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Groundwater Quality Deterioration along the Libyan Mediterranean Coastal Strip (2000–2026): A Critical Review

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تدهور جودة المياه الجوفية على طول الشريط الساحلي الليبي المطل على البحر الأبيض المتوسط (2000–2026): مراجعة نقدية

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Abstract:
Seawater intrusion is widely named as the main cause of groundwater degradation along the Libyan Mediterranean coast, yet the evidence behind that claim has not been appraised as a whole. This review examines studies from Zuwara in the west to Tobruk in the east, sector by sector, recording the data used, the main findings, and the strengths and limitations of each source. Groundwater is saline in nearly every sector, with TDS of about 3,300 to 8,200 ppm in Wadi Jarif (Sirte) and EC up to 8,320 µmhos/cm in Misrata. The evidence is concentrated in the northwest, especially Tripoli and the Jifarah Plain, while Zuwara, Janzour, Garabulli and Derna lack dedicated studies. Most work rests on single sampling campaigns. Only Zawiya, Al-Khums and Zelten offer a baseline or repeat sampling, so deterioration is usually inferred rather than observed. Attribution to seawater is also weak in many cases, because sabkha and evaporite dissolution, evaporation and relict brines are seldom separated from marine sources, and the studies that did separate them (Zliten, Sabratha, Tripoli) reached more qualified conclusions. Over-abstraction is better supported, with drawdown reaching 25 to 30 m below sea level near Tripoli and Sabratha. The record therefore supports statements about present condition, but not about trend or cause. Priorities are repeat monitoring at fixed wells, source-diagnostic tracers applied together, and a single method used along the whole coast.

Keywords: Groundwater Quality; Seawater Intrusion; Salinization; Critical Review.

الملخص
ترجع تدهور المياه الجوفية على امتداد الساحل الليبي المطل على البحر المتوسط إلى تداخل مياه البحر بوصفه السبب الرئيس، غير أن الأدلة التي يستند إليها هذا الطرح لم تُقيَّم حتى الآن في مجملها. تستعرض هذه المراجعة الدراسات المنجزة من زوارة غربًا إلى طبرق شرقًا، قطاعًا بعد قطاع، وتوثّق لكل مصدر البيانات المستخدمة وأبرز النتائج ونقاط القوة والقيود. تتسم المياه الجوفية بالملوحة في جميع القطاعات تقريبًا، إذ تراوحت المواد الصلبة الذائبة الكلية بين نحو 3300 و8200 جزء في المليون في وادي جارف (سرت)، وبلغت الموصلية الكهربائية 8320 ميكروموز/سم في مصراتة. وتتركز الأدلة في الشمال الغربي، ولا سيما طرابلس وسهل الجفارة، في حين تفتقر زوارة وجنزور وقصر الأخيار (قرابولي) ودرنة إلى دراسات متخصصة. ويقوم معظم الأعمال على حملات أخذ عينات منفردة، ولا يتوفر خط أساس أو أخذ عينات متكرر إلا في الزاوية والخمس وزلطن، ولذلك يُستدل على التدهور في الغالب استدلالًا ولا يُرصد رصدًا مباشرًا. كما أن إسناد التملح إلى مياه البحر ضعيف في حالات كثيرة، لأن إذابة السبخات والمتبخرات والتبخر والمحاليل الملحية الأحفورية نادرًا ما تُفصل عن المصادر البحرية، أما الدراسات التي أجرت هذا الفصل (زليتن وصبراتة وطرابلس) فقد خلصت إلى استنتاجات

أكثر تحفظًا. وفي المقابل يحظى الإفراط في السحب بدعم أقوى، إذ بلغ الهبوط في مناسيب المياه 25 إلى 30 مترًا دون مستوى سطح البحر قرب طرابلس وصبراتة. ومن ثم فإن السجل المتاح يدعم الأحكام المتعلقة بالحالة الراهنة، ولا يدعم الأحكام المتعلقة بالاتجاه أو السبب. وتتمثل الأولويات البحثية في الرصد المتكرر عند آبار ثابتة، وتطبيق المتتبعات التشخيصية لمصدر الملوحة تطبيقًا متكاملًا، واعتماد منهجية موحدة على امتداد الساحل كله.

