



Pathways to magnesium supplementation of drinking water: An overview of the saline water conversion corporation experience

Christopher M. Fellows^{a,b,*}, Ali A. Al Hamzah^{a,b}, Seungwon Ihm^a

^a WTIRA, Saline Water Conversion Corporation, Al Jubail, 31951, Kingdom of Saudi Arabia

^b The University of New England, Armidale, 2351, Australia

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ABSTRACT

Magnesium (Mg) in drinking water is essential for human health, with low concentrations in drinking water being reported to be correlated with poor cardiovascular health outcomes. Based on the literature and suggestions that the World Health Organization would soon announce guidelines for Mg content of drinking water, the Saline Water Conversion Corporation (SWCC) announced specifications in October 2020 targeting 15–25 ppm of Mg in product water. SWCC produces approximately 6 million m³ of potable water daily for domestic and industrial use in the Kingdom of Saudi Arabia, so meeting this Mg target will require the allocation of significant resources. In this report the different approaches to adding Mg in post-treatment of the product water from the SWCC's network of desalination plants are reviewed in order to optimise the additional capital investment and ongoing operational expenses. The most cost-effective option is to mix produced water with groundwater containing Mg, but where this is not feasible the next most cost-effective method for achieving a 15 ppm target was assessed to be treating desalination brine with nanofiltration (NF) to generate a magnesium-rich brine fraction that can be mixed with produced water. A one-stage NF process can meet the 15 ppm Mg target only with levels of chloride and total dissolved solids exceeding regulatory maximums in the produced water, so a multi-stage NF process with intermediate dilution was designed. While this has a significantly higher capital expenditure and energy requirement than one-stage NF, at the cost of energy in the Kingdom of Saudi Arabia it is still significantly less expensive than alternative approaches (0.009 USD/m³). This solution was implemented at an SWCC desalination plant on the Red Sea and has been delivering Mg-enriched water (~15 ppm) to approximately 1.3 million people since May 2022 at an estimated additional operational cost of 0.007 USD per m³. For lower target levels of Mg supplementation (~5 ppm), replacement of limestone with dolomite in post-treatment limestone contactors has been found to be a cost-effective process in plant-scale trials at another SWCC plant on the Red Sea.

1. Introduction

Magnesium (Mg) levels in drinking water have been reported to be strongly correlated with human health, with epidemiological studies finding low concentrations in drinking water associated with poor cardiovascular health outcomes [1–5] and more tenuous indications of possible associations with dementia [6,7] and cancers [8–10]. Increasing magnesium concentrations in drinking water may alleviate the impact of pre-existing health conditions, with biochemical markers associated with heart disease reduced in rats given water containing 15 ppm Mg [11] and a recent study finding beneficial effects of 20–50 ppm in magnesium in drinking water for reducing the symptoms of diabetes

in human subjects [12]. It has been suggested that as little as 14 mg of Mg²⁺ consumed daily in water could be protective [5]. This is low compared to recommended daily allowances of magnesium and the mechanism of the impact of low Mg²⁺ in drinking water on human health remains unclear [13]. Two litres of typical North American tap waters have been reported to provide between 6 % and 31 % of the daily recommended intake of magnesium [14], while it has been reported that magnesium in drinking water may be the main intake channel for infants and children [15].

Due to the omnipresence of Mg in ground and surface waters, low levels of magnesium in drinking water are primarily a concern in locations dependent on desalination; commercial desalination processes

* Corresponding author.

E-mail address: cmichael@swcc.gov.sa (C.M. Fellows).

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Table 1
Representative natural waters as sources of magnesium.

Source	Mg ²⁺ (ppm)	Ca ²⁺ (ppm)	Na ²⁺ (ppm)	Na/ Mg	Citation
Rhodes Groundwater	58	42	28	0.48	[22]
Dead Sea	46,000	17,000	36,500	0.79	[23]
High Selectivity NF Reject of Seawater	10,000	2600	14,700	1.47	SWCC
Palestine Groundwater	75	168	138	1.84	[24]
Riyadh Groundwater 2	48.4	224	115	2.38	SWCC
Riyadh Groundwater 1	57.5	149	160	2.78	SWCC
Low Selectivity NF Reject of Seawater	4850	830	15,600	3.22	SWCC
Morocco Groundwater	139	331	730	5.25	[25]
Seawater	1530	450	12,400	8.10	SWCC
Colorado River	35	95	333	9.51	[26]

deliver water with low overall total dissolved solids content (TDS), which is typically increased in post-treatment with calcium carbonate to give 100–200 ppm TDS and a low corrosivity (Langelier Saturation Index of 0.0–0.3). Large epidemiological studies studying populations before and after connection to desalinated water supplies strongly suggest negative effects on cardiovascular health (e.g., [16]). While only a few jurisdictions in the world currently have guidelines for minimum Mg levels in potable water (Czechia 20–30 ppm; Slovakia 10–30 ppm; Israel 30 ppm; India (bottled water) 10–30 ppm [17], <https://www.gov.il/he/Departments/Guides/food-service-magnesium>, https://www.fssai.gov.in/upload/media/FSSAI_news_Water_Stateman_04_01_2020.pdf), there has been an expectation based on the literature that the World Health Organization would soon announce guidelines for Mg content of drinking water. In October 2020 the Saline Water Conversion Corporation (SWCC) announced quality specifications targeting 15–25 ppm of Mg in product water in its network of desalination plants. The SWCC produces approximately 6 million m³ of potable water daily for domestic and industrial use in the Kingdom of Saudi Arabia, so meeting this Mg target unavoidably requires the allocation of significant resources.

