

Case Study

Saudi Water Authority strategies for raising the total dissolved solids concentration of water produced and transported from desalination plants: Advantages and challenges

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Abstract

Maintaining the total dissolved solids (TDS) content of desalinated seawater within regulated levels is critical for meeting regulatory limits and maintaining public confidence in the quality of the water supply. A number of strategies for maintaining TDS above the target value of 100 ppm while maintaining all other water quality parameters are described as employed in case studies in seawater desalination plants in the Kingdom of Saudi Arabia: These are reduction of second-stage reverse osmosis, addition of seawater, and increasing the extent of remineralisation. The main operational challenge found in increasing TDS is avoiding corrosion by maintaining the Larson–Skold index below acceptable levels. While acceptable results above 100 ppm can be achieved with relative ease, values above 150 ppm are invariably accompanied by Larson–Skold index levels above 1.2, which cannot easily be remedied without significant capital investment. As legacy thermal desalination plants are retired, it will no longer be necessary to take specific action to maintain TDS above minimum levels, and maintaining system stability at higher levels will become the more significant challenge. Finding means to address the high Larson–Skold index levels is thus a priority in the medium-term to avoid potential corrosion of the existing transmission systems, which were designed for conveyance of product water from thermal desalination plants.

Impact Statement

Desalination of seawater is a large and growing source of potable water on which many communities in arid regions are dependent. Maintaining the total dissolved solids (TDS) content of this water within regulated levels is important for maintaining public confidence in the quality of the water supply. Water with low TDS is corrosive to transmission and distribution systems and has an undesirable taste. The Saudi Water Authority is committed to meeting the regulated lower bound for TDS in the most cost-effective manner possible, and this work outlines several case studies of different strategies employed at desalination plants within the Kingdom of Saudi Arabia in order to make this information publicly available for the assistance of operators of desalination plants worldwide.

Keywords: Desalination; Remineralisation; Reverse osmosis desalination; Thermal desalination; Water quality

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1. Introduction

While provision of clean water for drinking, hygiene, and other purposes is a critical part of modern civilisation, removal of 100% of dissolved solids from water is undesirable. Pure water with a low mineral content has an unpalatable ‘flat’ taste and has potentially negative impacts on human health, with reported associations with cardiovascular disease and other disorders for water deficient in calcium and magnesium [1]. The specific mechanisms of these associations remain unclear. Pure water is

also highly corrosive to concrete and many metals [2, 3]. For these reasons, most jurisdictions mandate a minimum concentration of total dissolved solids (TDS) in potable water. In the Kingdom of Saudi Arabia, for example, the minimum guideline concentration for TDS in potable water mandated by the Saudi Arabian Standards Organisation (SASO) is 100 ppm [4].

Seawater desalination is the main source of potable water in the Kingdom of Saudi Arabia, and if operating according to design, produces water with very low TDS. Approximately 10 million m³ of potable water are produced daily, with a large proportion of the production being transported hundreds of kilometres to inland population centres (Figure 1). This combination of large production volumes from seawater desalination

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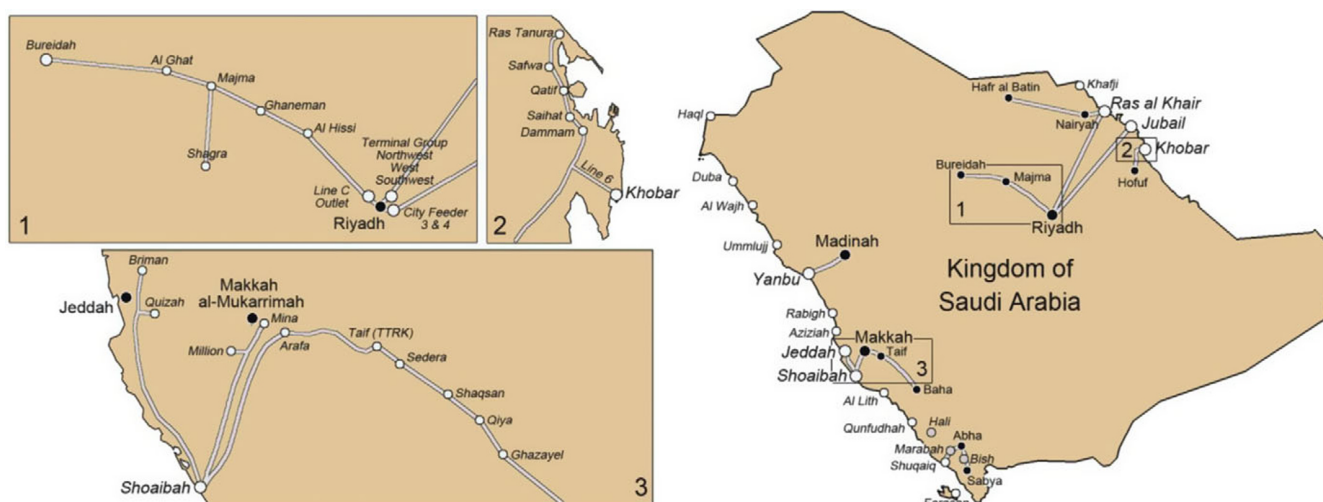


Figure 1. Water production and transmission system in the Kingdom of Saudi Arabia indicating locations mentioned in this report. Reproduced with permission from Al-Hamzah and Fellows, 'Drinking water quality in the Kingdom of Saudi Arabia', *Water*, 2024, 16, (13), pp. 1810 [4].

and long transmission distances is unique in the world. Before transmission, calcium and hydrogen carbonate ions are added in post-treatment to raise calcium and alkalinity in the produced water, with the quantity added adjusted to give an appropriate Langelier Saturation Index (LSI) to avoid corrosion of transmission and distribution pipelines [5, 6]. The LSI model is currently used in transportation systems to estimate the ability of transported water to form a layer of calcium carbonate deposits, which helps protect the cement lining of the pipelines from corrosion during water transport [7]. This model is easy to apply, requiring only five variables to calculate the LSI value: pH, TDS, temperature, calcium concentration, and total alkalinity. However, this model only considers the thermodynamic favourability of calcium carbonate formation and does not consider any other chemical reactions potentially relevant to pipeline corrosion. A useful complement to the LSI is the Larson–Skold index, which is the molar ratio of the anionic charge of chloride and sulfate (ions potentially involved in corrosion) to the anionic charge of carbonate and hydrogen carbonate [8].

Typically, thermal methods of desalination (Multiple Effect Distillation, MED, and Multi-Stage Flash, MSF) produce water with a lower TDS than membrane-based desalination methods (Seawater Reverse Osmosis, SWRO). In general, low TDS values are an issue primarily with water produced from thermal desalination; as the operation of SWRO plants in the Kingdom of Saudi Arabia tends to produce water with relatively high TDS, exceeding upper TDS values is the more significant issue for water produced by SWRO desalination [4]. However, optimised SWRO systems may also produce water that fails to meet minimum TDS levels, especially if a second pass is carried out to reduce boron levels below regulatory limits.

Representative values for the water produced at a number of desalination plants and locations in the transmission system are given in Table 1. Unless otherwise noted, all values given are measured after remineralisation of the product water with carbon dioxide and calcium carbonate in limestone contactors. Several of the plants listed in Table 1 readily achieve TDS values exceeding the minimum. For example, the MSF plant Al Khobar Ph2, where TDS of produced water is higher than 100 ppm due to

the high TDS of seawater in the intake area for the Al Khobar plant ($54,300 \pm 2300$ ppm) compared with typical Arabian Gulf Seawater (TDS $\sim 45,000$ ppm) [11]. At other locations, water from different sources with differing TDS is mixed so that the value in the final product exceeds the minimum. This includes sites such as Al Jubail, where desalination product water is mixed with groundwater before transmission, or Yanbu, where transmitted water is produced with a mix of SWRO and thermal desalination. However, there are also a number of sites where low TDS water production is dominant, and the water transmitted to consumers has not typically met the minimum TDS specifications. In Table 1, these are Ras al Khair and the pumping stations leading downline from the Shoaibah desalination plant campus. At Ras al Khair approximately 70% of production is MSF and 30% SWRO. At Shoaibah, there are a large number of plants feeding into a complex storage and transmission system, with an aggregate production that is approximately 80% MSF and 20% SWRO, with up to $90,000 \text{ m}^3 \text{ day}^{-1}$ (an additional 5%) added seasonally from surface water (Hali dam). The Shoaibah pumping stations listed in Table 1 all draw primarily water produced by MSF.

Increasing TDS in water produced from thermal desalination plants (MSF & MED) can be potentially achieved by a number of strategies. These are: (1) Adding seawater (typically $0.5\text{--}0.75$ litres per cubic metre of produced water); (2) Addition of groundwater with a higher TDS (typically several hundred litres per cubic metre of produced water) [13]; (3) Increasing the amount of carbon dioxide at a given residence time in the post-treatment, thus increasing the concentration of calcium and hydrogen carbonate ions; (4) Installing an alternative remineralisation method that gives more rapid dissolution, such as use of the micronised limestones produced by Omya International and Lhoist [14, 15]; (5) For increasing TDS in water produced from reverse osmosis and dual-use plants (reverse osmosis + thermal plants), the additional strategy of reduction of 2nd pass RO may be employed. In any particular case, combinations of these strategies may be advisable. Application of any method for increasing TDS is constrained by the need to simultaneously fulfil the other key quality parameters for water quality mandated by SASO and the

Table 1. Selected water quality parameters at selected sites in the Kingdom of Saudi Arabia, measured between 6th January and 17th February 2019.

Plant		TDS (ppm)	Total alkalinity, ppm (as CaCO ₃)	Total hardness (ppm CaCO ₃)
Al Khobar	Phase 2 (AK2)	164 ± 21	24 ± 3	48 ± 8
	Phase 3 (AK3)	129 ± 28	25 ± 3	43 ± 7
Jubail ^a	Phase 2	71 ± 9	33 ± 7	43 ± 7
Ras al Khair	PW	76 ± 17	43 ± 3	45 ± 7
Shoaibah	PS1	74 ± 32	36 ± 7	54 ± 13
	Jeddah PS	83 ± 28	34 ± 5	43 ± 7
	Mina PS	95 ± 13	36 ± 5	49 ± 6
Yanbu	PS1 (Phase 1)	66 ± 20	36 ± 5	43 ± 5
	PS1 (Phase 2)	443 ± 91	36 ± 5	85 ± 8
	PS1 (Phase 3)	173 ± 39	38 ± 3	61 ± 12
Jeddah	Odd line ^b	608 ± 710	9 ± 9	115 ± 128
	RO1 ^c	501 ± 178	34 ± 2	94 ± 12
	RO2 ^c	401 ± 270	19 ± 12	94 ± 52
	RO3 ^b	583 ± 429	5 ± 2	107 ± 49
	Even line ^b	77 ± 35	4 ± 1	27 ± 17
Saudi Arabian Standards Organisation (SASO) guideline levels		100–600 ^d		30–300

^aProduct water is mixed with spring water to increase TDS before transmission.

^bNon-remineralsed.

^cRemineralsed by addition of hydrated lime and carbon dioxide.

^dNote that because of the high corrosivity of excessive chloride and sulfate ions, the Saudi Water Authority has a guideline of maximum TDS = 130 ppm and maximum Cl[−] = 25 ppm and maximum SO₄^{2−} = 2 ppm [9] and a mandated maximum of 200 ppm introduced in 2023 for produced and transmitted water from desalination plants [10]. These concentrations of individual ions are key to managing corrosion, but are not systematically reported by the plants and must in many cases be inferred from seawater composition, alkalinity, and TDS.

Saudi Water Authority (SWA) code for the activity of transporting desalinated and purified water (Table 2).

The goal of this work is to identify the most cost-effective means of meeting TDS targets in desalinated product water while maintaining all other quality parameters within acceptable levels. In this report, the implementation of various strategies for simultaneously meeting all water quality requirements at a number of sites within the water production, transmission, and distribution system overseen by the SWA is described, with discussion of the advantages and disadvantages of different strategies.

An ideal strategy for increasing TDS will balance the following criteria: human health, meeting lower limits for calcium and magnesium while maintaining bromate levels below 10 ppb and boron levels below 2.4 ppm; protection of existing water transport systems, giving an LSI in the range of 0.0 to 0.3

Table 2. Mandated water quality requirements for desalinated seawater [10].

Parameter	Units/definition	Value
Langelier saturation index	pH – pH _s pH _s = 9.3 + A + B – C – D A = ((log(conductivity (μS.cm ^{−1})) – 0.70)/10) B = 34.95 – 13.22(log(T (K))) C = log(Ca ²⁺ (ppm as Ca ²⁺)) D = log(M-alkalinity (ppm as CaCO ₃))	0.0–0.3
Larson–Skold index	$\frac{[Cl^-] + 2[SO_4^{2-}]}{[HCO_3^-] + 2[CO_3^{2-}]}$	<1.2
pH		8.1–8.5
Temperature	°C	<40
TDS	mg L ^{−1}	100–200
Magnesium	mg L ^{−1}	>5
Calcium hardness	mg L ^{−1} CaCO ₃	50–80
Total alkalinity	mg L ^{−1} as CaCO ₃	50–80
Chloride	mg L ^{−1}	<60
Sulfate	mg L ^{−1}	<250
Bromate	μg L ^{−1}	<10
Boron	mg L ^{−1}	<2.4

Note: Larson–Skold approximation is from Fellows and Al-Hamzah [12].

and Larson–Skold value below 1.2; technical feasibility; and economic feasibility.

