

Water Supply: RO Desalination Versus Conventional Water Treatment

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Abstract. Water scarcity threatens the health and development of countries worldwide due to the rapid expansion of population and climate change, pushing the government to find more innovative and sustainable ways to address water stress. Governments have adopted reverse Osmosis (RO) seawater desalination technology for its cheap raw water intake and stability. However, its environmental and financial sustainability remains disputable. In this study, three metrics, carbon footprint, cost, and waste discharge, are defined and analyzed to identify which water supply technology has greater prospects. Accounting for a full water treatment process from raw water intake to transportation and distribution, the RO desalination plant outruns traditional water treatment facilities due to less carbon emission, limited operation cost and maintenance, and less hazardous waste discharge. The qualitative and quantitative analysis of environmental and financial sustainability of existing solutions to the water supply may provide a more comprehensive understanding and further supports policy making.

1 Introduction

Water is a precious and increasingly scarce resource. It is critical for ecosystem functions (as both habitat and resource) and equally essential for humans [1]. Water resources refer to the water that can be used or used in people's lives which requires a certain quantity and appropriate quality to meet the specific needs of a certain place in a period. Although a large amount of the earth's surface is covered by water, approximately 70 % of it is covered with salty water, which cannot be drunk or used without being treated [2]. There is very little water that can be directly used for production and domestic. Accessible freshwater resources are rivers, lakes, and groundwater, accounting for about 0.28 % of the earth's total water storage. Global water shortage and imbalanced regional distribution have become a rising concern. With the rapid expansion of population, it is estimated that water shortage will affect 3 billion people in the world and 40 countries and regions. Therefore, how to reach a more sustainable, reliable, environmentally, and economically friendly water supply solution becomes a global problem, particularly in arid and semiarid areas.

Various innovative solutions to address urban water shortage have been recognized in the recent decade, of which a definite trend to develop alternative water sources such as desalination cannot be neglected [3]. Currently,

desalination methodologies based on thermal distillation such as multistage flash distillation (MSF) and thermal vapor compression (TVC), and membrane desalination including reverse osmosis (RO) are the most prevalent, implemented, and industrialized desalination plants [4]. Advantages of RO technology, such as high efficiency and low carbon emission, gained wider acceptance than TVC. Another approach to attain domestic freshwater is the traditional water treatment plant, often using surface water as raw water intake and converted into drinkable water through a series of processes.

The meaning of sustainability in water resources management has changed over time [5]. With global warming and high frequency extreme weather, more attention is being paid to stable water supply and regional sustainability. This study focuses on the sustainability of the two approaches-RO, the desalination plant, and the water treatment plant, dealing with carbon footprint and the entire process from raw water intake to transportation and distribution. Special focus is placed on the total carbon footprint of the two typical water treatment methods, including project construction, operation, and maintenance, post-treatment, and transportation and distribution of product water. The financial sustainability of reverse osmosis plants and a currently applied urban water treatment plant are described, and the cost structure of both methods is outlined. Finally, field statistics of residual concentration and current practices of waste

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management and disposal are addressed.

2 Methodology

2.1 Water Treatment Plant

The study chooses Carlsbad Desalination Plant, a world-famous and technologically advanced water agency in San Diego, California, USA. Miramar Water Treatment Plant, located about 20 miles away, is selected to represent the traditional water treatment facility to reach comparable results. Since both plants mainly provide purified water to San Diego, regional differences in economy and additional transportation costs can be reduced to the minimum, rendering more accurate and meaningful conclusions. The study uses carbon footprint, cost, and waste as metrics to determine which plant is more sustainable and environmentally friendly. The functional unit for the analysis is per gallon drinking water (MGD). To simplify the model, the life span of both water process plants was assumed to be 30 years, as used in previous life-cycle assessments of water supply systems.

2.2 Carbon Footprint

Defined by the World Health Organization, a carbon footprint is the total greenhouse gas (GHG) emissions caused by an individual, event, organization, service, or product [6]. This report, however, mainly focuses on researching respective carbon dioxide emission, as one of a typical example of greenhouse gases, in the two plants and reach a conclusion for which one belongs to a sustainable plant by comparison. Carbon footprint is closely associated with the embodied energy consumption of the water purification process [7]. Generally, there is a multiplicative factors relationship between energy consumption and carbon emissions. Not only are factors among different industries not identical, but also in one industry, the data is not the same for every year [8, 9]. Thereby, accurate data can only be found on water authority websites in different regions. In this study, all data and diagrams are looked up from authority websites.

