Official Journal of the World Water Council
Water Policy

Water Policy Vol 24 No 6, 980 doi: 10.2166/wp.2022.012

Diversification of urban water supply: An assessment of social costs and water production costs

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ABSTRACT

The incorporation of new water sources into a supply system requires an assessment of their economic feasibility, which, in turn, demands knowledge of their associated costs. This study calculates water production cost and evaluates social cost by applying the residual value method and calculating the shadow price for several water sources. The results indicate that desalination and industrial reuse incur similar costs, with the former being more competitive in terms of investment (US dollar (USD) 0.28/m^3) and the latter in operation and maintenance (USD 0.57/m^3). Cisterns and greywater reuse incur higher investment costs (USD 2.20/m^3 and USD 2.60/m^3, respectively), while well water has the lowest total cost (USD 0.08/m^3). Desalination showed the lowest degree of distortion between shadow price and water cost and between shadow price and the average tariff; meanwhile, there was moderate distortion for industrial reuse and groundwater sources. The conclusions suggest that desalination and industrial reuse offer good flow at feasible costs and are, therefore, strategically sound sources. However, for these sources and for wells, tariff policy does not reflect a significant part of the social cost they incur.

Key words: Cost, Residual value method, Shadow price, Urban water supply

HIGHLIGHTS

- Diversification of water supply is essential to increase water security of urban areas.
- Industrial reuse has the highest shadow price and desalination, the highest water cost among alternative water sources.
- Industrial reuse and wells have a higher distortion between shadow price and average water tariff than desalination.

GRAPHICAL ABSTRACT

INTRODUCTION

Water scarcity restricts development (Bai *et al.*, 2021). The challenge of water policy and management is to provide various stakeholders with the water supply to meet the needs of social life (Rey *et al.*, 2019). Hence, it is important to balance investments in technology and infrastructure with issues related to governance, so that concrete – infrastructure – is not privileged at the expense of management – governance (Webber *et al.*, 2017).

Certain contexts promote scarcity and affect water security, thus amplifying the intrinsic challenges of water provision (i.e. unlimited demand and finite supply); they are climate change, population growth, and increased economic activity (Bai *et al.*, 2021). Regarding these scarcity promoters, Liu *et al.* (2019) point out that urban and industrial pressure increases water-pollutant levels, thus exacerbating supply problems.

Scarcity inevitably stems from a continuous (and increasingly intense) growth in domestic and productive demand for a good for which there is a finite supply; in the case of water, demand is enhanced by climate change, which can intensify extreme events, such as droughts and floods. Maliva *et al.* (2021) report the impacts of climate change on urban water supply, such as the intrusion of saline water into aquifers, caused by rising sea levels, and the reduction of water availability in reservoirs, caused by increased evaporation. Alves *et al.* (2021) point to a greater variability of rainfall due to climate change, causing longer and more intense drought periods, especially in Northeast Brazil, which affects water availability.

Furthermore, although climate change is a key discussion topic among policy and supply decision-makers, it remains unclear whether it guides adaptive planning to any great extent (Maliva *et al.*, 2021). The use of alternative supply sources has played a positive role in reducing scarcity and increasing water security.

Water transposition among basins is often presented as a supply-problem solution that helps guarantee urban water security; however, it also generates conflicts (Ioris, 2001) vis-à-vis donor-basin shortages (Webber *et al.*, 2017) and impacts supply costs (Braga *et al.*, 2009). Therefore, it is important to ascertain alternative water sources within a given region itself and seek out a supply–demand balance.

Thus, the diversification of the supply matrices of urban centres is a strategy to ensure water security. Diversification means not only increasing the water supply, but also providing a number of opportunities to develop new productive supply chains linked to the water-resource sector and democratizing water access. Diversification has been carried out using desalination plants, water reuse, groundwater, and water transfers, among other sources. These alternative supply sources are a reality in several parts of the world, and they are enacted to reduce scarcity and ensure water security (Zhu *et al.*, 2018; Maliva *et al.*, 2021). In the US state of Florida, seawater desalination and wastewater reuse complement the groundwater supply system (Maliva *et al.*, 2021). In Costa del Sol, Spain, reservoir water stocks are complemented by other sources, including desalination plants, transfers, wells, and water recycling, especially in periods of drought (Webber *et al.*, 2017).

Incorporating new water sources into a supply system requires knowledge of the associated costs, to assess their economic feasibility. In this context, this study calculates the cost of water production and evaluates its social cost. We used data provided by water management institutions and undertook budget calculations to obtain water production costs. We also employed the residual value method (Young & Loomis, 2014) to obtain the shadow price of water, which reflects its social cost. Here, we calculate the shadow price to evaluate the benefits and costs of the water supply company when making water available from the following sources: desalination, industrial reuse, and wells (the water company does not take into account costs and benefits from cisterns and greywater reuse, hence these were excluded from the shadow price calculation). If the shadow price estimate exceeds the cost of producing water from a given source, decisions will tend to favour using that source. Therefore, our study answers questions related to (i) the identification of supply costs and shadow prices and (ii) the degree to which the supply costs and shadow prices of various supply sources diverge.

According to Young & Loomis (2014), for water uses involving government decision-making, estimations of the social price (also called the shadow price) are often needed to support decisions regarding the efficient system allocations and investments. From a social perspective – which differs from a private perspective – benefits and costs are evaluated through social prices, which can be understood as the social willingness to pay for or receive goods and services; economic transactions scarcely reflect these prices. The shadow price of water indicates the social opportunity cost of water for society, in the case of both final use (domestic) and intermediate use (productive sector). When the social price of water diverges from the prevailing price (tariff), then social and private valuations also diverge. Researchers have developed shadow price estimates for water in different sectors and under different methods and have found that these prices diverge from the practiced tariffs (Ziolkowska, 2015; Qamar *et al.*, 2018; Wang *et al.*, 2018). There is a lack of empirical research that obtains shadow price estimates by using the residual; despite the simplicity and robustness of this method, it is infrequently observed in the literature (Ziolkowska, 2015; Rodrigues *et al.*, 2021).

