Economic viability and analysis of wastewater treatment processes in Kuwait

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Abstract: A full and comprehensive economic analysis of wastewater treatment is a prerequisite for ensuring long-term economic, environmental, and social sustainability. The aim of this study is to improve the economic evaluation of treated wastewater reuse. In 2001, the Government of Kuwait built an advanced wastewater treatment plant (WWTP) at Sulaibiya. This plant is designed to treat up to 375 million imperial gallons (IG) of water, but the volume can be extended to 600 million IG. This WWTP is the first of to be built in the Middle East and is the largest plant worldwide that uses a combination of ultrafiltration (UF) and reverse osmosis (RO) for water purification. The UF step removes all suspended solids and promotes a substantial reduction in microbiological contaminants. We identify and compare the advantages and costs between using treated wastewater and desalinated fresh water. We show that while treatment costs are highly dependent on the incoming effluent quality and plant size, the benefits and advantages are reasonably high.

Keywords: economic; cost; wastewater reuse; reverse osmosis; RO; ultrafiltration; UF; wastewater treatment plant; WWTP.

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1 Introduction

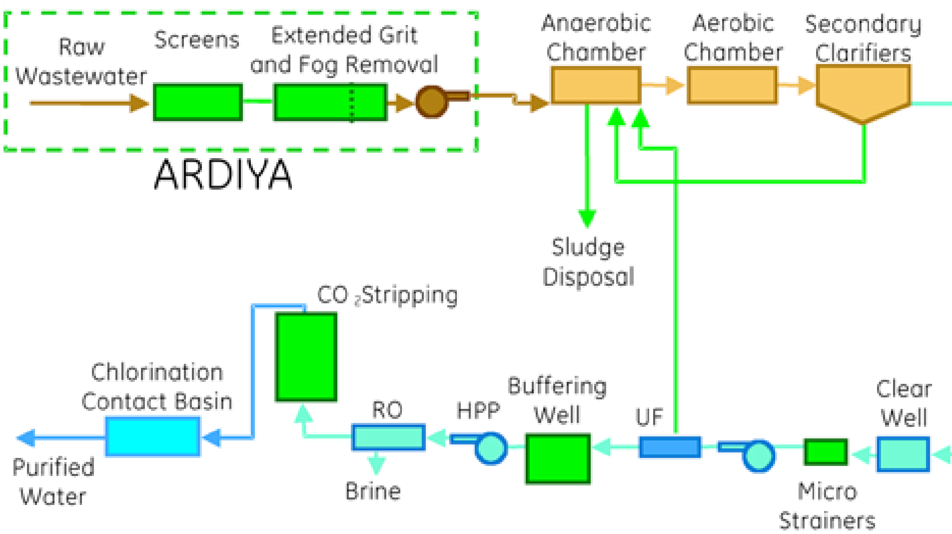
Ultrafiltration (UF) is now a generally accepted process used in wastewater treatment plants (WWTPs) for the pretreatment of the influent into a spiral wound membrane based on reverse osmosis (RO). An alternative method would require an extensive sequence of treatment steps, incurring high investment and operating costs, and even this type of treatment would not necessarily guarantee that RO feed water would be acceptable 100% of the time. More importantly, the UF process guarantees that a constant quality level of the pretreated water will be produced at a low cost, virtually independent of the quality of the feed water. Additionally, it is now accepted that UF systems can serve as an alternative to conventional technologies for pretreatment in brackish surface water RO systems. For example, a UF plant in the Netherlands has operated successfully since 1999 (Garcia and Pargament, 2015; Bruin et al., 2002).

The UF pretreatment of seawater is employed in many plants worldwide. All plants achieve the target quality of filtrates required by suppliers of spiral wound RO elements, which are typically set at a turbidity of 0.1 NTU and an SDI level of 3. Despite their success, few dual-membrane desalination plants are currently in operation. However, plants of this type are currently being constructed in the United Arab Emirates (UAE), Saudi Arabia, Bahrain, and China (Beecher and Gould, 2018; Bergion et al., 2018; Basha et al., 2005). While decision makers generally consider the use of UF for wastewater treatment to be technically feasible, it is not considered economically viable (Djukic et al., 2016; Côté et al., 2005). This report summarises an economic evaluation of the Sulaibiya WWTP, which uses the UF pretreatment process.