2.3 Cost

In any study of sustainability, financial sustainability is an important factor not to be neglected. Consequently, a complete analysis of both water treatment methods is included in this study. To form a more comprehensible contrast, two specific plants were selected, both located in San Diego, California, with the same economic climate and water demand. Applying the life-cycle access technique, data was collected from San Diego from the San Diego Official Website and San Diego County Water Authority (SDCWA) to form a cash flow for further comparisons. Though differs in technology, the total costs can be divided into four parts: pre-construction, construction, operation, and other costs.

Based on documents available on the SDCWA, Miramar Water Treatment Plant has been in use for several

decades under the city water treatment program and has recently been renovated by the city government. Net cost of Miramar Water Treatment Plant mainly consists of initial construction cost and improvements costs (pipelines, pump station, clearwell, storage tank, etc.) [9].

Under a private-public contract, Carlsbad Seawater Desalination Plant received more social attention for being the largest seawater desalination using reverse osmosis technology. The total cost of completing the plant is estimated to be approximately \$500 million [10]. The expected cost is funded with the Series 2012 Plant Bonds and equality contributions made by Poseidon Resources Channelside Holdings LLC. The Water Authority Financing Agency pays pipeline construction with the Series 2012 Pipeline Bonds, including developing, designing, and acquiring, and constructing the pipeline. Operating and maintenance are subcontracted to IDE Americas. Monthly compensation for IDE Americas includes a fixed fee, a variable fee, and a chemical fee. The monthly fixed fee will be in an amount equal to \$981,103.89; the variable fee will consist of \$0.1425 per thousand gallons (kgal) of Product Water delivered; the chemical fee will consist of \$0.1758/kgal for Product Water delivered [10].

As an unneglectable source of operating cost, electricity is estimated to account for approximately 50% of the operating budget. The company is obliged to purchase electricity from SDG&E under a standard program for large industrial users, including a fixed and variable Electricity Charge [10].

2.4 Waste discharge

The data for this study is obtained from the United States Environmental Protection Agency (EPA) [11]. This investigation estimates the annual average pollutant concentrations (long-term averages) for each model plant, based on source water treatment type in place and use NPDES Discharge Monitoring Reports (DMR) data supplied with the 2007 industry questionnaire from WTP, and assume WTP size or discharge status do not affect the concentration in the effluent discharge. To calculate the annual average pollutant concentrations, the study takes the arithmetic mean of the samples taken in 2006. For samples showing the presence of a chemical but at concentrations below detection limits, the study used one-half of the method detection limit value to estimate pollutant loading. The study used a concentration of zero for the loading estimates for chemicals never detected in the effluent.

The annual average pollutant concentrations are assumed the data about Miramar Water Treatment Plant and Carlsbad Seawater Desalination Plant. In normal tap water treatment technology, as in Figure 1, there are four steps: Coagulation and Flocculation, Sedimentation, Filtration, and Disinfection [12], with coagulation and filtration being the main processes that produce residuals. The volume of coagulation sludge generated depends on the plant production, amount of coagulant or other treatment chemical added (dose), and the amount of suspended solids in the source water [11]. In contrast, as

in Figure 2, there are seven steps in the process of desalination: Seawater intake, Screening, Filtration, Reverse Osmosis, Treatment, Water supply, and Seawater concentrate outlet. Reverse Osmosis Desalination uses

