

Article

Urban Water Demand and Supply Dynamics in a Hyper-Arid City: A Longitudinal Assessment of Sharjah City, United Arab Emirates

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Abstract

Water scarcity poses significant challenges to urban water management for long-term sustainability in hyper-arid regions. This study presents a longitudinal assessment of water demand and supply dynamics in Sharjah, United Arab Emirates, from 2016 to 2022 using operational data obtained from the Sharjah Electricity, Water and Gas Authority (SEWA). Temporal trends in water production, sectoral consumption, and source transitions were evaluated using descriptive statistics and operational performance metrics: Demand–Production Ratio (DPR), Operational Production Margin (OPM), Production Adequacy Index (PAI), Source Dependency Ratio (SDR), and Seasonal Variability Index (SVI). Results showed that Sharjah maintained a production capacity consistently exceeding billed consumption, with an average DPR of approximately 72% and a PAI of 1.0. Desalinated water became the dominant supply source (~90%), while groundwater reliance declined substantially to support aquifer conservation. The residential sector accounted for approximately 62% of total water demand, highlighting the importance of demand-side management strategies. Seasonal variability analysis indicated peak demand during summer months, while desalination capacity supported relatively stable supply conditions throughout the year. The findings provide localized empirical insights into urban water management, supply diversification, and long-term water security in a hyper-arid Gulf city.

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Keywords: desalination; urban water management; demand–supply dynamics; operational performance; Middle East and North Africa (MENA) region

1. Introduction

The Middle East and North Africa (MENA) region is widely regarded as one of the most water-stressed regions globally. The United Arab Emirates (UAE), located on the Arabian Peninsula in Western Asia, is characterized by a hot and extremely arid climate, with long summers and minimal rainfall. Precipitation is scarce and is typically concentrated in the brief winter period [1,2]. Rapid urbanization and population growth in the UAE have significantly increased water demand [3–6]. Rising temperatures and declining precipitation trends further exacerbate water stress in the region [7–9]. The highest precipitation was recorded in the year 1982 and the lowest in 1985. The Emirate of Sharjah (falling under the scope of this study) has seen a fluctuating rainfall pattern as well [10]. These factors have placed significant pressure on limited groundwater resources, necessitating a shift toward non-conventional water sources [11,12]. Consequently, GCC countries have increasingly invested in desalination to meet rising demand [11]. In particular, the UAE has made significant strides in replacing reliance on groundwater with desalinated water following an approach that also helps alleviate potential geopolitical tensions arising from water scarcity [13]. Despite these efforts, there remains a lack of localized, data-driven analyses at the Emirate level, particularly for Sharjah. Addressing this gap is essential for understanding sector-specific consumption patterns and infrastructure transitions in hyper-arid environments. Historically, water scarcity has been examined through geopolitical and regional perspectives, with studies highlighting its role in trans-boundary tensions and resource security [14–17]. More recently, research [18–20] has increasingly adopted supply–demand assessment frameworks and integrated system-based approaches to support urban water management, operational decision-making, water security, and regional water-resource planning under diverse environmental conditions. However, such approaches provide limited insight into the operational characteristics and management of hyper-arid urban water systems, underscoring the need for localized, data-driven analyses.

Numerous studies have been carried out to assess the scarcity of water, water consumption and the need for management of water consumption in the MENA region, including the UAE. Mahmoud [21] conducted research on water within the context of Gulf security and gave some policy guidance for the Gulf Arab states to properly manage the available water and energy resources. The article discusses the potential risks facing the Gulf countries as they move toward sustainable water resource management, taking into account the crucial role that water plays in a nation's survival and the development of civilizations. It offers a thorough examination of the political, economic, and environmental issues involved in the problem of water security. Murakami [22] highlights the importance of water governance for promoting harmony, especially within the Middle East region. Additionally, Joffé [23] investigated the potential outcomes of the imminent water shortage in the MENA region by digging into water availability, water use, and future water supply amidst the global climate change scenario as well as the increasing social and political implications that are probably going to be brought about by increasing water deficit in the MENA region. The paper also alludes to the fact that desalination presents a way to overcome the scarcity of water and hence, its after-effects as well. Michel et al. [15] conducted an in-depth study of the various water-related issues facing the MENA region beginning with an overview of the region's available water resources, followed by an examination of key socio-economic and environmental trends that are expected to shape future water supply and demand. The study then explores current water management strategies being implemented or considered across the region. Within this framework, the study presents three case studies: the Tigris–Euphrates basin, the Nile basin, and a comparative analysis of water stewardship approaches in Yemen and Oman. These case studies are used to highlight the diverse policy options and governance challenges currently

faced in the region. The paper concludes with a set of recommendations aimed at enhancing water management capacity and promoting cooperative approaches to addressing water scarcity in MENA. To add, Saif et al. [11] examines the present water situation in the GCC exploring numerous options for supplying the GCC's future water demands, including desalination driven by renewable energy and foreign capital inflow into agricultural land, while also discussing the multiple balancing factors at play. Further, Qureshi [24] suggested the challenges and prospects associated with utilizing treated wastewater to address water shortages in GCC countries. These studies emphasize macro-scale challenges but often lack detailed Emirate-level analysis. More recently, several studies have focused specifically on the UAE. Szabo [25] addressed concerns related to water stress and potential water crises at both global and UAE-specific levels, outlining the key challenges currently facing the UAE's water sector, while also highlighting ongoing government initiatives aimed at mitigating the national water deficit. The brief concludes with several targeted policy recommendations focused on optimizing water consumption and improving overall water resource management. In addition, Albannay et al. [26] evaluated residential water demand management in Abu Dhabi and demonstrated the effectiveness of water-saving fixtures in reducing household consumption. Also, Paul et al. [27] reviewed the water and energy sectors in Abu Dhabi and emphasized the importance of adopting a water–energy nexus approach to optimize future infrastructure planning and operation. Meanwhile, Rizvi et al. [28] developed residential water demand profiles in Dubai and showed that socio-demographic factors, Ramadan, and the COVID-19 pandemic significantly influenced consumption patterns. Similarly, Saihi and Al-zaatreh [29] analyzed utility consumption patterns in Dubai and identified significant sectoral differences and distinct community clusters based on consumption behavior. Furthermore, Alsarhan and Rizk [30] provided a comprehensive assessment of the UAE's water resources and proposed integrated water resource management strategies.

While these works contribute important insights into national-level efforts and water management in major cities like Abu Dhabi and Dubai, they tend to focus on individual aspects of the water system, such as residential demand management [26], water–energy nexus planning [27], household demand profiling [28], or sectoral consumption clustering [29], rather than the integrated operational behavior of the production–demand system as a whole. Moreover, despite the broadly similar arid conditions and shared reliance on desalination across the Emirates, empirical investigations focusing specifically on Sharjah's long-term demand patterns, sector-specific consumption, source transitions, and operational system performance remain limited. Accordingly, this study presents, to the best of the authors' knowledge, the first longitudinal operational-data-driven assessment of Sharjah's urban water system between 2016 and 2022 using validated data obtained from SEWA, addressing the limited availability of localized empirical analyses of long-term urban water demand and production dynamics in the UAE. Unlike national-scale reviews or single-issue city studies, the analysis integrates four dimensions within a single framework: (1) temporal trends in water demand and production; (2) sectoral consumption patterns; (3) the transition from groundwater to desalinated water sources; and (4) a set of system-level operational performance indicators, complemented by a scenario-based sensitivity analysis of demand and production conditions. By providing this integrated localized assessment, the study offers empirical evidence that may inform urban water planning, source diversification, and demand-side water-management strategies in hyper-arid Gulf cities.

2. Materials and Methods

2.1. Study Area and System

The study focuses on Sharjah City (as illustrated in the contextual reference map given in Figure 1), the primary urban center of the Emirate of Sharjah. The region is located along the Arabian Gulf (25.3462° N, 55.4211° E) and is characterized by a hot, arid climate with summer temperatures exceeding 40°C [31], placing substantial pressure on municipal water resources. Mean annual precipitation in Sharjah is typically below 120 mm and occurs mainly during the winter months [1,2,30], whereas potential evapotranspiration greatly exceeds precipitation [30], resulting in negligible natural groundwater recharge and limited availability of renewable freshwater resources. Hence, Sharjah's water supply system comprises desalination plants, limited brackish groundwater abstraction, storage reservoirs, pumping stations, and an extensive water distribution network operated by the Sharjah Electricity, Water, and Gas Authority (SEWA). SEWA receives desalinated water primarily from multistage flash (MSF) and multi-effect distillation (MED) facilities at Layyah, Hamriyah, Sajaa, and Al Bedai, supplemented by reverse osmosis (RO) treatment of brackish groundwater. Conceptually, the system operates as a supply–distribution–demand network in which desalination and groundwater constitute the main inputs, followed by storage, transmission, and sectoral consumption.