2. Materials and Methods

Water samples were collected on dates between 2019 and 2025 at desalination plants operating in the Kingdom of Saudi Arabia (Figure 1): Khafji, Ras Al Khair, and Al Khobar on the Arabian Gulf coast and Shoaibah on the Red Sea coast. Different plants carried out different sample regimens at different times, with quality parameters typically measured between two and six times per day. Analysis of the parameters of interest for this study was carried out on site (pH, TDS, T, total hardness) or within three weeks of collection in the laboratories of the Water Technologies Innovation Institute and Research Advancement (WTIIRA) of the SWA in Al Jubail, Kingdom of Saudi Arabia. On site, total hardness was measured by Hach total hardness kits (HA-71A, Hach-MENA, Dubai, UAE) and TDS by conductivity using an empirical factor of 0.52 mg·cm L^{−1} μS^{−1} for waters of conductivity <300 μS cm^{−1} and 0.55 mg·cm L^{−1} μS^{−1} for waters of conductivity between 300 and 800 μS cm^{−1}, based on over a hundred samples collected of product water at Ras al Khair, Shoaibah, Al Jubail, and Al Khobar desalination plants. At the WTIIRA laboratories, the on-site measurements were validated parameters were measured using standard methods as follows.

pH: AWWA Standard Method #4500-H+ B/ASTM D1293 (Potentiometry using a standard hydrogen electrode).

Total Dissolved Solids: ASTM D1193 (Gravimetry).

Total Hardness: AWWA Standard Method #2340/ASTM D1126 (EDTA titration).

Residual Chlorine: AWWA Standard Method #4500-Cl D/ASTM D1253-14 (Direct amperometric titration). Limit of detection 3 ppb.

Bromate and Sulfate: AWWA Standard Method #4110 B/ASTM D6581 (Ion chromatography with chemical suppression of eluent conductivity. Limits of detection: Bromate 2 ppb, sulfate 50 ppb.

Boron, Calcium, Sodium: AWWA Standard Method #3120B (Inductively coupled plasma optical emission spectroscopy, ICP-OES). Limits of detection: Boron 1 ppb, Calcium 6 ppb, sodium 6 ppb.

3. TDS Increase in SWRO Plants

The TDS concentration in water produced from SWRO plants operating a second stage (often referred to as Brackish Water Reverse Osmosis, BWRO) may be increased by only passing a portion of the water produced from the first stage through the second stage, or by eliminating the second stage entirely. This approach has been applied in recent years to two sites in the SWA system, the Phase 4 SWRO plant at Shoaibah (RO4), and the Khafji SWRO plant (Figure 1).

There are several positive impacts of this approach. Besides the possibility of raising TDS to the approved value, reducing the amount of BWRO reduces the operating expenditure of water production. Reducing or eliminating BWRO in construction could also reduce capital costs, but this is not advisable as it reduces operational flexibility and may make it impossible to meet other water quality parameters. In particular, for the high salinity waters of the Arabian Gulf and Red Sea, boron is an element of concern. At ocean pH, boron is present primarily as uncharged boric acid, H_3BO_3 , which readily passes through SWRO membranes. Once buffering carbonate species are removed from seawater, the pH can be increased to give ionised borate species which are readily rejected in BWRO; however, making the same pH adjustment before initial SWRO to reduce boron levels in product water below the 2.4 ppm mandated limit will require prohibitively expensive quantities of alkali. A critical issue with boron is the sensitivity of many common crops to boron levels in excess of 0.5 ppm, which will limit the re-use of municipal wastewater in agricultural applications [16]. Another potential issue is the likelihood of bromide ion concentration in product water exceeding 600 ppb, which is in turn likely to lead to bromate formation exceeding the regulatory limit (10 ppb) when hypochlorite is used as a disinfectant [17]. Bromate formation is more likely at higher temperatures and longer periods of time in transmission and storage, and bromate levels exceeding regulated norms are a recurring issue in summer in Saudi Arabia at sites relying on water pumped significant distances inland [17].

3.1. Shoaibah RO4 Plant

The Shoaibah RO4 plant began operation in 2020 with a total design capacity of 400,000 m³ per day and is one of the world's largest

SWRO plants. Between 26 and 30 November 2023, Shoaibah RO4 desalinated water plant was operated in turn with 100%, 84%, 79%, and 59% of the first-pass product water treated with BWRO (Table 3).

Note that a relatively small reduction in the amount of first-pass water treated with BWRO is sufficient to bring TDS above the 100 ppm threshold value. At 84% second pass, a TDS of 150 ppm was obtained, with boron levels still far below the regulatory limit (1.5 cf. 2.4 ppm), chloride and sulfate levels also well below the recommended values, and a bromide level that is unlikely to give excessive bromate in properly managed transition lines. However, negative impacts are seen on both the LSI and Larson–Skold index, with values well outside the target ranges obtained. Provision of a larger fraction of first-pass product to the second pass (~95%) look likely to give TDS > 100 ppm and an acceptable Larson–Skold index, although the LSI will still fall below the acceptable range.

Increasing the extent of remineralisation is an alternative approach to achieve acceptable TDS, LSI, and Larson–Skold index values, with the predicted values of quality parameters with 60 ppm calcium hardness shown in Table 4. However, while reduction of BWRO will save costs, any increase in the extent of remineralisation will incur unavoidable increases in expenditure, either through increased use of carbon dioxide and sodium hydroxide, use of micronised limestone, or construction of additional limestone contactors. In the last column of Table 4, it can be seen how this has been balanced in practice at Shoaibah RO4 where a small reduction in the amount of second pass RO (to approximately 90%) is balanced with remineralisation to a lesser extent than 60 ppm CaCO₃ equivalent, resulting in LSI and Larson–Skold index values that are just within acceptable limits.

3.2. Khafji RO Plant

The SWRO plant at Khafji on the Arabian Gulf has a design capacity of 60,000 m³ day⁻¹. It is not co-located with any thermal desalination plant and has no source of available groundwater. Historically, it has used efficient two-stage SWRO and BWRO to produce water with TDS below the 100 ppm guideline. In 2019, this plant reduced the fraction of permeate from SWRO going to BWRO by 25%, with a phased introduction over three weeks, increasing TDS from ~80 ppm to ~105 ppm (Figure 2). Current practice remains the same, giving a TDS of 105 ± 6 through August–October 2025.

This increase in TDS was accompanied, as expected, by an increase in chloride concentration, which remained well below the maximum concentration guideline (Figure 3). Overall calcium concentration did not change significantly with the reduction of BWRO (Figure 4), but there was a small but significant increase in alkalinity (Figure 5). There was no significant overall change in LSI (Figure 6).

In 2025, a reduction in calcium (Figure 4b) and alkalinity (Figure 5b) is reflected in a reduced LSI (Figure 6b) and increased Larson–Skold index (Figure 7b), suggesting a potentially increased risk of corrosion after the reduction of the BWRO.

4. TDS Increase in Dual Stage Plants

The Ras Al Khair dual-stage plant is a combined MSF and SWRO plant with operational capacity of 770,000 m³ day⁻¹ MSF and 330,000 m³ day⁻¹ RO, at the time of its construction in 2017 the largest desalination plant in the world. It was consistently

Table 3. Values of key water quality parameters of remineralised product water at different operating ratios of the second stage of water produced from the Shoiabah RO4 SWRO plant.

Parameter	Unit	100% 2nd Pass	84% 2nd Pass	79% 2nd Pass	59% 2nd Pass
pH		8.4	8.4	8.4	8.4
Temperature	°C	33	33.6	33.6	32.5
TDS	ppm	81	150	208	300
Total alkalinity	ppm CaCO ₃	45	35	37	45
Calcium hardness	ppm CaCO ₃	41	33	34	41
Magnesium	ppm	0	0.6	2	1
Chloride	ppm	17	59	110	152
Boron	ppm	1.1	1.5	1.8	2.1
Bromide	ppb	36	172	372	442
Sulfate	ppm	0.08	0.75	3.48	2.22
Iron	ppb	10	10	10	10
Copper	ppb	2	2	2	2
Turbidity	NTU	0.1	0.1	0.1	0.1
Residual chlorine	ppm	0.17	0.22	0.21	0.23
LSI		−0.06	−0.28	−0.26	−0.13
Larson–Skold index		0.48	1.96	3.51	3.94

Table 4. Projected impact of reducing second pass RO combined with additional remineralisation at the Shoiabah RO4 plant. Data illustrating current practice at Shoaibah RO4 (November 2025) is shown in the last column of Table 4.

Parameter	Unit	100% 2nd Pass	84% 2nd Pass	79% 2nd Pass	59% 2nd Pass	2025 Practice
pH		8.4	8.4	8.4	8.4	8.3
Temperature	°C	33	33.6	33.6	32.5	31
TDS	ppm	110	191	246	325–358	137 ± 29
Alkalinity	ppm CaCO ₃	60	60	60	60	50 ± 2
Calcium hardness	ppm CaCO ₃	60	60	60	60	43 ± 1
Magnesium	ppm	0	0.6	2	1	ND
Chloride	ppm	17	59	110	152	46 ± 16
Boron	ppm	1.1	1.5	1.8	2.1	ND
Bromide	ppb	36	172	372	442	ND
Sulfate	ppm	0.08	0.75	3.48	2.223	ND
Iron	ppm	0.01	0.01	0.01	0.01	ND
Copper	ppm	0.002	0.002	0.002	0.002	ND
Turbidity	NTU	0.1	0.1	0.1	0.1	0.1
Residual chlorine	ppm	0.17	0.22	0.21	0.23	0.18 ± 0.02
LSI		0.22	0.20	0.19	0.16	0.02
Larson–Skold		0.33	1.15	2.17	2.96	1.3 ± 0.6

Note: ND = not determined.

producing water with overall TDS below specifications, but in 2019 reduction of the BWRO from 100% to 50% was done to increase TDS of the final combined product water. Before reduction of the BWRO on 29 April 2019, a TDS of 80 ± 12 ppm was observed, while afterwards TDS of 122 ± 13 ppm was recorded (Figure 8).

Chloride concentration was strongly correlated with TDS as expected, but remained well within acceptable levels (Figure 9). Calcium concentration (Figure 10) showed no significant change over the period in which BWRO was reduced at the Ras al Khair dual-stage plant, which is not surprising considering that the

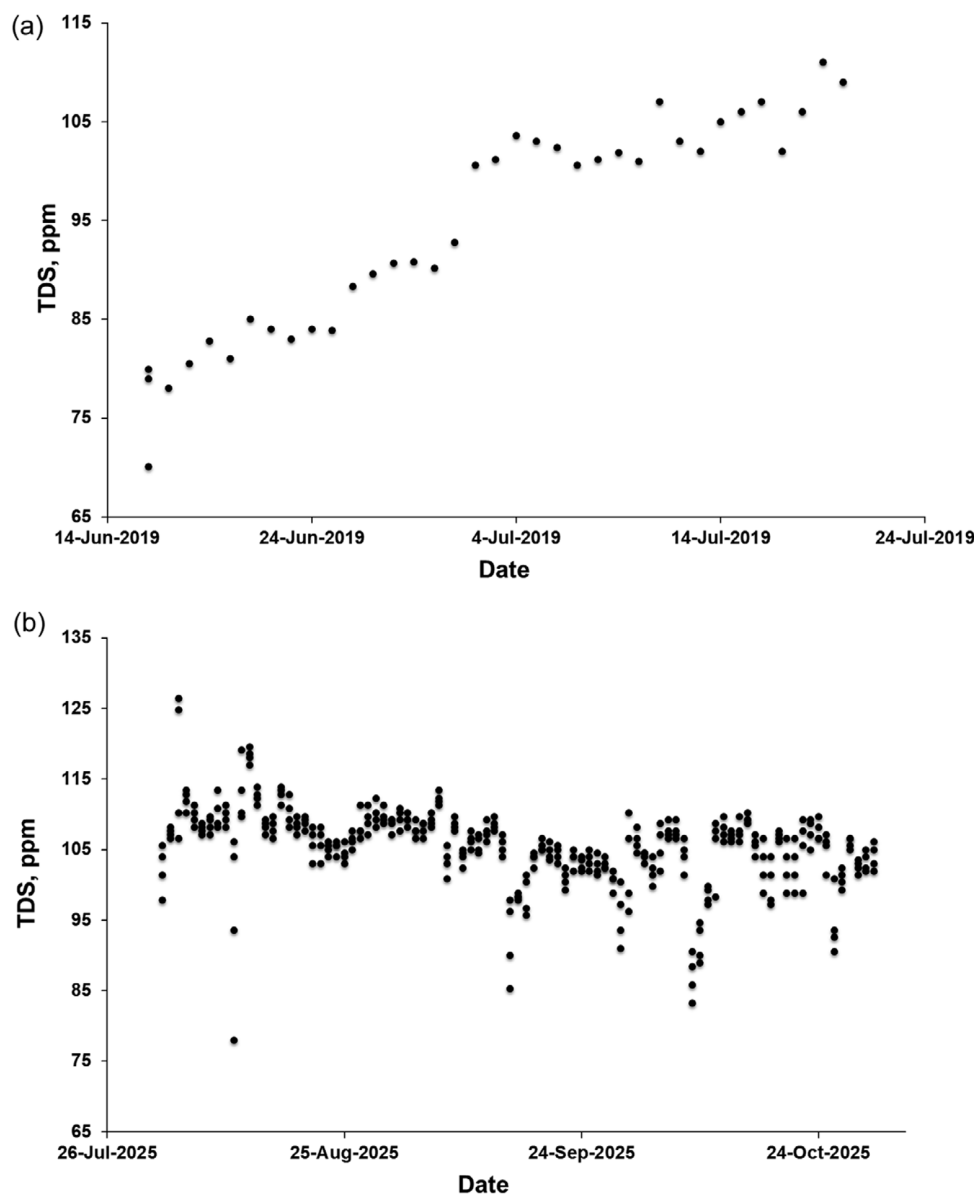


Figure 2. (a) TDS increase at Khafji SWRO plant, 2019; (b) TDS values at Khafji SWRO plant, 2025.

overwhelming majority of calcium in the product water comes from post-treatment and any additional calcium comes from the RO stream may not be significant compared to the range of variation in this value. In contrast to the situation at Khafji when BWRO was reduced, no increase was seen in the total alkalinity at Ras al Khair (Figure 11), which may be related to the relatively small contribution of RO to the overall product water composition at Ras al Khair.