In May 2001, the Government of Kuwait awarded a ‘build, operate, and transfer’ (BOT) contract to Mohammed Abdulmohsin Al-Kharafi & Sons company (The Kharafi Group) for financing, designing, building, and operating an advanced WWTP at Sulaibiya (Figure 1). Al-Kharafi, a Kuwaiti family-owned group, is the largest contractor in Kuwait, with an annual turnover of KWD 1 billion, having completed over 1,250 projects, 30 of which have been sewage treatment construction contracts. The BOT contract awarded in 2001 has a 30-year life, divided into 30 months of design and building and 27.5 years of operation and management. Construction started in July 2002 and was completed in November 2004,with a total cost of KWD 116 million, and the project is expected to provide total revenues to the Utilities Development Company (UDC) in excess of KWD 5.9 million. The winning bid by the consortium was KWD 0.142/m^3. Shortly after its completion, the project won the ‘Wastewater Project of the Year’ 2005 Global Water Award. The judges described it as a ‘powerful statement of the future of water resources across the whole Middle East and North Africa region' (Alhumoud et al., 2010; Gottberg et al., 2003; Gottberg and Vaccaro, 2003; Young Ko et al., 2004).

The Sulaibiya WWTP currently treats up to 375 million imperial gallons (IG), and its design enables it to be extended up to 600 million IG. It is the first of its kind to be built in the Middle East and the largest worldwide facility that uses a combination of UF and RO for water purification. The major steps in the treatment process are schematically shown in Figure 1 (Alhumoud et al., 2010; Gottberg et al., 2003; Gottberg and Vaccaro, 2003; Young Ko et al., 2004). The basic goal of the project was to have the Sulaibiya Wastewater Treatment and Reclamation Project (WWT&RP) replace the existing Ardiya WWTP, which was no longer capable of treating the increasing amounts of wastewater produced in Kuwait. Moreover, the tertiary treated effluent from the Ardiya plant contains a high level of flocculated suspended solids, which require a significantly greater filtration capacity than that used to treat sea or ground water. Because the amount of brackish water is no longer sufficient to meet the increasing demand for non-potable water, the municipal effluent arising from preliminary treatment at Ardiya is now piped 25 km (16 miles) to the Sulaibiya facility.

Figure 1 Major steps in the treatment process at Sulaibiya WWTP (see online version for colours)



The water quality parameters used as basis for the design of the Sulaibiya plant are listed in Table 1. The WWTP is designed to transform the influent, which is typically domestic sewage, to an effluent with average monthly values lower than 20 mg/L BOD and 20 mg/L TSS, to accommodate peaks in water quality arising from perturbations in plant performance. The average total dissolved solids (TDS) in the feed stands at 1,280 mg/L, and the plant produces water with less than 100 mg/L TDS, a value that exceeds the potable water guidelines of the World Health Organization (WHO) (see Table 1).

Table 1 Water quality parameters used for designing Sulaibiya WWTP

Water quality parameters	*Conventional treatment plant*[a]	*Advanced treatment plant*[a]	*WHO guidelines*[b]
pH	7	6-9	6.5–8.5
TSS (mg/L)[c]	12	<1	
BOD (mg/L)	5	<1	
Ammonia nitrogen as N (mg/L)	<2	<1	
Nitrate (mg/L as N)	<9	<1	10
Phosphate (mg/L as PO4)	<15	2	
Fat, oil and grease (mg/L)	<0.5	<0.5	
TDS (mg/L)	<1,280	100	1,000

Notes: [a]Average monthly value;
[b]For potable water;
[c] ± 50%.