الكلمات المفتاحية: جودة المياه الجوفية؛ تداخل مياه البحر؛ التملح؛ مراجعة نقدية.

Introduction

Coastal plains are where people, farms and industry crowd together, and in dry regions the aquifer beneath them is often the only supply that does not fail in a bad year. Rivers flood and then vanish, reservoirs silt up, and desalination needs money and a steady power supply. A coastal aquifer, by contrast, is usually just there, close to the wells that use it [1].

Arid and semi-arid coasts make the problem sharper. Rainfall is low and erratic, evaporation is high, and recharge arrives in a few short events, often concentrated along wadi channels rather than spread evenly over the plain. The freshwater body that results is thin, sits on or beside saltwater, and has very little spare storage to absorb a dry decade. Studies of coastal aquifers worldwide place arid settings under heavy pumping among the most vulnerable [2], and the wider pattern of aquifer degradation, from depletion through salinization to contamination, has been recognised for two decades [3].

The pressure comes mostly from the demand side. Growing towns, irrigated agriculture and industry draw water faster than the aquifer is refilled, and the shortfall is made up from storage. Well records and satellite gravimetry now agree that groundwater storage is falling across much of the world's drylands [4].

The mechanism is old and well understood. Fresh groundwater floats above denser seawater, and the position of the interface depends on the balance between the freshwater head and the density difference between the two fluids. When heads drop, the interface moves inland and rises, and heavy pumping close to the coast can draw a cone of saline water upward beneath a well [5]. What makes the process treacherous is its delay. An aquifer can go on delivering water long after its gradient has reversed, so users notice a change in taste, corroded pipes or scorched crops late, and recovery may take far longer than the damage [6].

Climate change adds a third pressure, though how much it adds is less certain than the headlines suggest. The Mediterranean basin is a recognised climate change hotspot, with projections pointing to higher temperatures, lower and more variable rainfall, and therefore weaker and less frequent recharge [7–9]. Sea-level rise would push the interface inland even without extra pumping [10]. For most arid coasts, however, abstraction is still the stronger driver of head decline in the short and medium term [11].

Libya shows all of this in an extreme form. The country has no perennial river, surface water meets less than 3% of national use, and groundwater supplies the rest, about 97% by one recent estimate [12]. Most Libyans live on the Mediterranean strip, and the Jifarah Plain around Tripoli alone is home to roughly 60% of a population of about six million [13]. Seawater intrusion around Tripoli has been documented since the 1930s, driven by growing demand on local aquifers [14]. Coastal wells kept pumping, sewerage in several places did not keep pace with the new supply, and, as Zliten found in 2024, imported water can lift the water table into contaminated ground [15,16]. The coast is squeezed from two sides: the sea advances whenever heads fall, and the land surface passes down whatever is spread, spilled or buried on it.

This review asks four questions: where has groundwater deterioration been documented between the Tunisian border and the Egyptian frontier, and how severe is it; which processes are invoked to explain it, and how securely they are identified; how reliable the underlying evidence is; and what would be needed to turn scattered surveys into a record that can support management. The review is critical rather than exhaustive: studies with transparent sampling, complete hydrochemical data and source-diagnostic methods (e.g., ionic ratios, isotopes) are given greater weight [5,17]. Because most studies within the 2000–2026 window are one-off snapshots and true time series are rare, we flag this limitation wherever it affects a conclusion.

2. Review approach

This is a critical narrative review. It does not pool data, because the sampling designs, analytical methods and reporting standards of the Libyan literature differ too much (Sections 5.1 to 5.3). We borrowed two reporting principles from PRISMA 2020 [17], explicit eligibility criteria and a stated search window, but the work is not a systematic review and makes no claim to be one.

2.1 Search strategy

We searched Google Scholar, Crossref, publisher platforms and the websites of Libyan journals during September 2026, and consulted institutional reports (WHO) [18]. The window runs from January 2000 to July 2026. Earlier foundational work is cited where later papers depend on it. Search terms combined the names of Libya and its coastal regions (Jifarah, Jefara, Gefara, Djeffara, Tripoli, Zawiya, Sabratah, Zliten, Misrata, Sirte, Benghazi, Jabal al-Akhdar, Derna, Tobruk) with terms for seawater intrusion, salinization, nitrate, hydrochemistry and groundwater quality.