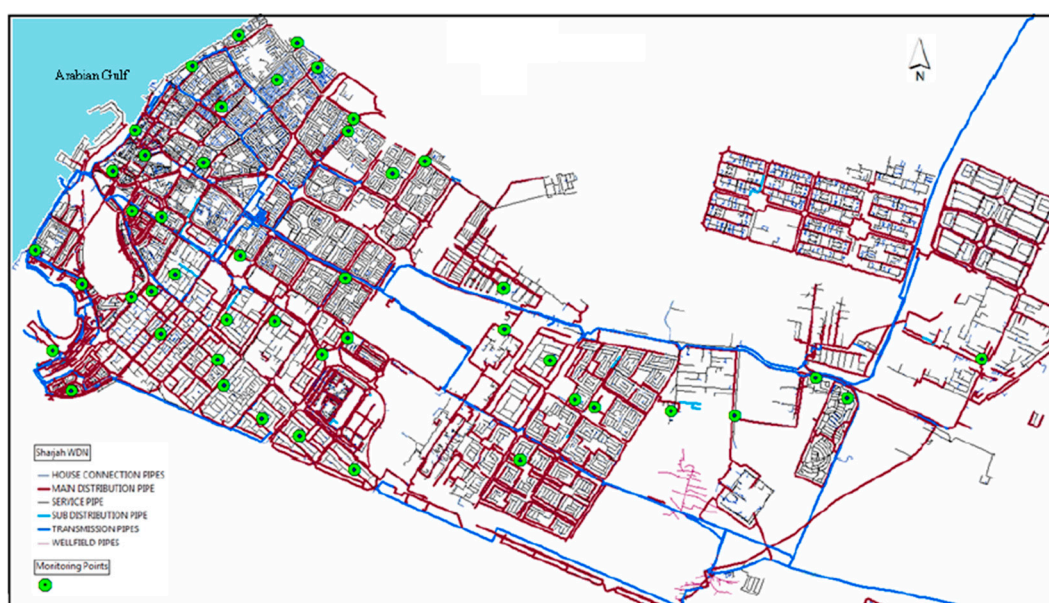


Figure 1. Study area showing Sharjah City and the corresponding water distribution network [32].

A data-driven engineering analysis was applied to evaluate Sharjah's water system performance from 2016 to 2022. The workflow consists of:

1. Acquisition and validation of operational data from SEWA.
2. Classification of supply sources and demand sectors.
3. Computation of statistical and system performance indicators.
4. Evaluation of temporal patterns and system behavior.

The framework assesses observed system performance and does not include predictive or simulation-based modeling. While advanced simulation models are widely used in water resource planning, the present study adopts a data-driven engineering framework that integrates system performance indicators and sensitivity thresholds to quantitatively evaluate observed system behavior without reliance on predictive assumptions.

2.2. Data Collection and Processing

Monthly water production and demand data were obtained from SEWA's Customer Care and Billing (CC&B) system and supporting operational databases. Data preprocessing included removal of duplicates, handling of missing values, and cross-verification with SEWA departments. Let D_t and P_t denote billed water consumption recorded and total volume of water generated at the source prior to distribution, respectively. Production was categorized according to SEWA's official operational categories into desalinated water and groundwater abstraction, which constitute the only significant production inputs, while demand was classified into residential, commercial, governmental, industrial, and agricultural sectors. Monthly and annual datasets were then constructed for the 2016–2022 period.

It should be noted here that, because D_t corresponds to billed consumption and P_t to the total water generated prior to distribution, the difference between total production and billed demand does not correspond to distribution losses alone but constitutes an aggregate quantity that also incorporates non-revenue water (NRW). NRW comprises physical losses within the transmission and distribution network, metering inaccuracies, unbilled authorized consumption, and volumes allocated to operational functions such as reservoir storage and aquifer recharge. As disaggregated NRW records were not available within the operational datasets provided by SEWA, these individual components could not be isolated. Consequently, this gap does not represent stored water alone; it corresponds to the sum of non-revenue water and the change in storage over the period.

2.3. Data Analysis

2.3.1. Descriptive Statistics

Descriptive statistics were computed to quantify variability in demand and supply using Equations (1)–(3) [33]:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

$$CI = \bar{x} \pm t \cdot \frac{\sigma}{\sqrt{n}} \quad (3)$$

where

n = number of observations and

t = 95% Student's value.

These metrics form the basis for the system indicators described below.

2.3.2. Operational Performance Indicators

To strengthen engineering relevance, system-level performance indicators were defined and computed. The following indicators were used to evaluate water system behavior [33,34]: Demand–Production Ratio (DPR) (Equation (4)), Operational Production Margin (OPM) (Equation (5)), Production Adequacy Index (PAI) (Equation (6)), Source Dependency Ratio (SDR) (Equation (7)), and Seasonal Variability Index (SVI) (Equation (8)). These indicators provide a quantitative basis for evaluating system performance, reliability, and vulnerability under varying demand and production/supply conditions.

$$DPR_t = \frac{D_t}{P_t} \quad (4)$$

where

D_t = billed water demand (Mgal) and

P_t = total water production/supply (Mgal).

$$OPM_t = \frac{P_t - D_t}{P_t} \quad (5)$$

where

OPM_t = operational production margin (dimensionless) = represents the proportion of total water production exceeding billed consumption during a given period,

D_t = billed water demand (Mgal) and

P_t = total water production/supply (Mgal).

$$PAI = \frac{N(P_t \geq D_t)}{N_{total}} \quad (6)$$

where

PAI = production adequacy index (dimensionless)—percentage of months during which total water production equaled or exceeded billed demand.

$N(P_t \geq D_t)$ = number of months where total water production/supply meets or exceeds billed water demand and

N_{total} = total number of months analyzed.

$$SDR = \frac{P_{desal}}{P_{total}} \quad (7)$$

where

SDR = source dependency ratio (dimensionless),

P_{desal} = desalinated water production (Mgal) and

P_{total} = total water production (Mgal).

$$SVI = \frac{\sigma}{\mu} \quad (8)$$

where

SVI = seasonal variability index (dimensionless),

σ = standard deviation of monthly values and

μ = mean monthly value.

It must be noted here that because the SVI value is based on the coefficient of variation, sectors with very low mean water demand may exhibit disproportionately high SVI values despite only minor absolute fluctuations. Consequently, SVI values for low-volume sectors should be interpreted with caution and considered alongside the corresponding absolute demand values.

2.3.3. Operational Sensitivity Scenarios

A scenario-based one-at-a-time (OAT) sensitivity analysis was conducted to evaluate the robustness of the proposed performance indicators under changes in water demand and water production. Following the local sensitivity analysis framework described by Saltelli [35], one input variable was perturbed at a time while all remaining variables were maintained at their baseline values. Demand increase and production-reduction scenarios (scenario A and scenario B, respectively) were simulated by applying prescribed fractional perturbations to the baseline values, expressed as (Equations (9) and (10)):

Scenario A (Demand increase):

$$D'_t = (1 + r) D_t \quad (9)$$

where

D_t = baseline water demand at time t ,

D'_t = perturbed value of water demand at time t ,

r = fractional increase in demand, taking values of $r = 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45$ and 0.50 , corresponding to 5% through 50% increase in demand, respectively.

Scenario B (Production reduction):

$$P'_t = (1 - d) P_t \quad (10)$$

where

P_t = baseline water production/supply at time t ,

P'_t = perturbed value of water production at time t ,

d = fractional reduction in production, taking values of $d = 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45$ and 0.50 , corresponding to 5% through 50% decrease in production, respectively.

The perturbation range of 5% to 50%, applied in uniform 5% increments, was selected to represent a series of hypothetical demand-increase and production-reduction scenarios spanning moderate to severe departures from baseline operating conditions. Rather than reproducing observed historical variability, which was comparatively low over the study period, these scenarios were intended to evaluate how the performance indicators respond to progressively larger deviations that could plausibly arise from long-term demand growth or production shortfalls. The 5% increment provides sufficient resolution to trace the incremental response of the indicators, while the 50% upper bound was adopted to ensure that the analysis extended across a sufficiently wide range to capture the conditions under which the available production margin is exhausted. This deterministic scenario-based approach provides a straightforward assessment of the influence of individual input variations on system performance while maintaining all other variables unchanged, consistent with the principles of local sensitivity analysis [35,36].

For each scenario, updated DPR and OPM values were calculated to examine potential changes in operational conditions under moderate demand growth and supply reduction scenarios. This incremental/decremental approach enables a systematic evaluation of system vulnerability across a spectrum of sensitivity levels, from moderate perturbations to severe demand growth and supply deficit conditions.

2.3.4. Data Visualization

Monthly and annual water demand and supply data were analyzed using descriptive statistical methods to identify temporal patterns, sectoral differences, and long-term trends. Key statistical metrics, including mean, minimum, maximum, and standard deviation, were computed and used to derive the system performance indicators defined in Section 2.3.2. Temporal dynamics such as seasonal variability, supply–demand balance, and source contributions were evaluated over the 2016–2022 period. The analysis primarily focuses on desalinated water, as renewable groundwater recharge is negligible [30]. All results presented in Section 3 are derived directly from the analytical framework described in Section 2.

3. Results

3.1. Water Consumption Analysis

Figure 2a presents a comparative overview of water supply and demand in Sharjah City from 2016 to 2022. As observed, both trends follow a broadly similar temporal pattern, with the supply consistently exceeding demand throughout the study period. This stability indicates a proactive water supply strategy that accommodates fluctuations in demand. Figure 2b illustrates the corresponding demand-to-supply ratio, calculated as

the ratio of total monthly water demand to total production, which averages approximately 72.36% over the observed period ($\pm 8.79\%$ deviation). The ratio remains relatively stable, reflecting a consistent surplus in water production relative to billed consumption. The excess water is typically directed to storage reservoirs or injected into aquifers via Aquifer Storage and Recovery (ASR) systems to ensure supply reliability, accommodate peak demand, and serve as a buffer during emergency or maintenance periods [30].