Moreover, most studies that address shadow price under the lens of the residual value method do so with respect to irrigated agriculture. There is a relative dearth of research that addresses the urban supply sector, especially when it involves various alternative supply sources. On the contrary, Wang *et al.* (2018) estimate the shadow price of water in the Chinese industry by using the directional distance function method; this method has also been used to estimate shadow prices related to the quality of supply in Chile (Maziotis *et al.*, 2020) and England and Wales (Molinos-Senante *et al.*, 2016).

To date, no study has applied the residual value method to evaluate the shadow price of urban water supplies. We attempt to fill this research gap and discuss the shadow price of water using the residual value method; we do so by undertaking empirical research into urban water supplies that comprise several alternative supply sources. In addition, we provide water production cost estimates for Brazil, a Latin American country whose socioeconomic context is quite different from that of other nations most frequently mentioned in the literature (i.e. Asian, European, and North American countries).

STUDY AREA

The methodology was applied to the city of Fortaleza, Ceará, which is located in the Brazilian semi-arid region. Fortaleza is the fifth most populous city in Brazil, with an estimated population of over 2.7 million. The city is the urban centre of the Região Metropolitana de Fortaleza (RMF), which includes 18 other small municipalities. From this point on, this paper refers to both Fortaleza and RMF as synonyms (when the focus is restricted to the city, we will mention it in the text).

Ninety-three per cent of Ceará's territory is in the Brazilian semi-arid region, with low rainfall (annual historical average rainfall of less than 700 mm), and a high spatial and temporal variability (annual and interannual), which makes dry periods common (the last drought lasted six years, from 2012 to 2017). These characteristics lead to low levels of water storage in surface reservoirs during the year.

Fortaleza is mostly supplied with surface reservoirs and transposition channels that make up the Jaguaribe-Metropolitan system. The Castanhão reservoir (capacity of 6700 hm^3) is the largest in Ceará and is located in the Jaguaribe basin, adjacent to the RMF. The Eixão das Águas, with 255 km of extension, is composed of channels, water mains, tunnels, and pumping stations that transfer water (maximum flow of 22 m^3/s) from Jaguaribe to the reservoirs that supply the RMF (Pacajus, Pacoti, Riachão, and Gavião).

The São Francisco River Integration Project (from Portuguese, PISF) transfers water to Ceará (with a maximum flow of 7.57 m^3/s) from the Submédio São Francisco basin, located in Bahia and Pernambuco (both also in Northeast Brazil).

METHODS

Data on cost and volume of water produced

The alternative sources of water supply for the Jaguaribe-Metropolitano system, which serves the city of Fortaleza, comprises a range of options. We obtained (or estimated with reference to several technical reports, articles, and databases) investment data and fixed and variable operation and maintenance (O&M) costs, as well as the volumes of water that the set of alternatives produced. These data sources were as follows:

- Desalination: we used data from the financial modelling of the desalination plant project for the RMF, obtained from a report by the Ceará Water and Sewage Company (CAGECE, 2020).
- Industrial reuse: we used data from the design of treatment plants for the RMF, obtained from the CAGECE report.
- Greywater reuse in plots: we used budgets prepared by Schroeder *et al.* (2017) to obtain costs and calculate the number of connections and volume of reuse, based on data provided by CAGECE.
- Wells: we used flow rate and well-drilling cost data provided by the Superintendence of Hydraulic Works (SOHIDRA) of the Ceará state government; we adjusted these data for use in our study.
- Cisterns: we used and adjusted budget data prepared by Sales (2016).
- Transposition: we sourced PISF costs and tariff data from Fundação Getúlio Vargas (FGV) reports.

When necessary, we updated all costs to December 2019 values, using the National Index of Construction Cost (INCC) and the General Price Index–Domestic Availability (IGP–DI), both of which are prepared by FGV. We applied the INCC to investment costs, as it is a specific civil construction index; we adopted the IGP–DI for O&M costs, as it is useful in updating the production values (income) of firms within the country. Our cost estimates apply the 2019 average exchange rate of the Brazilian real (BRL) against the US dollar (USD)–namely 3.9451 (BRL/USD). Another common procedure in the analysis is the use of a capital recovery factor, $FRC = [(1+i)^n \cdot i]/[(1+i)^n - 1]$, which considers an interest rate (i) and a period (n) to obtain annuities associated with the investment costs of the various alternative sources.

Calculating the shadow price of water

The social or opportunity cost of a factor is a value that is rarely used in economic transactions. In the literature, this cost can be called a shadow price, and it can be obtained by using the residual value method (Kim *et al.*, 2020; Young & Loomis, 2014).

Using the residual value method, we can obtain the shadow price of water. Through it we can determine the contribution of each factor to the total output, while considering that if the price of all factors (except water) is defined in the market, the remaining residual of the total output can be identified as the shadow price of water (Young & Loomis, 2014; Qureshi *et al.*, 2018; Rodrigues *et al.*, 2021). Assuming that technology is constant and all other factors are variable (except water), the total value of water production $(Q \cdot p)$ can be defined as a function of the marginal contribution of each factor – that is, the opportunity cost of factors:

$$(Q \cdot p) = \sum_{i=1}^{n} (vmp_i \cdot X_i) + (vmp_w \cdot X_w), \tag{1}$$

where Q is the quantity of water demanded or produced, p is the average water tariff, vmp_i is the value of the marginal product of the ith factor used in water production, X_i is the quantity of the ith factor, vmp_w is the value of the marginal product of water, X_w is the quantity of water produced, and n is the number of factors considered (besides water). It is worth mentioning that while calculating the benefit $(Q \cdot p)$, the water tariff was applied to 100% of the produced volume and the sewage tariff to 80% of the consumed volume; this is CAGECE practice.