2.2 Eligibility, extraction and appraisal

We retained studies that reported primary hydrochemical data, modelling or remote-sensing analysis for coastal Libyan aquifers and that gave enough information to establish where, when and how samples were taken. Studies whose location, dates or methods we could not establish were set aside. For each retained study we extracted location, number of samples and campaigns, parameters, the standards applied and the source attribution offered, and appraised it against five questions:

- How many samples were taken, and from how many campaigns?
- Was analytical quality control described?
- How were salinity or contamination sources attributed?
- Which standards were applied?
- Were the data available?

Two limits apply. Theses, ministry reports and Arabic-language literature are only partly indexed and are certainly under-represented, and the search was not run in a citation database with reproducible export. Readers should treat the coverage as broad but not exhaustive.

2.3 Objectives

The review has three objectives:

To assemble, harmonise and critically appraise the evidence on groundwater quality deterioration along the Libyan Mediterranean coastal strip published between 2000 and 2026.

To disentangle the relative contributions of hydrogeological predisposition, abstraction pressure, land use and sanitation failure, climatic forcing, and governance collapse.

To translate that synthesis into a monitoring, management and research agenda that is realistic under conditions of political fragility, an explicit design constraint that most technical recommendations for Libya have ignored.

3. Scientific background and conceptual framework

Coastal groundwater degrades through several processes that are easy to confuse in the field. Salinity can rise because seawater is moving inland, because irrigation return flow is concentrating salts, or because the aquifer matrix is releasing them. This section separates these processes so that the Libyan studies in Sections 4 and 5 can be read against a common set of mechanisms.

3.1 Geological and hydrogeological characteristics

Libyan coastal aquifers are not a single system but several distinct hydrogeological units. In the northwest, the Jifarah Plain is a Quaternary–Neogene coastal basin whose productive units are shallow sands, calcarenites, and fractured carbonates, underlain by deeper and more mineralised Mesozoic formations [19], whereas the flat, sabkha-fringed Sirte Basin coast hosts groundwater that is already brackish before abstraction, and the Eocene–Miocene carbonate plateau of Jabal al-Akhdar is governed by karstification and fracture flow that control recharge and contaminant transport. Aquifer response to stress is determined by hydraulic conductivity, the thickness and continuity of confining layers, and the degree of hydraulic connection to the sea: unconfined, high-conductivity units permit rapid seawater advance, while confined or semi-confined units respond more slowly but are harder to flush once salinised, yet most published studies still treat the coastal aquifer as a single homogeneous unit [19].

3.2 Climate variability and groundwater recharge

The Libyan coastal strip is semi-arid to arid, with rainfall highest along the northwestern coast and Jabal al-Akhdar and declining steeply southward with strong interannual variability, so recharge is episodic and depends on a few intense events, ephemeral wadi flow, or rapid karst infiltration [20]. Recharge estimates in such settings remain highly uncertain, as chloride mass balance, water-table fluctuation, and numerical models often diverge by more

than the signal measured. Climate change compounds this through reduced or erratic rainfall and sea-level rise, although changes in abstraction may outweigh sea-level rise in driving intrusion [21], a view consistent with Libyan evidence but not yet directly tested there.

3.3 Groundwater abstraction and water-balance changes

An aquifer in natural balance discharges fresh water to the sea, and that discharge is what holds the saltwater interface in place. Pumping reduces it. Once abstraction exceeds recharge, the deficit is paid by storage, by a falling water table and, near the coast, by the sea.

Along the Libyan coast, abstraction for agriculture, municipal supply and industry has run above sustainable yield for decades. Drawdown cones have formed around the largest wellfields, and in places the water table now sits below sea level. The Great Man-Made River has supplied some coastal demand with water transported from the south, which should in principle relieve local pumping. Whether it has done so, and for how long, depends on conveyance reliability and on whether local abstraction actually fell. This is an open question: we found few studies that report pumping rates or water-level trends at a resolution that would allow the water balance to be closed.

