, followed by multi-effect distillation (MED) and vapor compression (VC) with 5 and 4%, respectively [89]. In general, thermal energy contributes to half the cost of the thermal desalination process. Furthermore, about 32% of the cost in thermal desalination is the cost due to amortization, 9% due to electricity, 3% for the chemical dosage, and about 6% is attributed to labor costs [90]. The National Research Council (NRC) reports the capital costs of MSF and MED to be 1.5–2.0 times the capital costs of RO, respectively.

Breakdown of cost of 100,000 m^3/d MSF and MED plants is shown in Fig. 17. Representative total costs of these two plant variants are approximately \$0.89/m^3 and \$0.72/m^3, respectively, according to [97]. Table 7 represents the latest general estimate of energy and cost of desalinated water for MSF and MED plants. The high capital and operation cost of MED and scaling problems (which limits top brine temperature) has in the past made MED less competitive than other phase change desalination processes. With technological development, however, new MED systems operate at low top brine temperature, and cogeneration with the use of thermal vapor compression has reduced MED operation costs [96]. This has improved the market for MED systems in recent years and with use of renewable sources such as solar energy this improvement may continue in the future. The production and capital costs of mechanical vapor compression are also higher compared to RO. The costs for small-sized plants for both mechanical vapor compression (MVC) and RO are illustrated in Fig. 18.

Desalined water cost has plummeted over the years, with hybridization and energy recovery devices helping to reduce energy use. Research into renewable resources to provide this energy is also underway. Karagiannis et al. (2008) performed the cost of some of these systems operating around the world. Some of the recent results of research are expressed in terms of desalination water cost for systems powered by renewable resources of energy such as wind and solar in Fig. 19.

For large-scale plants, hybridization can be used to bring down the operation and capital costs. A MSF

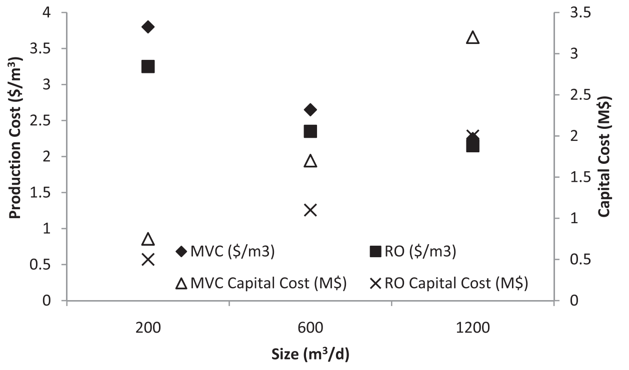


Fig. 18. Comparison between production and capital costs of small sized MVC and RO plants [98].

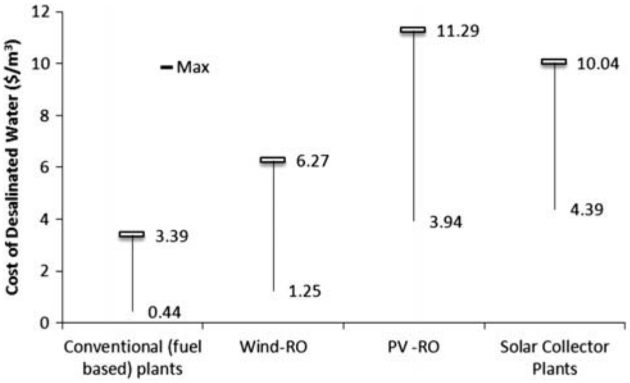


Fig. 19. Range of the current costs of desalinated water produced by thermal and membrane systems operated using fossil fuels, wind, and solar energy [98,99].

desalination plant of 20,000 m^3/d run by natural gas has a desalinated water cost of \$2.02/m^3, while a dual purpose MSF power/water plant water will cost only \$0.08/m^3 which seems quite low[98].

4. Decentralized water treatment: based on specific impurity removal

Ground and surface waters should be tested for specific impurities before the treatment. Recent quality regulation initiatives such as the EPA's total maximum daily loads impose stringent requirements for diffuse contaminants such as underground inorganic ore deposits. Most well water has the probability of being polluted with site-specific contaminants and microbes. Since geologic contaminants vary from location to location, the treatment also differs with respect to the contaminant. Table 8 lists the major point source contaminants, the treatment corresponding to the contaminants, and the annual economic expenses incurred.

4.1. Point of use water supply and treatment in developing nations

Potable water availability is a necessity in rural and economically poorer regions around the world. Table 9 provides some of the most common point of use household water treatment measures. The developing countries in Africa, Asia, and South America are dotted with many recent projects for providing improved potable water after filtering most of the biological and chemical impurities. For example, ceramic water filtration has been introduced in Cambodia, while in Nepal chlorination at home is adopted with Piyush chlorine solution. MIT–Kanchan bio-sand water filters have also been used to fight arsenic in water and solar water disinfection (SODIS) has been used for small potable water quantities [101].

Ceramic filters have become a promising low-cost option for needy developing countries to provide improved potable water at point of use [101]. The major feature is that these filters can be easily manufactured on site without much technical knowhow.

Table 8
Well water treatment and their annual costs [100]

	Potential groundwater contaminant	EPA maximum contaminant level value	Treatment	Approximate treatment cost per well (\$)*
1	As	10 μg/L–0.01 mg/L	Oxidation/Filtration, activated alumina, anion exchange: prior to RO	800–3,000
2	Bacteria	0	Disinfection	≥150
3	Cu	1.3 mg/L	Activated carbon, alumina, ion exchange resins: prior to RO	80–3,000
4	F	4 mg/L	Activated alumina, distillation, electrodialysis: prior to RO	800–3,000
5	Fe	300 μg/L–0.3 mg/L	Shock chlorination	≤3,000
6	Pb	15 ppb–0.015 mg/L	Activated alumina or carbon, ion exchange: prior to RO	80–3,000
7	Mn	50 ppb–0.05 mg/L	Shock chlorination	≤3,000
8	Hg	2 ppb	Inorganic: distillation; Organic: granular activated carbon	800–4,000
9	CH_4	10 mg/L	Well vents	100–4,000
10	MTBE	20–40 ppb	Air stripping	3,000–4,000
11	NO^{2-}	10 ppm	Ion exchange, electrodialysis: prior to RO	≥800
12	NO^{3-}	1 ppm	Ion exchange, electrodialysis: prior to RO	≥800
13	Ra	5–228 picocuries/L	Cation exchange, distillation: prior to RO	≥800
14	Rn	10,000 pico curies/L	Granular activated carbon; Aeration	3,000–6,000
15	Na	20 mg/L	Distillation: prior to RO	≥800
16	SO^{4-}	250 ppm	Ion exchange; RO	≤3,000
17	H_2S	No limit set	Shock chlorination; Oxidation/Filtration	≤4,000
18	U	30 μg/L	Coagulation/Filtration; anion exchange; distillation; electrodialysis: Prior to RO	≥800

*All costs are in 2009 US dollars.

Table 9
The different POU water purification measures, their effectiveness, quality, and cost [101,102]

Process	Cost of water ($/m^3)	Removal	Comments
Boiling	10–40	Most of the pathogens	Cost varies with fuel source; high energy expense
MIT Bio-sand Kanchan Filter	≈1.2	80–100% bacteria and protozoa; Low virus inactivation	Cost of filter $15–70; Multiple parts
Ceramic Pot Filters	2.2–5	95–99.99% bacterial removal	Easy Manufacture
Chlorination	0.25–8; 1.1		PUR®
Site Produced Chlorine (WATA)	0.05–55		
SODIS [Solar disinfection]	≈0.5	Inactivate bacteria and viruses	PET bottles. Assuming 100 uses before bottle cannot be used further
Aeration	–	Removes H_2S, Fe, Mn, volatiles, etc.	Manual work to create turbulence in water
Kolshi Filters (storage type)	≈2.5–3	50% of all bacteria can be killed by storing	Principle of storing and settling

The details of manufacturing, cost, effectiveness, and use are illustrated in Table 10.