semi-permeable membranes to remove dissolved salts and other impurities

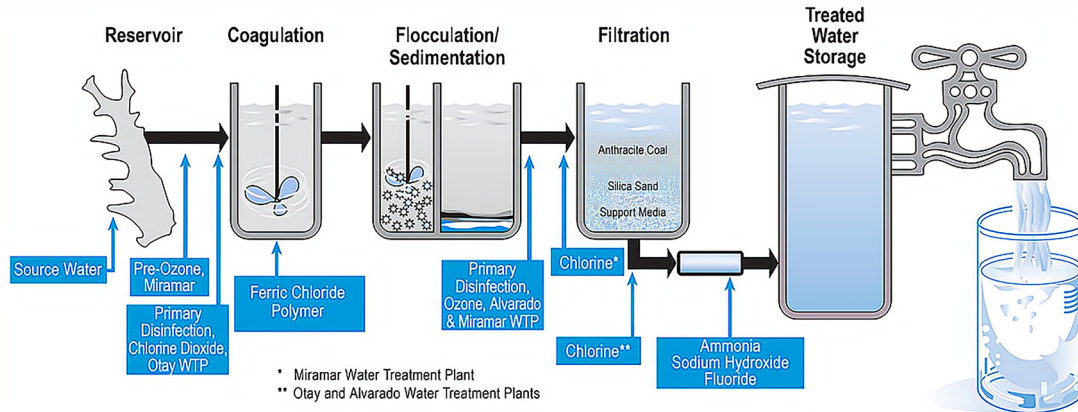


Figure 1. Miramar Water Treatment Plant process [12].

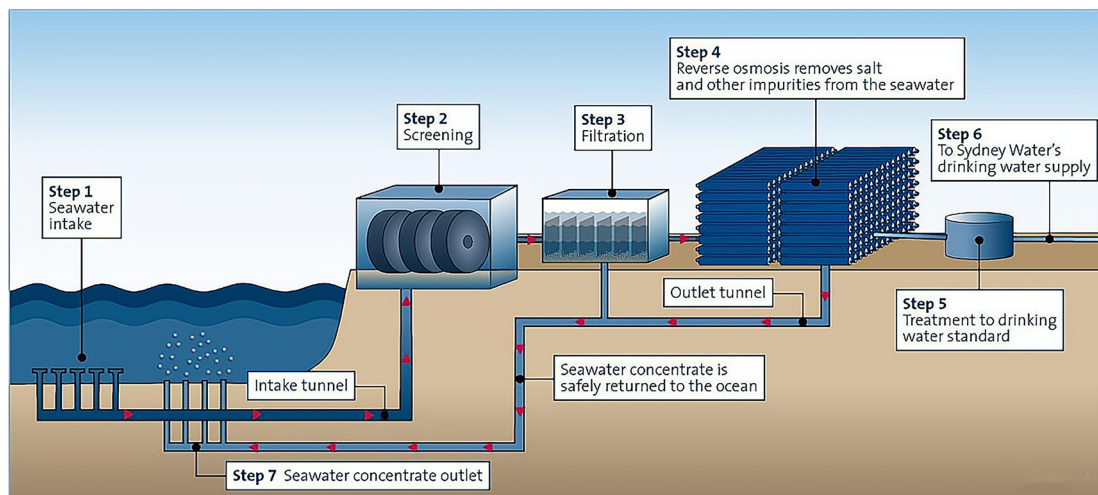


Figure 2. Carlsbad Seawater Desalination Plant process [13].

3 Results and discussion

3.1 Carbon footprint

We compare two actual plants to study the two methods of desalination and conventional water supply: more sustainable in terms of carbon emissions. As for desalination plants, this study chooses Carlsbad Desalination Plant, a world famous and technologically advanced water agency in San Diego, California, USA [8]. This plant typifies the whole world development direction of advanced water supply in the future. One of the conventional water supply plants, Miramar Water Treatment Plant locating just about 20 miles away, was selected to limit in an identical climate and geological location, reaching a comparable result [9].

In this part, the study focuses on the data of greenhouse gas (GHG) emissions of the two plants. As for the desalination plant, based on Table 3 [9], the initial total annual emissions were about 61004 tons CO₂/year, generating from seawater desalination and product water

delivery. However, using local water, there were about 47240 tons CO₂/year carbon emissions reduction due to reduced water imports, no CO₂ produced by facilities' operation utilized in water transportation, as well as net power. As a result, total net power use and carbon emissions currently diminish by a large amount percentage. The sum is about 13764 tons CO₂/year (61004 - 47240). In addition, the desalination plant, at the same time, had its on-site carbon dioxide emission reductions such as the use of warm cooling water, green building design, and use of CO₂ for water production, formulating into a circulation. The total recycling amount is about 5909-5958 tons of CO₂/year. Meanwhile, this plant also includes off-site carbon dioxide emission mitigation, which utilizes other methods to absorb carbon emissions besides recycling CO₂ to use as fuels to operate devices. This plant not only chooses to layover places that used to be wildfire zones replaced by many plants that can absorb extra CO₂, but they purchase some renewable products to promote decreasing carbon emissions. This mitigation process can absorb in terms of 7806-7855 CO₂/year. In that way, total carbon emission has a balance with total carbon absorption. Indeed, this shows that even though an

enormous amount of carbon dioxide is released during the treatment part, absorption of carbon dioxide utilized in the operation of facilities efficiently offsets emissions.