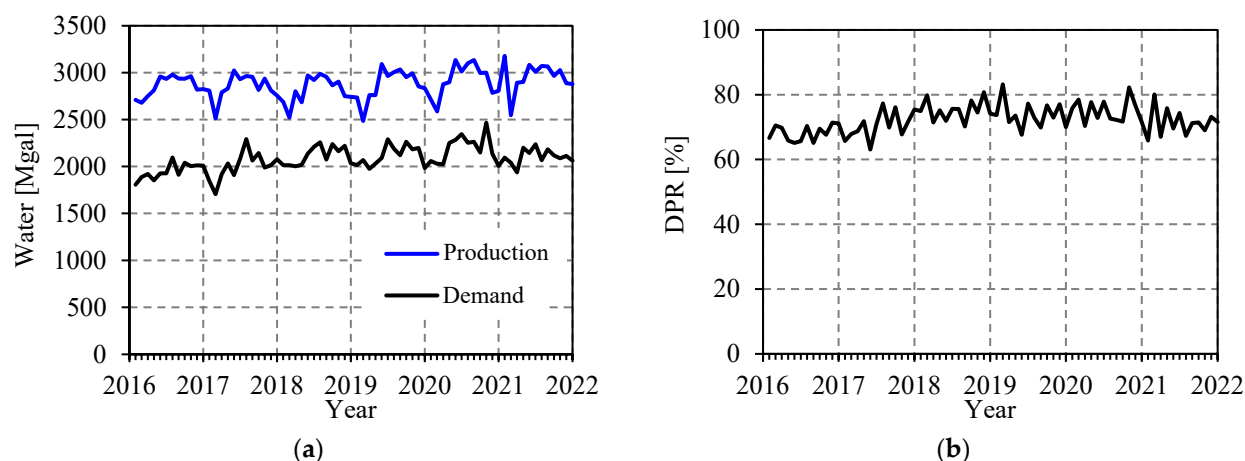


Figure 2. Yearly distribution: (a) Yearly distribution of demand and production of water. (b) Yearly distribution of DPR expressed as percentage.

Further insights into annual and seasonal water use patterns are depicted in Figure 3. The yearly average water demand in Sharjah City is approximately 2100 million imperial gallons (Mgal), whereas the average supply reaches around 2800 Mgal, highlighting a notable surplus in overall water availability (Figure 3a). Figure 3b shows that monthly demand is lowest during the cooler months, January through March and December, while consumption increases during the hotter months, particularly from May to July. Interestingly, a dip in demand is observed in August, despite it being a peak summer month. This anomaly may be attributed to reduced industrial or commercial activity during vacation periods or other seasonal socio-economic factors. Monthly supply trends closely mirror those of demand, indicating responsive supply management practices.

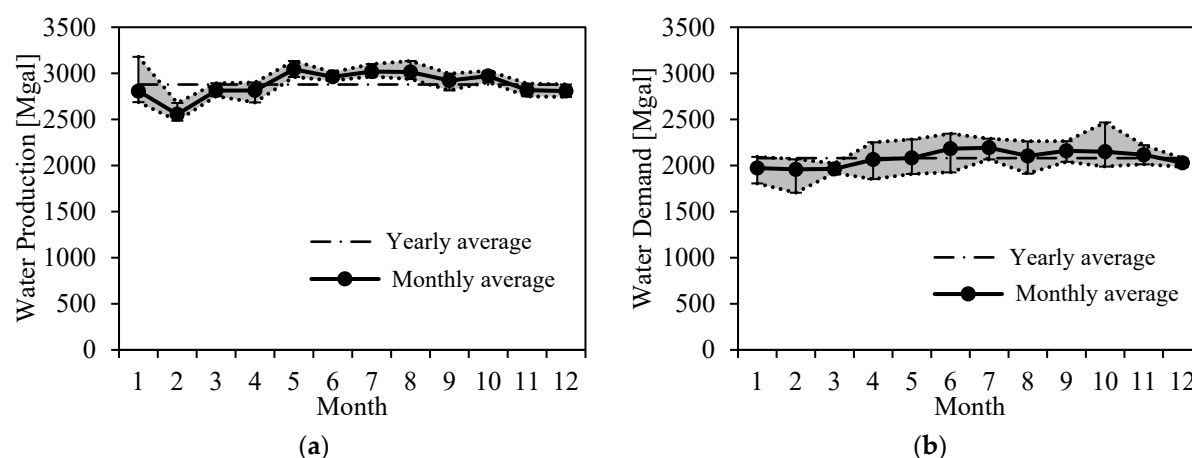


Figure 3. Yearly and monthly average: (a) Water supply. (b) Water demand in Sharjah Emirate.

As shown in Figure 4a, mean monthly supply consistently exceeds mean monthly demand throughout the year, confirming that the system maintains an adequate operational buffer under baseline conditions, with desalination-supported supply sustaining a

stable margin above billed demand across all months. Each monthly value presented in this study represents the arithmetic mean of six corresponding monthly observations (2016–2021). This temporal aggregation was adopted to characterize representative seasonal demand and supply patterns while reducing the influence of isolated year-to-year fluctuations and extreme observations.

Figure 4b presents the monthly standard deviations in absolute terms, highlighting that demand exhibits greater variability than supply across most months, with notable peaks occurring in the early and latter months of the year. Supply, being primarily reliant on desalination, remains comparatively stable throughout the year.

Figure 4c confirms that the seasonal variability of demand is consistently higher than that of supply across all months, further reinforcing the relative stability of the supply system. Overall, while both production and demand exhibit low absolute seasonal variability, the comparatively higher fluctuation on the demand side suggests that consumption patterns are more susceptible to seasonal influences, which has implications for short-term operational planning and reserve capacity management.

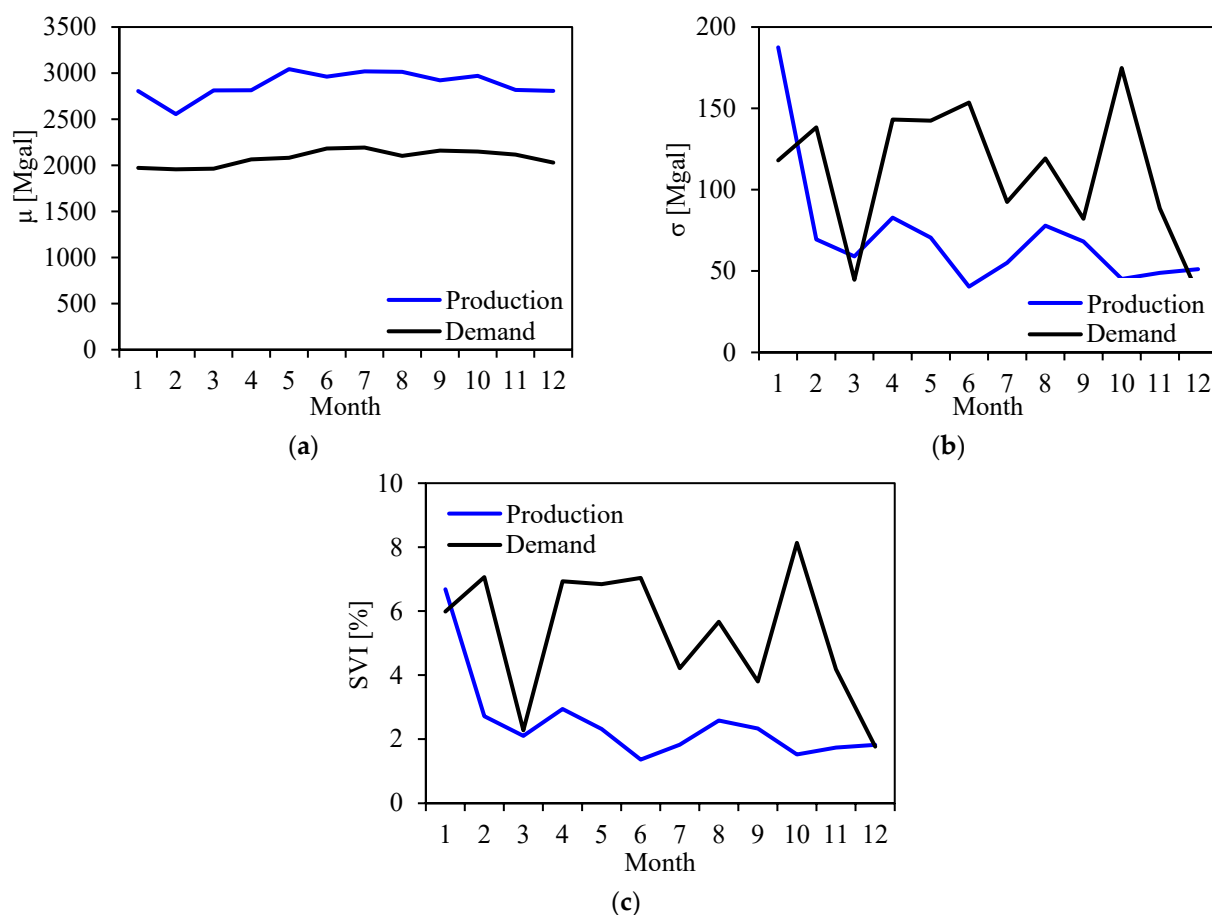


Figure 4. Monthly statistics of water supply and demand in Sharjah: (a) μ . (b) σ . (c) SVI.

3.2. Analysis of Water Supply Based on Source

To distinguish the contributions of individual water sources, the total annual water supply was disaggregated into desalinated water and groundwater components. The temporal evolution of each source is presented in this section (Figures 5 and 6). With increased use of desalinated water in the region, the load on groundwater as a source of water supply has been greatly reduced. Figure 5a illustrates the contribution of different water sources over time, showing a marked shift from groundwater to desalinated water between 2016 and 2022. This transition is further quantified in Figure 5b, which presents the

groundwater supply ratio relative to total supply. The trendline indicates a general decline in the proportion of groundwater used, reflecting strategic efforts to conserve non-renewable aquifers. The seasonal variability evident in the data may be associated with fluctuations in water demand, availability of desalinated water, or operational factors affecting groundwater abstraction.