4.2. End use: transition of water cost to water price

To ensure good health in humans, a daily minimum requirement of approximately 20–50 liters of water per person is required [8]. Several questions arise on proper allocation of water and what price the end-user has to pay for this water. The present price of water is a reflection of cost for pumping, treating, and distributing. In addition, infrastructure costs, engineering cost, operation and maintenance cost, and labor charges are also included. Further, the price will also have an influence on availability of water to the area for which the price is calculated. The price of water calculations are complicated by political decisions, governmental subsidies, and regulation. From an economic point of view, price should be the marginal cost of water delivery or supply [8]. Capital and operational costs are used to estimate the cost incurred for the water supply in Asia, Africa, and Baltic States [103]. Table 11 provides the water supply costs for several Asian countries. These values represent a sum of the pumping, treatment, storage, and distribution expenses incurred to supply water to these cities in Asia [103].

The yardstick of the UN on assessing the affordability of water is that water price should not exceed 3–5% of household income [30]. At present, the developed countries pay a price of about 1% of their household income for purchasing water, while in the developing nations water price ranges 3–11% of household income due to wide variability in income levels within a country [30]. The per capita consumption of water increases with a nation's GDP [103].

The price of water supplied by the government utility to a household in Dhaka, Bangladesh, is about $0.08/m^3, but from a private utility it is $0.42/m^3 [5]. From Fig. 20, it is clear that lowest prices for household water are found in countries of East Asia and the Pacific. Water for household connection in Mongolia was priced at $0.04/m^3, while a private vendor provided water at a hefty cost of $1.51/m^3. Similarly, informal water vendors in Philippines sold water at a very hefty cost of $4.74/m^3. Another form of water used by households is bottled water. The price of a 500 mL water bottle is approximately $1.25 [104]. The price of household water supply is very cheap compared to bottled water. Further, the energy costs for producing bottled water are approximately 75% more than energy cost for local production of water [105]. Carters are vehicles delivering comparatively small volumes with respect to other water supply options shown in Fig. 20. Fig. 20 also points out that as volume of sales go down, the prices soar. For example, water carters are the costliest water supply options compared to the other options illustrated in Fig. 20.

Large centralized utilities are supplying water in most of developed countries. The national average cost of water is $3/m^3, while the average price of water in the USA is approximately $0.4/m^3 [107]. The water prices in Europe vary from a low of $0.53/m^3 in Spain to approximately $1.81/m^3 in Germany [104]. Water prices from centralized utilities in developing nations in Latin American countries are shown in

Table 10
The different point of use clay ceramic household water filters marketed across the globe [101]

Filters	Material	Additive	Coating	Cost per filter [$]	Microbial efficiency [*E. coli*]	Flow rate
Ceramic Filter, Australia	Clay	Tea leaves/coffee grounds/rice husk	Nil	Nil	96.4–99.8	0.5 L/h
Siphon Filter, India	Clay candle (Pozzani or Stefani)	NA	Nil	$2.00	Depends on height of water	2–5 L/h
Terafil disk Filter	Red Terracota Clay	Sawdust, Rice husk ash	Nil	$0.49	93–99.9%	1–11 L/h
Pelikan/ Indian Candle	White Kaolin Clay	sawdust	Nil	$8.00–21.00		300–840 mL/h/candle
Nepal Candle	White Kaolin Clay	Charcoal powder	Colloidal Silver (CS)	$4.07	99.90%	240–400 mL/h
Capped Candle Filter, Nepal	Clay	Sawdust, Rice husk ash/Flour	CS	NA	99%	678 mL/h
Ceradyn	Clay	–	Nil	$190	98%	641 mL/h
Gravidyn	Clay	–	Nil	$160	98%	845 mL/h
Doulton	Diatomaceous Earth	Loose Carbon(Interior)	CS	$40	99.90%	1.34 L/h
Disk Filter	Red Clay	Flour/Rice husk	CS	$2.00–3.00	99.90%	756 mL/h
Disk filter	Black Clay	Flour/Rice Husk	CS	$2.00–3.00	99.30%	341 mL/h
Indu. For Poor Inc Filter	Sediment	Activated Carbon/Chlorine	Nil	$15	99.40%	9.5 L/h
Kisii Filter Kenya/Burkina Faso/Niger	Kaolin Clay	Activated Coal	CS	$1.00	–	3 L/day
Filtron/Kosim [frustum Shape]	Clay	Sawdust	CS	$6.00	99–100%	1–2 L/h
Filtron [Frustum Shaped]	Terracotta Clay	Sawdust	CS	$6.00	97.60%	1.7 L/h

Table 11
Household water supply cost in Asia [103]

City	Country	Capital cost ($\$/m^3$)	Operational cost ($\$/m^3$)
Badung	Indonesia	0.43–0.72	0–0.42
Ho Chi Minh	Vietnam	0.17–0.21	0–0.17
Chennai	India	0.18–0.33	0–0.18
Vientane	Laos	0.23–0.47	0–0.22
Davao	Philippines	0.28–0.31	0–0.27
Dhaka	Bangladesh	0.11–0.32	0–0.1
Medan	Indonesia	0.39–0.59	0–0.38
Mumbai	India	0.07–0.10	0–0.06
Port Vila	Vanuatu	0.40–0.52	0–0.39
Shanghai	China	0.30–0.47	0–0.29
Suva	Fiji	0.33–0.86	0–0.32
Tianjin	China	0.20–0.36	0–0.18
Bangkok	Thailand	0.54–1.44	0–0.53
Jakarta	Indonesia	0.97–1.59	0–0.95
Tashkent	Uzbekistan	0.05–0.09	0–0.04

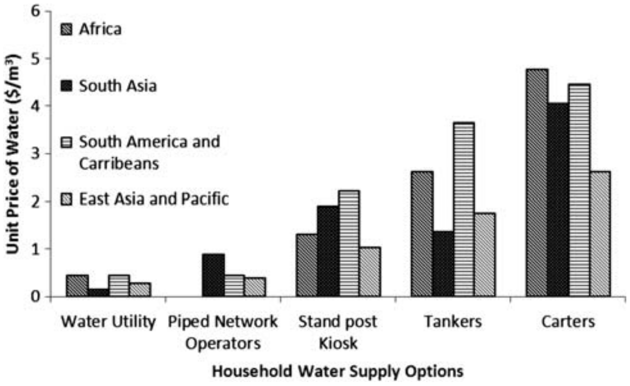


Fig. 20. Mean water prices around the world [106].

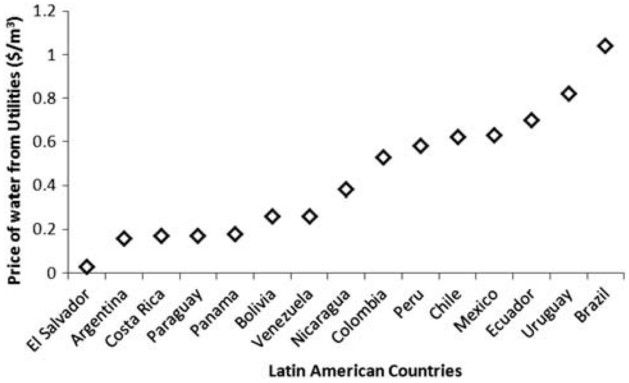


Fig. 21. Recent prices of water from utilities in Latin American countries [108].