The period of the study covered a large seasonal variation in temperature of the product water (Figure 12), which appeared to be the primary factor in the variation in LSI observed (Figure 13). In order to maintain LSI at a more consistent level and avoid scaling by calcium carbonate in the transmission system, reduction of the amount of sodium hydroxide dosed in the final treatment during the summer (from May to October) was advised.

The Larson–Skold index also saw a significant increase upon reduction of BWRO (Figure 14). In 2019, values were well below the suggested limit value of 1.2 before the change was made, but exceeded it by a small degree afterwards. (Note that while chloride and hydrogen carbonate ion concentrations were measured, the sulfate contribution was estimated based on the chloride:sulfate ratio obtained for product water at the same plant in 2025. As the composition of seawater is essentially identical at a given location, this ratio should not have changed appreciably over the period).

The situation at Ras al Khair as of 2024 was entirely different, as operational decisions with the SWRO system led to consistently high TDS values. Operating under conditions where only a fraction of the SWRO output was passed through BWRO, TDS greater than 200 ppm was consistently reported (Figure 15), leading to very high values of the Larson–Skold index (Figure 14b). Boron

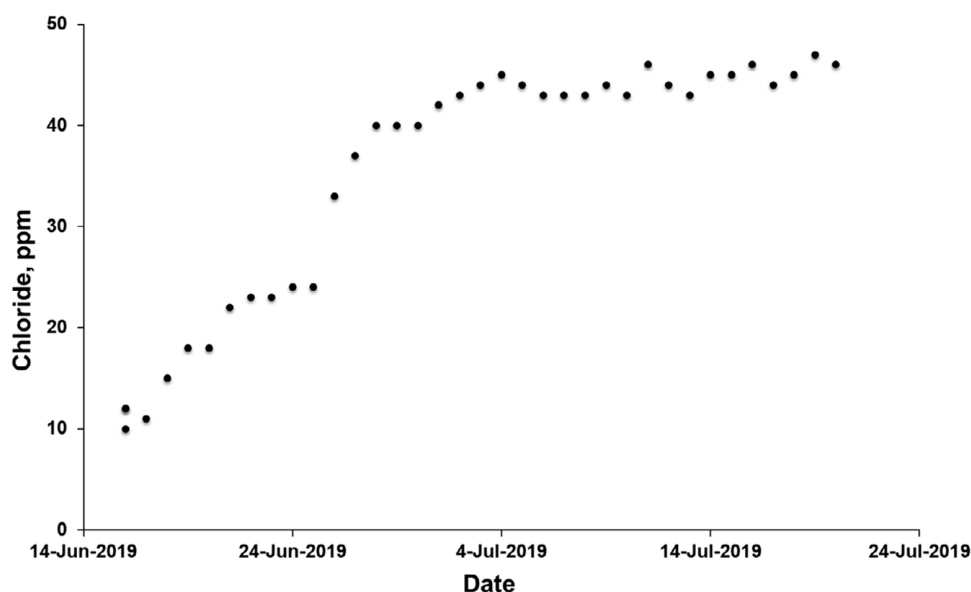


Figure 3. Chloride increase at Khafji SWRO plant.

concentrations in the final mixed product water remained stable throughout 2024 around an average value of about 1.1 ppm (Figure 16). This corresponds to a value of about 3.6 ppm in the RO product water. Bromate, which is derived from both RO and MSF product water, varied more widely in concentration through 2024 (Figure 17), with an average value of 4.8 ± 1.7 ppb.

5. TDS Increase in Thermal Plants

The Shoaibah Ph2 MSF plant, completed in 2007, has a design capacity of $455,000 \text{ m}^3 \text{ day}^{-1}$. In the absence of an RO process stream, seawater (which will have approximately the same composition as RO brine) is the obvious source of additional dissolved solids to raise TDS values above a target threshold. In order to avoid excessive bromate formation, addition of seawater at the Shoaibah Ph 2 MSF plant has been carried out in combination with addition of ammonia at the sub-ppm level [17]. In 2019, water reaching the storage tanks after post-treatment had a TDS of 64 ± 5 . The system used involves addition of 700 mL m^{-3} of seawater treated by sand filtration only, injected after post-treatment and chlorination (Figure 18). TDS over the period illustrated in Figure 19 was 80 ± 14 ppm in the period before addition of seawater and 110 ± 10 ppm after addition (from 14 April 2024 onwards).

As expected, chloride was highly correlated with TDS (Figure 20). No significant change was observed in calcium concentration (Figure 21) or alkalinity (Figure 22) over the course of the trial, reflecting that the overwhelming majority of both of these is derived from post-treatment with limestone and carbon dioxide. LSI was consistently negative over the course of the study period. However, the product water from Shoaibah Ph2 is mixed with waters from other sources before transmission, and adjustment of LSI to appropriate levels is done at this stage. The Larson–Skold index increased slightly upon seawater addition but remained generally below the target value of 1.2, closely paralleling the trend in TDS (Figure 23).

Bromate concentration normally increases in the summer months due to increasing water temperature and would be expected to increase with increasing seawater-derived TDS. However, bromate was measured at 3.0 ± 1.4 ppb before seawater addition ($T = 36.2 \pm 0.4$ °C) and 2.3 ± 1.5 ppb after seawater addition ($T = 38.6 \pm 0.8$ °C), indicating a protective effect of the ammoniation (Figure 24).

Chlorine dioxide has been reported to have a lower probability than chlorine of oxidising bromide to bromate, and at the Shoaibah Ph2 MSF plant as well as the plants at Ras al Khair and Khafji there has been a transition to use of chlorine dioxide for disinfection in order to reduce bromate formation [18].

6. Discussion

Maintaining TDS above the target value of 100 ppm while maintaining all other water quality parameters is an ongoing effort within the system of seawater desalination plants overseen by the SWA, with reduction of BWRO, addition of seawater, and enhanced remineralisation being the main strategies employed through the efforts of operational staff at numerous sites. Cost and availability are the main determinants of which strategy is employed at each location. WTIIRA continues to conduct chemical analyses and physical measurements of samples of the transported water across the SWA network to assess the success of these efforts, with a priority on maintaining the concentration of boron and bromine-derived disinfection byproducts within acceptable levels and avoiding changes in anion concentration that could lead to corrosion of transmission systems.

The main operational challenge found in increasing TDS is avoiding corrosion by maintaining the Larson–Skold index below acceptable levels. Necessarily, increasing the amount of hydrogen carbonate ions is required to balance the additional sulfate and chloride introduced from seawater [6]. While acceptable results above 100 ppm can be achieved with relative ease, TDS above 150 ppm is invariably accompanied by Larson–Skold

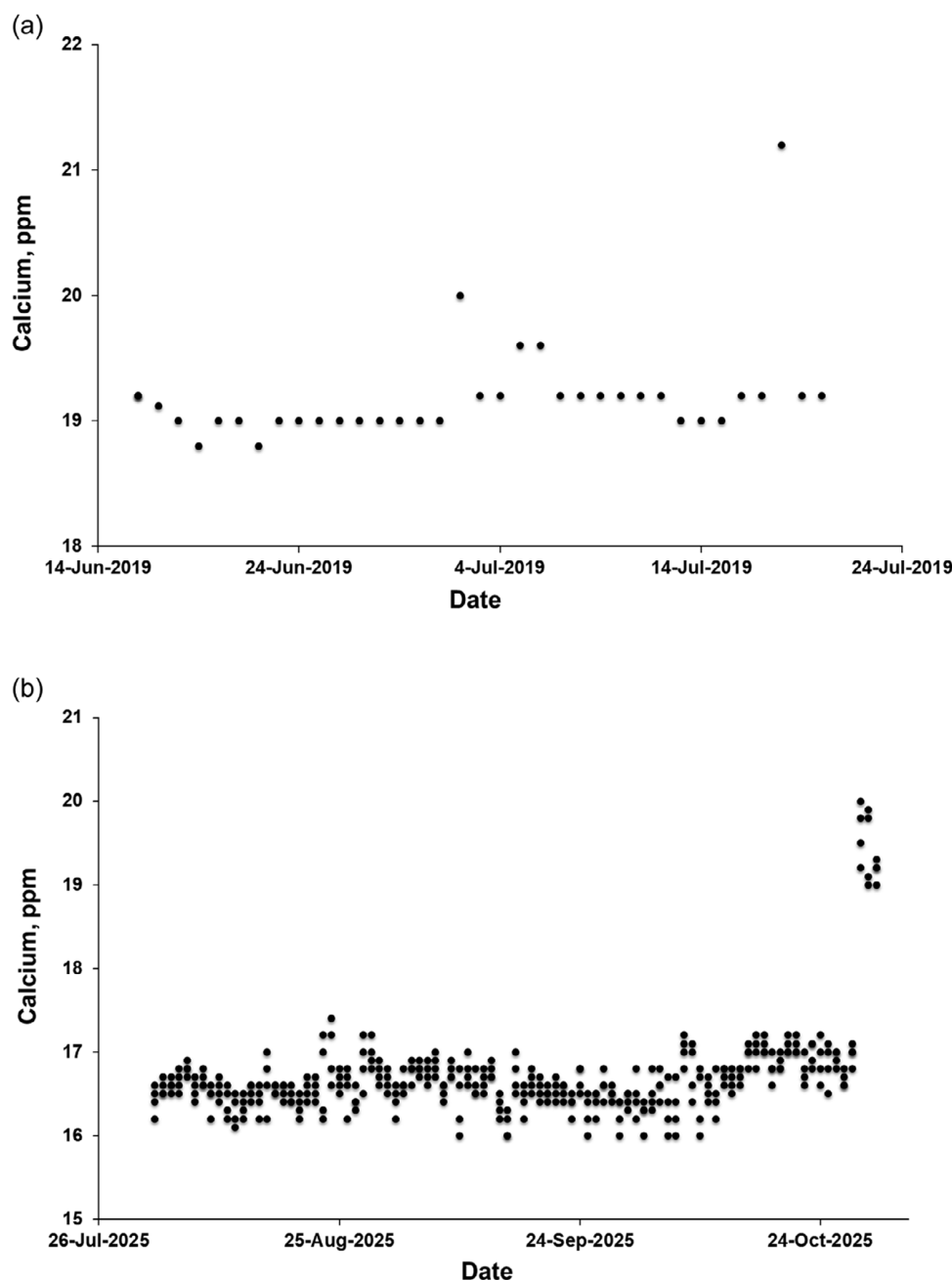


Figure 4. Calcium concentration (mg L^{-1}) for product water at Khafji SWRO plant; (a) period of introduction of reduced BWRO, 2019; (b) Values in August–December 2025.

index levels above 1.2, which cannot readily be remedied without significant capital investment (Figure 25). Higher chloride and sulfate levels must be balanced with increased hydrogen carbonate levels to avoid potential corrosion of the existing transmission systems, which were designed for conveyance of low TDS product water from thermal desalination plants. In existing post-treatment systems, this can only be achieved by increasing the rate of dissolution of calcium carbonate, which in turn requires an increased concentration of carbon dioxide. This incurs increased costs directly for the additional carbon dioxide, and the increased levels of carbonic acid formed may potentially cause corrosion in limestone contactors which were designed for

lower flow rates. Cost is also increased through the increased requirement for sodium hydroxide to neutralise the excess carbonic acid, and the increased dosage will potentially lead to scaling near the dosage point in systems designed for use with lower levels of sodium hydroxide, as well as a generally undesirable increase in sodium concentration in the product water. A more tenable long-term solution to increasing hydrogen carbonate concentrations would be to increase residence time in the post-treatment system, rather than carbon dioxide concentration – which would require capital investment in additional contactors to maintain the same water production levels. Alternatively, the surface area for the dissolution reaction could be