Thereby, the result shows that total GHG emission is zero, with no greenhouse gas pollutants because of these reductions and mitigation.

Table 1. Carlsbad Desalination Plant Carbon Footprint [14].

Source	Total power use (MWh/year)	Total emissions (tonsCO ₂ /year)
1. High-energy efficiency design	246,156	61,004
2. Carbon emission reduction	189,800	47,240
3.Total use and emissions(item1-item2)	56,356	13,764
On-site carbon dioxide emission reductions		
4. Energy efficient plant design	Described in item 1	Described in item 1
5. Use of warm cooling water	(12,308)	(3,057)
6. Green building design	(300 to 500)	(75 to 124)
7. On-site solar power generation	(777)	(193)
8. Use of CO ₂ for production	NA	2,100
9. Reduced energy for water reclamation	1,950	484
10. Subtotal reduction (items 4 through 9)	(15,335 to15,535)	(5,909 to 5,958)
Off-site carbon dioxide emission mitigation		
11. CO ₂ sequestration	(NA)	(166)
12. CO ₂ sequestration in coastal wetlands	(NA)	(304)
13. Regional green power generation projects	(2,260)	(561)
14. Other carbon offset and renewable credits	(38,561 to 38,761)	(6,775 to 6,824)
15. Subtotal reduction (items 11 through 14)	(40,821 to 40,021)	(7,806 to 7,855)
Total net GHG emission balance(item3-item10-item15)		0

As for Miramar Water Treatment Plant, based on Table 2 [15], Miramar Water Treatment Plant found that the main GHG emissions were generated from the following factors: mobile sources, wastewater process emissions, refrigerant use, diesel generators, waste, and amortized construction emissions. Unlike Carlsbad Desalination Plant, Miramar Water Treatment Plant adopts a conventional strategy to treat water, causing enormous carbon emissions, not recycling. Especially in the part of wastewater process emissions, which causes the appearance of most of the carbon emissions, because in this plant, as a typical conventional plant, it does not have the process to absorb extra carbon emission. By adding those data, we calculated that the total annual GHG emissions of the Miramar Water Treatment Plant are about

1732.78 tons CO₂/year. By comparison, the GHG emission of Miramar WTP is higher than that of the Carlsbad Desalination Plant. This result confirms our previous assumption of the advantages of reverse osmosis.

Based on the comparison, one can find that the total carbon emission is zero in Carlsbad Desalination plant in terms of carbon emission since absorption offsets emissions. In contrast, Miramar WTP carbon footprint has a huge amount of emissions, approximately 1,732.78 tons of CO₂/year. The result is obvious: the desalination plant has a more sustainable future than the conventional water supply plant due to less emissions per year. Meanwhile, the desalination plants consume less energy to treat water than conventional methods, considering recycling.

Table 2. Miramar WTP Carbon Footprint: Summary of Estimated Annual GHG [15].

Emissions Source	MT CO ₂	MT CH ₄	MT NO ₂	MT CO ₂
Mobile sources	217.37	0.01	0.00	217.64
Wastewater Process Emissions	0	16.68	2.46	1,149.98
Refrigerant Use	12.41	0.00	0.00	12.41
Diesel Generation	19.04	0.00	0.00	19.11
Waste	10.53	0.62	0.00	26.10
Amortized construction Emissions				307.54
Total Project Emissions				1,732.78

3.2 Cost

As a state-of-art RO plant, Carlsbad went through various feasibility analyses, environmental impact evaluations, and pilot experiments before construction. As a result, pre-construction cost, particularly in engineering & technical and permitting/environmental, takes up a larger proportion. As for construction cost, which accounts for 81 % of the

total, plant EPC alone takes up over 50 % of the total construction cost though the plant was converted from an old water treatment plant. Two reason accounts for this. First is that reverse osmosis tech, though energy-efficient, requires expensive equipment and more onsite adjustments. The second is that seawater needs to be drained from the nearest coast, which requires a water intake facility. The construction cost also comes with a large proportion of interest on project bonds. Under a

public-private contract, Carlsbad Desalination Plant released a series of bonds both on plant and pipeline construction, a total of \$754million. The debt services will be paid during construction and along the 30 years of operation. Poseidon Company is devoted to wetland restoration, biodiversity protection, and carbon neutrality under government requirements as an ecofriendly project. Accordingly, environmental and miscellaneous spending along with sub-station construction accounts for a large proportion.