While in many parts of the world reliant on desalination, drinking water is sourced mainly from bottled water, reducing the need to address low Mg²⁺ content in product water, it might also be of advantage to fortify desalination plant produce water with Mg²⁺ to increase its suitability for agriculture [18]. With continuing efforts to reduce the cost of desalination, it is becoming more viable to use it to supplement or replace ground and surface water resources, especially indirectly through use of wastewater [19], but Mg²⁺ is essential to photosynthesis and prolonged use of water with insufficient magnesium will lead to poor yields and poor plant health [20]. The benefits of a sufficiently inexpensive method of supplementing seawater desalination product water with magnesium are therefore potentially very significant.

There are many different possible approaches to adding Mg in post-treatment of the product water [21]. In this work the options considered by the SWCC are considered: mixing with natural waters, dissolution of commercial magnesium salts, dissolution of magnesium-containing minerals, dissolution of magnesium hydroxide generated on site as a by-product of brine mining operations and mixing with nanofiltration (NF) reject of seawater. Each of these methods have benefits and limitations. The aim of this work is to determine quantitatively which option or options are the most cost-effective in delivering desired Mg supplementation levels (between 5 and 20 ppm) while meeting the other water quality requirements of the SWCC.

2. Magnesium supplementation strategies

2.1. Addition of natural waters

Mixing with a naturally occurring surface or ground water that is available near the point of consumption of the Mg-depleted water is always going to be the most cost-effective solution in terms of operating expenditure. If these water sources are not already utilised, it may of course involve significant capital expenditure. In the Riyadh region, the SWCC Mg target is currently achieved by the contribution of treated groundwater to the potable water supply. The aquifers drawn upon supply water with approximately 50 ppm Mg, so if they continue to supply a third or more of Riyadh's water supply the ambitious SWCC Mg targets will be met. There are two main limitations of this approach. Firstly, the availability of such a source of acceptable quality: desalination is usually employed where there is limited ground and surface water availability. Even if cost-effective, it would be undesirable to use ground or surface water if that source was not being replenished sustainably, and at most desalination plant locations these sources are under considerable stress. Secondly, the composition of natural waters is always such that addition of magnesium will be accompanied by the addition of other cations, which may increase TDS to unacceptable levels before reaching the desired level of Mg (Table 1). It can be seen that addition of seawater, which will clearly always be available next to a SWRO plant, is limited as a source of Mg because of the high Na/Mg ratio but will be a viable strategy if a high TDS is acceptable. From an environmental perspective, the low energy required for supplementation with other waters makes it an attractive option, with the important proviso that the use of these waters is sustainable.

2.2. Adding commercial magnesium salts

A simple way of increasing magnesium concentration would seem to be dissolving readily soluble commercial magnesium salts, such as epsomite (magnesium sulfate heptahydrate) commonly available as

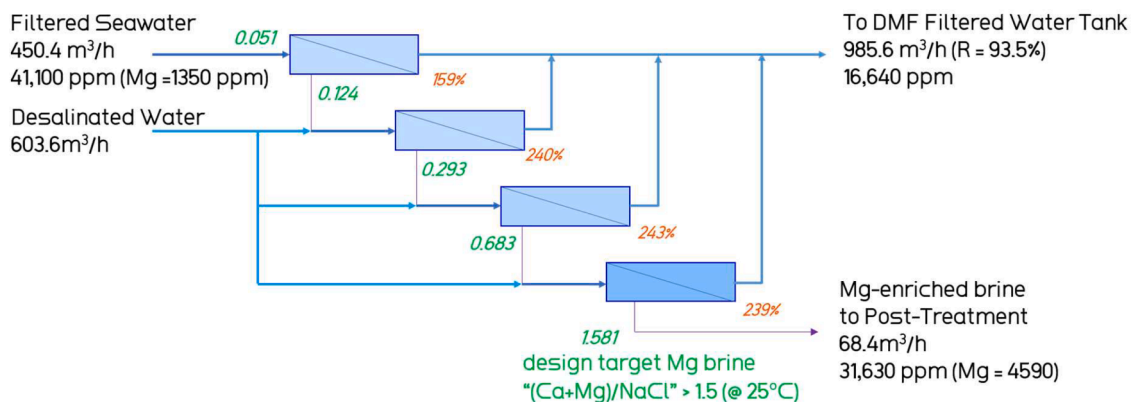


Fig. 1. Process schematic as commissioned of one stream of multi-stage nanofiltration plant, Shoaibah phase 4. Green numbers indicate the mass ratio of divalent cations to NaCl; orange numbers indicate the saturation index of calcium sulfate.