3.4 Mechanisms of seawater intrusion

In its simplest form, a freshwater lens floats on denser seawater. The Ghyben–Herzberg relation puts the interface at roughly forty times the freshwater head above sea level, so a 0.5 m drop in head can raise the interface by about 20 m [22]. Real aquifers depart from this sharp-interface picture through a mixing transition zone, tidal and seasonal oscillations, heterogeneity and density-driven flow [5]. Four pathways can deliver saline water to a well (Figure 1) [23]:

Lateral intrusion advances the wedge inland along the aquifer base.

Upconing raises saline water beneath a pumping well when the cone of depression reaches the interface.

Vertical leakage moves brackish water through poorly sealed boreholes or across aquitards.

Surface inundation from storm surge or tidal channels infiltrates in low-lying areas.

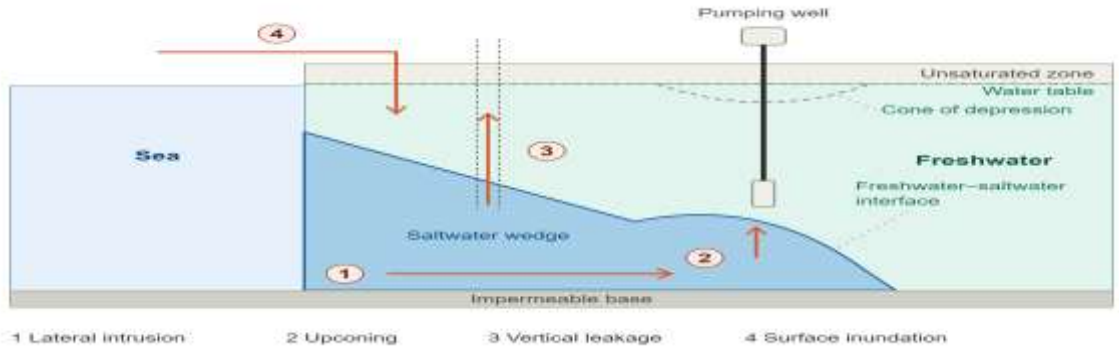

Figure 1. Pathways by which saline water reaches a coastal well: lateral intrusion, upconing, vertical leakage and surface inundation, shown on a schematic coastal cross-section with the freshwater–saltwater interface and a pumping cone.

These mechanisms leave different hydrochemical fingerprints, so the choice between them matters for management. A single high-chloride sample cannot tell them apart.

3.5 Hydrogeochemical processes and salinization

Seawater is only one possible source of salinity; others include evaporite dissolution, evaporative concentration of irrigation water, return flow carrying fertiliser and wastewater salts, and mixing with deeper, more mineralised water, so total dissolved solids alone cannot discriminate among them. Ionic ratios are the main diagnostic tool: an Na/Cl molar ratio near the seawater value (about 0.86) indicates marine mixing, whereas strong deviations point to other processes, and cation exchange during intrusion (sodium uptake and calcium release, with the reverse during freshening) raises $Ca/(HCO_3 + SO_4)$ [24]. Cl/Br ratios separate seawater from halite dissolution and wastewater [25], saturation indices of calcite, dolomite, gypsum, and halite reveal carbonate or evaporite

contributions, and stable ($\delta^{18}O$, $\delta^{2}H$) and strontium isotopes provide independent evidence, although they remain less used in Libyan studies.

Groundwater vulnerability indices describe how easily contaminants reach an aquifer, and they depend heavily on data quality. DRASTIC combines seven hydrogeological parameters into one score [26], while GALDIT was designed specifically for seawater intrusion [27]. Both run on sparse data, but their weights are subjective and their results are rarely validated against measured concentrations, and conventional models perform poorly when intrusion is driven by pumping-induced lateral flow (Environmental Impact Assessment Review study cited below). In Libya, DRASTIC has been applied to the unconfined Jifarah Plain aquifer, whereas measured evidence from Sabratah and Tripoli documents seawater intrusion, gypsum/anhydrite dissolution, and high nitrate [28], so measured indicators are the more convincing basis, as summarised in Table 1(a-k).