2 Ultrafiltration system

It is important to point out that pretreatment is required to use today's highly efficient membranes in the RO process. Membrane filtration was selected for use in the Sulaibiya WWTP for robust pretreatment of the secondary-treated municipal effluent before being fed to the RO. In contrast to conventional tertiary clarification and filtration procedures, RO reduces chemical consumption and guarantees that water has low turbidity after the pretreatment process. In addition, it was expected that the higher quality pretreatment provided by using this method would lead to a longer life of the membranes, lower operating pressure, and reduce the frequency of cleaning the TFC membranes based on a quick fouling RO system. Additionally, the combination between UF and RO used in the Sulaibiya plant removes bacteria and pathogens, providing potable quality water suitable for agriculture or groundwater recharging (Yong Ng et al., 2018; Iwahori, 2005; Caneja et al., 2005; Tortajada, 2006).

A thorough evaluation of the bids for the membrane filtration system at the Sulaibiya WWTP, solicited from major suppliers, led to the selection of the Norit UF system, which has favourable life cycle costs. The UF process at Sulaibiya utilises Norit's X-Flow membranes, composed of capillary hydrophilic hollow fibres packaged in 8” × 60” (20 cm × 152 cm) membrane elements, with per element areas of 35 m^2. Four membrane elements are incorporated in each membrane housing and 32 membrane housings are contained in each UF unit. This plant has 68 skids, each containing 32 membrane housings, giving a total of 8,704 membrane elements. The UF units are operated individually and each is backwashed regularly to remove suspended matter. The backwash water is re-introduced upstream of the plant to gain the highest possible overall water recovery efficiency. Finally, the Sulaibiya plant operates continuously and is fully automatic and, thus, requires limited operator attention.

Occasionally, low doses of chemicals are added during the backwash process, called chemically enhanced backwash (CEB), to remove matter that has adhered to the membrane surface and was not removed by the hydraulic backwash alone. Because the backwash and CEB processes are scheduled on an individual unit basis, only a minor portion of the plant's UF capability is removed at any time. This procedure ensures the continuous flow of the effluent from the plant. The effluent fed to the UF first passes first through a disk filter, after which a small amount of coagulant is added to coagulate fine particulates and allow some TOC removal. The SDI of the UF output is below 2, an important criterion for smooth performance of the following RO process. Previous experience, gained from treating secondary municipal effluents by using UF, has shown that SDI values below 1 are possible (Bruin et al., 2002).

A summation of the main characteristics of the new membrane system utilised in the WWTP at Sulaibiya are as follows:

- ultrafiltration provides good removal of suspended solids and results in a low turbidity and SDI
- hydrophilic polyethersulfone is used because of its high permeability and low fouling tendency
- operation by using dead-end flow minimises energy consumption
- pressurised inside-out filtration enables direct feeding from the intake into the RO high pressure pumps, thus eliminating inter-stage tanks
- short cleaning cycles employing chemically enhanced backwashes minimise the fluctuations of flow into the RO system.

3 Reverse osmosis system

The salinity of the municipal effluent has an average monthly value of 1,280 mg/L TDS and a maximum value of 3,014 mg/L. RO is used to lower the salinity of the effluent to 100 mg/L TDS, as well as provide a second barrier to bacteria and viruses. The RO technology used in the system at Sulaibiya consists of 42 identical skids in 4:2:1 arrays. Approximately 200,000 membranes are used in the RO system, which is limited to operate at 85% recovery by calcium phosphate precipitation, frequently a limiting factor for water recovery in membrane systems utilised for desalinating municipal effluents. The RO product passes through a stripper to remove carbon dioxide and adjust the pH using a minimum amount of sodium hydroxide. The product is then chlorinated before leaving the plant and the RO brine is pumped into the Gulf.