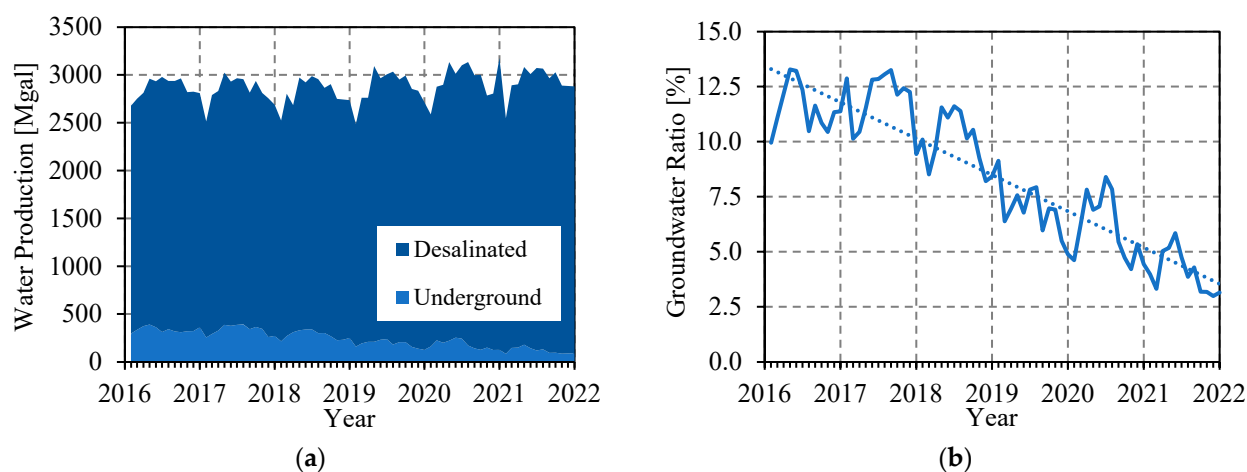


Figure 5. (a) Water production source. (b) Groundwater ratio based on water supply source in Sharjah City.

Figure 6a,b provide a detailed comparison of average monthly and yearly supply volumes by source. The annual average supply from desalinated water stands at approximately 2600 Mgal, while groundwater contributes only around 250 Mgal annually. Thus, desalinated water accounts for approximately 90% of total supply, based on SEWA source classification, reflecting a significant shift away from groundwater dependence. The monthly desalinated supply pattern closely follows the overall supply trend, reaffirming its dominant role in meeting Sharjah's water needs. In contrast, the monthly supply from groundwater remains relatively steady throughout the year, consistent with its minimal share in the total water portfolio.

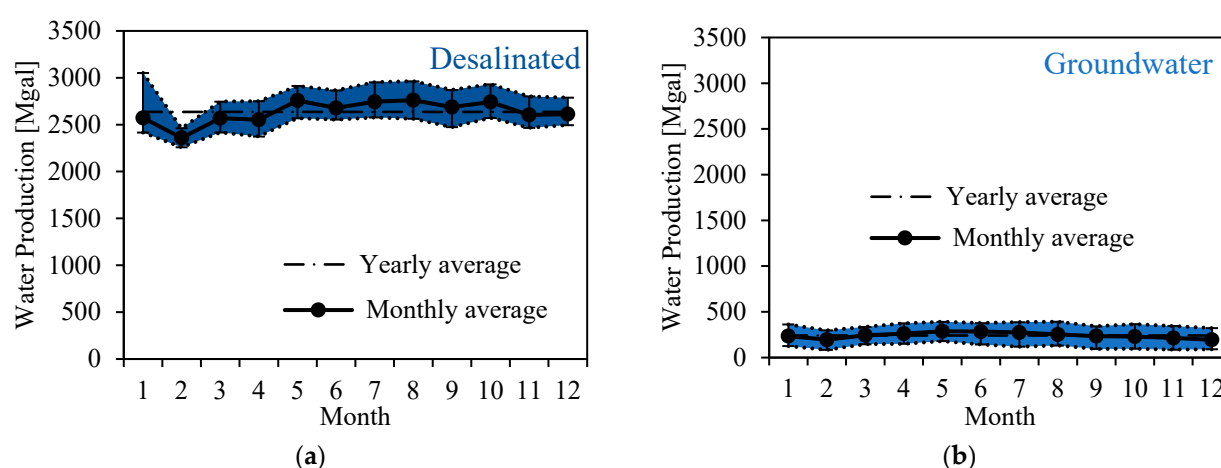


Figure 6. Average yearly and monthly water supply from: (a) Desalination source. (b) Groundwater source in Sharjah Emirate.

Collectively, these findings underscore the Emirate's growing dependence on desalination as a sustainable, albeit energy-intensive alternative to traditional groundwater extraction.

3.3. Analysis of Water Demand in Various Sectors

To identify the primary contributors to water consumption in Sharjah City, a sector-wise analysis of water demand was conducted. Figure 7 illustrates the distribution of water usage across five key sectors: residential, commercial, governmental, industrial, and agricultural. The residential sector was the dominant consumer of municipal water, accounting for approximately 62% of total demand. The commercial sector ranked second, representing approximately 25% of total demand, followed by the governmental sector at approximately 8% and the industrial sector at about 5%. In contrast, the agricultural sector contributed only a negligible share of total demand of around 0.04%.

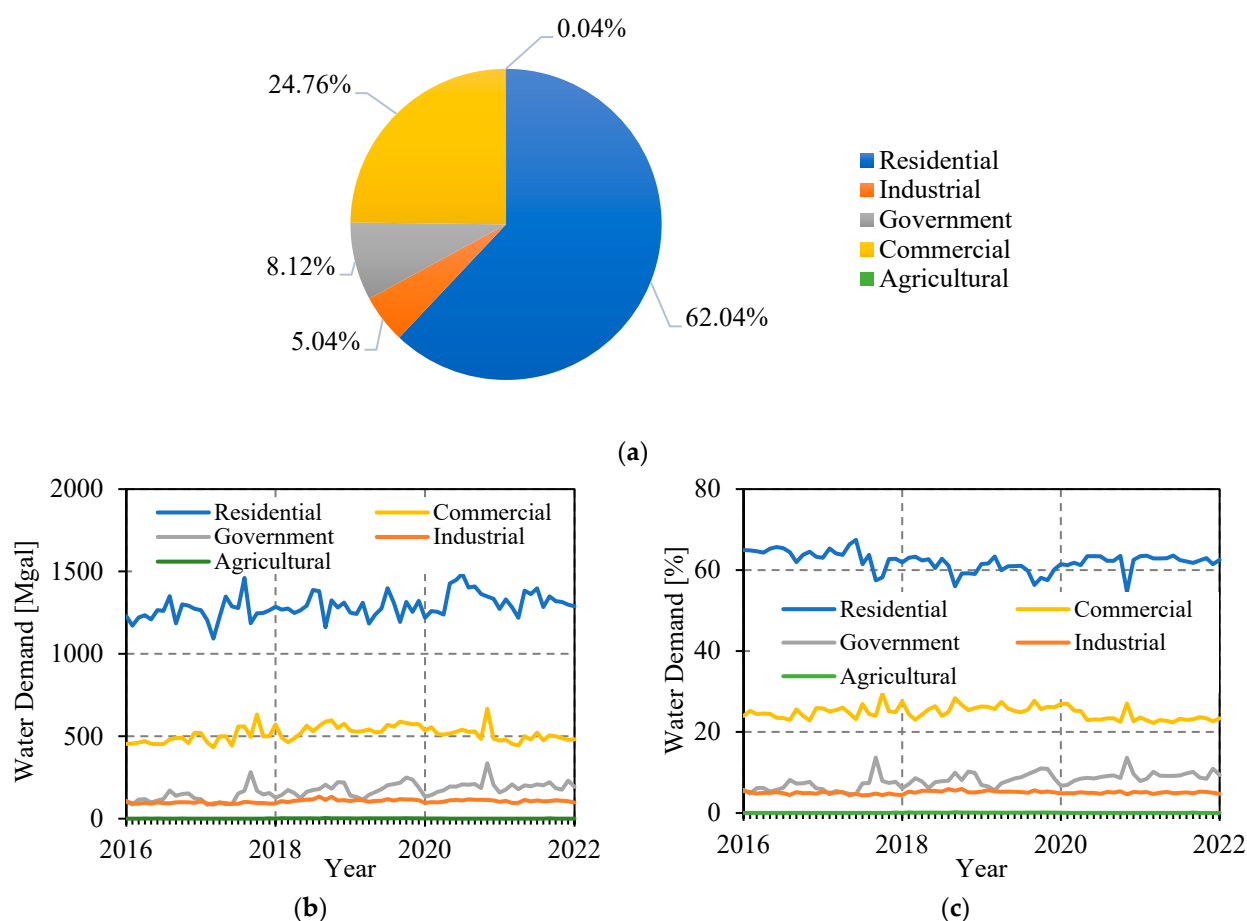


Figure 7. Water demand per Sector: (a) Pie chart distribution. (b) Water demand in Sharjah City (Mgal). (c) Water demand (%).