4. Review of studies by sector

4.1. Western coast (Jifarah Plain and Misrata)

The western coast is treated first, in six sub-sectors from west to east. It is generally better documented than the east, particularly around Tripoli, but several towns have little or no dedicated literature. Sirte and the eastern sectors follow Table 1(a-k).

4.1.1 Zuwara and Zelten

Table 1a Studies reviewed for Zuwara and Zelten

City / locality	Source	Data and approach	Main findings as reported
Zelten (west of Sabratha, Jifara Plain)	Ghawar et al. [29]	Nine groundwater samples collected in 2023 and 2024 from wells north and south of the city (unconfined Quaternary aquifer), analysed for EC, TDS, pH, total hardness, chloride, calcium, alkalinity and NaCl.	NaCl is high in the north and northwest, averaging about 3000 mg/L. The water is classed C5 and unsuitable for irrigation. High calcium, chloride and TDS point to sabkha deposits and seawater intrusion, and the water needs treatment before use.
Zuwara (regional context)	Elosta [30]	Conference abstract on a geological simulation of water shortage in the Jifara Plain basin.	The abstract describes saline sediments south and west of the basin, a large groundwater accumulation extending from Khoms to Zuwara, and an aim of locating fresh-water zones among saline water.

4.1.2 Sabratha and Surman

Table 1b Studies reviewed for Sabratha and Surman

City / locality	Source	Data and approach	Main findings as reported
Sabratha area (Sabratha-Surman coast)	Alfarrah et al. [19]	50 groundwater samples analysed for indicators of salinization and pollution, in an area of about 20 km of coast and 22 km inland.	High EC, sodium, potassium, magnesium, chloride and sulphate are attributed to seawater intrusion. Heavy pumping creates drawdown cones, with the water table as much as 30 m below mean sea level. High sulphate near the shore reflects intrusion and upconing of deep saline water, with local anomalies from sabkha dissolution and gypsum dissolution further inland.
Sabratha region	Boufars and Omar [31]	revealed variations in the hydrochemical characteristics of groundwater wells in the Sabratha region	The total dissolved solids (TDS) concentrations ranged from 975 to 30,800 mg/L, while the pH values ranged from 7.4 to 8.8. Furthermore, the hydrochemical indicators, including the Na/Cl and Ca/Mg ratios and the Base Exchange Index (BEX), indicated varying degrees of seawater intrusion into the groundwater.
Az-Zawiya to Sabratha strip (Joudeim,	Khitreesh et al. [32]	Four coast-perpendicular cross-sections with ten wells each. Indices used:	The highest contamination was at a Surman well 827 m from the coast (Simpson ratio 98.74), and the lowest at an Al-Harsha well 600 m from the sea (20.8).

City / locality	Source	Data and approach	Main findings as reported
Al-Harsha, Surman)		Jones (Na/Cl), Ca/Mg ratio, base exchange index (BEX) and the GALDIT vulnerability model.	GALDIT indicates moderate vulnerability to intrusion across the study area.

4.1.3 Zawiya

Table 1c Studies reviewed for Zawiya

City / locality	Source	Data and approach	Main findings as reported
Zawia upper coastal aquifer	Ganfoud et al. [33]	Chemical analysis used to map the extent of seawater pollution in the upper coastal aquifer, compared with an earlier study.	Pollution intensity and extent have increased compared with 1995, especially in the second sector.
Suburban farms of Zawiya (Juda'im, Al-Harsha, Abu Sarah, Al-Matrad), 2000–2024	الطاهر وآخرون [34]	Analysis of 40 wells for TDS and chloride, GIS modelling of the extent of intrusion, and NDVI remote sensing of salt stress on vegetation.	The saltwater wedge advanced 1.5 to 3 km inland, and TDS rose by more than 370% compared with 2000. Irrigation with highly saline water led to soil salinization.
Jifarah Plain and coastal groundwater resources	Pallas [35]	Synthesis and evaluation of available hydrogeological data on groundwater resources, aquifer characteristics, water availability and groundwater development in Libya.	Provides a regional hydrogeological background on Libya's groundwater resources, including coastal aquifers and groundwater exploitation. It serves as a historical reference for understanding groundwater availability and pressures on water resources.