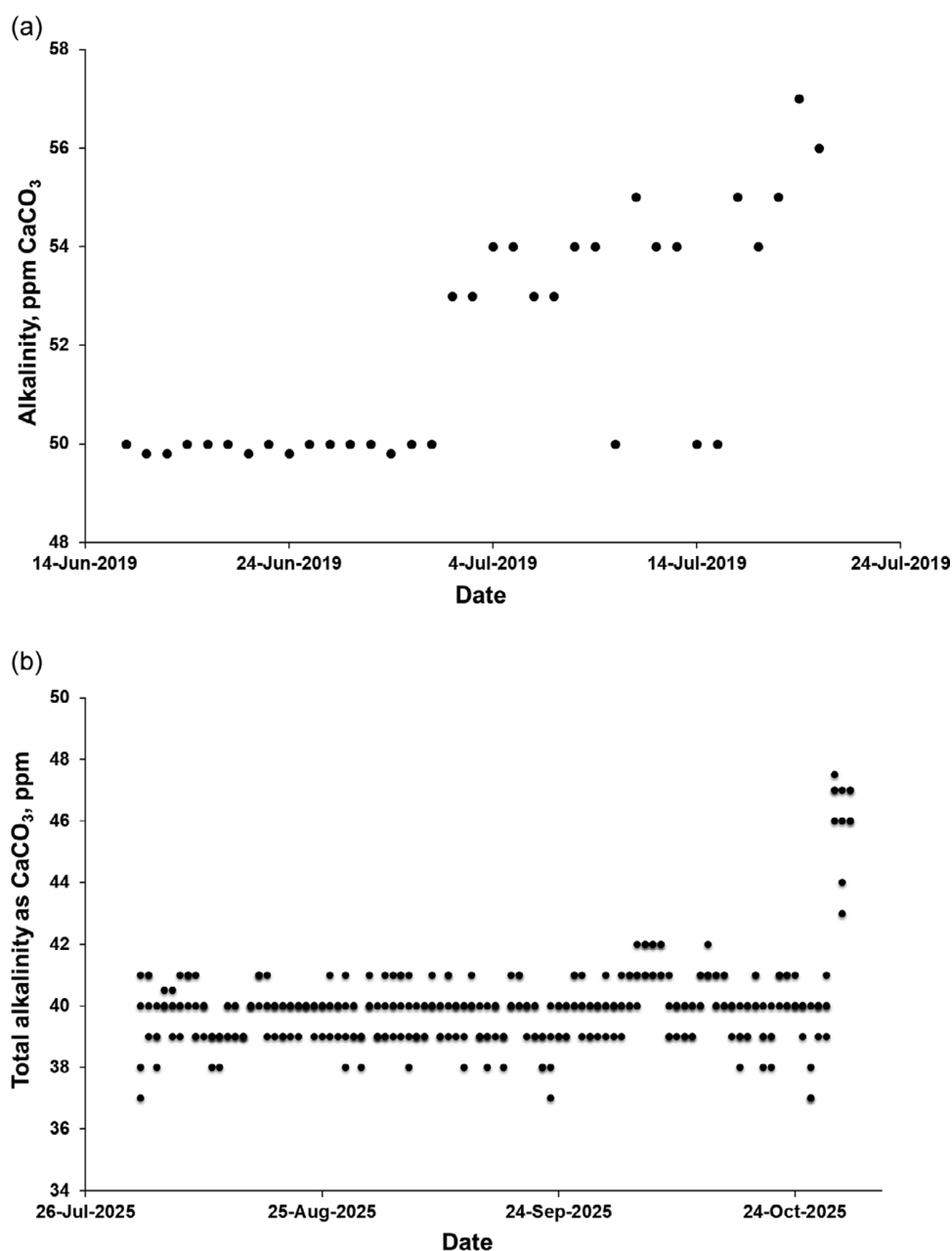


Figure 5. Alkalinity (mg L^{-1} as CaCO_3) at Khafji SWRO plant for product water; (a) period of increase, 2019; (b) levels in August–October 2025.

increased to increase the rate of reaction, through the use of micronised limestones provided by suppliers such as Omya and Lhoist [14]; this would require additional operational expenditure and alterations to existing contactor infrastructure. Studies of increasing the efficiency of remineralisation are currently under way within the SWA system of seawater desalination plants.

The main characteristics of product water obtained from SWRO plants with reduced BWRO (Shoibah RO4 and Khafji), combined SWRO and MSF plant (Ras al Khair) and MSF plant with seawater addition are compared in Table 5. Recalling that Shoibah Ph2 output is not fully remineralised before combination with other water sources, it is evident that targeting

TDS values between 101 and 137 ppm can be achieved by addition of seawater without negative impacts on key water quality parameters.

This study has been limited by the exigencies of collecting data and adjusting operational procedures around the day-to-day requirements of water production and transmission within a commercial network, but conversely has benefitted greatly from access to the world's largest integrated system for production of desalinated potable water. Work on increasing the efficiency of remineralisation is ongoing within the SWA network, but in the medium term the problem of low TDS water is likely to disappear, to be replaced with the problem of managing high TDS water. Thermal desalination processes, which provide

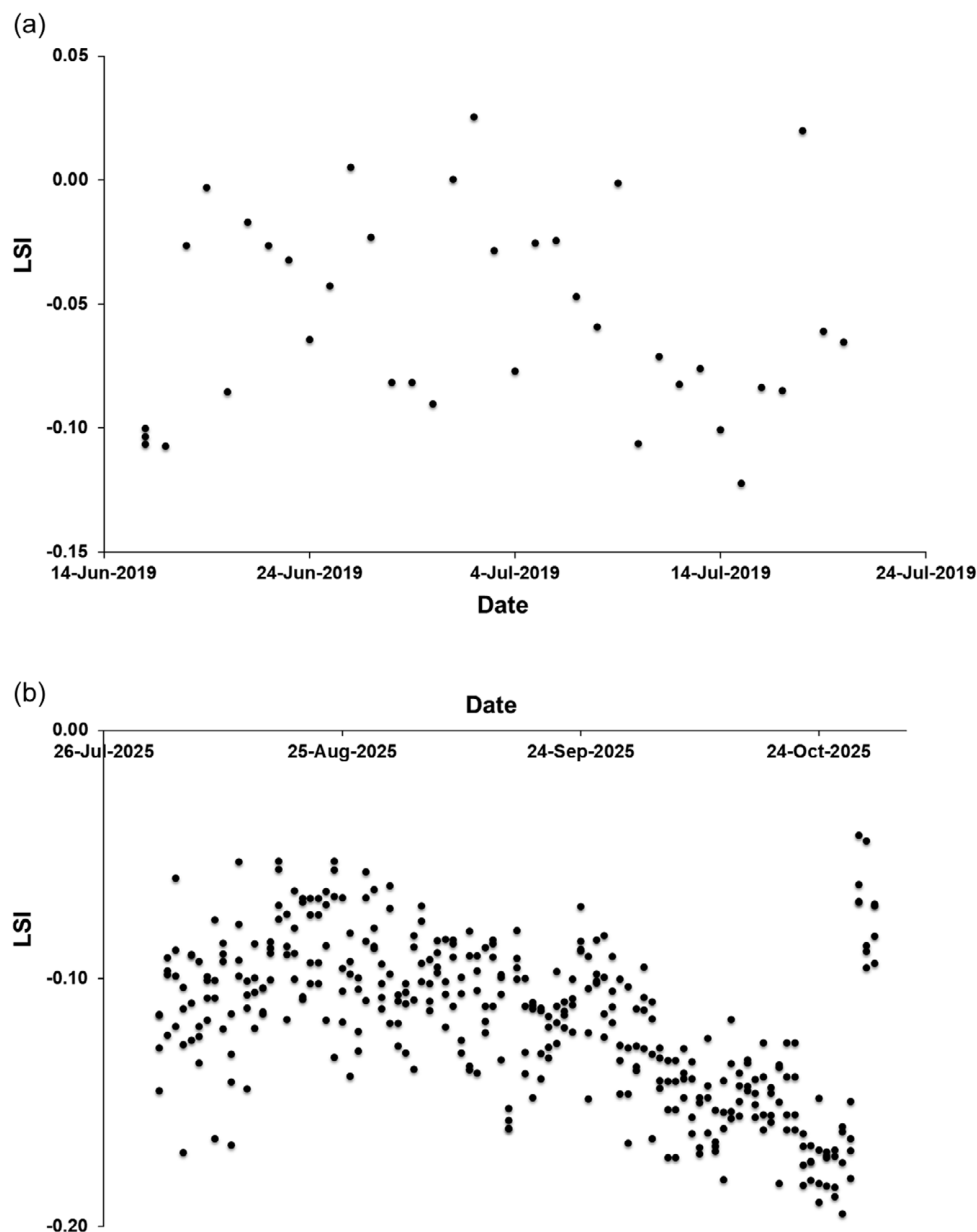


Figure 6. LSI variation at Khafji SWRO plant (a) over the period of time of introduction of reduced BWRO; (b) in August–October 2025.

approximately half of the seawater desalination capacity in the Kingdom of Saudi Arabia, are being systematically replaced with more energy-efficient SWRO systems. As operated in the Kingdom of Saudi Arabia, SWRO plants consistently deliver higher TDS water than the legacy MSF and MED plants, and there is strong pressure to reduce operational costs in such a way as to raise TDS further. In the longer term, replacement of the existing transmission system with materials less susceptible to corrosion (e.g., use of non-metallic pipelines and tanks) is envisioned as the way to safely delivery higher TDS water to consumers in the Kingdom of Saudi Arabia, with the goal of lifting typical TDS

values beyond 200 ppm. The other potential issues observed, such as excessively high LSI or unacceptable bromate and boron levels, are likely to become significant only at these higher target TDS values. Increased bromate levels can be avoided by changes in disinfection processes, for example, by moving from chlorination to the use of chlorine dioxide or chloramine as alternative disinfectants. To maintain boron levels within the levels required to meet health standards and to ensure wastewater is suitable for agricultural uses, specific technologies for boron removal will need to be implemented for treatment of high TDS desalination product water [19].

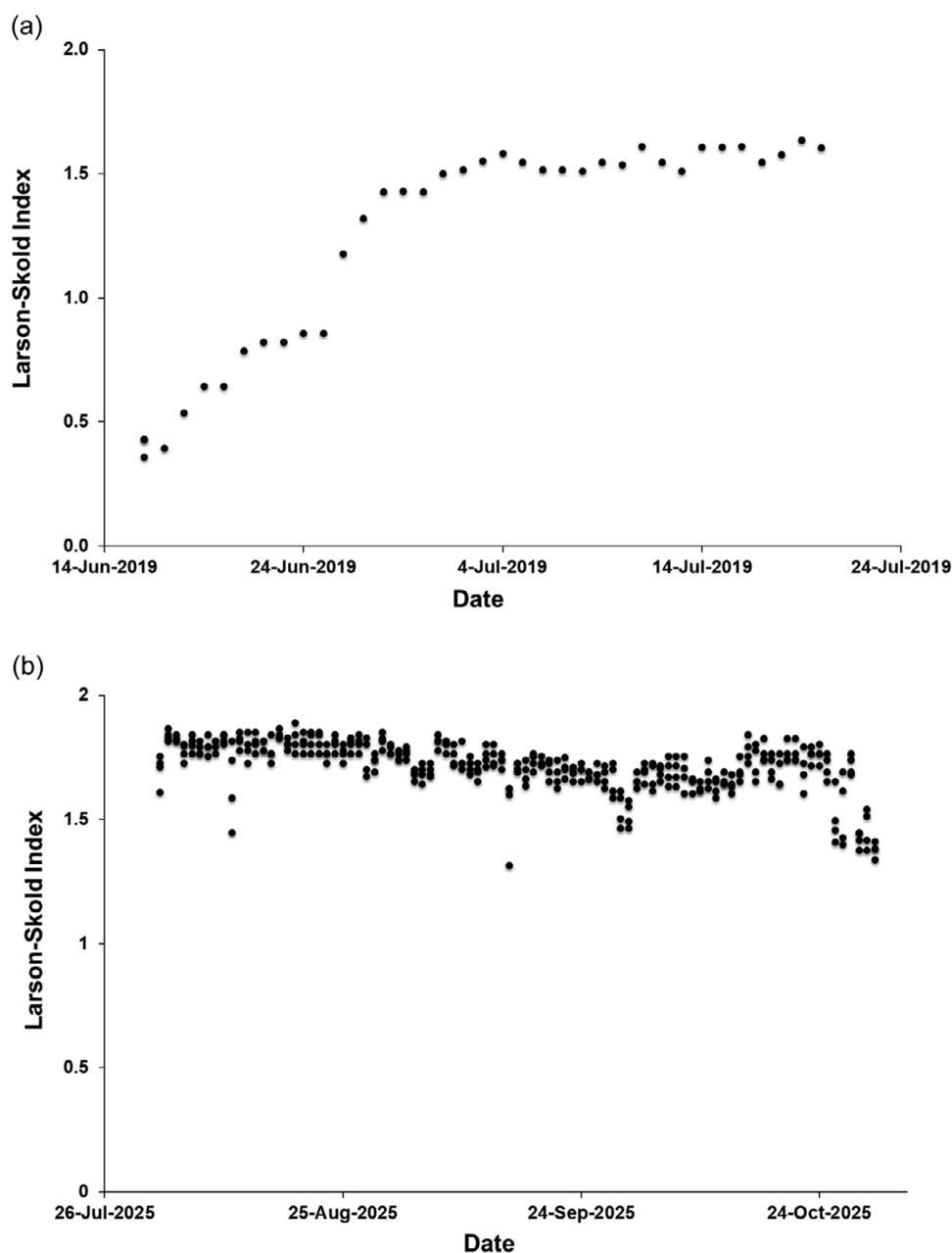


Figure 7. Estimated Larson–Skold index variation at Khafji SWRO plant (a) over the period of time of introduction of reduced BWRO and (b) in August–October 2025.