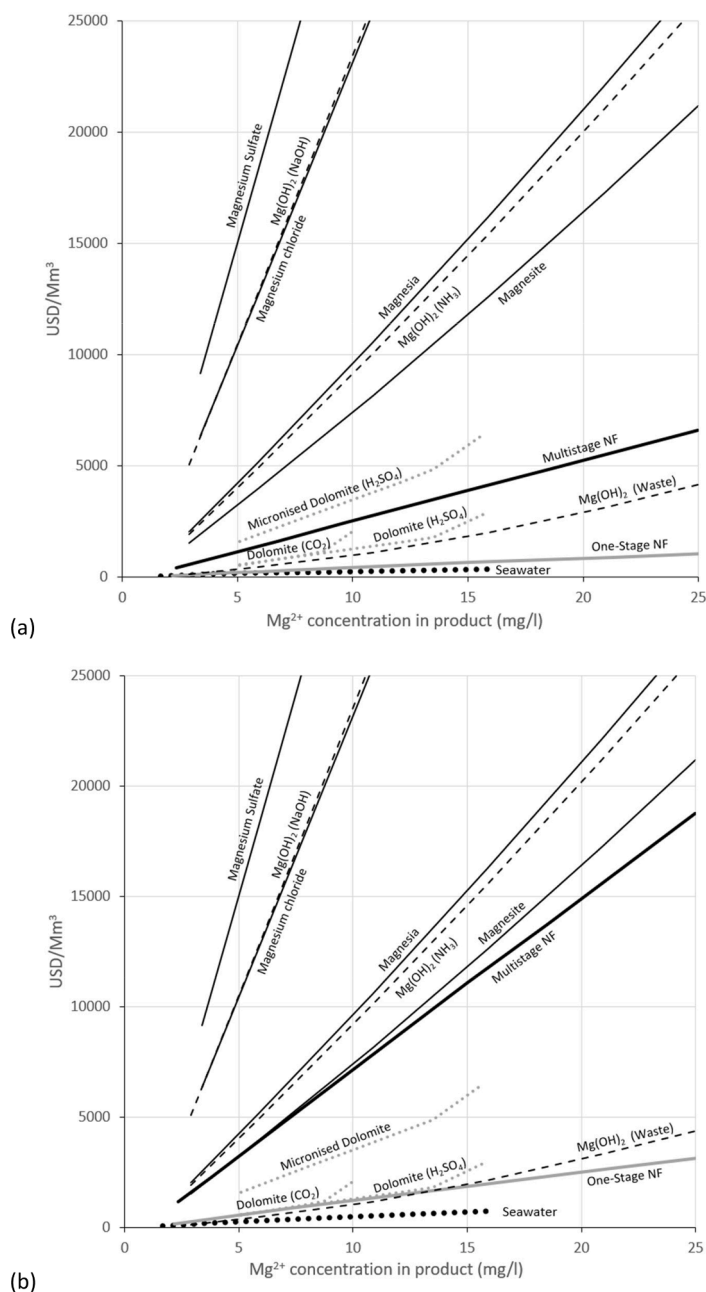


Fig. 2. Operating expenditure for different Mg supplementation methods at (a) 0.048 USD/kWh and (b) 0.144 USD/kWh (opportunity cost of fuel oil at USD 50/bbl).

fertilizer and bischofite (magnesium chloride hexahydrate). These would require little operating expenditure beyond the cost of the chemical, and a small additional capital expenditure for a hopper for feeding solids, make-up tanks and associated low-capacity pumps, control valves and piping. The limitations of this approach are the price of the salts: due to the large quantities of water that must be treated and the low unit price of potable water, even inexpensive salts may incur a cost per m^3 of treated water that is prohibitive. This will be exacerbated by regulations, which are likely to mandate use of a higher-cost food grade salt. The main source of magnesium sulfate is hard-rock mining of kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) from ancient evaporites which requires reprecipitation to obtain product of food-grade purity; alternatively, it may be obtained from magnesite, dolomite, or brines via magnesium oxide and sulfuric acid with a significant input of chemicals and energy. Similarly, commercial magnesium chloride may be obtained by decomposition of carnallite from ancient or anthropogenic evaporites, or via reaction of hydrochloric acid with magnesium oxide obtained from magnesite,

dolomite, or brines. The mining, transport, and chemical and energy footprint of the chemical transformations required mean that addition of these commercial salts is likely to be environmentally unfavourable. An additional concern with adding magnesium as magnesium sulfate to produced water is that sulfate ions can potentially accelerate corrosion processes in the transmission system.

Another class of magnesium containing chemicals which are readily commercially available at low cost are the sparingly-soluble salts magnesite (magnesium oxide) and magnesium hydroxide. The slow dissolution rate of these salts would require them to be applied in a pre-existing remineralisation system where carbon dioxide or mineral acid is used to dissolve lime (CaO) or calcium carbonate (CaCO_3). To maintain the desired calcium concentration and alkalinity in the product water, it would almost certainly be necessary to expand the capacity of these systems, adding capital and operational costs. Alternatively, a slurry of magnesium hydroxide could be prepared in a similar way to the solutions of soluble magnesium salts and administered in such a way that