4 Total ownership cost

The government of Kuwait subsidises water production heavily. While the cost paid by the Ministry of Electricity and Water (MEW) for the production of 1,000 imperial gallons (IG) is KWD 10.836, customers are charged KWD 0.8. The Al-Kharafi company sells 1,000 IG of treated wastewater produced at the Sulaibiya plant to MPW for KWD 0.800, while MPW charges customers (farmers) only KWD 0.200. The cost of tertiary treated wastewater is MPW KWD 0.400. However, because wastewater is treated using both the UF and RO processes, treated water coming from this plant costs an additional KWD 0.500. In view of the rapidly increasing costs of the water supply systems caused by several factors, including inflation, the rate charged by the MEW seems to be unreasonably low.

In general, the weighted contributions of the components inthe operation of a WWTP to the total cost of ownership (TCO) are (Nordman et al., 2018; Smith et al., 2018; Frone and Frone, 2012):

- ±17%: pretreatment
- ± 6%: RO membrane replacement and cleaning
- ±27%: other fixed costs (amortisation of other equipment, etc.)
- ±50%: other variable costs (energy costs, etc.).

When UF is utilised instead of conventional technologies as pretreatment for the input into the RO system, the contributions to the TCO of a plant change. If the sum of the individual inputs into the TCO for UF is lower than a TCO estimated above KFills 24/m^3, the use of UF is not only technically feasible but also economically attractive. Consideration should be given not only to the actual cost of the pretreatment system but also to changes in other costs (both fixed and variable) associated with using this pretreatment system. All contributions to the TOC of a WWTP are assessed in the following and the impact of using UF as pretreatment process is identified and quantified.

4.1 Pretreatment

Many different conventional systems can be employed for pretreatment in sea water reverse osmosis (SWRO) systems. The generally recommended methods for proper conventional pretreatment are flocculation, dissolved air flotation and filtration, or flocculation, settling, and filtration (Clunie et al., 2005). It should be noted that the disinfection, flocculation, and filtration sequence does not always provide an adequate quality of the effluent (Birol et al., 2010).

When conventional technologies are used, the pretreatment contribution to the TCO is approximately 17% of KFills 24/m^3, which corresponds to KFills4/m^3. The pretreatment costs can be split into amortisation of investment and operating costs (mainly chemicals for coagulation and disinfection). However, when UF is employed for pretreatment, investment costs increase. Moreover, while the costs for chemicals (mainly coagulant) decrease or are eliminated, the new cost of the UF membrane replacement needs to be factored in.

Approximately KFills 2.1 of the total KFills 4.1 that contribute to pretreatment costs are attributed to chemical dosing. This amount is reduced by at least 25–50% when UF is used for pretreatment. The other half of KFills 4.1is attributed to the amortisation of the pretreatment system, which increases by approximately 10–20% when UF is utilised, owing to the fact that the additional cost of membrane replacement is approximately KFills 3/m^3 (considering a membrane life time of eight years). Therefore, by utilising the UF technology, the pretreatment component of the TCO will decrease by 0–20%. When the additional KFills 3/m^3 needed for UF membrane replacement is considered, the contribution of 'pretreatment' to the TOC is approximately KFills 3.2–4.3/m^3.

4.2 RO membrane replacement and cleaning

When a conventional technology is utilised for pretreatment, the RO replacement and cleaning components of TCO are approximately 6% of KFills 24/m^3, corresponding to approximately KFills 1.4/m^3. However, when UF is employed for pretreatment, the RO cleaning frequency is significantly reduced. Pilot studies have shown that the frequency of cleaning RO membranes is virtually eliminated when the UF pretreatment is used. Therefore, the cleaning frequency can typically be reduced from once every 2–3 months to once every 6–12 months. Because the extent of RO fouling and chemical degradation is reduced by using UF, the RO membrane life time increases. It is thus accurate to state that the RO life can be increased from 6 to at least 7 years conservatively, with 8 years or longer being perhaps more realistic (Molinos-Senante et al., 2011). The costs of membrane replacement and cleaning are nearly equal (Young Ko et al., 2004). By using UF pretreatment, RO cleaning will be reduced by 50% and replacement by 15–30%, while the weighted average of both costs will be reduced by 30–40%. As such, by using the UF pretreatment technology, the 'RO membrane replacement and cleaning' input into the TCO will be approximately KFills 1.1/m^3.