The breakdown of yearly water demand by sector from 2016 to 2022 is presented in Figure 7b, with corresponding percentage distributions shown in Figure 7c. The data indicates that the demand from the agricultural and industrial sectors remained relatively stable throughout the study period. Although the industrial and government sectors showed comparable annual consumption levels, the government sector exhibited greater variability over time. Interestingly, demand in the commercial and governmental sectors followed nearly parallel trends. Additionally, the residential sector displayed the highest variability and largest overall consumption, consistently accounting for between 60% and 65% of the total water demand. This underscores the significance of domestic consumption in the Emirate's overall water usage profile and highlights the importance of targeted conservation measures in this sector. To further investigate intra-annual patterns, the average yearly and monthly water demand in each sector was assessed separately (Figure

8). The residential sector recorded an average annual demand of approximately 1300 Mgal. Monthly residential consumption fluctuated seasonally, peaking during the hot summer months of June and July, and reaching its lowest levels during the cooler months of February and March. This trend is likely attributable to increased water use for cooling and hygiene during the summer period.

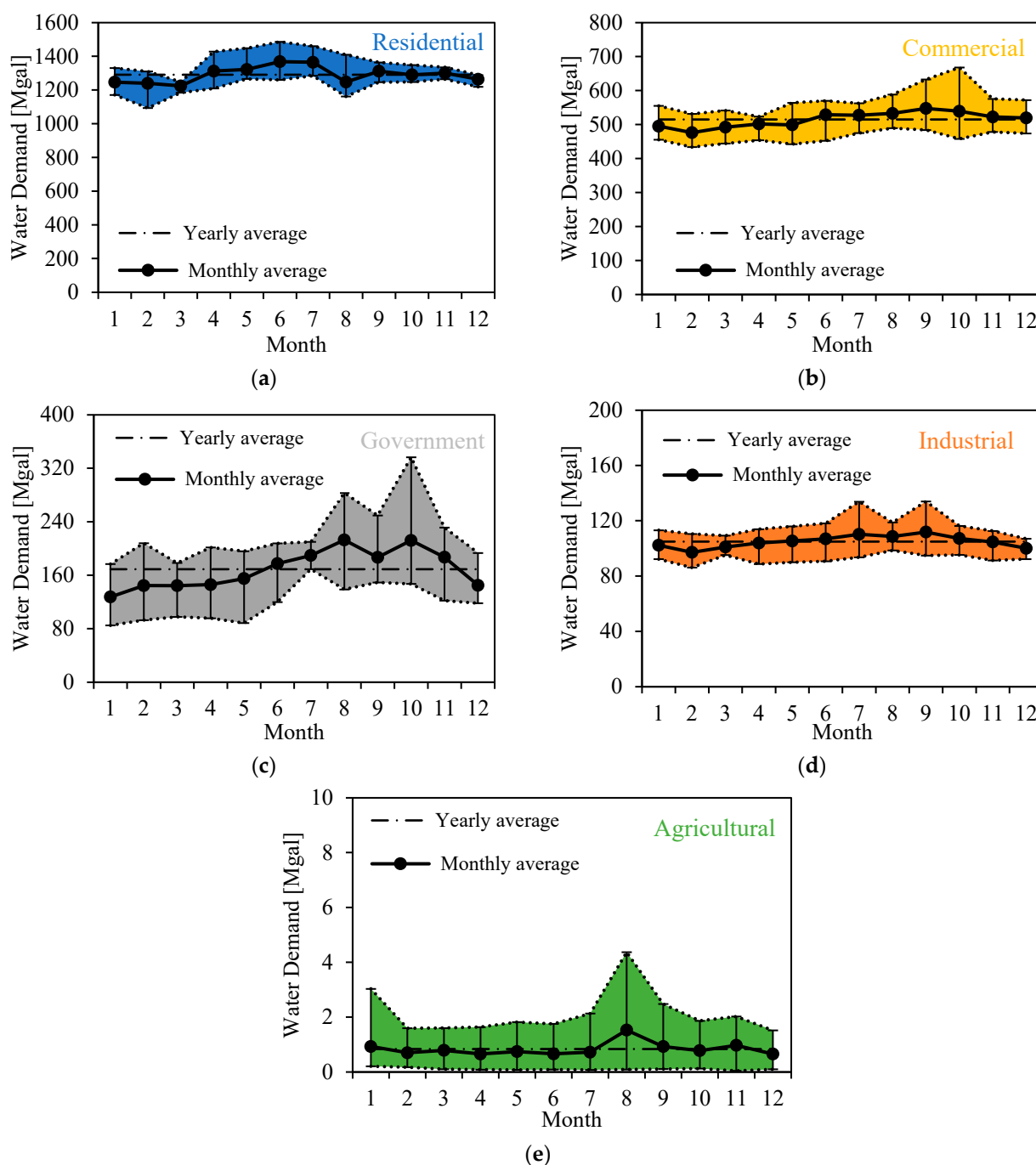


Figure 8. Water demand per Sector: (a) Residential. (b) Commercial. (c) Government. (d) Industrial. (e) Agricultural in Sharjah.

Further, the commercial sector recorded an average annual demand of approximately 510 Mgal, with higher monthly consumption occurring between June and November. Government sector demand averaged about 170 Mgal annually but exhibited greater seasonal variability, ranging from approximately 130 Mgal in January to around 220 Mgal during August and October. Industrial water demand remained relatively stable through-

out the year, averaging approximately 100 Mgal annually with only modest seasonal fluctuations. By comparison, agricultural demand remained minimal, averaging approximately 1 Mgal per year, with only a slight increase observed during August. Additionally, Figure 9 depicts the monthly statistics of water demand across sectors in Sharjah. Figure 9a summarizes the mean values as obtained from Figure 8, while Figure 9b gives the standard deviation values and Figure 9c depicts the corresponding SVI values.

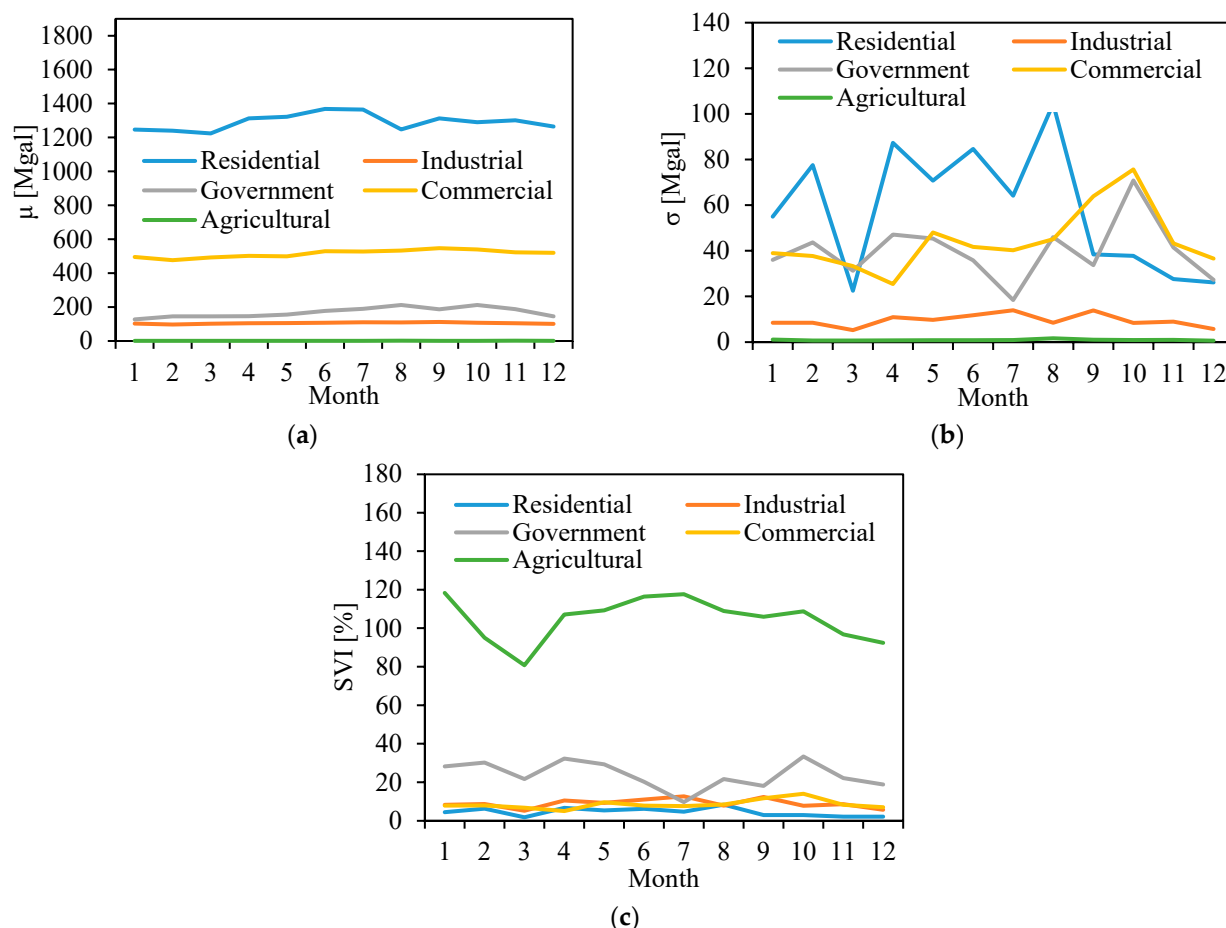


Figure 9. Monthly statistics of water demand across sectors in Sharjah: (a) μ . (b) σ . (c) SVI.