In the residual method valuation, it is assumed that factor prices, except that of water, are defined in the competitive market (known constants); maximizing behaviour occurs and the market price reflects the value of marginal product (opportunity cost) of factors, except water (Young & Loomis, 2014). Thus, only water is admitted with its shadow price, and Equation (1) can be rewritten as:

$$(Q \cdot p) = \sum_{i=1}^{n} (p_i \cdot X_i) + (sp_w \cdot X_w) \tag{2}$$

where p_i is the market price of the ith factor used in water production and sp_w is the shadow price of water.

Thus, since the only unknown is sp_w, it can be isolated by subtracting the cost of all other factors from the total value of production, leaving a residual that works as an estimate of the value of water (Young & Loomis, 2014; Qureshi *et al.*, 2018; Rodrigues *et al.*, 2021). Therefore, we obtain sp_w as the ratio of the net returns of production to the amount of water produced:

$$sp_w = \frac{\left[(Q \cdot p) - \sum_{i=1}^{n} (p_i \cdot X)\right]}{X_w} \tag{3}$$

This method provides the average value of water (USD/m^3); it is considered the residual value, since all remaining inputs have a market cost. In the residual valuation, for water supply projects, the total company benefit $(Q \cdot p)$ represents the opportunity cost of all the inputs used for water production. The total cost $(p_i \cdot X_i)$, excluding the cost of water, comprises all the items that make up the factors used (investment and O&M costs) with prices defined in the market.

After estimating the shadow price, we calculated a water price-performance index (Wang *et al.*, 2018) to measure the distortion of the price currently charged (water tariff) by the utility. This index is obtained by:

$$PPI_w = 1 - \left(\frac{ap_w}{sp_w}\right) \tag{4}$$

where PPI_w is the water price-performance index and ap_w is the average price (average tariff) of water. The shadow price indicates the marginal product of water, which is always greater than 0. If $ap_w = 0$ – which is unreasonable and unlikely in practice – then $PPI_w = 1$. If $ap_w = sp_w$, then $PPI_w = 0$. It could occur if the price of water truly indicated its opportunity cost; from a strictly economic perspective, this is somewhat wishful, and it may not correspond to political and social expectations. We very much expect to find that $ap_w < sp_w$, resulting in $0 < PPI_w < 1$. This hypothesis is supported by empirical results found by other studies that calculated the shadow price of water, such as Wang *et al.* (2018) and Ziolkowska (2015). The closer PPI_w is to unity, the greater the price distortion.

RESULTS AND DISCUSSION

Costs and volume of water produced

Desalination

The desalination plant offers an alternative means of increasing water availability in the Jaguaribe-Metropolitano system; it uses reverse osmosis technology and seawater, and has a production capacity of 1 m^3/s (equivalent to 12% of the RMF's current supply demand, according to information from CAGECE). The construction and management of the desalination plant is considered a public–private partnership (PPP) project, as per a financial modelling study conducted by CAGECE (2020). As a PPP project, the granting authority (i.e. CAGECE) makes payments of consideration to a concessionaire to enable the project; the concessionaire is then responsible for investment and O&M costs.

According to the modelling carried out by CAGECE (2020), both costs and the volumes of water produced can be divided into fixed and variable components:

- Fixed components: fixed cost, USD 0.54/m^3 (whether in operation or incorporating investment cost recovery); annual fixed consideration, USD 17,011,229; maximum annual production volume, 31,536,000 m^3 (or 1 m^3/s); and utilization rate, 100%.
- Variable components: variable cost, USD 0.46/m^3; annual variable consideration, USD 13,797,369; annual production volume, 30,239,870 m^3 (or 0.959 m^3/s); and utilization rate, 95.89%.

Therefore, the total unit cost is USD 0.993/m^3, and the total annual cost of consideration is USD 30,808,598. The fixed cost admitted in CAGECE's financial modelling incorporates the return on investment. To obtain better clarity vis-à-vis unit costs, we proceeded to disentangle the investment cost from the fixed cost, starting with the calculation of annuities and subtracting the investment cost per 1 m^3 associated with the fixed cost.

Investments into the construction of the desalination plant totalled USD 122,807,280; these costs include those related to interconnections with CAGECE's network and energy supply (CAGECE, 2020). Assuming an annual interest rate of 6.04% – the internal rate of return admitted in the financial modelling – and a 30-year term, we obtained the annual value of investment recovery: USD 8,960,035. Table 1 summarizes the costs per 1 m^3 of desalinated water.

Notably, the O&M cost is more than double the investment cost, largely because of electricity expenditures (which account for approximately 87% of the variable cost and about 39% of the total cost); it amplifies the

Table 1 | Cost of water supply and volume produced by desalination.

Cost type	Unit cost BRL/m^3 (USD/m^3)	Volume
O&M cost	2.81 (0.71)	1.0 m^3/s (or 31,536,000 m^3/year)
Fixed O&M cost	1.01 (0.25)	
Variable O&M cost	1.80 (0.46)	
Investment cost	1.12 (0.28)	
Total cost	3.93 (0.99)	

Source: Research data.
Notes: These costs assume full production capacity.

variable costs. The O&M cost can be expected to be more expensive than desalination plant construction, and higher than the O&M cost of other more conventional sources (Brahim-Neji *et al.*, 2019). In an evaluation of a seawater desalination plant with a capacity of approximately 0.58 m^3/s in a semi-arid region in Tunisia, Brahim-Neji *et al.* (2019) cited an investment cost of around USD 95.8 million, resulting in an investment cost of USD 0.38/m^3. Becker & Ward (2015), in Israel, reported a desalination cost of around USD 0.70/m^3. Our calculated investment cost is more competitive than these values, but our total cost is more than 50% higher.