4.3 Other fixed costs

Whena conventional technology is employed for pretreatment, the 'fixed costs' component of the TCO is approximately 27% of KFills 24/m^3, corresponding to KFills 6.5/m^3. The fixed costs are a function of the on-line time of the plant, with a shorter on line-time leading to a higher fixed cost. The reason for this is that fixed costs correspond to cost divided by the amount of total filtrate produced over the complete life cycle, so that when the plant is off-line and not producing water, the fixed costs expressed in costs per m^3 increase.

Compared to conventional technologies, UF has the following benefits:

- Shorter construction time. This is an important factor in BOT contracts having a fixed lifetime. When the construction time decreases, the plant produces clean water for a longer time. It is assumed that the construction period can be reduced by 3–6 months. For a typical lifetime of 20 years, this means net production can be increased by 1–2%.
- Because of the decreased RO cleaning frequency, a RO plant using UF pretreatment will have more operational days per year. When the time for RO cleaning decreases by 5 days per year, the net RO output increases by approximately 2%.
- Other fixed costs, such as land purchase, will be reduced as well.

It is safe to assume that an overall reduction of approximately 4% in other fixed costs will occur when UF as opposed to conventional technologies is used for pretreatment and, consequently, the 'other fixed costs' component of the TCOwill be approximately KFills 6.2/m^3.

4.4 Other variable costs

When conventional technologies are used for pretreatment, the 'variable costs' portion of the TCO is approximately 50% ofKfills 24/m^3, which corresponds to KFills 12.2/m^3. It can be argued that variable costs will be reduced when conventional pretreatment is replaced by UF technology. Lower RO fouling will lead to a lower decline in flux and, consequently, a lower RO operating pressure. Additionally, a UF pretreatment-based plant has a higher degree of automation and, thus, the labour requirement will be lower. However, it is difficult to quantify these cost savings. Therefore, they have not been considered. As a result, it is assumed that the variable costs when UF pretreatment is used will also be KFills 12.2/m^3.

4.5 Total cost of ownership

The total cost of ownership of a SWRO desalination plant using conventional pretreatment technologies is approximately KFills 25/m^3. When UF is employed for pretreatment, the TCOof dual membrane desalination using UF-pretreatment will be KFills 25/m^3. This factor results in a 2–7% reduction in the TCO compared to plants using conventional pretreatment methods. In addition, the use of UF pretreatment provides the following non-quantifiable benefits:

- Less construction risk because building an UF pretreatment facility requires a substantially lower civil work force. Unstable soil conditions have a lower impact on the UF facility and UF skids can be constructed in workshops and then shipped to the site after the construction work has finished.
- Smaller footprint. Apart from cost savings arising from the purchase of land, additional benefits, such as a greater freedom of choice for the site location and a potentially easier process for obtaining a permit for civil construction, are possible.

Variations in the quality of input water will have a negligible influence on RO performance.

5 Water use and cost

Over the past three decades, Kuwait has witnessed an unprecedented economic and social transformation. Specifically, a significant portion of its oil revenues has been used to modernise infrastructure and improve the living standards of the population. As a result, water supply and sanitation services have been made accessible to a large percentage of the population. Moreover, life expectancy has increased from 64 to 74 years over 1980–2015and literacy rates have increased from 20% to around 90% over the same period. Finally, the gross national per capita income (GNI) was estimated to be around USD 137,069 in 2016, the gross domestic product (GDP) around USD 135,109 and the average population growth rate at 3.5% (CSB, 2017).