Fig. 21. There is wide variability in end use prices of water. This may be due to policy, regulations, quality requirements, water scarcity, size of supply, water transportation costs, government subsidies, political decisions, competition between private market vendors, economic situation of the location, and various other aspects. These many aspects make it difficult to calculate a benchmark price of water.

Large centralized systems may not be good for serving dispersed unplanned rural areas, and hence a decentralized point of use household technology is found to be viable. The operation and maintenance cost of water supply systems across Africa and Baltic States also ranged from \$0.15 to \$0.45 per cubic meter of water supplied [103]. Typical rural Cambodian families spend 5% of their income on water [109]. They are supplied, piped, metered, and purified water at a cost of approximately \$0.30–0.50/m^3. They purchase from vendors untreated water delivered to the house at \$2.5/m^3 and they also harvest free rainwater. Since rainwater is collected for drinking and cooking, they treat it individually costing approximately \$2.5 /m^3. Therefore, the rainwater also has a price associated with it [109]. Government supplies water in Cambodia costs \$ 0.09/m^3 [5]. Decentralized drinking water sources in Africa are household connections, public standpipe or hand pumps, small piped networks, water tanker, etc. [110]. A recent study performed by the World Bank predicted that supplying drinking water to households using water tankers was the costliest source, with Africa paying an average of \$4.67/m^3, and the least costliest was for household connections [run by utilities], with an average price of \$ 0.49/m^3 [110]. Public standpipes are the most common alternative to dispense drinking water in cities of sub-Saharan Africa. More than 55% of the unconnected populations in these cities pay an average price of \$ 1.93/m^3 and use standpipe kiosks to get water [110].

5. Residential water use

The most energy intensive part of the water life cycle is the end use [2]. The energy use in this stage is primarily for heating water for activities such as cooking, disinfection of water before drinking, washing, and personal cleansing. Heating water has two variable components of cost. They are the cost of the energy (specific fuel or electricity) and time for which the water is heated. Energy intensity for heating water to 60 ℃ using electrical energy or natural gas sources is found to be 73 kWh/m^3 and 35 kWh/m^3 [in equivalent electrical energy value], respectively [2]. Assuming 2011 end use price of electricity to be \$0.117/kWh, the cost of heating a cubic meter of water will be approximately \$8.5/m^3 and \$4/m^3 using electricity and natural gas, respectively [111]. The cost of boiling water in India using liquefied petroleum gas as an energy source is approximately US\$5/m^3, while by using wood as energy source would cost US\$190/m^3 [112].

Energy consumption and cost analysis for boiling 0.002 m^3 of water was performed using different energy sources found in Nigeria [37]. It is observed from Fig. 22 that using kerosene and petroleum gas is the most expensive even though they have higher energy efficiency than fuel wood. Electric heating devices were the most efficient heating appliance and also were comparatively cost efficient compared to kerosene and petroleum gas. These results were also true in case of cooking cost and energy expenses in Nigeria [37].

5.1. Centralized waste water treatment: conventional

Wastewater treatment consists of primary, secondary, and sometimes tertiary treatment stages. Common processes in wastewater treatment include pumping, filtration, aeration, sludge dewatering, and thickening which require electricity. Processes such as heating of anaerobic digesters use natural gas. Total operating cost of a wastewater treatment plant is shown in Fig. 23. Compared to a centralized water treatment facility, the percentage energy expenditure is low in wastewater treatment plants [73]. The EPA defines total O&M costs as the sum of costs incurred per year on labor, electricity, chemical, maintenance, and taxes/insurance. It also considers maintenance and tax/insurance expenses to be approximately 4% and 2% of the total capital cost for the centralized waste treatment plant [113].

Furthermore, the cost incurred due to regulatory policies and framework is equal to sum of the cost of the technology specific treatment equipment and procedural costs. Equipment used at the three different stages of treatment has wide technological differences and therefore, costs vary almost randomly. Installation of equipment, piping, and controls is in the range 25–55, 31–66, and 6–30% of technology specific equipment costs [113].

Primary treatment activities include influent wastewater pumping, comminution or sizing, and screening as well as removal of inorganic suspended solids. The major operational cost is the cost for electricity consumed for running the influent primary sludge pumps. This process of collection and pumping con-

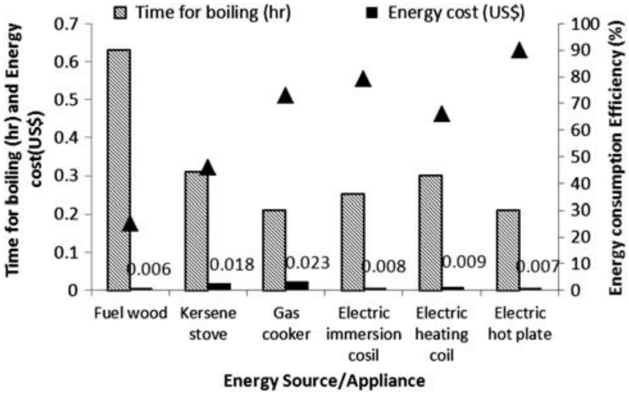


Fig. 22. Cost analysis for boiling 2.25 liters of water in Nigeria [37].

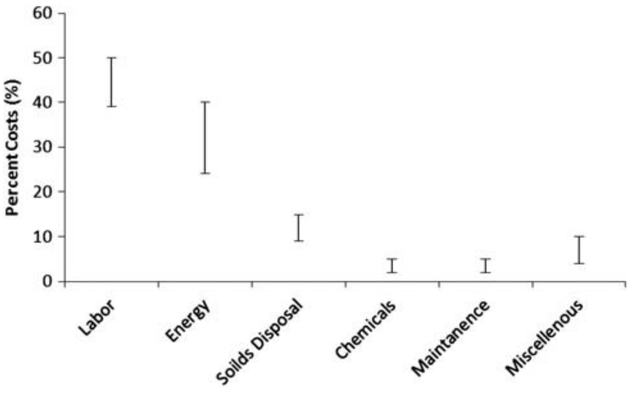


Fig. 23. Variation in operating cost in a centralized wastewater treatment plant in the USA [73].

sumes an average electrical power of 0.04–0.19 kWh/m^3 [2]. Assuming a unit kWh of electricity costs US $ 0.117/kWh, then the process of collection and pumping will cost in the range of US$ 0.005–0.022/m^3. Influent wastewater collection and pumping is followed by comminution or size-based grit removal. Grit removal is followed by sedimentation. The shape of the clarifier helping in sedimentation can influence variation in operation costs [114]. Total electricity consumption for primary treatment ranged from 0.01 to 0.37 kWh/m^3 [2]. Chemicals are also sometimes used to increase the biological oxygen demand as well as to reduce the organic load in the sludge. Rapid mixing, chemical pumping, polymer pumping, and chemical transfer pumping are some of the pumping processes when chemical addition is performed. Poor primary treatment design and operation could affect the overall energy footprint of the waste treatment plant.