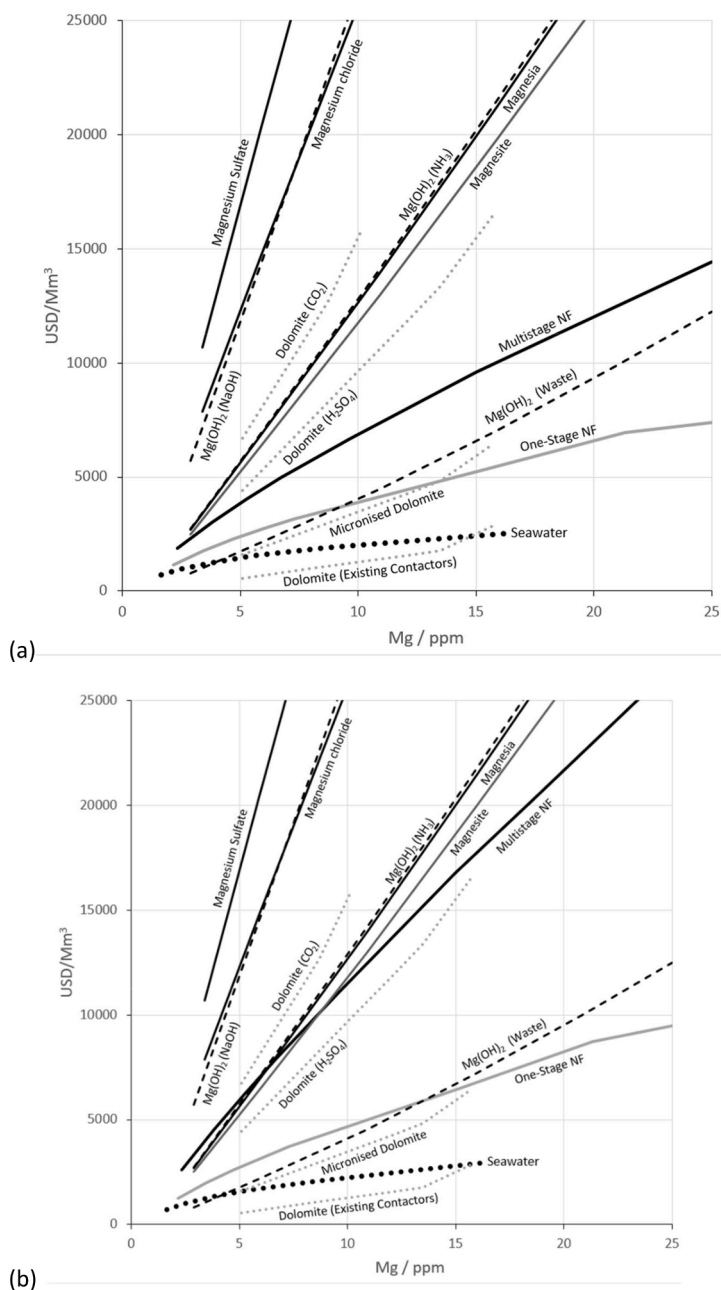


Fig. 3. Total expenditure for different Mg supplementation methods at (a) 0.048 USD/kWh and (b) 0.144 USD/kWh (opportunity cost of fuel oil at USD 50/bbl).

dissolution occurs before the water is delivered to the consumer, however, this possibility has not yet been tested. Commercial magnesium oxide and magnesium hydroxide are largely derived by thermal decomposition of magnesite obtained by hard-rock mining and thus have a relatively high environmental impact in terms of energy use and the unavoidable carbon footprint of generating the oxide from the carbonate.

2.3. Addition of minerals

Magnesite (MgCO_3) and dolomite ($\text{MgCa}(\text{CO}_3)_2$) are readily available in the Kingdom of Saudi Arabia. While magnesite is significantly more expensive than limestone, dolomite is about the same cost as limestone and could be added to the limestone contactor systems used for remineralisation at the majority of seawater desalination plants. Thermodynamically dolomite and magnesite are attractive, as their solubility limits are such that adequate levels of magnesium could be

provided in product water without risk of scaling. Unfortunately, the dissolution rates of these minerals are significantly less than limestone. Under equivalent conditions dolomite dissolves more slowly (by a factor of approximately 2–4 between 20 and 40 °C [27]) and magnesite very much more slowly (by a factor of >1000 between 20 and 40 °C [28]) than calcium carbonate. Replacing limestone in existing contactors with dolomite or magnesite is thus likely to be impracticable. While Greiserman et al. have reported that dolomite dissolution is a viable pathway for remineralization [29], it appears that extensive re-design of contactors would be required to pursue dolomite and magnesite sources of magnesium. Possible strategies would include increasing the residence time of water in the contactors, providing more turbulent flow through the contactors, and increasing the effective concentration of carbonic acid and/or mineral acids in the system which would in turn require greater use of sodium hydroxide in post-treatment to achieve a desirable LSI [30]. In general, a slower dissolution rate would be expected to require an increase of contactor capacity.

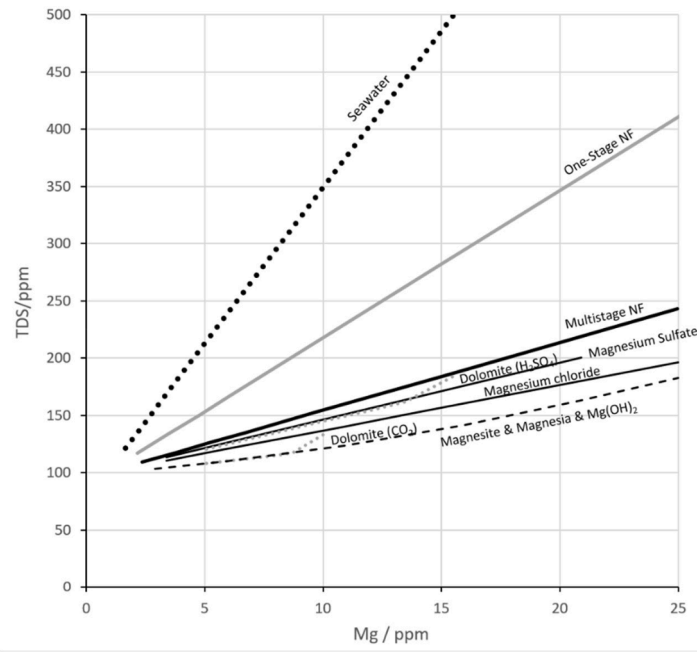


Fig. 4. Total dissolved solids content for different magnesium supplementation methods.

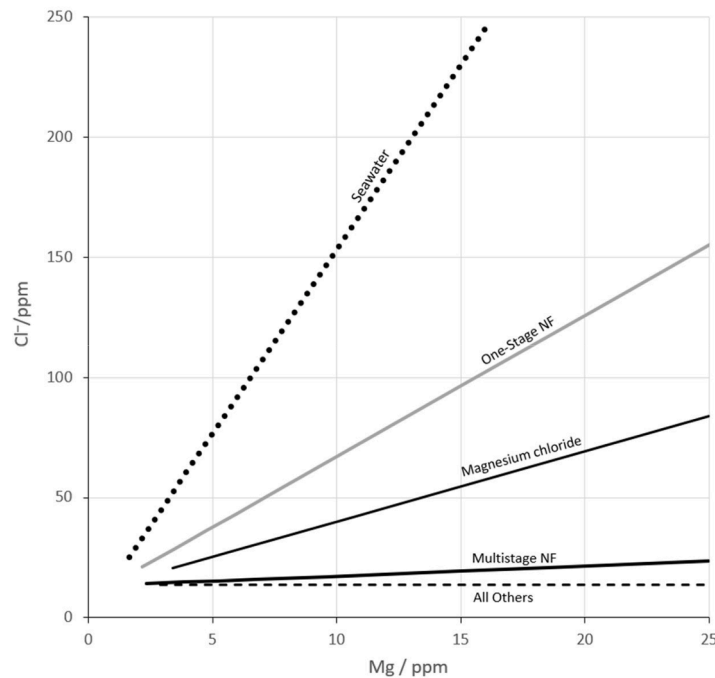


Fig. 5. Chloride content for different magnesium supplementation methods.