Figure 2 Water consumption in Kuwait during 1954–2015 (see online version for colours)

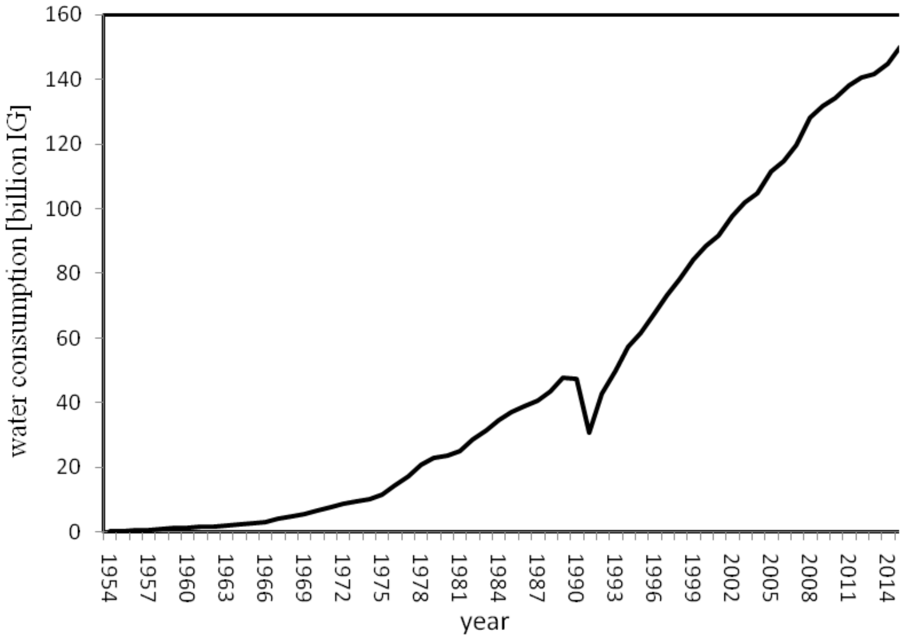
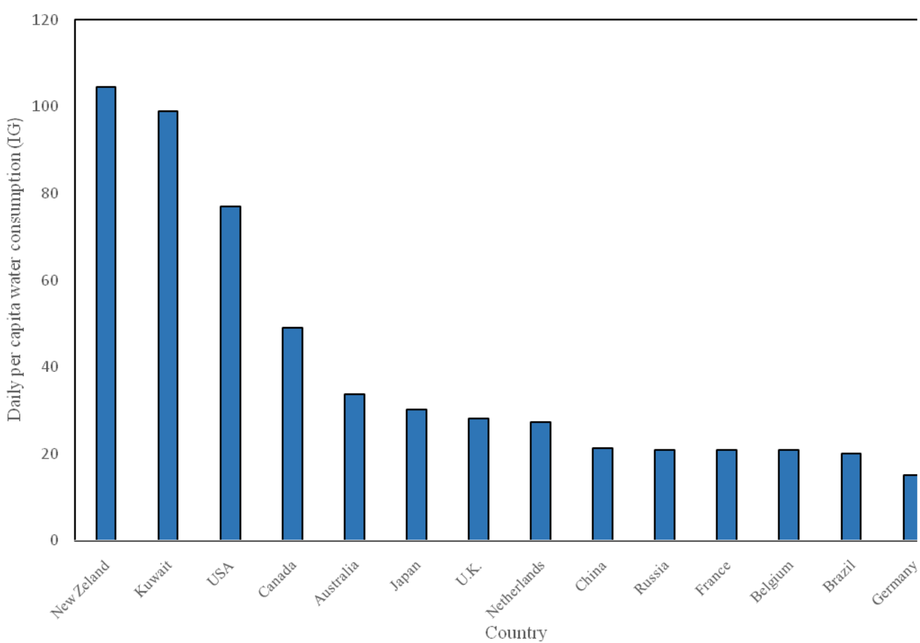
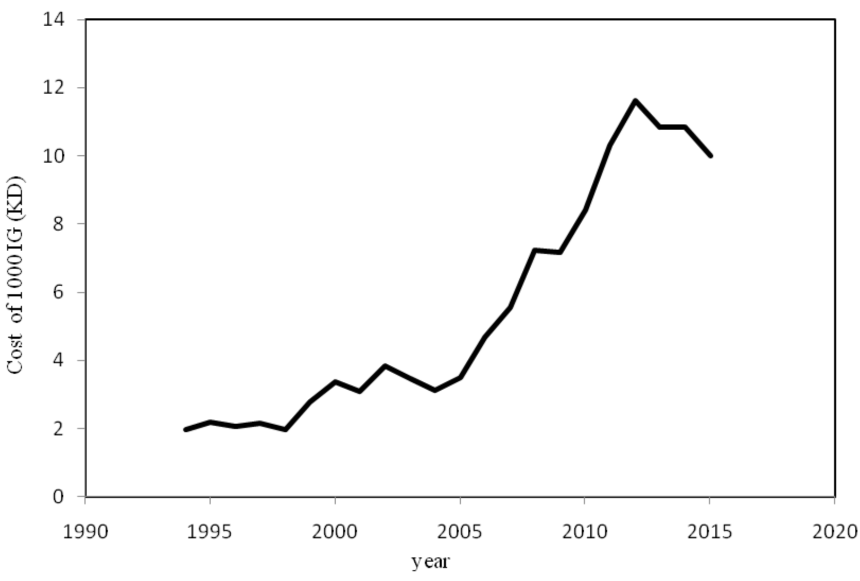