Energy usage includes electricity consumed for running the equipment and its controls and lighting the treatment plants. Fig. 24 provides an approximate percentage variation in electricity costs for operating an activated sludge secondary treatment plant. Even though the energy intensity of aeration is the same for plants of different sizes, it can be observed from Fig. 20 that cost of aeration scales up with plant size [2]. Assuming electricity cost is approximately $0.117/kWh, the cost of electricity used for conventional secondary wastewater treatment depicted in Fig. 24 ranges from $0.06 to 0.09/$m^3$ with a decrease in size of the plant.

The cost for water pumping increased with an increase in size. Suspended growth waste treatment techniques include aeration as well as activated sludge treatment and their modification for specific purposes. Digestion is the process of converting the organic solids to more inert forms suitable for disposal. The process of digestion, shown in Fig. 25, is found to incur more than 50% of the operation cost of a 4,000 m^3/d plant, while for large-sized plants [<40,000m^3/d] aeration costs are more than 50% of the total electricity cost for the corresponding plant. Another major aspect of these large plants is that energy can be recovered by recovery of biogas [49]. For anaerobic digestion, half of the cost is for the use of precipitation chemicals such as caustic soda [115]. About 23% of the operation cost of an anaerobic digester is contributed by nutrients in the wastewater and 12% each are contributed by electricity and labor [115].

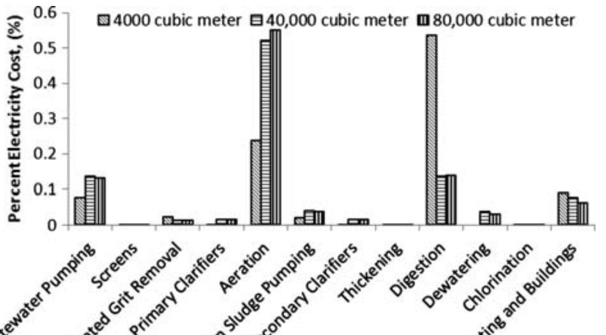


Fig. 24. Percent electricity costs for different step-by-step processes in an activated sludge secondary wastewater plant [2].

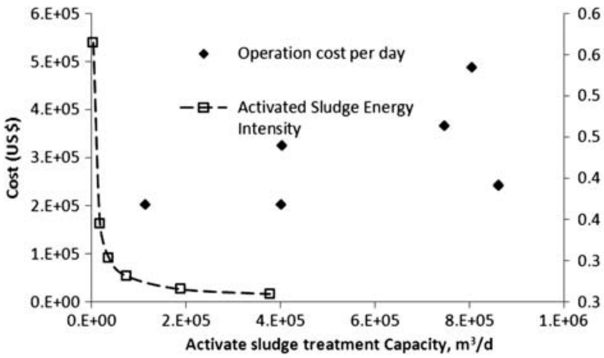


Fig. 25. Plot of actual operation costs of activated sludge treatment technologies in Valencia, Spain irrespective of its different types [2,116].

Suspended growth treatment processes such as extended aeration and activated sludge process have energy intensities in the range of 0.026–0.04 kWh/m^3 and 0.33–0.1.89 kWh/m^3, respectively [2]. Aeration operates with small quantities or low loading of waste but with large residence or holding time for these wastewaters [2]. Further, the activated sludge processes are performed for the removal of organic matter from the waste and are 10–15 times more energy intensive than extended aeration processes [2]. Additionally, the simple mechanical aeration process stage uses almost 50–60% of the total electricity consumed by a wastewater treatment plant with an activated sludge system [73]. With increases in plant capacity, energy usage decreases as illustrated in Fig. 25.

Table 12 compares the percentage contribution of various parameters for the operating cost of municipal, petroleum, chemical, and dairy activated sludge water treatment plants. Vanderhaegan et al. (1994) predicted that municipal sludge treatment costs were approximately in the range of 17–36% of the total operation cost and consumed almost 25–30% of the total electricity consumed by the wastewater treatment plants [73]. The energy costs are directly correlated to the sludge treatment costs [117]. Therefore, the energy

Table 12
Operation cost of activated sludge water treatment plants for different industries [118]

Parameters/ Industry	Percent operation cost (%)			
	Municipal	Petroleum	Chemical	Dairy
Energy	10	10	14	9
Maintenance	14	20	3	10
Chemicals	7	4	7	18
Labor	13	15	5	12
Amortization	23	30	31	10
Sludge treatment	25	17	27	30
Levies	5	3	12	5
Miscellaneous	3	1	1	6

consumption and sludge treatment are two major parameters, either of which can help to manage costs in an activated sludge waste treatment plant. Also energy expenses have been observed to be proportional to legalities in effluent disposal distinct for each industry [117]. Capital costs are predicted with a power law function of the size of the water treatment plant [118,119]. The power to which the size is raised ranges from 0.25 to 1.00 according to the type of the treatment processes [118]. From Table 12, the operating costs form the dominant part of the overall wastewater treatment cost.

Other than suspended growth systems, attached growth systems such as trickling filters are also used for oxidation of organic matter as well as nitrification. Tricking filters are less energy intensive than activated sludge systems [2]. In larger plants (<40,000 m^3/d), energy may be recovered by taking advantage of biogas production [49]. The percentage contribution of wastewater pumping as well as filtration costs toward total electricity cost increased with size of the trickling filter treatment plant, while the contribution of digestion decreased. This is also apparent by the facts that 50–55% of the total electricity use of a trickling filter plant is for pumping waste sludge and that sludge treatment (settling, thickening, and digestion) almost consumed 40–45% [73]. The cost for trickling filter plants shown in Fig. 26 ranges from \$0.02 to 0.05/m^3 of wastewater and decreases with an increase in the size of the plant. This range is comparatively much smaller than those of activated sludge treatment plants.

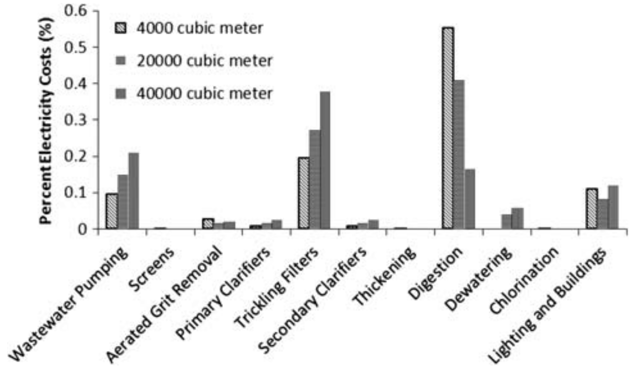


Fig. 26. Percent electricity costs for different step-by-step processes in a trickling filter secondary wastewater plant [2].

There are different attached growth trickling filter processes. The rock media, plastic media, rotating biological contractor, and trickling filter/solids contact are trickling filter processes which can be used for the removal of carbonaceous compounds from the waste sludge. Rock media filters are the costliest of the trickling filter processes [120]. For organic removal, rotating biological contactors are least expensive. Considering a 378,000 m^3/d treatment plant with respect to rock media filters, plastic media, trickling filter/solids contact, and rotating biological contactor, trickling filters are approximately 58, 49, and 48% less costly, respectively, for organics removal [120]. Additionally, plastic media and rotating biological contactors are also used for nitrification. Rotating biological contactors are cost efficient compared to the plastic media trickling filters for nitrification [120].

The presence of ammonia in the wastewaters, even after the secondary treatment, is controlled using advanced treatment with biological nitrification processes. Fig. 27 presents the percentage of electricity cost for operation of tertiary treatment processes with biological nitrification for the removal of ammonia and protein from municipal wastewaters.