The slow kinetics of dolomite dissolution has been experimentally addressed by using an excess of acid, leading to a reduced pH in the treated water which then needs to be adjusted with base to give a reasonable pH and LSI. The high costs and increased solids loading resulting from such a treatment has led Lahav et al. to discount dolomite addition as a credible alternative for increasing magnesium content of product water [30]. However, more recently pre-treated micronized dolomite has been found to dissolve at rates suitable for desalination plant operations [31,32]. This is consistent with the observation that most reported values of dissolution rate constants of minerals arise from physical rather than chemical processes [33].

Dolomite can partially substitute for the limestone currently used in

most current post-treatment systems for protecting transmission systems against corrosion. However, to maintain the desired calcium concentration and alkalinity in the product water it was assumed for the purposes of this study that it would again be necessary to expand the capacity of current post-treatment systems, adding capital and operational costs.

Within the SWCC, plant trials are currently underway at Shoiabah Stage 2 desalination plant in order to assess the feasibility of dolomite for increasing Mg concentrations to ~5 ppm without additional capital work. Replacement of limestone by dolomite (Saudi Lime Industries, Jeddah, Saudi Arabia) of 1–4 mm particle size within a single contactor over a period of two months at a water temperature of 39–40 °C gave

Table 2
Summary of approaches for achieving 15 mg/l magnesium in drinking water.

Method	Total cost at current energy cost (USD/Mm ³)	Total cost at 50 USD/bbl opportunity cost (USD/Mm ³)	TDS (mg/l)	Cl (mg/l)	Environmental impact & notes
Seawater	2438	2816	408	231	Low TDS too high to achieve 15 ppm Mg
One-stage NF	5263	6508	284	98	Low/Moderate (Energy dependent and CAPEX) Exceeds Cl limits for older distribution infrastructure and current TDS limit
Magnesium hydroxide (waste)	6449	6584	136	14	Low Only practical if waste stream exists
Current multi-stage NF	9597	16,797	184	19	Moderate/High (Energy dependent and CAPEX)
Dolomite (with CO ₂)	18,873	18,940	193	14	LSI impractically high at 15 ppm Mg. Possible carbon dioxide sink.
Magnesium oxide	19,800	19,867	136	14	Very High (Mining, Calcination & Transport)
Magnesium hydroxide (via NH ₃)	20,048	20,183	136	14	High (Chemicals and CAPEX)
Dolomite (with H ₂ SO ₄)	28,388	28455	179	14	High (Chemicals, Mining & Transport)
Magnesium chloride	38,930	38,964	157	55	Very High (Mining, Transport, and Synthesis)
Magnesium sulfate	54,641	54,675	171	14	Very High (Mining, Transport, and Synthesis)

Table 3
Comparison of estimated magnesium fortification costs. Where known, the price of energy used in the calculation is provided.

2022 USD/Mm ³	Mg ²⁺ source	USD/kWh	Mg ²⁺ ppm	Reference
36,629 OPEX	Mg(OH) ₂ via NaOH	0.048	10	This work
9127 OPEX	Mg(OH) ₂ via NH ₃	0.048	10	This work
16,046 OPEX	Mg(OH) ₂ via CaO		10	[42]
426 OPEX	One-stage NF	0.048	10	This work
329 OPEX	One-stage NF		10	[42]
12,021 Total	Multi-stage NF	0.048	20	This work
12,272 Total	Multi-stage NF	0.084	20	[39]
37,260 Total	NF + Ion-Exchange		20	[41]
72,000 OPEX	MgSO ₄ ·7H ₂ O	0.048	20	This work
40,000–68,000 OPEX	MgSO ₄ ·7H ₂ O		20	[41]

remineralised water meeting TDS (118 ± 13 ppm), total hardness (52 ± 3 ppm CaCO₃) and Langelier Saturation Index (0.12 ± 0.06) and Mg concentration of 4.3 ± 0.4 with no operational changes required.

Mineral addition of dolomite is preferable to addition of magnesium salts from an environmental perspective as energy is required only for mining, reducing to an appropriate particle size, and transport of the product. There are no additional processes requiring elevated temperature, stoichiometric amounts of chemical reagents, or large quantities of freshwater, unlike the main pathways for producing magnesium sulfate, chloride, and oxide.

2.4. Addition of brine mining by-product

As part of current initiatives within the SWCC to exploit non-water sources of revenue, removal of residual magnesium from an NF permeate stream intended for use by the chlor-alkali industry is required [34,35]. This leads to the generation of a volume of finely divided magnesium hydroxide slurry such that if the brine mining process is implemented on a commercial scale, sufficient material will be available as a by-product to meet Mg targets. This slurry should be amenable to administration by pumping from a make-up tank, as with a commercial magnesium hydroxide slurry discussed above (Section 2.2). This possibility is attractive in that the supplementation substance has a negative price – it would otherwise incur a cost for disposal. In addition to the as yet untested status of this process, the cost of transporting a slurry containing a high fraction of water will be high relative to the cost of transport for other magnesium sources, so this method would most likely only be appropriate where the magnesium hydroxide slurry is generated on the same site where supplementation is required. It remains undetermined whether commercial scale production of sodium chloride for the chlor-alkali industry will begin in the SWCC network; on current trends, magnesium supplementation will be required before such a plant becomes operational. The environmental impact of using a waste stream for magnesium supplementation will be minimal if it is used on the same site as it is generated, but the impact of the energy used in transporting it to distant sites is likely to be environmentally as well as economically prohibitive.