Figure 3 Daily per capita fresh water consumption in different countries (see online version for colours)



During this period, the total demand for water has also increased dramatically as a result of the high population growth, improvements in living standards, industrial development in major urban centres, and efforts to increase food self-sufficiency. From Figure 2, with the exception of 1990 and 1991 (period of the second Gulf war), the consumption of water in Kuwait has gradually increased. Additionally, the per capita consumption of water in Kuwait and in various other countries is displayed in Figure 3 (MEW, 2016). Two factors are responsible for the current increase in urban water demand in Kuwait, namely the rapid population growth and the increase in per capita consumption. The average population growth in Kuwait over the last two decades has been among the highest worldwide (around 3.5% per annum). More strikingly, the average daily water consumption per capita was only around 27 IG in the 1960s and is now around 111 IG. Nowhere else in the world has the per capita water consumption risen so rapidly over such a short period. A close inspection of Figure 2 suggests that water consumption in Kuwait experienced exponential growth over the sample period for the reasons above. The plot suggests a constant proportional growth rate of approximately 8% per annum. Further, the cost of water production in Kuwait has increased dramatically. From Figure 4, 1,000 imperial gallons produced in 1994had a cost of KWD 1.993, however, which value has increased more than five time by 2015.

Figure 4 Cost of water in Kuwait per 1,000 IG during 1994–2015 (see online version for colours)



6 Economic evaluation of treated wastewater

In a monetary analysis of water reuse projects, it is important to distinguish between the cost and price of water, while only the future flow of resources invested in or derived from a project should be considered. Past investments are considered irrelevant in making future investment decisions. Therefore, debt service on past investments is not included in the economic analysis. The price of water is the amount paid to a water wholesaler or retailer to purchase water, being usually a combination of current and past expenditures for a combination of projects, as well as water system administration costs, which are generally fixed. For economic analysis, only the costs for future construction, operation, and maintenance are relevant.

To estimate the cost of the tertiary treatment system at Sulaibiya, several extant studies were used (Asano et al., 1996; Tchobanoglous and Angelakis, 1996; MPW, 2015; MEW, 2016). Wastewater effluent reuse costs derive from two factors. The first is the additional treatment needed to reach the reuse water quality requirement and the second is the extra transportation of the effluent to the reuse sites. The financial benefits of reusing wastewater effluent are associated with the value of the water saved and the costs for alternative systems for the safe disposal of the effluent. The price of water in Kuwait is low compared to other countries. As previously mentioned, Al-Kharafi company sells 1,000 IG of the water produced at Sulaibiya plant to MPW for KWD 0.800 and MPW charges customers (farmers) only KWD 0.200. Water prices in Kuwait are amongst the lowest in the developed world, with an average price of approximately KWD 0.18 per 220 IG compared to KWD 0.65 in Germany. In Singapore, the costs of the domestic consumption of water up to 8,799 IG per month and nondomestic uses are uniform, at a rate of KWD 0.25 per 220 IG. For domestic consumption of more than 8,799 IG/month, the cost is KWD 0.35per 220 IG (Licciardello et al., 2018; Feuillette et al., 2016). The average treated cost for agricultural reuse in Puglia, Italy, ranges from 0.06 to 0.09 KWD/m^3. However, the use and option value that farmers may derive from reclaimed wastewater reuse are in the range of 0.07 to 0.08 KWD/m^3 (Arborea et al., 2017).