From Fig. 27, it can be noticed that costs of aeration and biological nitrification increase with size. The electrical energy intensity for aeration (irrespective of size) in Fig. 27 is approximately 0.113 kWh/m^3 [2,49]. Also the costs shared by nitrification are lower than the share for aeration processes. The electrical energy intensity of biological nitrification (irrespective of the plant size) is approximately 0.085 kWh/m^3 [2,49]. Tertiary treatment technologies also include use of membrane processes such as bioreactors, MF, UF, NF and RO. The operations of tertiary treatment technologies are costlier than primary and secondary treatment technologies [2].

5.2. Recycling and reuse

Treating wastewater for a beneficial purpose as well as augmentation of potable water supplies with

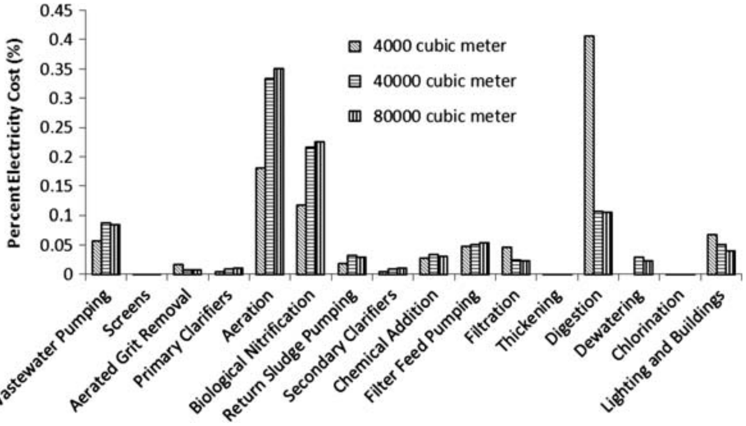


Fig. 27. Percent electricity costs for different step-by-step processes in an advanced wastewater treatment waste water plant (with biological nitrification) in the USA [2].

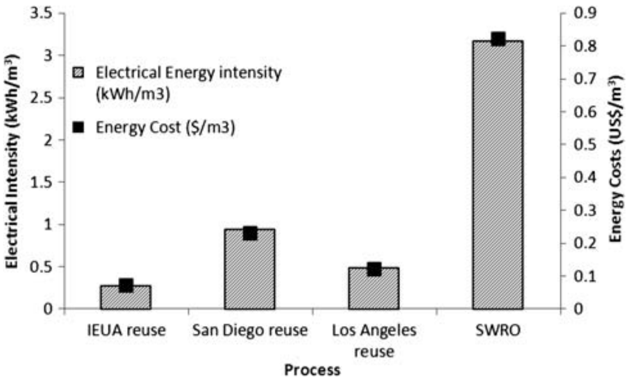


Fig. 28. The energy use and energy cost for production of water using reclamation processes as well as desalination [119]. Here, IEUA refers to Inland Empire Utility Agency.

this reclaimed wastewater is gaining importance with looming water scarcity. Reclaimed water is also used for industrial and agricultural applications. There are also situations where recycled wastewater is used but remains unaccounted due to conservation practices. This has reduced the per capita wastewater flows in recent years in the USA [119]. Therefore, water conservation and water reuse are highly correlated.

For water reuse to be practiced, it has to overcome several hurdles. The most persistent of these are public skepticism about health risks due to wastewater reuse and the resulting decision-making processes related to water use [119]. Wastewater which has been discharged to natural fresh water rivers and spends a specific time was considered “indirectly” potable water in Massachusetts a century ago [119]. Thus, indirect potable water reuse was practiced before, even though it is gaining importance today. Another alternative is to instead redirect treated wastewater directly or blended into the drinking water distribution system to fresh water rivers or aquifers. This is known as direct potable water reuse and recent studies state that this methodology can save more than 50% of the energy cost for pumping water from its source [121].

While thinking about costs, the first question is location specific. Does the region need to reuse water and, if so, how much is the water demand and what will it be used for? Factors affecting the financial costs for water reuse include: plant capacity, location, treatment infrastructure, influent water quality, transmission and pumping, timing and storage requirements, energy requirements, concentrate disposal costs, regulations, savings, and revenue availability.

The wastewater treatment plants are where water reclamation starts. Wastewater treatment plants are normally constructed in close proximity to discharge locations such as the sea or other receiving water bodies. There is a need for a separate water system to provide recycled water back to the consuming residential, commercial, industrial, and agricultural sectors. Further, the quality of water should be similar to secondary or advanced water treatment effluents for nonpotable uses of water. This means that a large investment for treatment is not necessary for nonpotable uses [119].

The calculation of water production costs is mainly dictated by water quality of the influent. This will increase capital investment into treatment technology. Another major aspect is delivery of recycled water that needs substantial capital investment. For example, Texas regulations require a separation between a reclaimed water pipeline and a potable water line of approximately 2.7 m horizontal as well as 0.6 m vertical [119]. The transmission and distribution costs of recycled water in southwest Florida Water Management district ranged from US \$5.00/inch-ft in rural areas to US\$9.00/inch-ft in urban areas [119]. Moreover, most of the urban locations around the world are bound by regulations to supply only high quality recycled water [122].

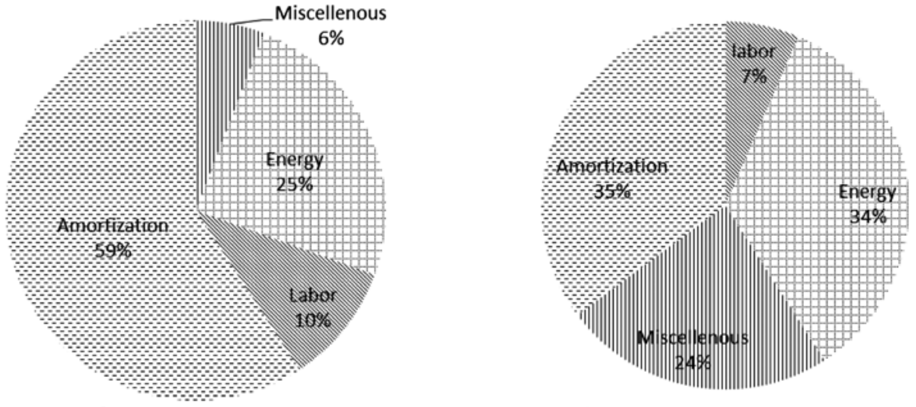
One of the major disadvantages of reclaimed water distribution is that with change in climate the production may vary. For example, in winter when water requirements for agriculture are minimal, facilities may face the problem of excess production. This can lead to time and storage costs during off seasons [119]. Further, energy costs are more location specific and can be very random. Energy costs are affected by distance from one treatment plant to end use, size of the treatment plant, regulation, and treatment technologies [2]. Fig. 28 compares the cost of nonpotable water reuse and seawater desalination using RO in California.

Fig. 29 provides a comparison of the percentage total costs of the reuse treatment facilities used for landscape irrigation in Las Vegas, NV. In terms of 2009 dollars, Desert Breeze had an annual cost of US \$0.22/m^3 of water reuse, while Durango Hills had a water reuse cost of \$0.276 [119]. The two plants used an activated sludge treatment technique appended with ultraviolet disinfection [119]. Capital costs were mainly incurred for pipeline installation for reclaimed water transport [119]. Energy consumption was the second largest contributor to total cost in both plants, while in the IEUA plant (which was 151,200 m^3/d) energy contribution toward total reuse cost was only 7.5%. The labor cost contributed 42.5% and amortization was 36% of the total cost of approximately \$ 0.53/m^3 [119].