2.5. Adding nanofiltration reject

Application of nanofiltration, which selectively rejects divalent ions over monovalent ions, will increase the total Mg concentration and reduce the Na/Mg ratio of any water [36]. Recent decades have seen a steady improvement in the selectivity of commercial nanofiltration membranes. Typical resulting values for treatment of seawater are shown in Table 1 (Section 2.1). As can be seen, even relatively low selectivity NF treatment of seawater reduces its Na/Mg ratio to the level found in Riyadh groundwater, but at a total concentration 100 times greater, meaning only 1 % of the volume would need to be added to the product water to meet the same Mg target. However, there are different quality requirements for desalination plant outputs than water delivered to the consumer (for example, TDS in desalinated transmission lines must be below 200 ppm, while acceptable drinking water is less than 1000 ppm TDS), which means that a composition that is suitable for distribution in Riyadh would have TDS and chloride values in excess of those allowable for transport from the coast to Riyadh. The additional capital and operational cost of an NF system is not large, as it would only have to treat a tiny fraction of the seawater or brine produced by a typical desalination plant in order to meet the need for Mg supplementation (0.2–2 %), but it would be unable to deliver >15 ppm Mg without unacceptably high TDS and chloride.

Nanofiltration cannot reduce the Na concentration from the initial concentration present in seawater, and calcium sulfate precipitation becomes an issue with highly concentrated NF reject, making it impossible to push the recovery to extremely high values, so NF alone is unable to reduce the Na/Mg ratio below 1 [37]. Although additional

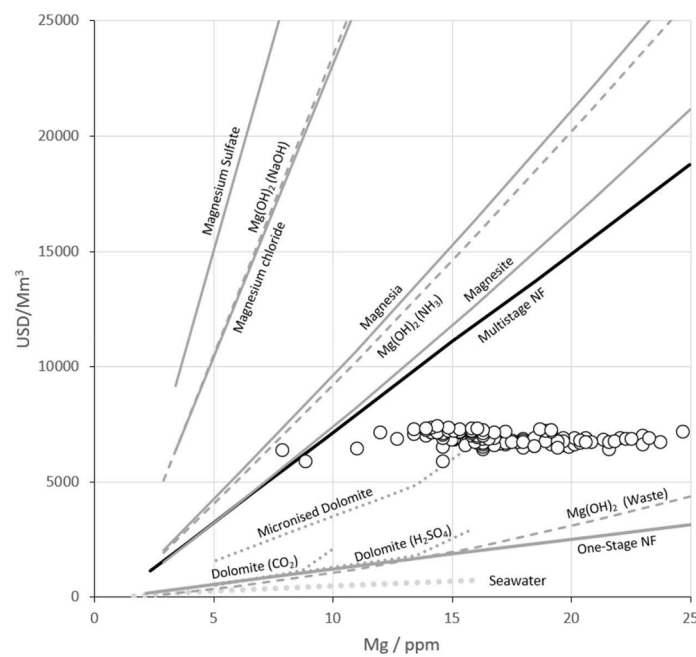


Fig. 6. OPEX calculated with measured power consumption at Shoiabah stage 4, assumed power cost 0.144 USD/kWh (opportunity cost of fuel oil at USD 50/bbl).

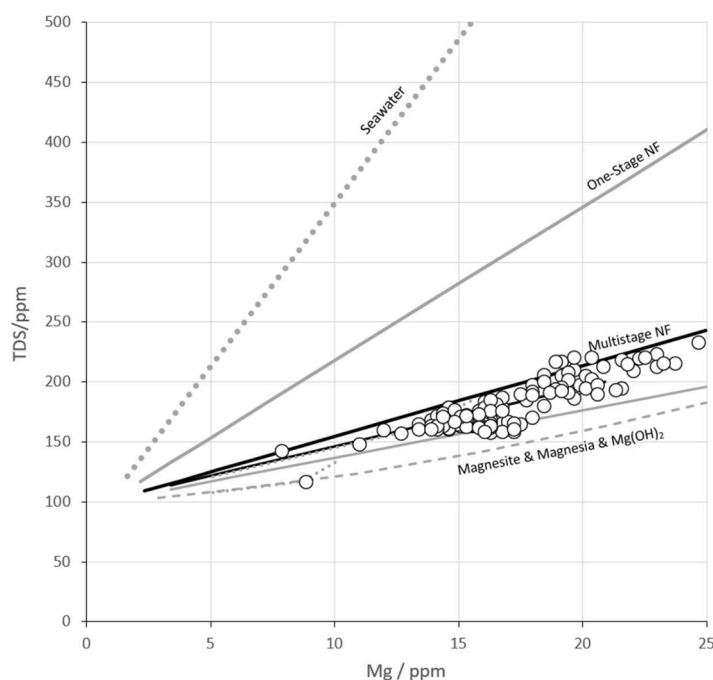


Fig. 7. TDS of magnesium-fortified water at Shoiabah stage 4.

improvement in membrane selectivity can improve the recovery for a given NF permeate quality and hence reduce the footprint and cost of a one-stage NF system [34], the retention of Na means that there is an inherent limit to one-stage NF for magnesium supplementation. This problem can be overcome by adding additional complexity to the NF system in the form of a process where the NF reject is diluted with product water, reducing the overall concentration of Na, and then subjected to another NF step where the Mg concentration is increased and the Na concentration remains relatively unchanged [38,39]. This may be repeated multiple times if required. This will clearly have a higher capital and operation cost than simple nanofiltration but will enable

achievement of Mg targets while avoiding excessive TDS and chloride.