Industrial reuse

In industrial applications, water reuse is defined as the use of treated wastewater for purposes that require a lower level of water quality (Féres *et al.*, 2012). The use of reclaimed water is of interest to many industries in the RMF. The results of a sample survey conducted by CAGECE (2017) indicate that approximately 60% of industries are interested in water reuse; among all industries surveyed, these industries are responsible for more than 85% of the water consumed, corresponding to a volume of 12,288,552 m^3/year (or 0.39 m^3/s) (CAGECE, 2017). The aforementioned report indicates that large consumers of water are most interested in reuse; it is reliable considering that approximately three-fifths of interested industries account for more than four-fifths of all water consumption. According to Féres *et al.* (2012), industries located in the Paraíba do Sul river basin (in southeast Brazil) that adopt water recovery systems may consume up to four times more water than those that do not explore reuse.

CAGECE considers water consumption by industries interested in reuse in addition to non-potable water demand (equivalent to 50% of the total industry demand), based on grant and consumption data obtained from a sample survey. The CAGECE report defines reuse demand as ranging from 25,134,192 m^3/year (or 0.797 m^3/s) to 57,742,416 m^3/year (or 1.831 m^3/s); these figures represent, respectively, the present demand (from grants for industries in operation) and future demand (from grants in effect). The sewage offer ranges from 26,395,632 m^3/year (or 0.837 m^3/s) to 136,487,808 m^3/year (or 4.328 m^3/s); therefore, this alternative has the minimum capacity needed to offer 0.8 m^3/year to the system.

In the RMF, there are 179 low-capacity sewage treatment plants that handle only 11% of the collected effluent (the remainder is disposed into the sea). The reuse project foresees that the treatment plants with higher capacity will be fully completed by 2045, with rollout of the Siqueira wastewater treatment plant (WWTP) scheduled to occur in three stages (Stage 1 in 2025, Stage 2 in 2035, and Stage 3 in 2045). The Miriú WWTP is scheduled for construction in a single phase, and is set to become active in 2030. CAGECE suggests a water reuse tariff of USD 0.52/m^3.

We estimated the investment costs of the WWTPs based on information from CAGECE (2017). We also calculated the annuities of the capital invested while assuming an annual rate of 7% and a 30-year term. Stage 1 of the Siqueira WWTP costs USD 118,207,256, with an annuity of USD 9,525,898; Stage 2 costs USD 95,813,930, with an annuity of USD 17,247,199; and Stage 3 costs USD 52,824,657, with an annuity of USD 31,030,044. For the Miriú WWTP, the cost was USD 92,688,173, and the annuity was USD 7,469,407.

Based on the CAGECE (2017) report, we divided the O&M costs of the WWTPs. Fixed costs relate to personnel costs and maintenance activities, while variable costs basically relate to electricity use, chemicals, and sludge transportation. The total O&M costs start at USD 13,394,654 (for Stage 1 of the Siqueira WWTP alone), and reach USD 49,557,912 for the Siqueira WWTP Stage 3. Table 2 summarizes the costs and production volumes relating to industrial reuse.

As with desalination, here, the O&M costs of industrial reuse are high, exceeding the investment cost by more than 22%. This O&M cost superiority is seen in several wastewater treatment systems (Goffi *et al*. 2018). The energy expenditures ranged from 54 to 80% of variable costs and from 26 to 67% of total costs, depending on the WWTP that CAGECE considers. Fontenele (2007) calculated the average cost of water supply for industrial reuse (USD 0.77/m^3); compare this value to that obtained by Féres *et al*. (2012) (USD 1.88/m^3). These values comprise our water-cost estimate of USD 1.03/m^3 (for industrial reuse). The benefits of adopting a reuse system in an industrial setting can be expressed as lower average water costs, since the reuse cost represents only one-third of the tariff charged by the supply company; water reuse also leads to lower dependence on the supply system (Féres *et al*., 2012).

Greywater reuse

Greywater reuse covers all water used in a household, except for toilet flushing; it can include or exclude kitchen sinks. Toilets and kitchen sinks produce low and high loads of greywater, respectively (Boyjoo *et al*., 2013; Zhu *et al*., 2018). Greywater typically serves non-potable functions, such as flushing toilets, watering gardens, and washing and cleaning floors. We estimated residential consumption and the number of connections based on CAGECE's 2009–2017 data for the city of Fortaleza.

The state of Ceará experienced a six-year drought period (2012–2017) that reduced water consumption between 2014 and 2017 by 5–14%. A drop was observed in the number of connections only in 2017, and so we used the number of 2013 connections. Since we had data only on total connections – data that involve the residential, commercial, industrial, and public categories – we assumed that 95% of all connections were residential.

We estimated that 741,998 consumer units used 125,176,439 m^3/year of water. These results are coherent: using them we can obtain a consumption of 116 L/inhabitant/day (while assuming residences contain four inhabitants). This number is similar to the average consumption in the state. We adopted a 40% reuse rate of residential water consumption, based on Zhu *et al*. (2018), Da Silva *et al*. (2019), and Boyjoo *et al*. (2013), while

Table 2 | Cost of water supply and volume produced by industrial reuse.

Cost type	Unit cost BRL/m^3 (USD/m^3)	Volume
O&M cost	2.24 (0.57)	0.8 m^3/s (or 26,392,478 m^3/year) to 4.5 m^3/s (or 141,363,274 m^3/year)
Fixed O&M cost	0.60 (0.15)	
Variable O&M cost	1.64 (0.42)	
Investment cost	1.83 (0.46)	
Total cost	4.07 (1.03)	

Source: Research data.

Notes: Costs are average values for the period; volume range is the minimum and maximum capacity volume for the period.

considering low-load greywater reuse. We admitted that only 20% of the consuming units would adopt reuse practices, due to low levels of acceptability among users (Boyjoo *et al.*, 2013; Never & Stepping, 2018). Finally, we assumed that 148,400 units would embrace a reuse system. We considered the consumption volume proportional to the amount of consumer units – that is, the consumption of these households represents 20% of the average residential consumption, implying a volume of 25,035,288 m^3. The volume of reused water (representing 40% of total consumption) provides greywater resources for reuse, equal to 10,014,115 m^3/year (or 0.3 m^3/s).