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Data Availability Statement. All data presented in this article is available upon request.

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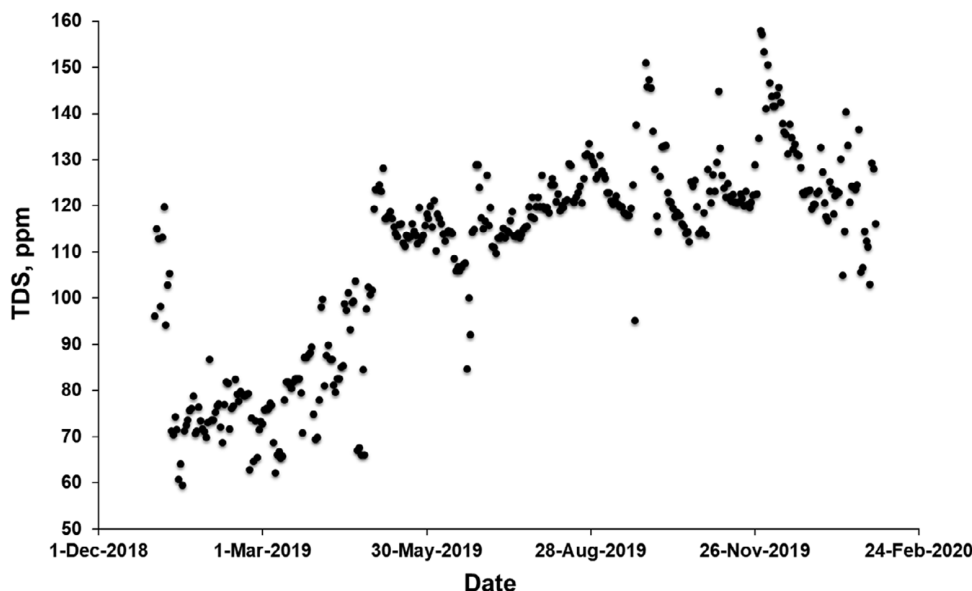


Figure 8. Increase in TDS at the Ras al Khair dual-stage plant. Two extremely high values during a period in which a significant portion of the MSF capacity was shut down (23 September, 208.9 ppm, and 26 September, 208.5 ppm) are beyond the range of the figure.

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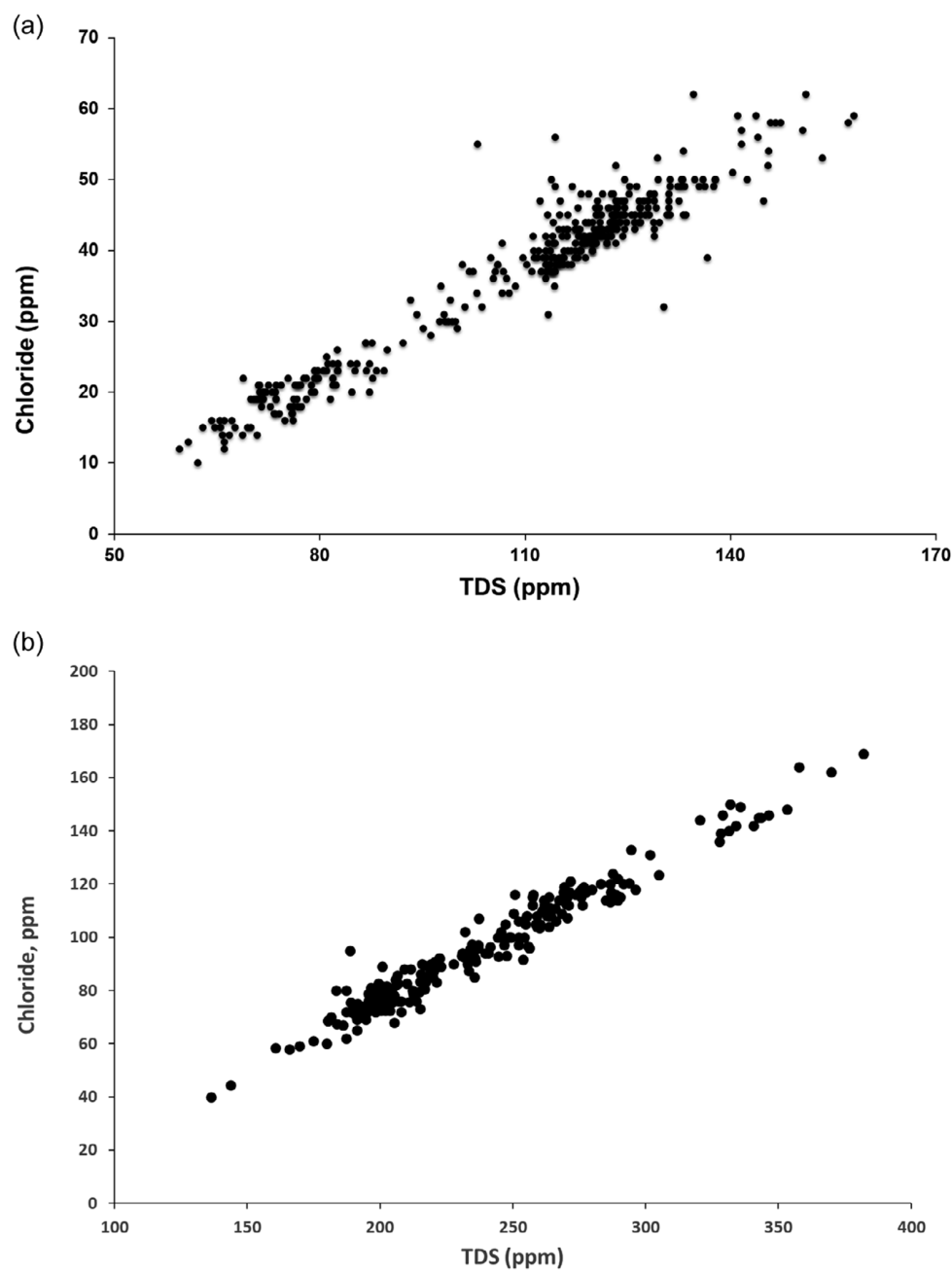


Figure 9. Relationship between chloride concentration and TDS at Ras al Khair dual-stage plant. (a) 2019; (b) 2024.

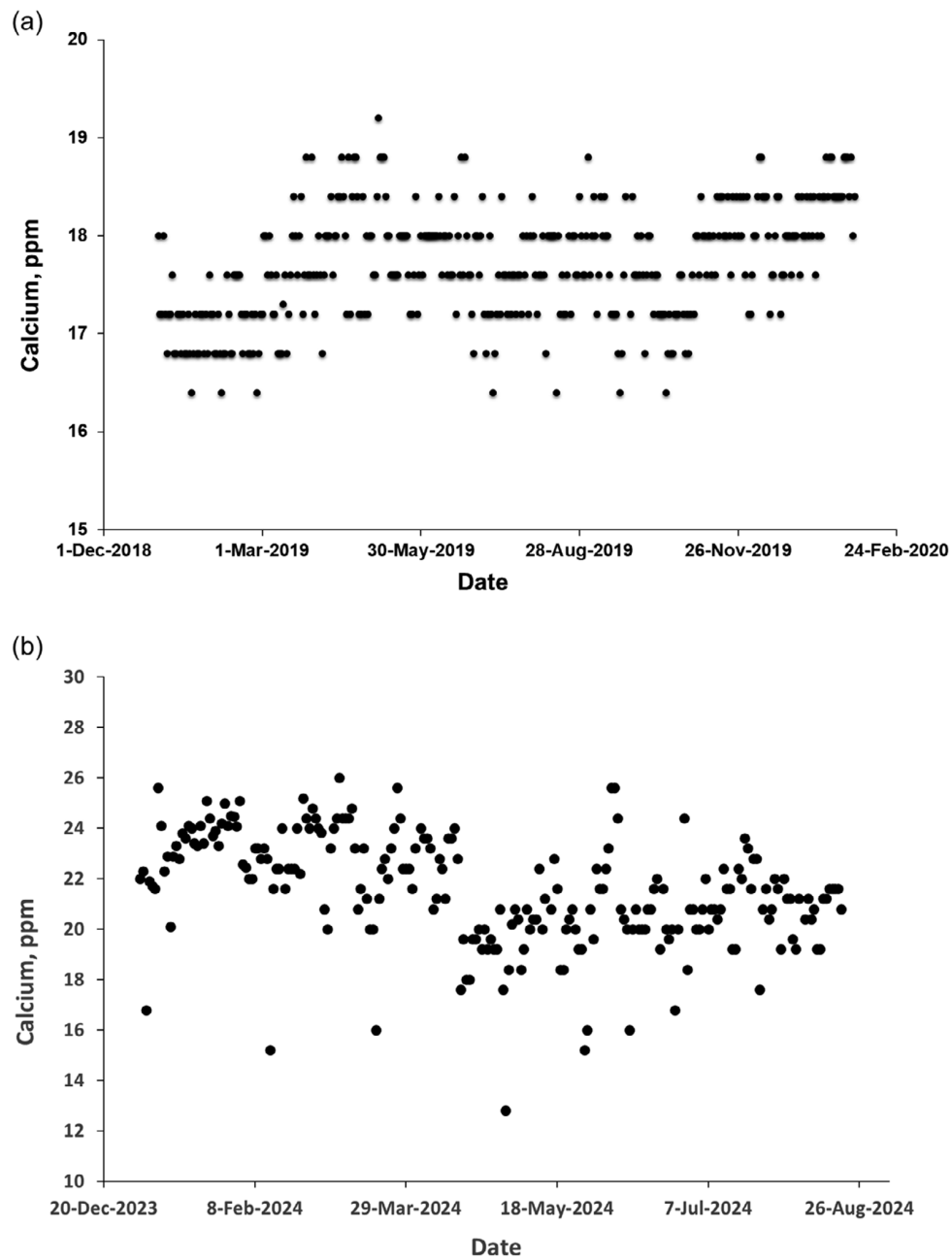


Figure 10. Variation in calcium concentration (mg L^{-1}) at the Ras al Khair dual-stage plant. (a) 2019; (b) 2024.