4.1.4 Tripoli (including Ain Zara and Tajoura)

Table 1d Studies reviewed for Tripoli (including Ain Zara and Tajoura)

City / locality	Source	Data and approach	Main findings as reported
Jifarah Plain, Tripoli coastal area	Al Farrah et al. [36]	134 wells analysed for major cations and anions, classified with the Stuyfzand system.	Over-pumping caused deterioration by seawater intrusion and exposed deep saline water, with chloride the major pollutant. Water types (CaCl, NaCl, Ca/Mg mix) reflect cation exchange during freshwater-seawater mixing, and 80% of samples show a composition indicative of intrusion.
Tripoli (city aquifer)	Al Farrah et al. [28]	64 groundwater samples analysed for salinization and pollution indicators.	High EC, Na, K, Mg, Cl and SO4 are attributed to seawater intrusion, with chloride as the major pollutant. Drawdown cones lower the water table to as much as 25 m below mean sea level, and high nitrate is probably linked to fertilizers and sewage.
Jifarah Plain coast (origin of high sulphate)	Al Farrah et al. [37]	134 sampling wells analysed for major ions, aimed at identifying the sources of rising sulphate.	Anomalies near the coast are explained by seawater intrusion and upconing of deep saline water, supported by high chloride and inverse cation exchange, with sabkha dissolution in some areas.
Jifarah Plain, Quaternary coastal aquifer (urban coastal strip)	Swaid & Eltariki [38]	59 groundwater samples from wells analysed for major cations and anions, to identify the hydrogeochemical processes controlling quality and the threats of	Groundwater quality is controlled mainly by dissolution of calcite and dolomite, by seawater intrusion linked to aquifer overexploitation, and by nitrate pollution. The nitrate is attributed mainly to intensive agriculture and leakage from septic pits.

City / locality	Source	Data and approach	Main findings as reported
		seawater intrusion and pollution.	
Tripoli coastal area	Abdalla et al. [39]	Physical and chemical parameters, Cl/Br molar ratios and mixing calculations between fresh groundwater and Mediterranean seawater.	Most wells show high EC linked to heavy pumping of shallow coastal aquifers. Cl/Br ratios indicate intrusion in some samples, and mixing calculations estimate the seawater fraction at 10 to 15 wt%.
Tripoli aquifer (pumping scenarios)	El Aswed et al. [40]	MODFLOW 2005 simulations of the Tripoli coastal aquifer under different pumping scenarios.	Two of the scenarios cause a significant fall in groundwater level, most wells are predicted to be dry by 2100, and intrusion extends to the southern boundary of the aquifer. A sustainable pumping scenario allows recovery, with seawater moving back towards the sea.
Tripoli coastal aquifer (long-term modelling)	Elaswed et al. [41]	Transient MODFLOW-2005 model calibrated and validated against measurements, simulating 2020 to 2100 in a densely urbanised area with more than 100 wells.	Groundwater levels are predicted to fall by more than 12 m in the south, and more than 70 coastal wells face intrusion by 2100. Doubling pumping would leave about 98% of wells at high salinity.
Ain Zara (south of Tripoli)	Ekhmaj and Alamari [42]	40 wells sampled in March 2023. EC-Cl relationship, Simpson's ratio, GQISWI, seawater mixing index and HEF diagrams, plus a fuzzy seawater intrusion index (FSWI).	The indicators show the area is at risk of seawater intrusion with a consistent spatial pattern, and the FSWI model estimates the degree of contamination. The authors call for mitigation measures.
Tajoura	Salem [43]	18 vertical electrical soundings (geo-electrical resistivity) in an area with wells previously studied by chemical analysis.	Seawater was clearly shown to have intruded into the groundwater of the study area.
Tajoura (Jifarah Plain, 20 km east of Tripoli)	Huwaysh & El Ahmar [44]	Chemical and physical parameters of groundwater from 26 wells sampled in 2021, interpreted with a Piper diagram and the Cl/HCO3 ratio.	Overexploitation has caused considerable deterioration, and salinization has reached an alarming level in many places over the past 25 years. About 90% of samples are sodium-chloride type, and salinity increases toward the coast, with the best quality in the south. About 70% of samples are strongly affected by saline water. Car wash stations and an unlined wastewater pond also contribute to the deterioration.