We adopted the budgets of Schroeder*et al.* (2017) for the implementation and management of greywater reuse systems and calculated the investment cost for each residential unit: USD 1721. This figure assumes that each unit has four inhabitants (i.e. per-capita cost of USD 430). Thus, the investment in greywater reuse systems in 20% of the consumer units is approximately USD 255,387,792. Considering an annual rate of 8% and a 20-year term, the annual value is USD 26,011,811. The O&M cost is equivalent to USD 10,084,239/year, or USD 68/year per household.

The fixed costs relate to tank-cleaning expenses and filter and pump maintenance costs, while the variable costs relate to energy and chlorination; these costs constitute about 75 and 25% of the total O&M cost, respectively. Table 3 lists the unit costs for greywater reuse, along with volume produced.

Greywater reuse incurs the highest cost, in terms of both investment and O&M; it suggests that government action, in the form of subsidies, is needed to promote the installation of greywater reuse systems (Boyjoo *et al.*, 2013). Due consideration needs to be taken with investments in greywater reuse, as this source serves only users within residential spaces (collection, treatment, and consumption) and reduces the risk of supply failure by the management company.

Groundwater wells

Groundwater sources constitute an important complement that helps meet demand. We adapted SOHIDRA's cost spreadsheet for well construction while considering the average depth of wells drilled in Fortaleza. We calculated the investment cost – including the complete installation of a 65-m deep well and supply system – to be USD 21,848 and the annuities to be USD 2225, based on an annual rate of 8% and a 20-year term.

According to flow data provided by the SOHIDRA regarding wells drilled in 2017 and 2018, the average flow rate was 4253 L/h, and the construction of 423 wells featuring this average flow rate would ensure an incremental flow rate of 0.5 m^3/s. Thus, we calculated the total investment cost as USD 9,241,838, with annuities totalling USD 941,302. The O&M cost was assumed to be one-third of the investment cost, based on the indicator expressed in Araújo *et al.* (2005); it totalled USD 313,767/year. Therefore, for a 0.5 m^3/s system increase, the total cost (O&M and investment) of water extracted from wells is USD 1,255,069/year or USD 0.08/m^3. Table 4 presents the cost and water volume results for this source.

Table 3 | Cost of water supply and volume produced by greywater reuse.

Cost type	Unit cost BRL/m^3 (USD/m^3)	Volume
O&M cost	3.97 (1.01)	0.3 m^3/s (or 10,014,115 m^3/year)
Fixed O&M cost	3.01 (0.76)	
Variable O&M cost	0.96 (0.24)	
Investment cost	10.25 (2.60)	
Total cost	14.22 (3.60)	

Source: Research data.

Table 4 | Cost of water supply and volume produced by wells.

Cost type	Unit cost BRL/m^3 (USD/m^3)	Volume
O&M cost	0.08 (0.02)	0.5 m^3/s (or 15,768,000 m^3/year)
Fixed O&M cost	–	
Variable O&M cost	–	
Investment cost	0.23 (0.06)	
Total cost	0.31 (0.08)	

Source: Research data.

It was difficult to break out the O&M cost into fixed and variable components. In any case, this water supply source is the cheapest of all the alternatives considered. Our values align with those calculated by Araújo *et al.* (2005), who arrived at costs of USD 0.03/m^3 and USD 0.06/m^3 for O&M and investment, respectively.

Cisterns

Cisterns constitute another alternative water supply source. They collect rainwater from roofs and store it in tanks, with or without treatment systems, depending on the intended use. Despite having the lowest supply flow rate among the options considered in our study (i.e. production of 0.1 m^3/s), it is a reliable source that helps fulfil urban water demand.

Based on a series of rainfall data for Fortaleza and data from Sales (2016), we constructed budgets concerning the investment cost; additionally, we carried out a cost–benefit evaluation of the best cistern dimensions and considered the design of cisterns whose volumes ranged from 16 to 100 m^3. In the simulations, we considered a 300 m^2 plot size and a 50% occupation rate (plot contribution area). Among the allowed sizes, the best option was the construction of cisterns with a 16-m^3 capacity, each of which would incur an investment of USD 2105. Using an annual interest rate of 6% and considering a 20-year term, we arrived at annual investment recovery values of USD 184 per cistern.

Based on analysis of historical rainfall data and considering a feasibly sized cistern (16 m^3), we obtained a served demand of 80 m^3/year (or 6.67 m^3/month) and an average residential water consumption of 16 m^3/month. In addition, we used parameters and tariff values practiced by CAGECE in 2019 for the normal residential category. In this way, we obtained indicators with and without a cistern:

1. With cistern: water consumption of 9.3 m^3/month (water consumption without a cistern minus the volume produced by the cistern); sewage consumption of 7.4 m^3/month (80% of water consumption); water consumption cost of USD 10/month; sewage consumption cost of USD 8/month; and total cost (water and sewage) of USD 18/month.
2. Without cistern: water consumption of 16.0 m^3/month; sewage consumption (80% of water consumption) of 12.8 m^3/month; water consumption cost of USD 18/month; sewage consumption cost of USD 15/month; and total cost (water and sewage) of USD 33/month.

With the total cost with and without cisterns in hand, we obtained the benefit accruing from water and sewage-cost savings (USD 16/month or USD 188/year). Thus, we gained an annual benefit that slightly exceeds the annual recovery of the investment in the cistern construction, on the order of 1.02. This result may suggest that the construction of cisterns is done through community work or subsidized by the government, as is common with this type of enterprise (Araújo *et al.*, 2005).

We assumed that 40% of the households that consumed 16 m^3/month or more of water would invest in cistern construction. This percentage, based on data from CAGECE, corresponds to 37,872 residential units. Thus, to guarantee a supply of 3,153,600 m^3/year (or 0.1 m^3/s), based on cost per cistern, a total investment of USD 79,723,675 would be required, which corresponds to an annual cost of USD 6,950,673 and a per-unit cost of USD 2.20/m^3.