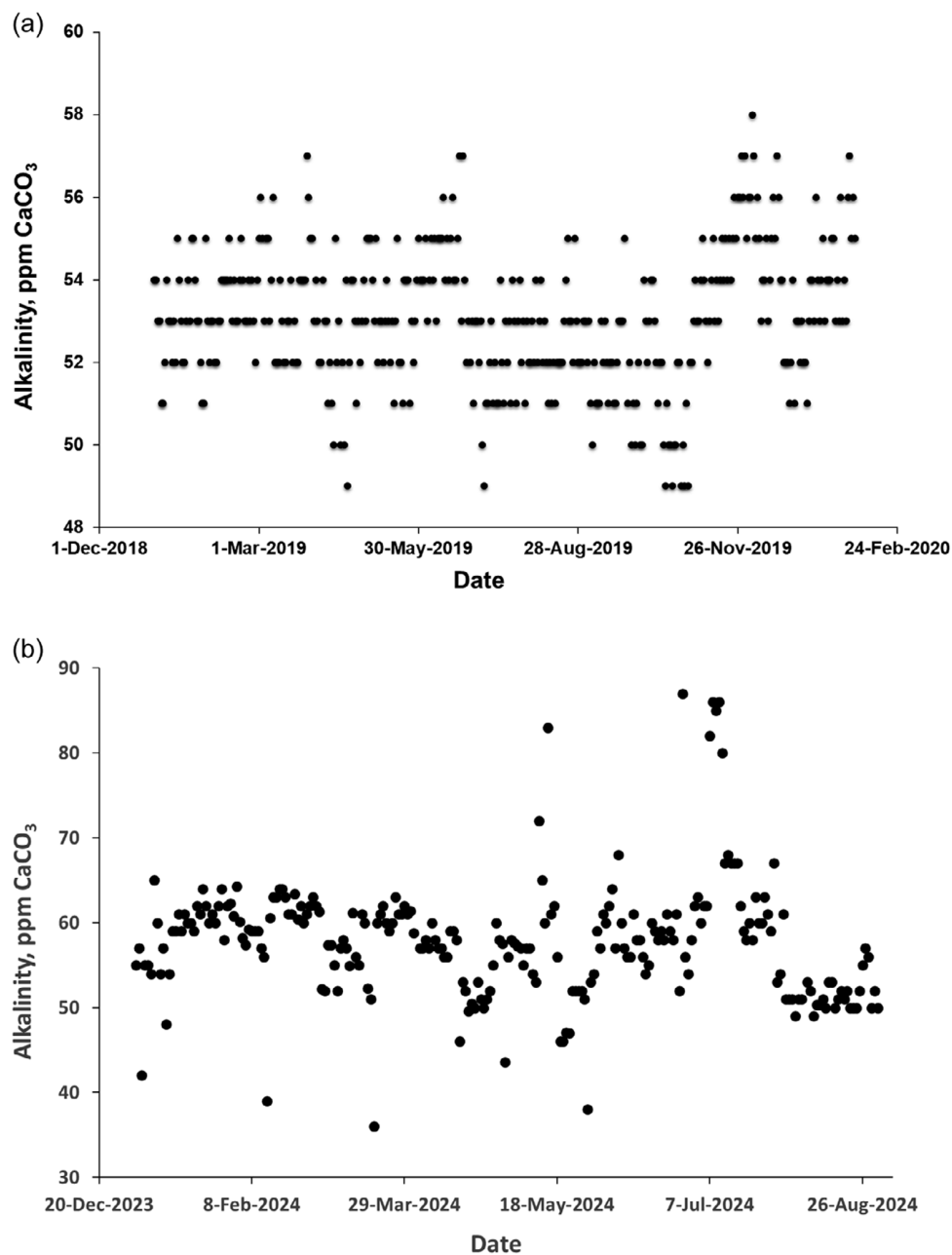


Figure 11. Variation in alkalinity (mg L⁻¹ as CaCO₃) at the Ras al Khair dual-stage plant. (a) 2019; (b) 2024.

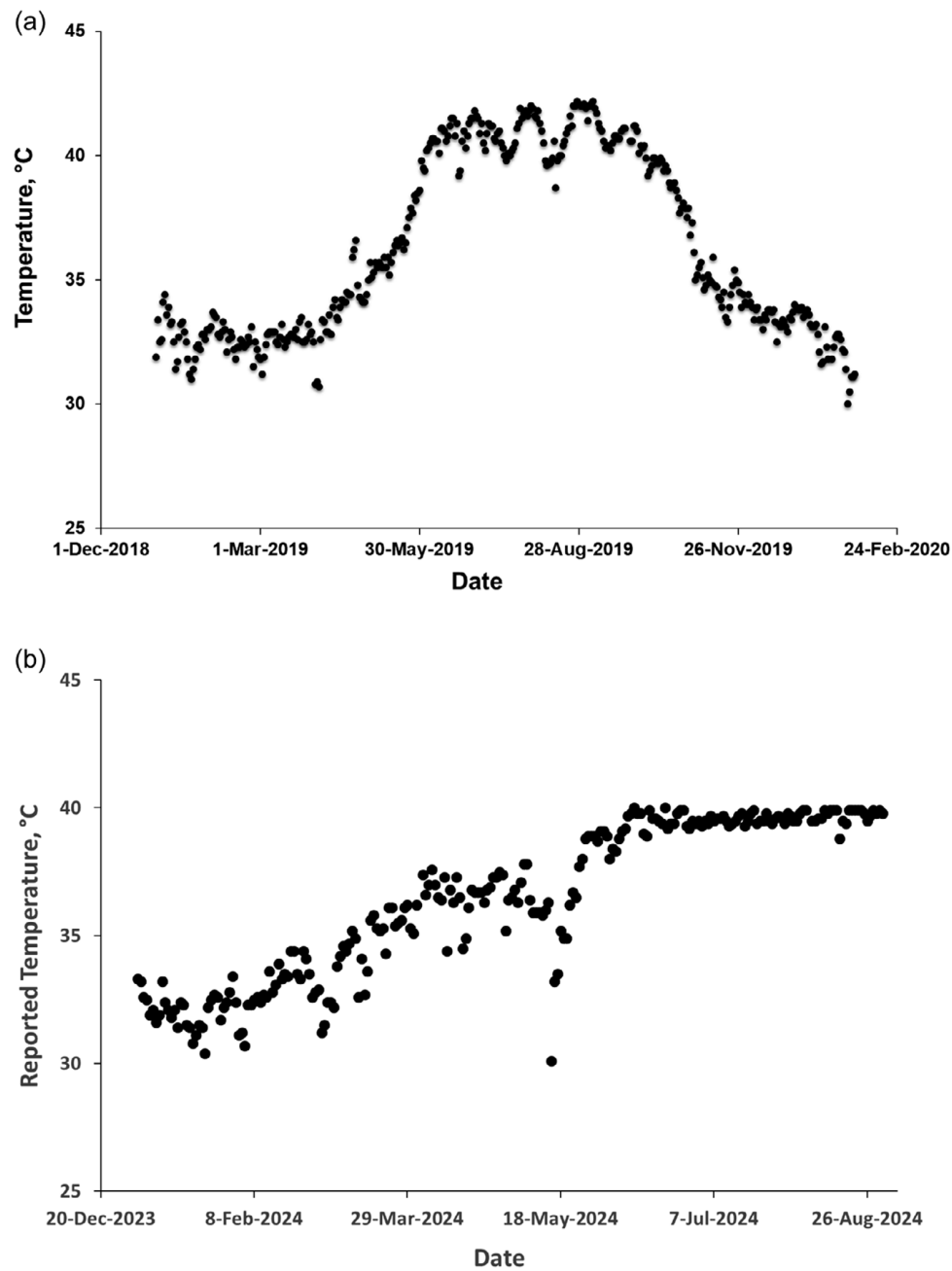


Figure 12. Variation in product water temperature reported at the Ras al Khair dual-stage plant. (a) 2019; (b) 2024.

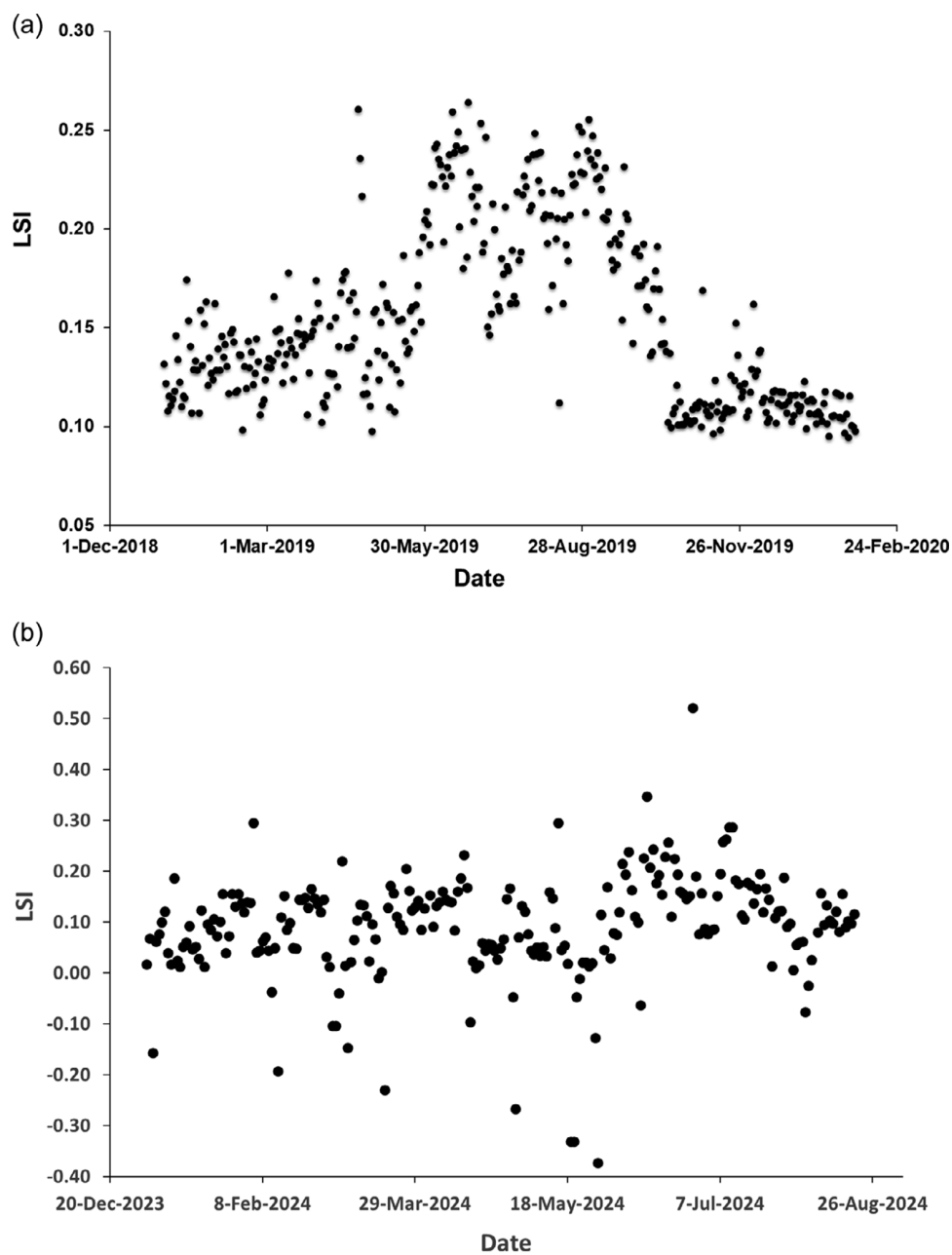


Figure 13. Variation in Langelier Saturation Index at the Ras al Khair dual-stage plant. (a) 2019; (b) 2024.

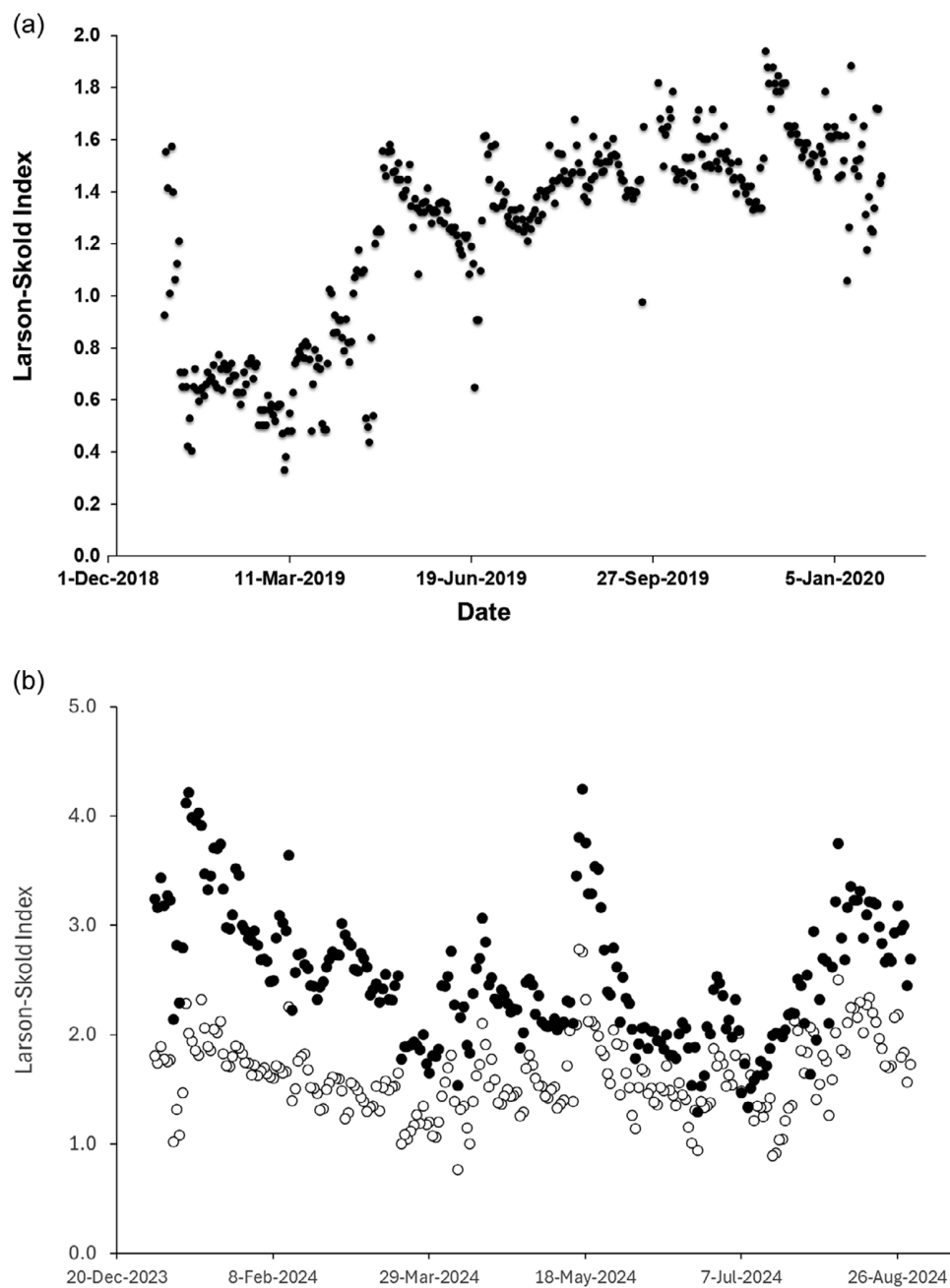


Figure 14. Larson–Skold index at Ras al Khair, (a) 2019 with estimated chloride:sulfate ratio from 2025 data, (b) 2024, with measured concentrations (solid circles) and with formula of Fellows and Al-Hamzah (open circles) [12].