In Miramar WTP, the cost for constructing takes up a large proportion of the total budget. There are 4 main contracts for construction in Miramar WTP, labeled A, B, C, and D [16]. They cost about \$153million, which accounts for 47.7 % of the total. Counterattracted a major construction component of the overall project, and it cost about \$81million, which accounts for more than 50 % of the budget for construction. It comprised the provision of 12 filters, pumps, rapid mix facilities, a de-aeration basin, and an ozone structure, together with chemical and main administration buildings. They are the infrastructure of the water treatment plant and part of the treatment facilities. In Contract B, the cost mainly focuses on some other

treatment facilities, including four flocculation and sedimentation basins constructed in place of the old basins. As a result, this part also cost about \$50million in the budget of construction. Contract C included the installment of saddles and concrete pads for the tanks, including conduits. Under Contract D, landscaping, construction of the entry gate, guardhouse, and security access and controls were undertaken. Drainage, fencing, and retaining walls were also constructed. Contracts C and D started after the completion of the overall structure and facilities of the plant, mainly to improve the construction, safety, and beauty, so the cost of these two contracts is much less than that of the main construction. The improvements of Miramar WTP also cost much in the total budget. Implemented in six component phases, the improvements include a new rapid mix facility, de-aeration basins, disinfection and chemical facilities, new and refurbished administration buildings, flocculation, and sedimentation basins, wash-water recovery system, and water filters. In addition, new pipelines have been laid, and other preparatory improvements have been undertaken outside the WTP site itself [18].

Table 3. Carlsbad Seawater Desalination Plant Sources and Uses (dollars in thousands) [10].

Sources	Uses	Budget
Construction	Plant EPC	429,856
	Pipeline EPC	144,473
	Power Substation Construction	19,733
	Interest on the Project Bonds During Construction	125,826
	Test on Seawater Intake	4,05
Total A		719,888
Pre-Construction Cost	Engineering & Technical	11,683
	Financing	1,645
	Legal	4,105
	Permitting/Environmental	16,805
	Site Costs	4,341
Total B		52,754
Other Costs	Owner's Contingency	20,000
	Reserve Funds	26,517
	Transaction Fees and Closing Costs	29,954
	Environmental, Insurance and Miscellaneous	38,309
Total C		114,780
Total A+B+C		887,422
Operation (2018)	Operations and maintenance	16,576
	Planning	9,754
	Remediation, Environmental, Ground Lease Costs	12,870
	General and Administrative	13,239
	Depreciation and Amortization	36,365
Total		88,804

From the table, the total cost of improvements is about \$167million, which accounts for 52.2 % of the total budget. Most of the spending is on Miramar Clearwell

Improvements, which costs about \$120 million. Another small amount of budget is on the operation. In Miramar WTP, fluoride for water treatment takes up a large

proportion, about \$98,570. As can be seen from the two tables above, Miramar WTP has the edge over the Carlsbad SDP in terms of construction, which was reduced by 79 %. The high initial investment results partly from expensive equipment and additional seawater intake pumps. The drastic distinction between pipeline EPC is particularly alarming. Though under a government contract, Carlsbad SDP needs huge investment in pipeline construction due to its geological limits. For water to be

transferred to the urban areas for domestic uses, the desalination plant most commonly features a high portion of transportation investment. Mitigation purchases to reach carbon neutrality and huge environmental restoration expense contribute to a higher accumulated construction cost. However, Miramar WTP required a major improvement in the overall project, which is less financially cost-effective than the desalination plant's low operational and maintenance fee.

Table4. Miramar Water Treatment Plant Sources and Uses (dollars in thousands) [16].