The O&M costs of this source are very low, as per Da Silva *et al.* (2019); it represents about 4% of the investment cost. We assumed this percentage and derived an annual O&M cost of USD 278,948 (per-unit cost: USD 0.09/m^3). Table 5 summarizes the results for the cistern source.

As in the case of greywater reuse, cisterns seem to incur high investment costs. This source also serves the user (collection and consumption) at the residential level at a low O&M cost, according to Da Silva *et al.* (2019). The low-cost contrasts with the high O&M cost of other sources, such as desalination and industrial reuse (whose O&M costs exceed their investment cost) and greywater reuse (where O&M represents almost 40% of the investment). Based on the data available from Da Silva *et al.* we found that investment cost in a greywater system is USD 2.46/m^3; meanwhile, Leong *et al.* (2019) calculate this source's water cost as USD 2.00/m^3, thus deriving values congruous with ours.

Transposition of waters

The São Francisco River Integration Project (PISF) is the largest water transfer construction in Brazil. It captures water from the river and supplies it to four northeastern states (Ceará, Rio Grande do Norte, Paraíba, and Pernambuco). A flow of 7.57 m^3/s is forecast for Ceará.

Ceará Water Resources Management Company (COGERH) manages the state's water resources and acts as the operator of the state water infrastructure interconnected to the PISF. COGERH pays the federal operator of the PISF–CODEVASF a water tariff associated with O&M costs for the service of water supplies to Ceará territories. According to Resolution No. 11 of 10 March 2020, issued by the PISF regulatory body National Water Agency, the availability and consumption tariffs in 2020 were USD 0.06/m^3 and USD 0.13/m^3, respectively.

Based on PISF tariff calculation spreadsheets prepared by FGV, the flow demand by PISF for Ceará in 2020 was 2.583 m^3/s (or 81,457,488 m^3/year). The consumption tariff was applied to it, which resulted in a variable charge component (variable cost) of USD 10,495,501. For the fixed component, we considered the availability tariff and the flow (volume) planned by PISF for the state (7.57 m^3/s), and determined the fixed portion of the charge (i.e. fixed cost): USD 14,274,571. Thus, the total O&M cost to be paid by COGERH as a result of the PISF water transfer amounted to USD 24,770,072. We did not appraise the investment costs as they are considered sunk costs, as only the O&M components are charged.

We thus obtained the O&M costs for supplying the PISF transfer, broken into fixed and variable components (Table 6).

Table 5 | Cost of water supply and volume produced by cisterns.

Cost type	Unit cost BRL/m^3 (USD/m^3)	Volume
O&M cost	0.35 (0.09)	0.1 m^3/s (or 3,153,600 m^3/year)
Fixed O&M cost	–	
Variable O&M cost	–	
Investment cost	8.70 (2.20)	
Total cost	9.05 (2.29)	

Source: Research data.

Table 6 | Cost of water supply and volume produced per transposition.

Cost type	Unit cost BRL/m^3 (USD/m^3)	Volume
O&M cost	1.20 (0.30)	2.6 m^3/s (or 81,457,488 m^3/year)
Fixed O&M cost	0.69 (0.17)	
Variable O&M cost	0.51 (0.13)	
Investment cost	–	
Total cost	1.20 (0.30)	

Source: Research data.
Note: Flow rate data are from 2020.

Apparently, the increase in scale with the PISF influences the reduction in the average cost per 1 m^3, thus making the transferred waters seem somewhat competitive than other water sources. It is important to note that among all the sources analysed, the transferred water consists of raw water, and there is no consideration of treatment costs, even as this item is embedded in the results of alternative sources. However, even if the O&M cost of the PISF were to double with the treatment needed before human consumption, it would still be lower than the O&M cost associated with desalination, for example.

Overview of costs of alternative sources

The various alternative water supply sources for the RMF considered in this study are realistic options by which to meet future demand. These sources are quite heterogeneous in terms of water-resource origin, the technology involved, and service scale.

Figure 1 compares the costs associated with the various sources. Desalination and industrial reuse incur similar costs, with the former being more competitive in terms of investment and the latter in terms of O&M. Our study incisively verified Brahim-Neji *et al.* (2019) and found that the O&M costs of desalination are higher than those of other conventional sources. Plans for the construction of desalination plants require information on how much users are willing to pay for the higher cost of desalinated water compared to other more conventional sources such as extraction from groundwater wells, rivers, or weirs (Brahim-Neji *et al.*, 2019). Similarly, access to information on the cost and acceptance rates of wastewater reuse is critical (Féres *et al.*, 2012).

These are strategic projects that work to supply desalinated water and industrial reuse water to the system. The production of water from the sea gives desalination an aspect of 'unlimited source' compared to other sources, and its production occurs independently of climate variability (i.e. it is available even during periods of drought). On the contrary, industrial water reuse allows for a double environmental gain: it reduces the flow of untreated effluents and the water demand, while also saving costs incurred by the additional expansion of supply infrastructure and allowing better allocations of treated water to applications that require higher quality (Féres *et al.*, 2012). With a combined capacity of almost 2.0 m^3/s, these two sources can be replicated in other areas of the state that have high water demand.