The residential sector exhibits the highest absolute variability, with monthly standard deviations reaching approximately 104 Mgal in peak months, yet its seasonal variability remains low (under 10%) due to its large baseline consumption. In contrast, the agricultural sector shows minimal absolute variation but persistently high seasonal variability (ranging between 80–120% across most months) when expressed as the SVI value. This reflects the mathematical sensitivity of the coefficient of variation to very small mean values rather than substantial fluctuations in absolute water demand. Accordingly, the high SVI values for the agricultural sector should be interpreted with caution and should not be viewed as indicating pronounced seasonal variability in practical terms. Government and commercial sectors demonstrate moderate seasonal variability in both absolute and relative terms, while industrial demand remains the most stable across all months. These results highlight distinct sectoral patterns, where residential use is both dominant and consistent, whereas agricultural demand, though negligible in volume, fluctuates considerably with season. Overall, this sectoral analysis reveals the dominant role of the residential sector in Sharjah City's water demand profile and suggests that effective water con-

servation strategies should prioritize domestic usage patterns, particularly during high-demand summer months.

3.4. Operational Performance Indicators

To complement the descriptive analysis, system-level performance indicators were computed to evaluate Sharjah's water system behavior over the 2016–2022 period. The average DPR across all months was 0.724, indicating that supply exceeded demand by approximately 38% as shown in Figure 10a. Monthly DPR values ranged from 0.684 (May) to 0.767 (February), reflecting moderate seasonal variability consistent with climatic patterns. The average OPM (Figure 10b) was $38.70 \pm 16.40\%$, with monthly values ranging between 31.1% and 46.7%. This confirms a structurally oversupplied system, driven primarily by desalination capacity. The PAI was 1.0, as supply met or exceeded demand in 100% of the 72 months analyzed. This reflects the stability of desalination output and the absence of seasonal supply constraints.

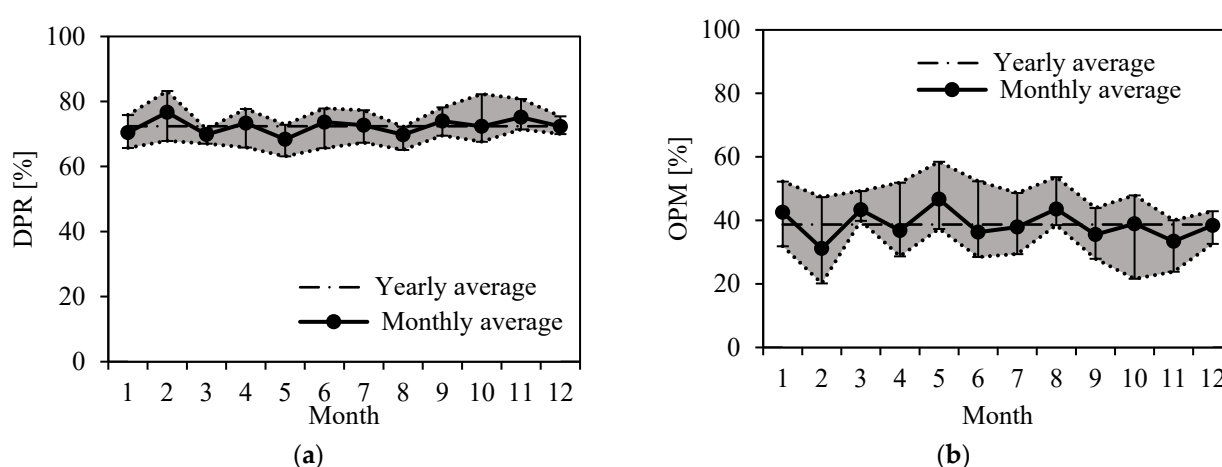


Figure 10. Monthly system performance indicators for Sharjah (2016–2022): (a) Demand–Production Ratio (DPR). (b) Operational Production Margin (OPM). Both indicators exhibit moderate seasonal variability, with supply consistently exceeding demand.

Desalination (Figure 11a,b) accounted for approximately 90% of total supply, while groundwater contributed 8.4%, confirming the Emirate's extreme dependence on non-conventional water sources. SVI values were 0.065 for demand and 0.053 for supply, indicating low intra-annual variability relative to annual means, as shown in Figure 12.

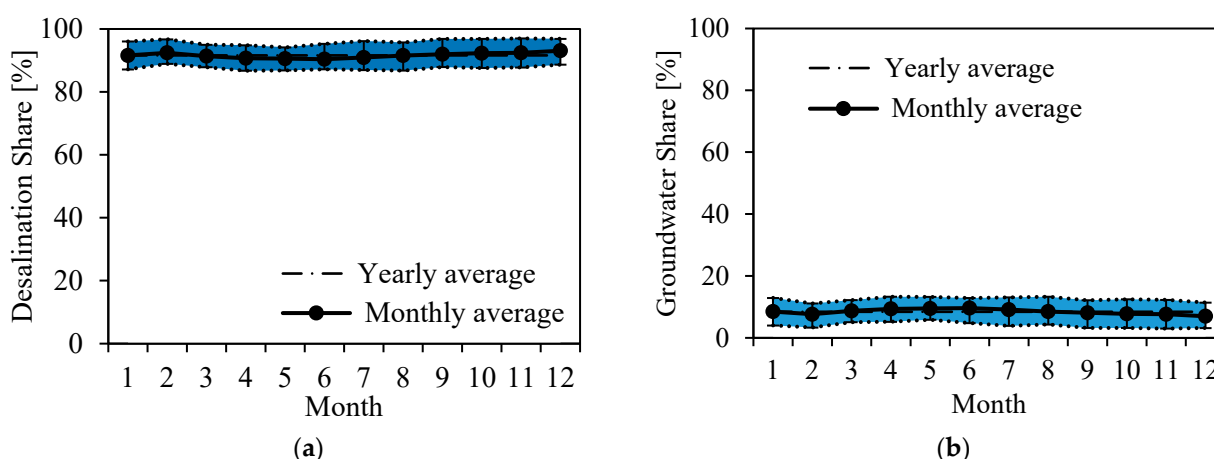


Figure 11. Monthly source dependency indicators: (a) Desalination share. (b) Groundwater share as a percentage of total supply. Desalination consistently accounts for ~90–93% of monthly supply.

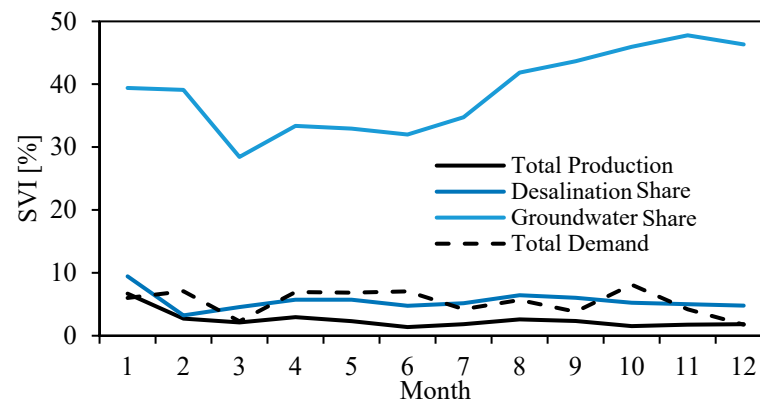


Figure 12. Seasonal Variability Index (SVI) for total supply, desalination, groundwater, and total demand. Groundwater shows the highest relative variability, while desalination and total supply remain stable.

3.5. Operational Sensitivity Scenarios

3.5.1. Scenario A: Demand Increase (Figure 13)

A hypothetical 5% increase in water demand increased the average DPR from 0.724 to 0.796 and reduced the OPM from 38.7% to 26.1%, while supply continued to exceed billed demand under the evaluated conditions. As demand increases escalated progressively to 50%, the DPR continued to rise while the OPM declined steadily, turning negative beyond the 40% threshold, while the PAI remained above 80% up to a 30% demand increase before declining, indicating that projected demand surpasses available production capacity under severe sensitivity conditions. The results suggest that while the system maintains a production surplus under moderate demand growth, escalating demand progressively erodes the available OPM and may place increasing pressure on desalination-supported production systems over time.

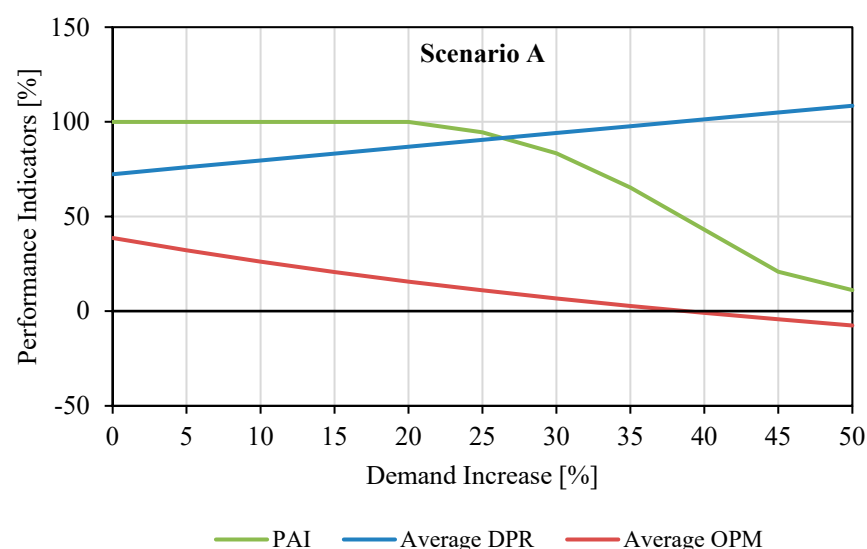


Figure 13. Operational response of the Sharjah water system under increasing demand conditions (Scenario A). Increasing demand resulted in higher DPR values and reduced OPM.