Sources	Uses	Budget
Construction	Construction D	4,000
	Miramar Plant Fleetractt Service Fac Imtracts	143
	Miramar Trunk Sewer Emergency Project	188
	Miramar PI Segment Replacement	318
	Miramar Valves Replacement	100
	Miramar Clearwell Improvements	120,300
	Miramar Pump Station Rehabilitation	8
	Miramar Pipeline Monitoring & Re-inspection	1,200
	Miramar Storage Tank & Raw Water Connection	13,100
Total		320,057
Operation	Fluoride for Water Treatment	986

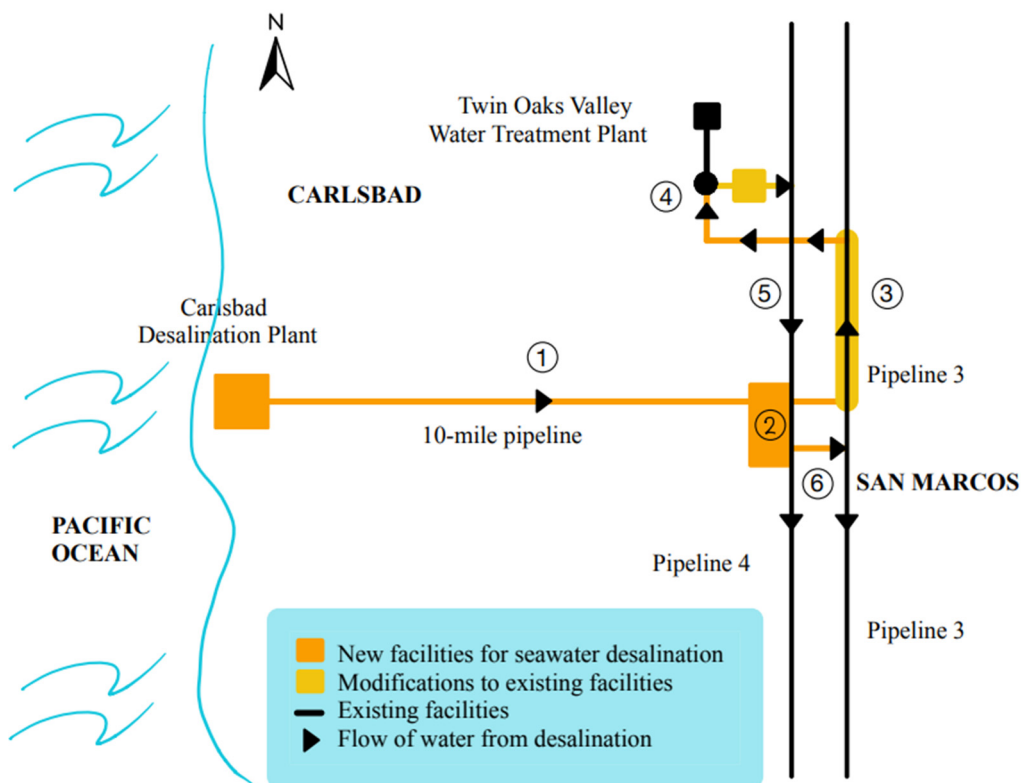


Figure 3. Adding Seawater Desalination to Water Authority System [18].

3.3 Waste discharge

Table 5 presents the annual average residual concentration during the process of Coagulation and Filtration. As shown in this table, total suspended solids (TSS) and metals take up the main proportion in Water Treatment Plant pollutant concentrations, especially the amount of TSS. One of the most influential factors in sludge generation in the WTP is the suspended solids present in the captured water [19]. TSS discharged by WTP may settle to form bottom deposits in the receiving water, creating anaerobic conditions. In addition, it also increases turbidity in receiving waters and reduces light penetration through the water column, thereby limiting the growth of organisms [11]. Moreover, metals, Copper, Lead, Nickel, Zinc, Aluminum, Calcium, Iron, and Magnesium also provide a large part in the model plant effluent discharges.

These all remaining metals produced in wastewater have the potential for bio-accumulation and bio-magnification in aquatic food chains and presence downstream in effluent receiving waters used as source waters for potable water supplies.