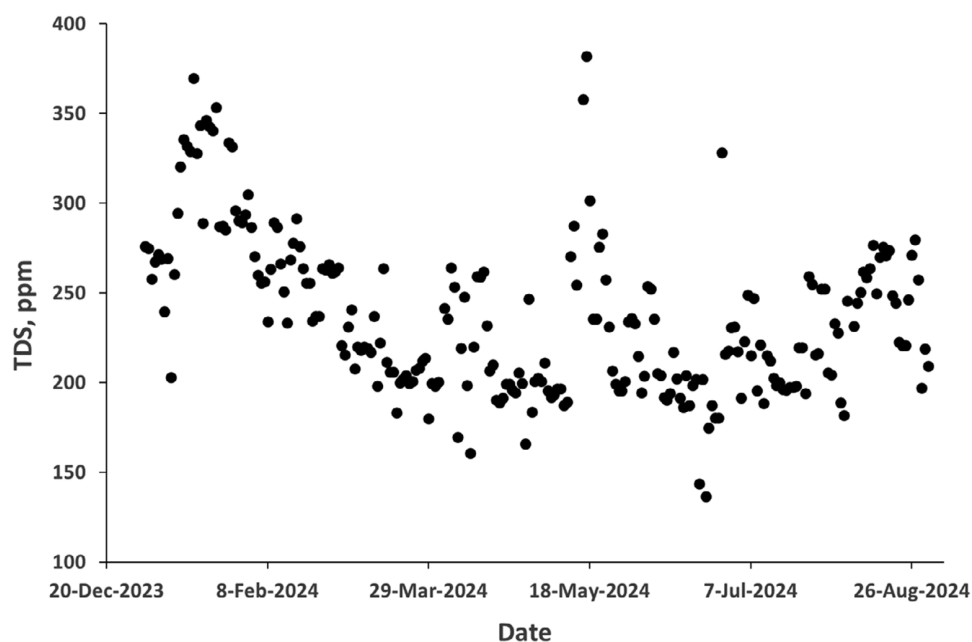


Figure 15. TDS of Ras al Khair plant product water, 2024.

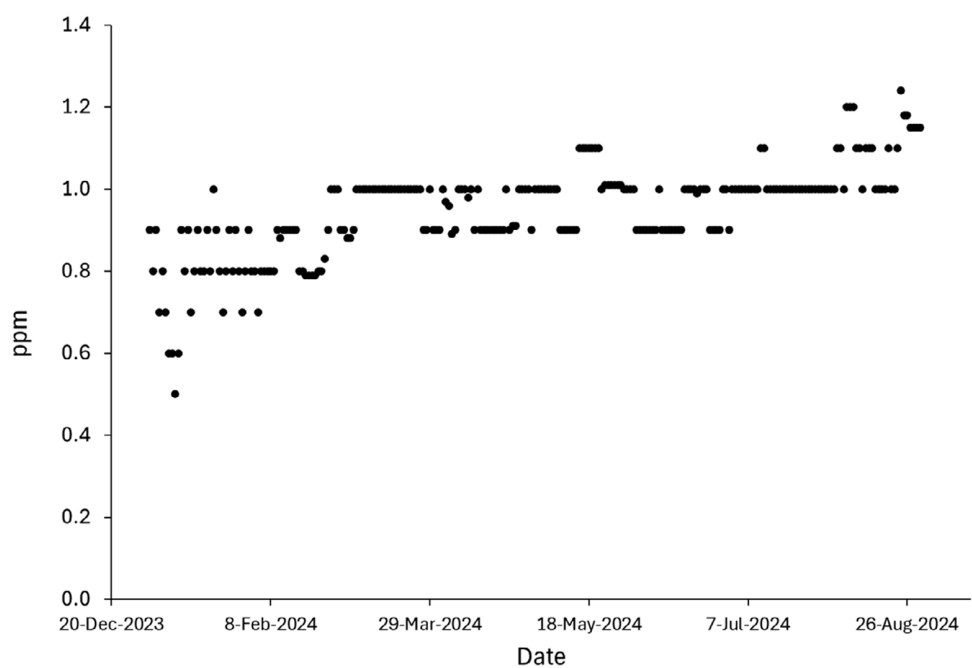


Figure 16. Boron concentration in Ras al Khair product water, 2024.

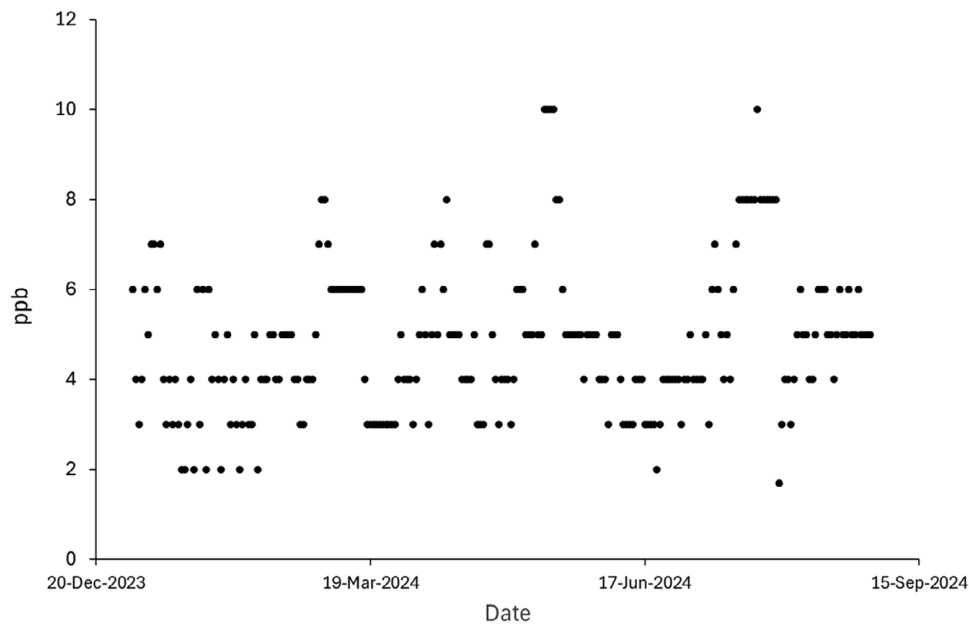


Figure 17. Bromate concentration in Ras al Khair product water, 2024.

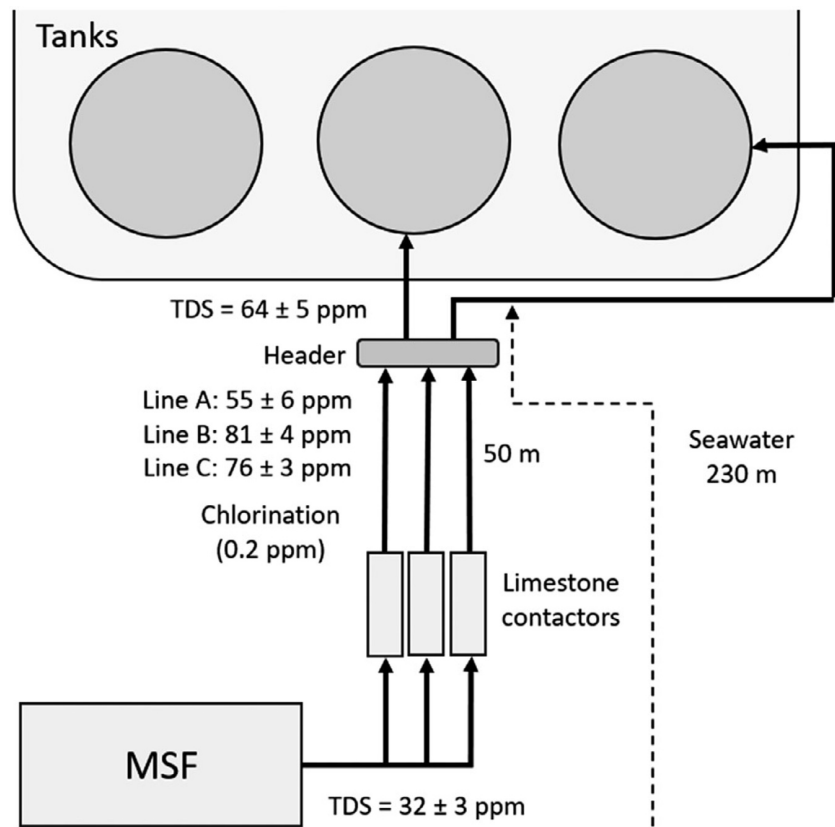


Figure 18. Schematic of Seawater addition at Shoaibah Ph 2 MSF plant with measured TDS values as of March 2019.

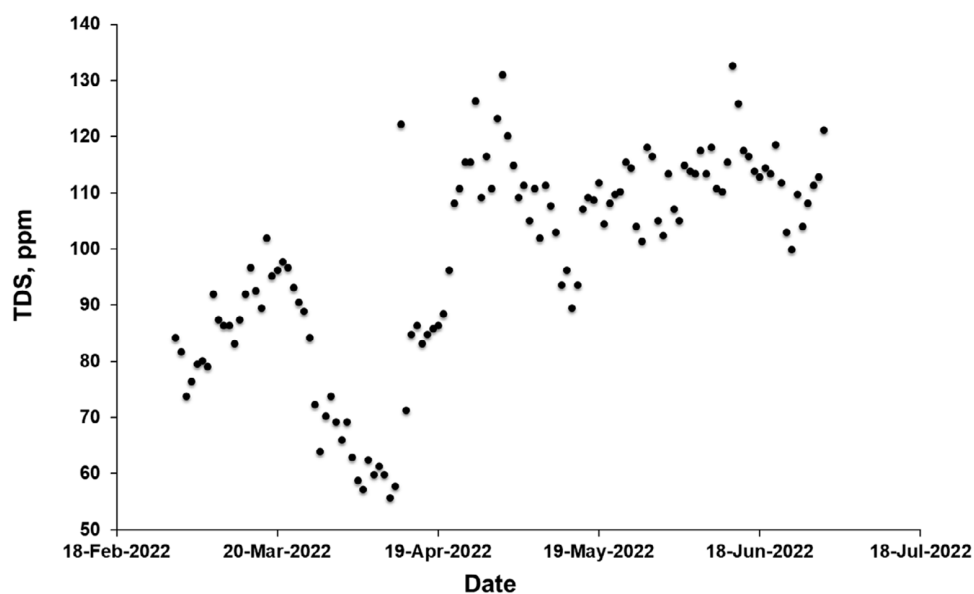


Figure 19. Increase in TDS at the Shoiabah Ph2 MSF plant.

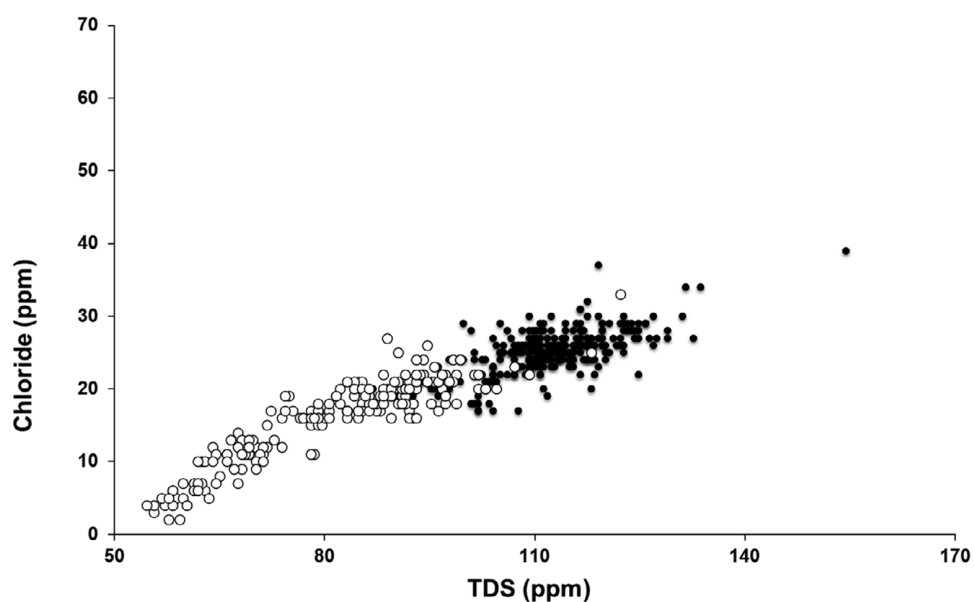


Figure 20. Relationship between chloride and TDS in product water at the Shoiabah Ph2 MSF plant, before (open circles) and after (solid circles) addition of seawater.