The type of water reuse also influences the cost of the recycling processes. The 2003 price of recycled water for irrigation in Australia was in the range of \$0.04 0–0.34/m^3 (in 2003, one Australian dollar = 0.6 US\$) and for use residential toilets and gardening it was in the range of \$0.17–0.50/m^3 [123,124]. The 2009 price of recycled water for nonpotable uses in Australia was in the range of \$0.56–0.82/m^3 [122]. Residents of Perth paid an annual flat rate of \$96 for its nonpotable recycled water use. This was far more economical than the price of potable water distributed by utilities in Australia, which ranged from \$0.68 to 2.00/m^3 (in 2009, one Australian dollar = 0.8 US\$), and also price for trucking potable water in Australia which ranged from \$5.04 to 13.71 [122,124].

5.3. Produced/processed water treatment

There are processes apart from municipal wastewater treatment that use and manage large amounts of water for their activities. For example, the produced water in fossil fuel exploration is recycled for reuse and consumption. It is the largest waste stream from oil/gas exploration: 34.2 million m^3/d of water is produced around the globe for 85 million barrels of oil extracted [125]. According to recent predictions, the market for produced water treatment systems will be roughly \$4.3 billion over the next five years [125]. With change in location, the produced water from oil and natural gas wells vary in chemical composition. The disposal, availability of fresh water source for hydrocarbon extraction, regulations, transportation costs, depletion of renewable or nonrenewable water sources, reduction in ground water quality, as well as geological changes are some of the key drivers for produced water management. Various technologies are available for produced water treatment. It is important to observe that variants of the available municipal treatment systems are used for produced



18900 m^3/d, Desert Breeze, Las Vegas, **37800 m^3/d, Durango Hills, Las Vegas, NV**

Fig. 29. Cost analysis for water reuse in two different facilities in Las Vegas, NV.

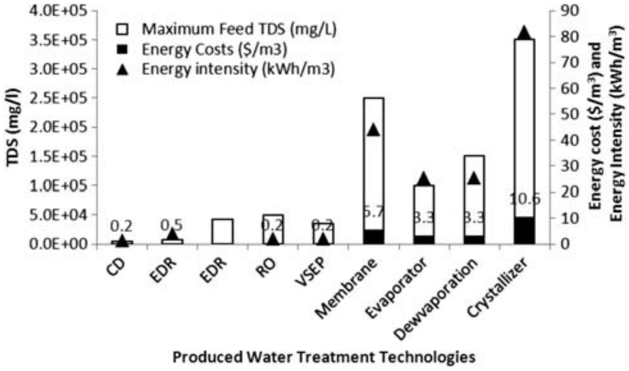


Fig. 30. Oil/gas produced water treatment technologies, their corresponding energy costs ($/m^3), energy intensities (in equivalent electrical kWh/m^3), and the maximum TDS (mg/L) they can treat [126,127]. Here, CD-Capacitive deionization, EDR—electrodialysis reversal, ED—electrodialysis, RO—reverse osmosis, VSEP—vibratory shear enhanced process using membranes.

water treatment. Different technologies available for produced water treatment are plotted corresponding to their operating feed total dissolved solids (TDS) (in mg/L) and energy intensities (kWh/m^3). With increase in TDS in the produced water, the amount of energy required for treatment increases. The energy cost of the treatment technologies increases with the energy intensity. Assuming an average electricity cost of $0.13/kWh, the energy cost for the corresponding energy intensities are calculated and plotted in Fig. 30.

The high TDS wastewater is treated using mainly TDS insensitive thermal technologies such as evaporation, crystallization, freeze-thaw, etc. As an example, the freeze-thaw process works following the principle that pure ice forms crystals at low temperature, while brine with high dissolved salts drains away. This runoff is stored and disposed. This technology is used for treating produced water with 40,000 mg/L or more TDS. A treatment site with a capacity of 10,000 barrels has a yearly operation cost of $0.008–0.01/m^3. This technology requires large spatial requirement and has a capital cost deduction in the range of $4.74–5.5/m^3 [127].

At many locations, the produced water is not treated and it is instead disposed of using methods such as deep well injection. Disposal costs of produced water depend on volume, chemistry, and disposal location [128]. Conventional transport of produced water using tanker trucks costs approximately $2–20/barrel of wastewater [128]. Costs of different produced water treatment and management methods are shown in Table 13.

From Table 13, deep well injection disposal of produced water is found to be costly compared to most of the treatment technologies. The cost of disposal is very much site-specific as well as owner dependent. Commercial deep injection of produced water with a cost range of $0.43–14/m^3 is more than in an owner operated deep injection well, which is approximately in the range of 0.16–12.6/m^3. The cost of produced water recycling in California was approximately $32/m^3 [127]. Comparing different technologies in Table 13, it is observed that the higher cost limit of commercial water hauling is more than most other management techniques available. Further, it is observed that constructed wetland systems have a very small unit cost associated with treating produced water. This may be due to the low energy intensity of these wetlands [132].

The use of desalted or treated produced water for agriculture is a beneficial reuse option [133]. Vegetables farming and aquaculture can be performed using

Table 13
Capital and unit costs for different produced water management and disposal techniques [127,129–131]

	PW Management Method	Unit cost ($/m^3)	Capital cost ($)
1	Induced air flotation (de-oiling)	0.31–0.32	
2	Anoxic/aerobic gas activated carbon filtration	0.5–0.6	
3	Fluid-bed resin exchange	0.74–3.7	325,000
4	Subsurface drip irrigation	0.98–1.48	6,000.0/acre
5	Freeze-thaw	1.48–6.1 [West US]; 16.7–31.8	1.75–2 million
6	Brackish water reverse osmosis	0.06–0.18; 0.185	0.2–2 million; 211–1,058/m^3
7	Electrodialysis	0.13–4	
8	Land applied using soil amendments	0.37–2.8;1.89–2.53 [Arkansas]; 32.7–114 [New Mexico]	2.4–4.1/m^3
9	Constructed wetlands	0.006–12.6	
10	Deep well injection	3–24.6	0.4–3 million
11	Commercial water hauling	0.06–34.8	

coal bed methane produced water [134]. Similarly, living machine treatment systems, which mimic wetlands, can be used for reusing produced water to grow beneficial crops such as ornamental, aquatic, and wetland plants [132]. There is not enough literature on the operation and cost of these farming techniques using oil/gas produced water.

6. Agriculture water costs

The water scarcity due to physical, economic, political, and socioeconomic structural influences are going to influence agricultural sector production and expenditure. More than 70% of the world's fresh water withdrawals are for agriculture [30]. This would increase the importance of cost analysis of water in the agricultural sector. Global annual ground water irrigation costs are in the range of \$20/ha–\$1,000/ha [44].

The cost of water can be defined in terms of cost of irrigation per unit volume or per unit area or per unit time. The cost to irrigate a field is dependent on the amount of water pumped, source of water, area, soil characteristics of the location, geology, slope, crops, precipitation, temperature, type of irrigation system, irrigation scheduling, human behavior, application effectiveness, pumping system type, pressure requirement at the point of use, electricity, and fuel cost [2]. The energy cost of irrigating a gravity fed farm will be lower than those irrigated using ground water pumping [135]. As observed from Fig. 4, the cost of ground water pumping will increase linearly with lift. Pressurized discharge will also contribute to cost. Pump efficiency and age of the pumping system will also affect variation in cost.