3.5.2. Scenario B: Production Reduction (Figure 14)

A hypothetical 5% reduction in water production increased the average DPR from 0.724 to 0.804 and reduced the OPM from 38.7% to 24.8%. As production reductions escalated progressively to 50%, the DPR continued to rise sharply while the OPM declined at

an accelerating rate, turning negative beyond the 30% reduction threshold; correspondingly, the PAI declined more steeply and approached zero by a 35% production reduction, indicating that production failed to meet demand in nearly all months under severe cuts—a markedly faster deterioration than earlier observed in Scenario A. The reduction in production produced a greater and more rapid decline in available OPM capacity compared with the demand-increase scenario, indicating higher operational sensitivity to production-side disruptions. These findings highlight the importance of maintaining stable desalination capacity and diversifying non-conventional water sources in hyper-arid urban systems.

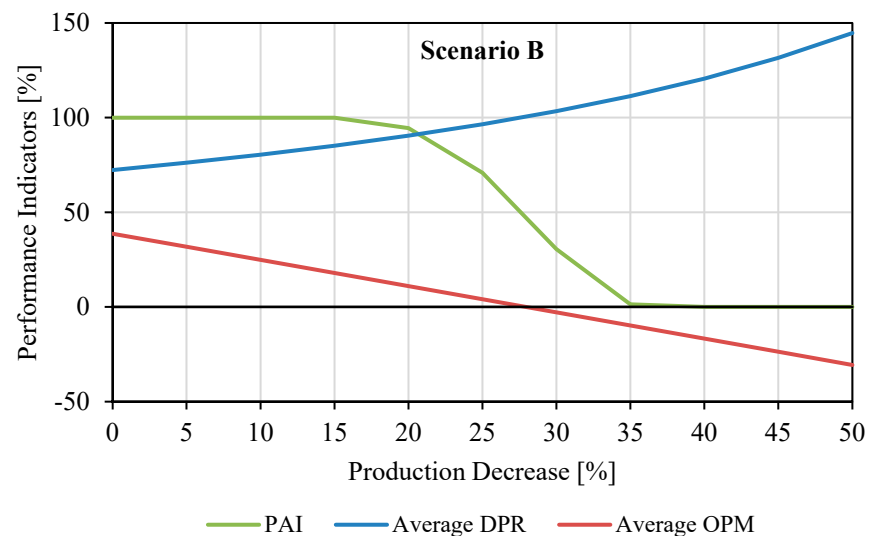


Figure 14. Operational response of the Sharjah water system under reduced supply conditions (Scenario B). Reduced production resulted in increased DPR values and lower OPM capacity.

3.6. Interpretation of Production Adequacy and Sensitivity Results

The consistently high PAI observed during the study period indicates that Sharjah's water system maintained stable supply conditions under normal operating scenarios. This stability is primarily supported by desalination-based production, which is less directly affected by seasonal hydrological variability compared with conventional freshwater systems. The production–demand sensitivity scenarios further demonstrated that reductions in supply or increases in demand substantially decrease the available OPM. Under more severe perturbation conditions, the system becomes increasingly vulnerable to operational disruptions, infrastructure limitations, energy constraints, or rapid demand growth. These findings suggest that while the system currently maintains stable operational performance, long-term water adequacy remains closely linked to desalination capacity, infrastructure continuity, and effective demand-side management.

The results also highlight the importance of supply diversification, treated wastewater reuse, infrastructure redundancy, and long-term planning strategies to support sustainable urban water management in hyper-arid environments.

4. Discussion

4.1. Urban Water Supply Transition in Sharjah

This study provides a longitudinal assessment of water demand and supply dynamics in Sharjah, United Arab Emirates, between 2016 and 2022 using operational utility data obtained from SEWA. Unlike scenario-driven modeling studies, the findings presented here reflect observed operational system behavior under real operating conditions,

providing localized empirical insights into urban water management in a hyper-arid environment. The results demonstrate a relatively stable production–demand relationship throughout the study period, supported by substantial desalination capacity and declining dependence on groundwater resources. The results reveal a major structural shift in Sharjah’s water supply system, with desalinated water accounting for approximately 90% of total supply, and groundwater contributions steadily declining during the study period. These changes should be interpreted within the context of Sharjah’s hydrological limitations. The Emirate is characterized by limited and highly variable precipitation, negligible natural groundwater recharge, and lacks permanent surface water resources, restricting the availability of conventional freshwater supplies. Under such conditions, the increasing reliance on desalination and the declining dependence on groundwater represent both an adaptive response to chronic water scarcity and a deliberate strategy aimed at conserving vulnerable aquifer systems [37]. From an ecological perspective, reduced groundwater abstraction may help mitigate aquifer depletion, slow groundwater quality deterioration associated with saline intrusion, and preserve groundwater reserves for strategic and emergency use. These benefits contribute to the long-term sustainability of fragile arid-region ecosystems and support broader groundwater conservation objectives in the UAE. Similar trends have been observed nationally through expanded groundwater monitoring programs and regulatory frameworks aimed at improving long-term water sustainability in arid environments [37]. The transition observed in Sharjah also reflects increasing dependence on non-conventional water resources across the GCC region due to limited renewable freshwater availability [38].

The strong reliance on desalinated water observed in this study highlights the central role of desalination in supporting urban water security in hyper-arid Gulf cities. In Sharjah, desalination facilities operated by SEWA, including the Hamriyah and Al Layyah plants, form the backbone of the potable water supply system. Similar trends have been reported across the UAE and neighboring Gulf countries, where desalination remains essential for supporting population growth, urbanization, and economic development [38]. However, the environmental implications associated with desalination, including high energy consumption, greenhouse gas emissions, and brine discharge, remain important regional concerns [39–43]. These considerations are particularly relevant given the continued expansion of desalination infrastructure across the Gulf region. Recent regional initiatives integrating renewable energy sources such as solar photovoltaic and solar thermal technologies into desalination systems may help reduce some of these environmental pressures [38–40]. These developments are particularly relevant given the strong dependence on desalination observed in Sharjah’s water supply system. In this context, Sharjah’s increasing reliance on desalinated water further emphasizes the importance of energy–water nexus planning, infrastructure diversification, and continued investment in non-conventional water resources.

The operational trends observed in Sharjah indicate that water production consistently exceeded billed demand throughout the study period. The average DPR (~72%) suggests that the Emirate maintained substantial production capacity under current operating conditions. As noted in Section 2.2, the production values reported here represent total water generated at the source rather than distributed volume; the gap between total production and billed demand therefore reflects non-revenue water alongside intentional operational reserves. Although disaggregated NRW data were unavailable in the present study, this observation underscores the importance of future infrastructure-level assessments focused on system efficiency and water-loss management.

4.2. Sectoral Demand Patterns and Seasonal Variability

Sectoral analysis showed that the residential sector accounted for approximately 60–65% of total water consumption during the study period, indicating that household demand remains the dominant driver of urban water use in Sharjah. Similar residential-dominated demand patterns have been reported across several GCC cities due to climatic conditions, population growth, and high domestic water use [5]. These findings emphasize the importance of demand-side management strategies, including water conservation campaigns, efficient household technologies, public awareness initiatives, and behavioral interventions targeting residential users [41–45]. Seasonal variability analysis further demonstrated clear increases in demand during summer months, corresponding with elevated temperatures and increased domestic water consumption. Residential demand generally increased during hotter periods, while commercial and governmental demand exhibited comparatively lower seasonal variation. The observed seasonal variability highlights the importance of maintaining stable desalination capacity in hyper-arid urban systems where climatic conditions strongly influence water demand.

Beyond these seasonal patterns, temporary sectoral shifts in water use have been reported elsewhere in the UAE during the COVID-19 pandemic. Studies of household demand in Dubai found that residential consumption rose appreciably under stay-at-home conditions, with increases of over 30% reported during Ramadan [28], while a Sharjah-based analysis of utility records similarly reported higher residential and lower non-residential consumption during the 2020 lockdown, even as total city-wide consumption changed only marginally [45]. Such shifts were driven by movement restrictions, remote working, and the temporary closure of offices, retail outlets, and educational facilities, which redistributed daily water use toward the home. Consistent with the marginal city-wide change reported in these studies, the present analysis shows no lasting deviation in the sectoral demand structure over 2016–2022: the residential sector maintained its dominant share throughout, including across the pandemic period. This indicates that, while such events can temporarily redistribute demand between sectors, they did not alter the longer-term structural composition of Sharjah's water demand.

Furthermore, in Sharjah, SEWA's conservation initiatives, including awareness campaigns, installation of water-saving devices, technical support programs, and treated wastewater reuse initiatives, contribute to broader efforts aimed at improving urban water-use efficiency and reducing pressure on potable water resources [41–46]. The reuse of treated wastewater has become an increasingly important component of water management strategies across the UAE [46]. In Sharjah, treated wastewater is utilized for non-potable applications such as irrigation and municipal cleaning, reducing pressure on potable water resources and supporting integrated non-conventional water-resource management. The results of this study also align with broader UAE water-security and sustainability strategies, including the UAE Water Security Strategy 2036 [47], which emphasizes water-use efficiency, diversification of supply sources, increased reuse, and long-term infrastructure planning. The observed decline in groundwater dependence, expansion of desalination capacity, and emphasis on demand-side management in Sharjah are consistent with these national objectives. The results also align with Sustainable Development Goal 6 (SDG 6), particularly targets related to water-use efficiency, sustainable urban water management, and improved access to reliable water services [46,48].

4.3. Operational Production Adequacy and Sensitivity Scenarios

The system-level indicators demonstrated relatively stable operational performance during the study period. Supply consistently met or exceeded billed demand, reflecting stable desalination-supported production capacity under current operating conditions. The average demand-to-supply ratio (~72%) and the observed production buffer further

indicate that Sharjah maintained relatively stable operational conditions throughout the study period.