4.1.5 Al-Khums and Qarabulli

Table 1e Studies reviewed for Al-Khums and Qarabulli

City / locality	Source	Data and approach	Main findings as reported
Al-Khums east coastal strip (20 km, between Wadi Libda and Wadi Kaam)	Okasha [45]	30 groundwater samples analysed for pH, TDS, chloride, sulphate, bicarbonate and other ions, aimed at the effect of seawater intrusion along the coastal stretch.	Salinity ranges from 4276 ppm near the sea to 3124 ppm landward, decreasing gradually inland. Salinity and chloride are higher than values reported by the Ministry of Agriculture in 1973 and 1978, and sulphate follows the chloride and salinity pattern. Wadi Kaam and Wadi Libda reduce intrusion around their basins.
Al-Khums city (Celine, Al-	Elyaagubi et al. [46]	Groundwater from wells located 0.5 to 9 km from the shore, analysed for pH, EC,	Water quality varies from site to site. Most results depart markedly from WHO limits, especially in wells near the coast (Suk Al-

City / locality	Source	Data and approach	Main findings as reported
Mergub and Suk Al-Khamis)		TDS, alkalinity, hardness, major ions and heavy metals (iron, zinc, cadmium). The stated aim was to assess pollution and seawater intrusion near the coast.	Khamis and Al-Khums). The water is judged unsuitable for drinking and domestic use without substantial treatment.
Al-Qarabulli municipality (coastal strip east of Tripoli)	Mountaser et al. [47]	12 wells at distances from about 200 m to 10 km from the coast, analysed for sodium, potassium, chloride, magnesium and calcium. Salinity sources assessed with the Jones ratio, base exchange index (BEX) and Ca/Mg.	Chloride ranges from 46 to 760 mg/L. The Jones ratio indicates salinization in most wells (below 0.86 in about 45% of samples), and BEX indicates it in about 40%, with several wells near the coast showing no signal. The authors conclude that seawater interference is significant and that the water is unsuitable for drinking and irrigation, except for salt-tolerant crops.
Al-Qarabulli (Garabulli) area (farms, up to 8 km inland)	Al-Arqat et al. [48]	24 shallow wells (35 to 56 m deep) sampled between March and July 2018, within about 8 km of the sea, and analysed for TDS, pH and EC, with spatial maps drawn in Geosoft.	EC ranges from 870 to 2260 µS/cm and TDS from 654 to 1500 mg/L, with values highest in wells near the shore and falling toward the south. About 79% of wells exceed the WHO limit of 1000 mg/L, and the highest TDS occurs in wells 1.6 to 3.8 km from the sea. The authors interpret this as a strong sign of seawater intrusion extending beyond 5 km, and judge most wells unsuitable for drinking and suitable only for salt-tolerant crops.
Al-Qarabulli	Boufaris et al. [49]	The study analyzed 15 groundwater wells extending approximately 8 km inland from the Mediterranean coastline to evaluate the extent of seawater influence	reported elevated values of electrical conductivity, total dissolved solids (TDS), total hardness, sodium, chloride, calcium, magnesium, and nitrate concentrations in several wells located near the coast