Mukherji [2007] performed well water supply cost studies in West Bengal, India. The ground water aquifers have depth beyond 150 m in West Bengal [136]. She reported that diesel centrifugal pump owners incurred an hourly operation cost of \$0.72 (assumed that US\$1.00 = Rs.44 Indian in 2003–2004) and had an hourly capital investment of \$1.12 [137]. The experiments conducted along with diesel submersible pump owners reported an hourly operation cost of \$1.87 and a capital cost of \$2.85 per hour [137]. A steep increase in diesel cost in India resulted in economic scarcity of groundwater [137].

Recently, Vietnam became the largest global pepper exporter overtaking India [138]. Dong Nai basin in Vietnam produces a major share of this crop with other high-value crops such as fruits, coffee, tea, and vegetables. The 70% of the farmers in this region used electricity, while the remainder used fuel for pumping ground water with \$17/ac cost for electricity and \$28.3/ac cost for fuel [in 2007 dollars] [138]. The average cost for ground water irrigation was approximately \$0.05/m^3 and irrigation using surface water ranged between \$ 34×10^{-5} and 0.40/m^3 [138]. Considering the total crop costs, the irrigation costs using fuel and electricity only contributed approximately 6.6 and 3.4% [138]. This was much lower than the labor costs and fertilizer–pesticide costs each of which contributed 40% to the total crop production costs [138].

Irrigation water tariffs in Tulkarm district, Palestine, based on ground water pumping and maintenance cost of the pump were in the range of \$0.25–0.37/m^3 [43]. The least expensive water in California was used for agricultural purpose and was approximately [in 2007 dollars] \$ 0.012/m^3 [40]. Water tariffs for irrigation in the USA are illustrated in Table 14. The 50% of the irrigation uses ground water and is supplied to a farm area 3.2×10^7 acres [139]. Average US energy costs were approximately \$40 /ac and total energy expenses were more than \$1.2 billion [139]. About 40% of irrigated farms in the USA received water from off-farm water supplies [139]. In 2003, the mean variable cost of supplying irrigation water was approximately \$50 per acre [139].

A wide variability is observed in costs of irrigation at different parts of the world. Ground water pumping as well as irrigation costs may be very high due to arid climatic conditions in the Middle East and North Africa. For example, the water depth in Saudi Arabia (SA) and Libya range 100–180 m and 400–1,200 m,

Table 14
Cost of irrigation water in the USA in 2003 [139]

Sources	Cost range in states of US (\$/ac)	Average US water cost (\$/ac)	Total cost of water for the USA (\$$*$ 10^6)
Energy expense for pumping ground water	7.0– 176	39.5	1277.54
Energy expense for pressurizing surface water	10.0–82	26.39	278.72
Water purchased from off-farm sources	5.0–86	41.73	578.75
Maintenance and repair expenses	4.0–80	12.29	491.77
Total irrigation water Capital Investment	16–187	42.18	1125.13

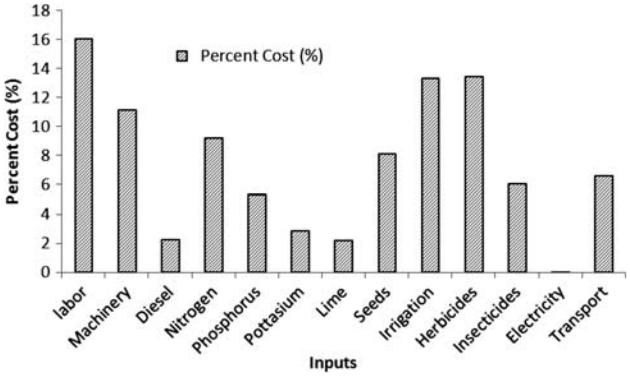


Fig. 31. Percent cost inputs for corn production (1 hectare) in the USA [143].

respectively, with withdrawals of 21.54 Gm^3/year and 4.3 Gm^3/year [140]. SA consumes 1.56 x 10^5 GWh of electricity (5% of the total electricity produced in SA) and burns fuel 13.2 million barrels for ground water pumping yearly. Saudi Arabia is a member of the Gulf Cooperation Council (GCC) States, which are the most water stressed and use most of their available water resources for agriculture [140,141]. This water scarcity and energy expense issue can be alleviated by substituting virtual water use instead of ground water use for agricultural production [141,142]. The import of water intensive crops and food can help save water and energy costs. Some countries are even bartering land in African countries to produce crops for their own consumption [141].

Corn is one of most productive cereal crops. Fig. 31 provides a comparative cost for the various inputs for corn production per hectare (1 ha = 2.47ac) in the USA [143]. The 16% of the total corn production cost of $926.97 is for labor cost. The labor cost in hours for US corn is 11.4 h, while for Indian corn it is 634 h. The high labor cost in India saves on cost for fossil fuels to run agricultural machinery [143]. The expense for agricultural machinery and diesel is approximately 11.1% and 2.2% of the corn production costs in the USA. Irrigation cost is about 13.2% of the US corn production cost, while in India and Indonesia irrigation is rain-fed [143]. Mechanized and irrigated corn yield in the USA is about 9,400 kg/ha, while hand-produced and rain-fed corn production in India and Indonesia is about 1,721 kg/ha [143].

Even though Indian cereal crops are considered rain-fed, India is the biggest groundwater miner in the world for agriculture [144]. India, Pakistan, Bangladesh, and Nepal mine about 210–250 Gm^3/year of ground water using more than 13–14 million electric and about 8–9 million diesel water pumps [144]. India's cost of energy used (84.7 billion kWh) for lifting water is about $4.2 billion, considering an electricity cost of $0.05/kWh. Total market value of pump irrigation in South Asia would then be approximately $11.34 billion. In some parts of Asia, water vendors follow an age-old rule (as previously cited from Arthasastra) by providing pumping water service at a cost of 33% of the total produce [144].

Fruits are water and energy intensive compared to vegetable crops [2]. High water requirement of crops increases the expenses for water. For example, sugarcane has a high water requirement but low water content per unit quantity of produce of about 200 m^3/ton [8]. This crop is not appropriate for arid conditions [8]. Similarly, the crops such as grapes and bananas listed in Table 15, which also require more spending on irrigation, cannot be considered appropriate for water scarce locations.

Water scarcity has led farmers to switch from conventional surface irrigation strategies to improved water efficient technologies such as drip irrigation. Even though the investment cost on drip equipment of more than US$1,000.00 is prohibitive for farmers, in the long run they save on irrigation costs over the use of surface irrigation as illustrated in Table 15 [8]. Drip irrigation helps to reap more than 50% savings for the crops listed in Table 15 with respect to crops under surface irrigation.

A comparative study of pressure range, energy, and cost of different irrigation technologies used in Australia are illustrated in Table 16. With an increase in the operating pressure range, the energy and cost expenses also increase. It should be noted that surface

Table 15
Comparative cost and energy analysis for water intensive crops [145]

Electricity consumption (kWh/ha)			Quantity of water (m^3/ha)		Productivity (10^5 kg/ha)		Irrigation Cost ($/ha)		Percent cost savings (%)
Crops	Drip	Surface	Drip	Surface	Drip	Surface	Drip	Surface	Over Surface
Sugarcane	1,325	2,385	9,400	21,500	0.14	0.11	98.2	176.7	55.5
Grapes	2,483	3,959	2,780	5,320	0.24	0.20	183.9	293.3	62.7
Banana	5,913	8,347	9,700	17,600	0.68	0.52	438	618.4	70.8

Table 16
Irrigation systems in Australia—their operating pressure ranges and costs of irrigation per unit volume of water used [146]

Irrigation system	Source	Pressure (bar)	Energy intensity (kWh/m^3)	Irrigation cost (\$/m^3)
Surface furrow	River	0.98	0.04	0.005
Surface furrow	Bore well	4.41	0.2	0.024
Pivot/linear move low pressure		3.92	0.18	0.022
Drip/micro		4.9	0.22	0.027
Spray	River	5.39	0.24	0.030
Spray	Bore well	6.37	0.3	0.035
Traveler gun	River	8.33	0.38	0.046
Traveler gun	Bore well	8.82	0.4	0.049
Traveler gun	–	11.76	0.54	0.065

irrigation leads to high seepage and evapotranspiration losses [8]. Therefore, even though they consume less energy they would not be cost effective in the use of water.