The SWCC plant at Shoiabah Phase 4, south of Jeddah, was selected to construct a demonstration scale multi-stage NF system with inter-stage dilution to implement this strategy, the first facility of its kind in the world (Fig. 1). After awarding the project in May 2021 and starting site works in July 2021, the first Mg-enriched brine was produced in March 2022, and the Shoiabah NF-Mg plant has been in full production of 1600 m³/day Mg-rich brine from seawater since May 2022. The produced Mg-rich brine is mixed with 400,000 m³/d of product water in Shoiabah Phase 4 to give Mg ≥ 15 ppm, serving about 1.3 million people in Makkah province with Mg-enriched water.

The NF permeate returned to the RO system reduces the initial feed TDS from the design value (nominal 43,706 ppm from a design value of 44,562 ppm) allowing the design water production of 400,000 m³/d to be maintained with the same RO feed pressure. The system comprises two parallel streams designed as in Fig. 1, each stream using 33 pressure vessels in the first stage, 30 in the second stage, 24 in the third stage, and 18 in the fourth stage. The total number of elements in the plant is thus approximately equivalent to one RO rack (the Shoaibah Phase 4 plant has 20 SWRO and 10 BWRO racks). While the Mg:Na selectivity of the membranes used in the current process is already high (>10), compounding any future improvements in selectivity over multiple stages means that any increase in Mg:Na selectivity will allow reduction of the total size of the system (reduced flow rates and number of vessels and membranes). Any small improvements in the Mg:Ca selectivity of NF membranes will also enable reduction of the size of the system by allowing higher recovery at each stage.

As mentioned above in the discussion of supplementation by direct addition of magnesium sulfate, the high levels of sulfate found in NF reject, while allowed by national regulations, will be of potential concern in corrosion of transmission systems and will require careful monitoring.

As NF as a means of magnesium supplementation requires no additional reagents, the environmental impact of the process will vary primarily according to the energy source used to operate the NF plant and the supply chain for the consumable membranes; if the energy used is derived in a way with a low environmental impact, the overall environmental impact of the process should compare favourably to other options. The chief negative of this approach is the environmental impact of the relatively large amount of on-site construction required relative to other approaches.

3. Methodology

In order to guide SWCC strategy in meeting the 15–25 ppm Mg target while retaining all required quality parameters over the whole SWCC system, operational costs were estimated for each of the possibilities outlined above. Inputs were:

- Chemical costs, based on current SWCC contracts and quotations provided by chemical suppliers on the Kingdom of Saudi Arabia.
- Energy costs, based on the pumping requirements and the known energy requirements of similar pumps used within the SWCC system. The cost of energy was estimated in two ways, using the current price for power applicable in the Kingdom of Saudi Arabia (0.045 USD/kWh) and on the opportunity cost of power generated by fuel oil which could otherwise be sold on international markets.
- Membrane replacement costs, based on projected lifetimes and quotations provided by suppliers.

It was assumed as a first approximation that all staffing and overhead costs could be accommodated within the existing staffing and overhead costs for operating post-treatment systems, and that if this is not the case that the costs of all options will not differ significantly.

Capital costs were also estimated, based on:

- Studies done within the SWCC previously for additional of seawater for increasing product water TDS.
- The cost of duplication of elements of the desalination remineralization plant according to the cost estimation model of Voutchkov [40].
- The actual costs incurred in construction of the demonstration multi-stage NF plant for magnesium supplementation of drinking water.

Annual CAPEX contribution to the cost of water was taken by

dividing the total estimated CAPEX by 12.

4. Technoeconomic analysis of different approaches

Results of the analysis for operational expenditure are shown in Fig. 2 and total expenditure in Fig. 3. Fig. 4 shows the projected total dissolved solids content corresponding to each Mg²⁺ concentration and Fig. 5 the projected concentration of Cl⁻.

Mixing with seawater is able to achieve approximately 16 ppm Mg²⁺ in product water before exceeding Saudi Arabian product water guidelines for Cl⁻ (250 ppm). Such a process can be implemented at a very low cost by linking existing lines and is currently in operation (to increase TDS, not Mg²⁺ per se) at sites within the SWCC network. However, older transmission lines are limited to waters with much lower Cl⁻ concentrations (25–50 ppm) making this unviable as a universal strategy (Fig. 5).

If power is costed at less than approximately 0.25 USD/kWh, the least expensive in terms of OPEX is a one-pass NF system, but it is limited by SWCC product water guidelines for Cl⁻ (100 ppm) and TDS (300 ppm). Compositions of NF reject were calculated using SWCC internal projections for two commercial membranes which gave very similar results; the average of the two calculations is shown. These currently available membranes can achieve 25 ppm Mg²⁺ in product water at Cl⁻ and TDS values which are within statutory limits, but are high (~150 ppm Cl⁻, ~400 ppm TDS) compared to typical potable water values in Saudi Arabia.

If a waste stream of magnesium hydroxide slurry is available, the next most expensive option will be addition of such a stream. This would allow the entire target range of 15–25 ppm Mg²⁺ to be accessed.

If dolomite is available at a cost similar to limestone (40 USD/ton), then it will be next most cost effective in terms of operational expenditure. At an estimated cost of 60 USD/ton for micronized dolomite, it would be more expensive than raw dolomite but still considerably less expensive than addition of other magnesium-containing compounds.