We can compare the costs of greywater reuse and cistern sources, as they have similar characteristics (e.g. residential-level collection and consumption). In fact, the investment costs of these two sources are very similar (cistern: USD 2.20/m^3; greywater: USD 2.60/m^3) and the highest among the sources analysed. As with industrial reuse, these sources present benefits vis-à-vis reductions in untreated effluents discharged into the sewage network and imposing lower demand on the public supply system, while also reducing the costs of supply

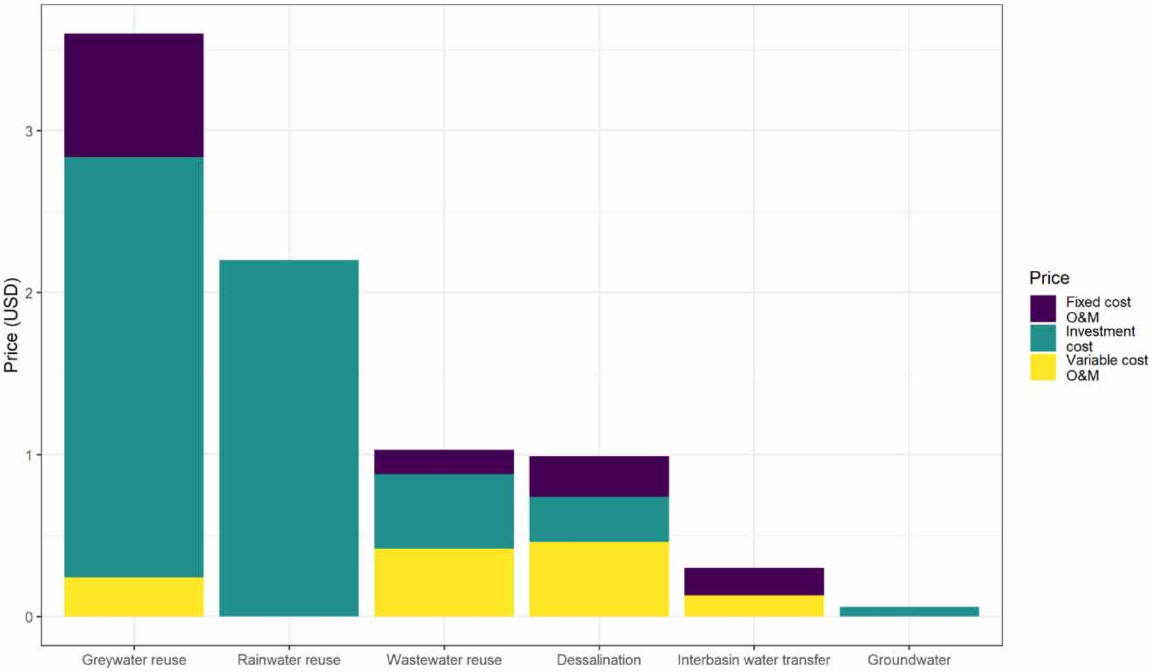

Fig. 1 | Comparisons of the costs of various water sources.

infrastructure and allowing for the adequate allocation of water to applications demanding high-quality water (Zhu *et al.*, 2018).

Given the estimated values, it is possible to save 47% in water costs by implementing cistern use. Greywater reuse involves residential-scale collection, treatment, and reuse, and has a smaller impact on the system's total water supply compared to other alternative sources. It generates an important volume of decentralized (diffuse) urban supply and reduces water stress; for these reasons, it is being increasingly considered in various regions worldwide (Zhu *et al.*, 2018).

Meanwhile, we found the costs of drilled-well groundwater to be the lowest, in terms of both O&M and investment. Wells can be a viable alternative source that incurs lower costs, and they offer higher flow rates than those of greywater reuse and cisterns combined. However, their limitations lie in the amounts of water available in aquifers located in semi-arid regions and the long period that can pass before sources are replenished.

The PISF has relatively low costs. We did not consider investments in its construction, because the water is made available against tariff payments for the availability and consumption of the waters of São Francisco. Even if we focus solely on O&M costs – which represent the collection of water tariffs for transposition – lower costs can be verified when drawing comparisons to competing sources (e.g. desalination, industrial reuse, and greywater reuse).

Of the sources presented, those on a large scale (desalination and treatment plants) end up having a greater involvement of the water supply company (Webber *et al.*, 2017; Zhu *et al.*, 2018), due to high costs of investment and O&M. In the case of desalination, the project would involve a PPP, i.e. a private company would be responsible for the investment and operation of the plant. CAGECE would be obliged, through a contract, to buy the desalinated water and sell it to users. In the case of industrial reuse, CAGECE would invest in the construction of treatment plants and sell the treated water to demanding industries.

In both cases, users would have a less proactive role, relying on the company's decision to implement these sources indirectly (desalination) or directly (treatment plant), but they would also benefit from increased water security as sources alternative to superficial reservoirs would be available.

The O&M requirements of the desalination plant can be hard to anticipate as it would be the first to be installed in Ceará, but the implementation of a wastewater plant should not present a challenge for the water supply company. On the other hand, O&M of diffuse, small-scale sources (e.g. cisterns and greywater reuse), require greater involvement of the users (since these are exclusive for domestic supply) but can be often subsidized by the government (Araújo *et al.*, 2005).

Groundwater is essentially a diffuse source but requires technical knowledge of where to drill wells and has a restricted availability due to the predominantly crystalline soils of Ceará, hence relying on government investments. PISF is a mega water transfer project that will pass through the entire state of Ceará to make raw water available to the Jaguaribe-Metropolitano system, managed by COGERH.

Large-scale, investment-intensive water projects (e.g. reservoirs, desalination and wastewater treatment plants, and inter-basin transfers) are usually paid for by the public sector; at most, O&M costs are shared by the public and private sectors. Smaller-scale, decentralized projects (greywater reuse on plots, and cisterns and wells), meanwhile may reflect shifts towards more sustainable solutions; they are challenging and provide greater user participation in investment costs.

In addition to policy propensities regarding the selection of supply options, users have preferences beyond the scale of service: the water-source origin can also make a difference. Generally, for human consumption, desalinated water is unlikely to be the first option (Brahim-Neji *et al.*, 2019), while wastewater reuse is likely to be the last option. The sources we reviewed differ in terms of scale, technology, and supply purposes.

Water shadow price

Under the residual value method, the net benefit to CAGECE stems from the value of water production, derived from two components: the product between the water tariff and the volume demanded by users, and the product of the sewer tariff and a part of the volume demanded (i.e. the fraction of water consumed that becomes wastewater). In this case, the sewerage tariff is applied to 80% of the volume consumed by the consumer unit; this is CAGECE practice. The costs relate to the investment in infrastructure construction and O&M expenses, except for water.