A comparative cost and energy analysis was performed recently in Spain on different technologies and their behavior with change in area under irrigation [147]. Fig. 32 illustrates that the cost of irrigation increases as the area under the drip irrigation increases. Fig. 33 plots cost and energy use for sprinkler irrigation systems used in Spain. The cost of irrigation per unit volume decreased with increase in volume of water applied. The cost per unit area of sprinkler irrigation is location specific in this case and will therefore have a random behavior [147].

As water application increases, energy cost also increases irrespective of irrigation technology [135]. With increase in farm size, the irrigation cost will increase. The cost of tomato irrigation in Turkey for farm sizes of 0.1–2.0 ha, 2.1–5 ha, and more than 5.1 ha was about \$29/ha, \$31/ha, and \$34/ha [148]. This indicates that tomato production can be a profitable crop in terms of water used and the cost of water.

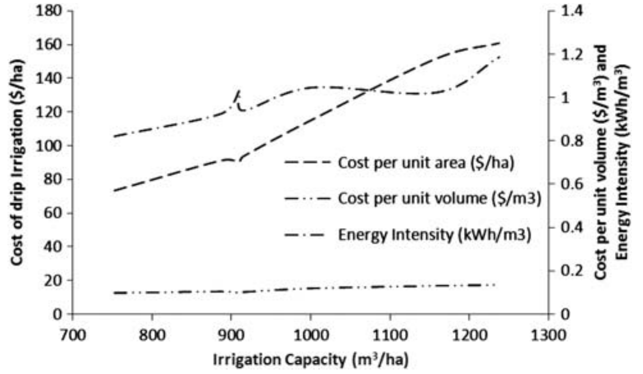


Fig. 32. The variation of cost and energy use for irrigation using drip systems in Spain [147].

Other than the factors discussed above, crop water use and expense depend on the plant type, size of plants, plant density, and climate [149]. Fig. 34 plots the percent cost inputs to pomegranate farming in Turkey using three different irrigation methodologies namely open canal system, flood of surface irrigation,

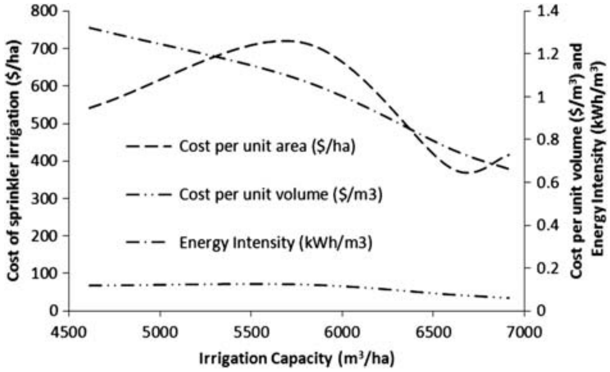


Fig. 33. The variation of cost and energy use for irrigation using sprinkler systems in Spain [147].

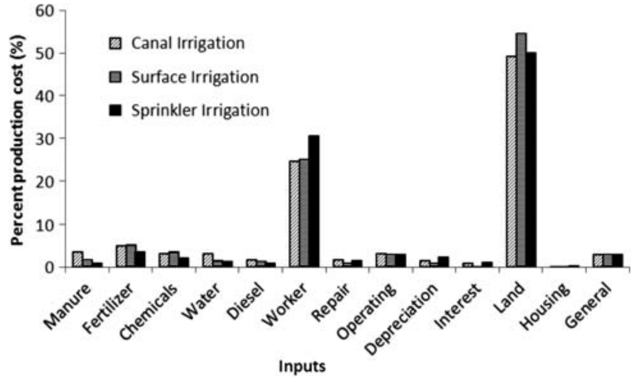


Fig. 34. Percent costs of pomegranate production using three different irrigation techniques [150].

and sprinkler irrigation using pressurized sprinkler system [150]. Their total pomegranate production costs were \$10,308/ha, \$9,785/ha, and \$15,955/ha, respectively. The percent cost of canal-based irrigation and surface irrigation was higher than a sprinkler irrigation system. Water contributed for 1.2% production cost of sprinkler-based pomegranate farming, 1.5% production cost using surface irrigation, and approximately 3.1% production cost using sprinkler irrigation [150]. Major reasons for the higher cost of canal-based and surface irrigation may be increased water loss in these systems due to seepage and evapo-transpiration. Because the sprinkler system is comparatively more water efficient, it showed high pomegranate production.

7. Conclusions

The cost of water production, treatment, supply, use, and recycling has been reviewed for the domestic, commercial, and agricultural sectors. In the water production stage, ground water pumping is usually found to be costlier than surface water pumping. Carting of small quantities of water is the costliest option in water supply. Site specific factors are very important in determining the processes used, and thus the costs in each stage of the water cycle differs with location.

Water treatment is necessary before consumption or use to remove impurities. With increasing regulation and preventive measures, treatment is becoming rigorous, energy intensive, and costly. Desalination processes are the costliest option in the water treatment stage. The capital cost of RO desalination processes was found to be less than the capital costs of pipeline transport of water over long distances. Membrane costs are in the range of 10–15% of the total project cost for membrane-based water treatment systems. Capital amortization and energy costs are the two major cost components of any membrane water treatment system. Two-phase desalination processes are costlier than single-phase processes. Hybridization can bring down both the operating and capital cost of most of the desalination plants. In water treatment systems, the cost of pumping is the largest fraction contributing to the operation costs. Cost of water at the treatment stage is dependent on the influent quality, effluent quality, regulations, technologies used, size of the plant, and energy source.

In the residential sector, the cost of heating water is the major cost associated with the use of water. Costs for boiling water vary with the cost of the energy source. Water utilities try to deliver water to its consumers at a low price. Bottling as well as delivering small quantities of potable water using tankers or trucks is very costly. The price of water depends on the production, type of use, type of delivery mechanism, location, quality, local policies, volume of water, and energy use.

In wastewater treatment plants, digestion is the costliest process in small capacity plants ($\leq$4,000 m^3). With an increase in plant size, the costs associated with aeration, filtration, and pumping increase. Advanced wastewater treatment is costlier than conventional treatment. The cost of wastewater treatment depends on influent waste loading, effluent water quality, plant size, treatment and management option, reuse options, and location.

In agriculture, with an increase in farm area, the cost of irrigation increases. For drip irrigation, there is an increase in the energy cost with increasing volume of water. The irrigation cost of fruits is more than for vegetables. The cost of irrigation will vary with change in crop or crop variety. High pressure irrigation technologies are costlier compared to low pressure technologies. Some low pressure technologies, such as surface or furrow irrigation, can lead to loss of water due to high evapotranspiration and seepage. The cost of irrigation is also dependent on climate, amount of irrigation water, source of water, area, soil characteristics of the location, spatial characteristics, crops, temperature, irrigation system and application effectiveness, pumping system type, pressure requirement at the point of use, electricity, and fuel cost.

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