Commercially available magnesia and magnesite give similar estimated operational expenditures. Despite the requirement for additional chemicals (carbon dioxide or mineral acid) to dissolve these minerals, they are less expensive than the commercially available soluble magnesium salts epsomite and bischofite. If magnesium hydroxide were to be generated on site for the purpose of post-treatment, and is not a by-product of another process, it would have similar operational costs to magnesite or magnesia addition using the cheapest base (ammonia) available.

At a low cost of power, the indicative multistage NF system investigated (that currently implemented at the SWCC Shoaibah Stage 4 plant) is less expensive than the mineral addition options, including micronized dolomite. It has a similar operational cost to the use of magnesium hydroxide waste. Above about 0.40 USD/kWh it becomes less competitive than magnesia addition and above 0.07 USD/kWh it becomes less competitive than micronized dolomite addition.

Incorporation of estimated CAPEX costs, which are more uncertain, changes the absolute costs significantly, but does not make a great deal of difference to the relative viability of the processes (Fig. 3). It may be possible to introduce dolomite to the system without incurring any additional capital costs for low target concentrations of Mg, which if this is the case makes this the most attractive option. Within the limited range in which TDS and chloride limits will not be exceeded, seawater addition is also clearly an option with low overall costs for increasing magnesium content.

A one-stage NF system is found to be the least expensive option up to about 15 ppm, at which level it begins to exceed the maximum allowable chloride and TDS values.

If a waste stream of magnesium hydroxide slurry is available, it would be cost-effective to make use of such a stream up to the maximum target range of Mg supplementation.

A multi-stage NF system can provide Mg²⁺ over the whole target

range while remaining beneath the 25 ppm limit for Cl^- for older transmission systems. This process appears to be the most competitive for accessing the whole desirable magnesium supplementation range at current power costs but becomes undesirable at higher power costs.

A summary of the different approaches for obtaining 15 ppm magnesium in drinking water is given below (Table 2). With reference to the qualitative discussion of environmental impact, it would clearly be beneficial to perform a more quantitative life cycle analysis of the different approaches and this work should be carried out before SWCC extends magnesium supplementation across its entire network.

The values estimated here can be compared to previous estimate for some supplementation options reported previously (Table 3). The OPEX for $\text{Mg}(\text{OH})_2$ as a source is dominated by the cost of the base used for precipitation and the value obtained in this work and by Lehmann et al. for three different bases is consistent, with the estimated OPEX calculated in that work for precipitation with CaO, intermediate in cost between NaOH and NH_3 , falling between the OPEX estimates made in this work. Very comparable values are also demonstrated for the OPEX estimated by Lehmann et al. and this work for a one-stage NF system. While the multi-stage system reported by Birnhack et al. is significantly different from the system implemented at Shoiabah, the inflation-adjusted total costs of magnesium fortification estimated for the two systems are almost identical ($1.21 \pm 0.01 \times 10^4$ USD/ Mm^3) and approximately a third of the cost of an alternative proposal combining NF and ion-exchange [41].

Data on OPEX costs based on the actual power consumption of the multi-stage plant at Shoiabah Stage 4 for several months in 2022 have been calculated and can be compared with the estimated values (Fig. 6). Data points are shown for all measurements where the target volume of final stage reject was delivered for treatment of the produced water. Unfortunately, the produce water volumes are not known so the target volume of 400,000 m^3/day has been assumed. The extension of the data above the cluster of points about 15 ppm is most likely due to treatment of a smaller volume of produce water than designed, so it can be seen that actual OPEX for a target of 15 ppm is about 2/3 of that calculated on an a priori basis.

TDS of the produced water at Shoiabah stage 4 shows a good match to the projected relationship between TDS and Mg concentration (Fig. 7).

It should be noted that the multistage NF facility at Shoiabah is a prototype. Design of a next generation unit has been completed with significantly reduced requirements for energy and fresh water and a lower CAPEX, delivering however water at a higher TDS consistent with projected new standards for RO desalinated water quality in the Kingdom of Saudi Arabia. For the same capacity, the designed values of the next generation of multi-stage NF would use 445 kW vs. 800 kW, require 140 m^3/h vs. 530 m^3/h , and have 80 % of the CAPEX of the extant. This would deliver water at a quality and cost intermediate between the values shown here for the 'One-Stage NF' and 'Multi-Stage NF'.

5. Conclusions

If dolomite can be used in existing remineralization systems without additional capital investment, it should be the most cost-effective means of magnesium supplementation up to 12–15 ppm Mg.

If water quality requirements are not stringent, the most effective way to reach a target Mg range of 15–25 ppm (the range at which evidence for health benefits is strongest, and the target range for legislation in a number of jurisdictions) is single-pass nanofiltration.

Where low TDS and chloride are mandatory, it may be possible to meet Mg supplementation in the 15–25 ppm range by addition of a magnesium hydroxide waste stream from 'brine mining' of desalination concentrate. However, no such mining facility currently exists, and there are commercial pressures to eliminate the polishing step of Mg removal with caustic by using more effective NF, and to find higher value outlets

for the magnesium hydroxide slurry produced, so this waste stream may never eventuate.

This leaves multi-stage NF processes as the method of choice to achieve Mg fortification levels between 15 and 25 ppm, for current prices of chemicals and energy in the Kingdom of Saudi Arabia. The cross-over point where other methods of addition become more competitive in this range is likely to be at an industrial energy cost of 0.15–0.20 USD/kWh. This is currently the case in most locations dependent primarily on desalination for potable water in the Middle East and North Africa, but not in Europe or the Caribbean. Choice of a system for meeting magnesium content limits will thus ultimately depend on the confidence of decision makers in predicting future energy prices.

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Declaration of Competing Interest

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Data availability

Data will be made available on request.

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