Table 7 presents the values associated with the estimated shadow price of water for desalination, industrial reuse, and wells. We excluded greywater reuse and cisterns from this analysis, as they are characterized as residential-scale sources, and thus, do not enter the cost–benefit composition of the supply company, CAGECE. We also excluded the PISF as it relates to raw water costs.

The shadow price of desalination is 67.8% higher than the cost of water and 11.8% higher than the average tariff considered for this source. As for desalination and wells, the average tariff is USD 1.49/m^3. This value was obtained from the weighted average between the water tariff (USD 1.43/m^3) and the sewage tariff (USD 1.57/m^3), considering that the latter is applied to only 80% of water consumption. As for industrial reuse, the calculated shadow price is 379.3% higher than the cost of water and 49.0% higher than the average tariff for the source. In this case, the average tariff is USD 2.80/m^3, obtained from the weighted average between the water tariff (USD 2.68/m^3) and the sewage tariff (USD 2.95/m^3), again the latter is applied in 80% of consumption. For well-based water supplies, the shadow price is 3162.5% higher than the cost of water and 74.6% higher than the average tariff (USD 1.49/m^3, as explained before). For the three sources considered, the unit cost of water represented only a fraction of the average tariff charged to users: around two-thirds for desalination, only 5% for wells, and about one-third for industrial reuse. This suggests that these sources are economically

Table 7 | Cost of water supply and volume produced per transposition.

Measures	Desalination	Industrial reuse	Wells
Benefits BRL/year	320,845,025	525,051,965	167,298,480
USD/year	81,327,476	133,089,647	42,406,651
Costs BRL/year	121,543,000	90,423,869	4,951,372
USD/year	30,808,598	22,920,552	1,255,069
Benefits – Costs BRL/year	199,302,025	434,628,097	162,347,108
USD/year	50,518,878	110,169,095	41,151,583
Volume produced (m^3/year)	30,239,870	26,392,478	15,768,000
Shadow price BRL/m^3	6.59	16.47	10.30
USD/m^3	1.67	4.17	2.61
Unit cost BRL/m^3	3.93	3.43	0.31
USD/m^3	1.00	0.87	0.08
PPI_w	0.1056	0.3289	0.4275

Source: Research data.
Note: For desalination and wells, we assumed that water tariffs were BRL 5.65/m^3 (or USD 1.43/m^3) and wastewater tariffs BRL 6.20/m^3 (or USD 1.57/m^3). For industrial reuse, water tariffs were assumed to be BRL 10.59/m^3 (or USD 2.68/m^3) and sewage tariffs BRL 11.63/m^3 (or USD 2.95/m^3). See CAGECE's Tariff Structure – Resolution of 14 March 2019.

viable, and users can bear the costs associated with them. The shadow price values provide a measure of the social value of water or the net return to water (Young & Loomis, 2014), and thus reflect the social opportunity cost of water. In investment decisions in public goods and services, such a measure offers a glimpse into the magnitude of the social value of the good or service under consideration, and in project feasibility analysis, it determines its net contribution to the generation of social welfare.

The PPI_w results show greater distortion in average tariffs relative to corresponding shadow prices for industrial reuse (0.3289) sources and wells (0.4275); there is also less distortion for desalination (0.1056). These findings demonstrate that tariff policy does not reflect a significant part of the social cost of these sources (Wang *et al.*, 2018). However, our results are much lower than the results found by Wang *et al.* (2018), regarding the calculation of the PPI_w for industrial reuse. The authors found a PPI_w ranging between 0.484 and 0.959. Qamar *et al.* (2018), found a PPI_w ranging between 0.966 and 0.999 for irrigation water. These results are really quite high, showing a great distortion between shadow price and average water tariff. Shadow water price estimation efforts can highlight the problem of undervaluing this key resource; however, setting tariffs that ensure water production and environmental water conservation requires decision-making that involves policy-makers and diverse *stakeholders* (Ziolkowska, 2015).

It should be made clear that with this type of approach, some costs may be ignored or not accounted for, and thus, it may overestimate the value of water.

CONCLUSIONS

The investment and O&M costs measured in the study reveal that the alternative sources generally incur reasonable costs that can be covered by CAGECE-charged tariffs. The costs associated with desalination and industrial reuse sources are lower than those of more diffuse sources, such as cisterns and greywater reuse; they can more strategically meet demand, with flow rates more than four times higher than those of diffuse sources.

Meanwhile, well water is the cheapest source, but it has limitations in terms of availability, despite being in the region with the highest proportion of sedimentary strata. Transboundary water from the São Francisco River can be considered only in terms of O&M costs that are not covered by the state of Ceará (through COGERH, the state government is obligated to pay for project benefits only with tariff money). In terms of O&M costs, the PISF is very competitive, with costs that are one-half those of desalination or industrial reuse and less than one-third that of greywater reuse. However, unlike other sources, the PISF offers raw water. Furthermore, the PPI_w value indicates a greater distortion of the average tariff relative to the shadow price in industrial reuse and groundwater well extraction.

This study has some limitations. It ignores certain externalities, such as the subsidies applied to the water tariff of the supply concessionaire and the environmental costs of desalination that relate to generated effluents. We also do not address the effects of climate change in our estimations, which can be considered in future research that assesses the cost of production and the shadow price of water due to droughts or floods. Nonetheless, it has broad applicability in evaluating alternative sources by which to diversify a supply matrix and manage the water sources.

FUNDING

This research was partially supported by grants from the Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico-FUNCAP (Project no. 11098079/2019), Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brazil (CNPq), and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES).

ACKNOWLEDGMENT

The authors thank the Cearense Foundation for Scientific and Technological and the Cientista-Head Resource Programme.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 9 January 2022; accepted in revised form 8 May 2022. Available online 19 May 2022