The unit costs incurred at various stages of wastewater treatment and from fresh desalinated water are shown in Table 2. These costs, based on the assumption that each person consumes 111 IG per day or 48,694 IG per year, include treatment (chemical addition, filtration, solids treatments), distribution, administration (accounting, monitoring, overhead), and replacement reserve fees.

Table 2 Costs of water produced using different treatment types

Type of effluent treatment	*Cost (KWD) per 1,000 IG*	*Cost (KWD) per person per day*	*Cost (KWD) per person per year*
Secondary (1,000 Fecal coliform/100 ml)	0.483	0.054	19.71
Tertiary (0 Fecal coliform/100 ml)	0.574	0.064	23.36
Advanced (UF and RO)	1.000	0.111	40.52
Desalinated water	10.836	1.203	439.10

Kuwait has a population of 4,577,626 and the country's annual total costs are KWD 90.225 million for secondary treated wastewater, KWD106.933 million for tertiary treated effluent, and KWD 185.5 million for advanced treated wastewater (UF and RO). These amounts should be compared with KWD 2 billion for water desalination. Therefore, the use of advanced treated effluent costs the country KWD 78.6 million a year more than that using the tertiary treated effluent. Moreover, using desalinated water would cost KWD 1.9 billion and KWD 1.8 billion a year more than using tertiary and advanced treated effluents, respectively. As the capital and operating costs of seawater desalination plants increase, the economic benefits of reusing water will also increase correspondingly. Therefore, a wider range of uses of treated effluents should be given serious consideration.

7 Conclusions and recommendations

The rate charged for water throughout Kuwaitis low. While the cost to the MEW for producing 1,000 IG of water is KWD 10.836, customers are charged only KWD 0.8. In view of the rapidly increasing costs of water supply systems, the user rates seem unreasonably low.

This study thus represents the first attempt to introduce and improve the economic analysis so as to enhance Kuwait's public investment planning. In addition, this work provides a scientific contribution that should facilitate a comprehensive evaluation of costs and benefits.

MPW and MEW should consider the reuse wastewater treated effluents. In many areas worldwide, secondary treated wastewater is used for irrigation. By contrast, purified treated effluents produced in Kuwait are of such high quality that they can be used in an unrestricted manner for various purposes. Alternatively, a viable option is that treated water could be used to irrigate the Abdali farms in the north and/or the Wafra farms in the south of the country; in addition, it could be discharges into the natural reserve in the north-east of Kuwait.

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Nomenclature

BOD	biochemical oxygen demand
BOT	build, operate, and transfer
CEB	chemically enhanced backwash
GDP	gross domestic product
GNI	gross national per capita income
IG	imperial gallon
KWD	Kuwaiti Dinar (1 KWD = 3.4 USD)
KFills	Kuwaiti Fills (1 KWD = 1,000 Fills)
MEW	Ministry of Water and Electricity
MPW	Ministry of Public Works
NTU	nephelometric turbidity units
RO	reverse osmosis
SDI	still density index
SWRO	sea water reverse osmosis
TDS	total dissolved solids
TCO	total cost of ownership
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration
WHO	World Health Organization
WWT&RP	Wastewater Treatment and Reclamation Project
WWTP	Wastewater Treatment Plant.