Scenario-based demand and supply sensitivity assessments demonstrated that the system remained operationally stable under moderate demand increases and supply reductions. However, the available production buffer declined substantially under more extreme perturbation conditions, indicating increasing vulnerability to supply disruptions or rapid demand growth. These findings are particularly important in desalination-dependent systems, where water production remains closely linked to energy availability, infrastructure continuity, and operational stability. The results therefore reinforce the importance of supply diversification, treated wastewater reuse, infrastructure redundancy, and long-term operational planning in supporting urban water security in hyper-arid environments. While desalination provides relatively stable production capacity compared with climate-sensitive renewable freshwater systems, dependence on energy-intensive infrastructure may introduce additional long-term operational and environmental challenges [38–43]. The observations also suggest that Sharjah’s water system is currently better positioned to manage gradual increases in demand than abrupt supply disruptions. This observation further highlights the importance of long-term infrastructure sustainability planning and diversification of non-conventional water sources to reduce vulnerability associated with heavy dependence on desalination infrastructure.

4.4. Implications for Water Management in Hyper-Arid Gulf Cities

To situate Sharjah’s operational water demand within the broader national landscape, Figure 15 is presented as a contextual benchmark comparing urban water consumption trends across selected UAE Emirates, based on publicly available utility data [40]. It is intended to provide qualitative context rather than a normalized, like-for-like comparison of utility performance, given that the Emirates differ in population size, service-area boundaries, and utility reporting characteristics. Within these limits, the figure illustrates how urban water demand evolved across the Emirates during the study period, highlighting both shared and distinct consumption trajectories. While all Emirates experienced varying degrees of growth in water demand, differences in the magnitude and rate of change reflect local demographic, economic, and urban-development characteristics. Viewed alongside the Sharjah results, this benchmark provides additional context for understanding how the observed demand patterns fit within the wider UAE urban water landscape.

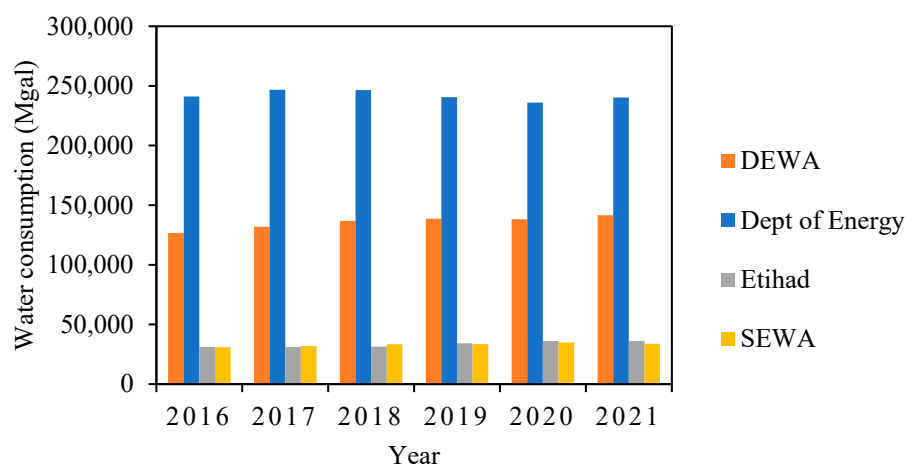


Figure 15. Contextual Benchmark Comparison of Urban Water Consumption Trends Across Selected UAE Emirates (2016–2021), based on publicly available utility data.

Collectively, the trends shown in Figure 15 demonstrate that increasing urban water demand is a nationwide challenge extending beyond Sharjah. Although the scale of consumption varies among Emirates, the overall trajectories underscore the importance of continued investment in water-source diversification, demand-management initiatives, and long-term water-security planning across the UAE.

Urban water-management challenges observed in Sharjah reflect broader trends across the MENA region, particularly in rapidly urbanizing arid cities facing increasing pressure on limited freshwater resources. Similar to Riyadh and several other Gulf cities, Sharjah relies heavily on desalination to maintain water supply reliability [5,49–52]. In contrast, cities such as Amman and Cairo continue to experience challenges related to groundwater overexploitation, infrastructure limitations, and constrained implementation of water-reuse strategies [53–60]. Tunisia has expanded treated wastewater reuse, particularly for agricultural applications, although seasonal and infrastructural limitations remain important constraints [61–64]. Table 1 summarizes selected characteristics of urban water systems across representative MENA cities. Population figures, in Table 1, are based on national census and official population data compiled by Brinkhoff [65] for the indicated reference years, and are provided for contextual scale only.

Table 1. Urban Water Management Characteristics in Selected MENA Cities.

Location	Primary Water Source	Reuse of Treated Wastewater	Demand Management Programs	Policy Framework	Challenges
Sharjah, UAE (current study) (Population: 1.4 M–1.8 M [65]; Year: 2015–2022)	Desalination supplemented by limited groundwater resources	Yes (SEWA initiatives)	Strong (SEWA conservation campaigns) [42]	UAE Water Security Strategy 2036 [47]	High energy use for desalination [38,66], residential demand
Amman, Jordan (Population: 4 M–4.6 M [65]; Year: 2015–2021)	Groundwater, limited surface water, rainwater harvesting, treated wastewater [53]	Limited (pilot projects) [53,55]	Weak (limited outreach) [56]	National Water Strategy 2016–2025 and 2023–2040 [57,58]	Over-extraction of groundwater, limited funding [53]
Riyadh, Saudi Arabia (Population: 6.7 M–8.5 M [65]; Year: 2010–2022)	Desalination and groundwater, limited surface water sources [50]	Expanding reuse programs [49–52]	Moderate (subsidies, public awareness) [51]	Saudi Vision 2030 and National Water Strategy [5,49]	Rising urban demand, energy–water nexus [5]
Tunis, Tunisia (Population: 1.05 M–1.07 M [65]; Year: 2014–2024)	Surface water and treated wastewater [59,62]	Moderate reuse for agriculture [55,61]	Emerging (metering, education) [64]	Water Code, regional planning [62,63]	Seasonal variability, limited infrastructure [61]
Cairo, Egypt (Population: 9.5 M–10.2 M [65]; Year: 2017–2023)	Nile River and groundwater [54,55]	Minimal reuse [59]	Limited (subsidized water prices) [54]	National Water Resource Plan (NWRP) [60]	Aging infrastructure, high population growth [54]

Despite differences in hydrological conditions, governance structures, and infrastructure capacity, several regional patterns emerge, including growing dependence on non-conventional water resources, increasing urban demand, pressure on groundwater systems, and the need for long-term system performance. In this context, Sharjah’s operational trends provide localized insights relevant to other hyper-arid urban systems undergoing similar water-management transitions.

4.5. Limitations and Future Research

This study relies on historical, aggregated operational data provided by the Sharjah Electricity, Water, and Gas Authority (SEWA) and focuses primarily on system-level descriptive analysis. Several limitations should therefore be acknowledged. Non-revenue water components, including leakage, metering inaccuracies, and unauthorized consumption, could not be disaggregated due to limitations in the available operational datasets. Although groundwater volumes were included in the total water supply assessment, long-term well-level records were inconsistent and therefore excluded from detailed analysis. In addition, the study focused mainly on desalinated water and groundwater trends, while treated wastewater volumes and virtual water flows were not analyzed separately. Infrastructure-level hydraulic modeling, including storage dynamics, transmission losses, and inter-district flows, was not possible because disaggregated network data were unavailable. The analysis also did not incorporate predictive forecasting, probabilistic uncertainty analysis, climate-driven simulations, or advanced scenario-based planning beyond the simplified sensitivity assessment presented. Despite these constraints, the combined use of validated operational data, descriptive statistics, and system-level performance indicators provides a reliable evaluation of Sharjah's observed water supply–demand dynamics. Future research should incorporate infrastructure-scale modeling, non-revenue water quantification, predictive demand forecasting, climate-driven scenario analysis, and resilience assessments to further evaluate long-term urban water sustainability under changing environmental and demographic conditions. Further, future studies could integrate climatic variables, particularly air temperature and precipitation, with utility operational data to better quantify the influence of climate variability on urban water-demand patterns in Sharjah.

5. Conclusions

This study presented a longitudinal assessment of water demand and supply dynamics in Sharjah, UAE, between 2016 and 2022 using operational utility data. The findings showed a major transition toward desalinated water, which accounted for approximately 90% of total supply, while groundwater reliance declined substantially during the study period. Sharjah maintained a relatively stable demand-to-supply balance, with an average demand-to-supply ratio of approximately 72%, indicating production capacity consistently exceeding billed consumption under current operating conditions. Sectoral analysis showed that residential consumption represented the largest share of total demand, emphasizing the importance of demand-side management and public awareness initiatives. Seasonal variability analysis demonstrated increased summer demand, while desalination capacity supported stable supply conditions throughout the year.

Overall, the study provides localized empirical evidence on urban water demand and supply dynamics in a hyper-arid Gulf city, highlighting temporal consumption patterns, source transitions, and operational system characteristics. These findings may help inform supply diversification, operational planning, and conservation-oriented water-management strategies to support long-term water security. The analysis is limited to aggregated operational utility data and descriptive system-level indicators; therefore, future work should incorporate infrastructure-level modeling, non-revenue water assessment, predictive forecasting, and climate-driven scenario analysis to provide a more comprehensive evaluation of long-term system performance and sustainability.

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Supervision, Writing—review and editing, Funding Acquisition; S.B.: Conceptualization, Methodology, Project Administration, Supervision, Writing—review and editing; F.S.: Conceptualization, Methodology, Project Administration, Supervision, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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