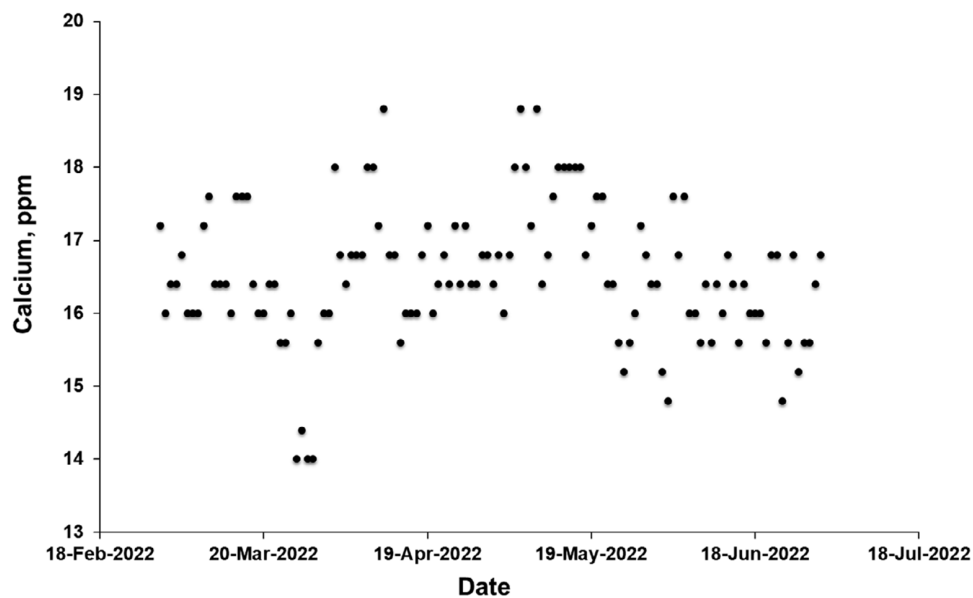


Figure 21. Variation in calcium concentration (mg L^{-1}) at the Shoaibah Ph2 MSF plant.

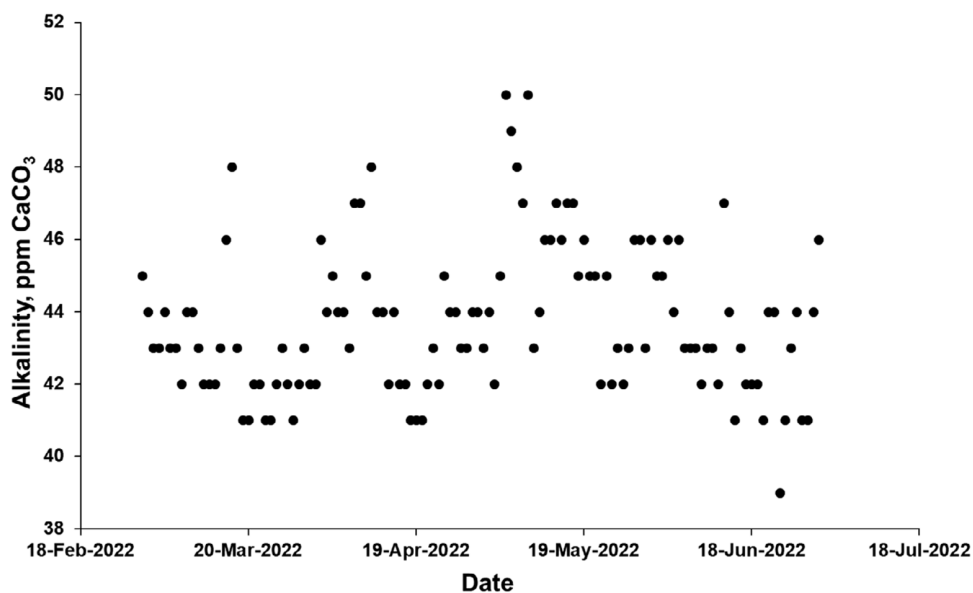


Figure 22. Variation in alkalinity (mg L^{-1} as CaCO_3) at the Shoaibah Ph2 MSF plant.

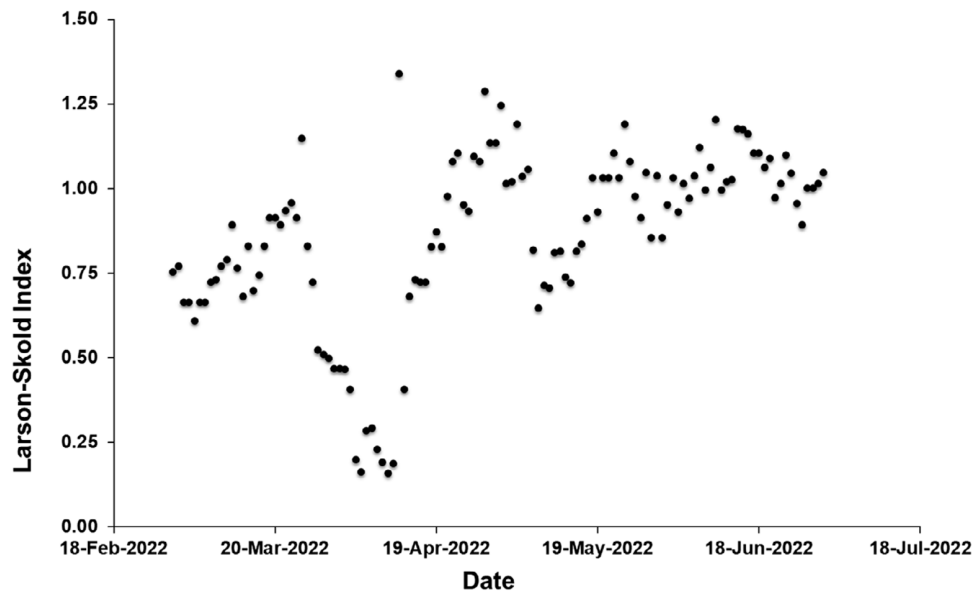


Figure 23. Larson–Skold index at Shoiabah Ph2, with estimated chloride:sulfate ratio from Ras al Khair 2025 data.

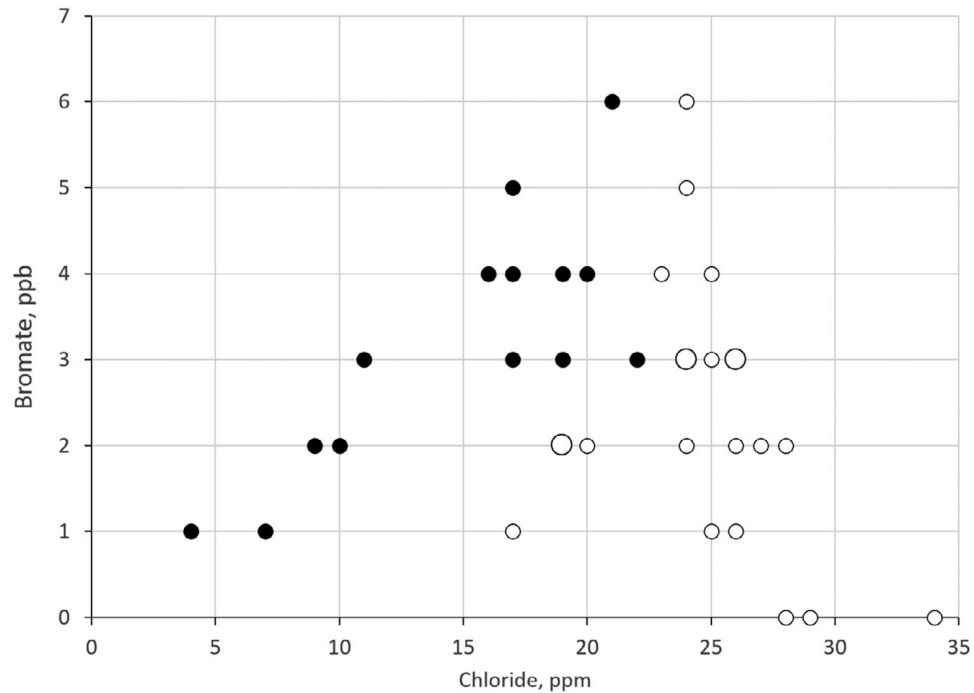


Figure 24. Variation of bromate concentration with chloride concentration at the Shoiabah Ph 2 MSF plant before (closed symbols) and after (open symbols) addition of seawater + ammoniation. Smaller symbols indicate a measurement obtained on one day, larger symbols indicate a measurement obtained on two days.

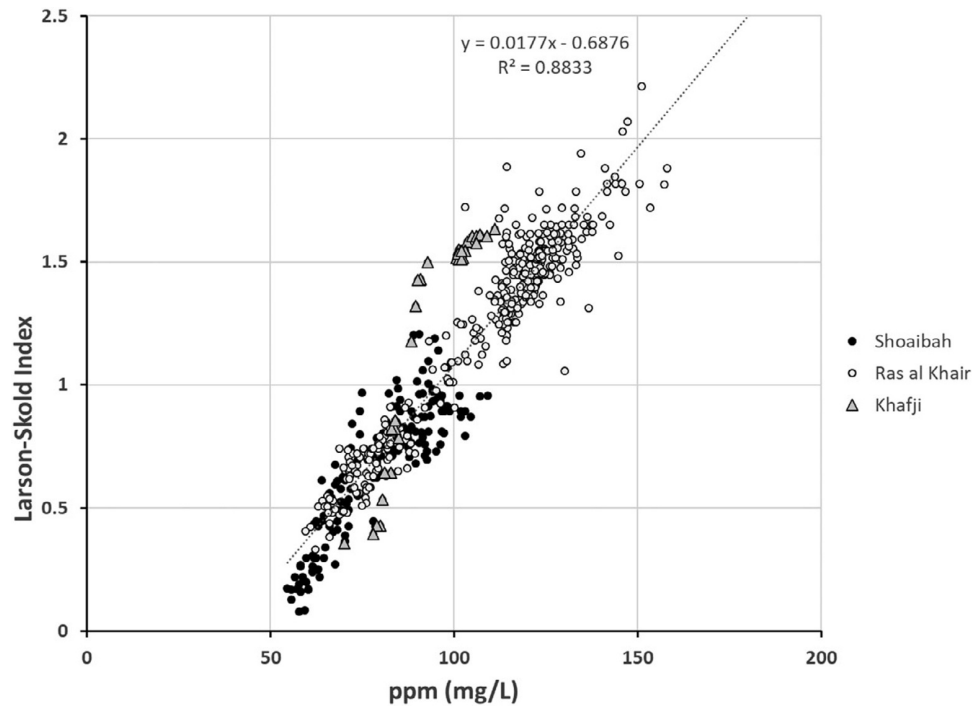


Figure 25. Correlation between calculated Larson–Skold index values and measured TDS at Shoaibah (filled circles), Ras al Khair (open circles), and Khafji (triangles) desalination plants.

Table 5. Summary of water quality parameters after actions to increase TDS to target range in SWA plants.

Parameter	Unit	Shoaibah RO4	Khafji	Ras al Khair	Shoaibah Ph2
		2025 Practice (90% BWRO)	2019 Practice (75% BWRO)	2019 Practice (50% BWRO)	2022
pH		8.3	8.4	8.5	8.0 ± 0.2
Temperature	°C	31	32 ± 1	38 ± 3	39 ± 1
TDS	ppm	137 ± 29	101 ± 6	122 ± 13	112 ± 8
Total alkalinity	ppm CaCO_3	50 ± 2	53 ± 2	53 ± 2	44 ± 2
Calcium hardness	ppm CaCO_3	43 ± 1	48 ± 1	45 ± 1	41 ± 2
Chloride	ppm	46 ± 16	43 ± 3	44 ± 6	25 ± 3
Residual chlorine	ppm	0.18 ± 0.02	0.27 ± 0.03	Not recorded	0.23 ± 0.09
LSI		0.02	0.19 ± 0.10	0.16 ± 0.05	-0.37 ± 0.21
Larson–Skold index		1.3 ± 0.6	1.5 ± 0.1	1.4 ± 0.2	1.0 ± 0.1