Table 5 also illustrates the annual average residual concentration during the process of reverse osmosis. According to the table, chlorides are of the highest concentration, which makes up the main part of the model plant effluent discharges. The discharge of untreated hypersaline wastewater results in the mineralization of water, increasing softening cost and corrosion in industrial equipment, and posing health hazards on humans and animals [20], thus disrupting ecosystem structure. The remain main pollutants are TSS, Total Nitrogen, Fluoride, Ammonia, Iron, and Copper. Most pollutants may cause the development of eutrophic conditions, impacting fish, populations, biodiversity, recreation, and potable water supply [11].

Table 5. Annual Average Residual Concentration in WTP and SDP [11]

Pollutant(mg/L)	Coagulation and Filtration	Membrane Desalination
Conventional		
BOD	1.44	
CBOD5		1.00
TSS	135	2.86
Other Solids		
TDS		
Chlorides		7,120
Nitrogen		
Nitrogen, Total	3.64	2.95
Ammonia	0.482	1.55
Metals		
Aluminum	2.16	
Barium	0.0100	
Cadmium		0.00104
Calcium	8.73	
Copper (g)	0.0693	0.000891
Fluoride	0.684	2.11
Iron	4.31	1.46
Lead (g)	0.00569	
Magnesium	2.58	
Manganese	0.442	
Nickel (g)	0.00	
Phosphorus, Total	0.423	0.0678
Zinc (g)	0.316	

Comparing with Water Treatment Plant and Seawater Desalination Plant, the study finds that most of the metals appear in the process of Coagulation and Filtration, and the quantity of metals in Water Treatment Plant is better than that in Seawater Desalination Plant. For example, Iron in WTP is larger than desalination. A distinguishable feature of metals is that, unlike any other toxic substance, they are not biodegradable and can accumulate in the sludge to potentially toxic concentrations [21]. The main cause of this toxic effect is the chemical binding of metals to enzymes and subsequent disruption to enzyme structure and function [22]. Moreover, the metal of Aluminum is toxic in the aquatic environment, and the direct effect of residuals on the aquatic environment is difficult to isolate from the effect of naturally occurring aluminum. Besides, the Total Nitrogen is another one that accounts for a high percentage in these two plants, but the amount of nitrogen in WTP is more than SDP. Nitrogen that readily biodegradable fraction of organic nitrogen is mineralized readily by microbial activity under both anaerobic and

aerobic conditions, which cause Eutrophic water [11]. Although the data of Chlorides is large in SDP, most of that may be Sodium chloride due to seawater. There are a number of methods developing to deal with Sodium chloride, such as Sodium chloride may be used to produce multiple high-purity solid salts, to eliminate the need and costs of solid waste disposal and to sell the high-purity salts and adopt a circular economy strategy [23] or company develop novel materials with advanced properties low-priced and cost-effective materials, etc. By the above comparison, this study considers that pollutants in Water Treatment Plant are more harmful than that of Seawater Desalination Plant.

4 Conclusion

This study mainly compares the water supply of two different water treatment plants, Carlsbad Desalination Plant and Miramar Water Treatment Plant, in San Diego,

USA. According to the comparison of Carbon footprint, Cost, and Waste discharge, Carlsbad Desalination Plant has obvious advantages. There are three reasons: 1) regarding carbon emission, Carlsbad Desalination Plant has less emissions per year and consumes less energy than Miramar Water Treatment Plant, since it uses absorption offsets emissions and recycling method. 2) in terms of cost, reverse osmosis requires a low operational and maintenance fee than the traditional water treatment plant. 3) In the area of waste discharge, Seawater Desalination Plant discharges less environmentally harmful metals in wastewater than Water Treatment Plant. Therefore, three metrics analysed from two specific plants can be used to infer environmental, financial, social sustainability between RO Desalination Plant and Conventional Water Treatment Plant. Environmentally friendly, low cost of the water treatment process and low social hazard are advantages of RO Desalination Plant compared with Conventional Water Treatment Plant, hence society may develop desalination technology. But some issues remain, such as huge costs in engineering & technical and expensive equipment in the plant. In addition, large discharge of Sodium chloride, although novel materials and economic strategy are developing to decrease the quantity and the hazard, these technologies are needed to assess the effectiveness and sustainability. Thus, further studies should focus on researching more effective and less costly techniques and equipment to reduce sodium chloride production or harmfulness. Conventional Water Treatment was and still is widely used in the world. However, with water scarcity and the urgency of managing the environment, maybe desalination will become the main stream approach of water supply.

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