4.1.6 Zliten and Misrata

Table 1f Studies reviewed for Zliten and Misrata

City / locality	Source	Data and approach	Main findings as reported
Zliten (60 shallow wells)	Ashmila et al. [50]	Water levels of 60 shallow wells referenced to sea level, Simpson and Jones ratios for salinity source, and ArcMap mapping.	The water table rose to 4.25 m above sea level only 1200 m from the sea, and the study found no correlation between the rise and seawater intrusion. Groundwater flow is mainly northward.
Zliten (groundwater upsurge)	Al-Monitor (news report) [51]	Journalistic report on groundwater flooding homes and fields in the town.	The article describes an unexplained upsurge of groundwater and notes that, elsewhere in the world, rising sea levels have been linked to coastal groundwater upsurges as dense salt water pushes up lighter freshwater.
Misrata (Eocene shallow unconfined aquifer)	Alfji & Swaid [52]	31 wells within the Misrata area sampled in 2014 and assessed for drinking and irrigation using indices such as SAR, Na%, Wilcox and USDA classification.	EC ranges from 1056 to 8320 micromhos/cm. All major ions exceed the permissible limits of Libyan, WHO and US standards, and the water is judged unsuitable for drinking and irrigation. A fragment of the abstract refers to sea intrusion, and intrusion is a keyword.
Al-Sawawah area (Mahjoub, Misurata)	Ibshir & Salim [53]	Groundwater analysed in 2021 for pH, EC, TDS, hardness, calcium and chloride, with digital maps	EC values range from 1788 to 6800, and the water is very hard (total hardness above 301 mg/L). Calcium is 120 to 400 mg/L and average chloride is 532.5 to 1881.5 mg/L, with indicators

City / locality	Source	Data and approach	Main findings as reported
		of the spatial distribution of the properties.	of agricultural land degradation and desertification.

4.2. Sirte

Table 1g Studies reviewed for Sirte

City / locality	Source	Data and approach	Main findings as reported
Wadi Jarif, Sirte City	Aboshaala & Bahroun [54]	30 randomly collected groundwater samples analysed for pH, EC, TDS, total hardness, major cations and anions.	Groundwater chemistry is influenced by the host formations and by seawater intrusion. TDS ranges from 3311 to 8187 ppm, with Na2SO4 (meteoric) and NaCl (marine) water types. All samples are unsuitable for drinking, and most are not recommended for irrigation under normal conditions (suitable only for salt-tolerant crops and permeable soils).
Sirte City	Amhamed [55]	Hydrochemical and bacteriological study of Wadi Jarif wells, assessment of water resources, and evaluation of quality for different uses.	The retrieved text gives only the aims, keywords and table of contents. It lists a section reviewing previous seawater intrusion studies, but the findings themselves were not available.
Sirte Basin (regional, paleo-scale)	Gossel et al. [56]	Numerical density-driven groundwater model of the Nubian Aquifer System over the past 140,000 years under rising sea level and climate-change recharge scenarios, with detailed focus on the Qattara depression and the Sirte basin.	Behaviour in the Sirte basin differed from the Qattara case. Possible causes include high evapotranspiration in past periods, saline solutions from pre-Quaternary layers, or infiltration from sabkha-like salt-bearing sediments.
Sirte sabkhas, western Libyan coast	Ageel [57]	MODIS satellite data for 2015 to 2021 used to examine sea-surface salinity.	Sirte sabkhas contribute to surface salinity along the western coast. Salinity is higher in spring and summer, lower in winter and autumn, and wind direction plays a role.
Zliten (comparative case)	Ashmila et al. [50]	Well locations, water levels and ground elevations referenced to sea level. Salinity sources identified with Simpson and Jones ratios, with spatial mapping in ArcMap.	The water table rose to 4.25 m above sea level only 1200 m from the sea, and the study found no correlation between the rise and seawater intrusion.

4.3. Benghazi

Table 1h Studies reviewed for Benghazi

City / locality	Source	Data and approach	Main findings as reported
Eastern Benghazi (coastal plain)	El Fallah, Al Faitouri & Elmaleky [58]	Integrated assessment combining hydrochemical analysis, statistical methods and geochemical modelling (saturation indices).	Salinity is bimodal, with some samples saline and the rest fresh (TDS < 1000 mg/L). This reflects combined effects of seawater intrusion along the coastal margin, evaporative concentration and intensive pumping. Chemistry is controlled mainly by water-rock interaction, evaporation and seawater mixing or intrusion.
Ar Rajmah (east of Benghazi, agricultural area)	Shaltami et al. [59]	Hydrochemical assessment of groundwater for drinking and irrigation, with an EC vs. Cl plot used to screen for intrusion.	Groundwater is hard to fresh, Ca-Mg-Cl type, controlled by weathering of carbonate rocks, and supersaturated with halite and gypsum. The EC vs. Cl plot places the samples in the normal water field.

City / locality	Source	Data and approach	Main findings as reported
Benghazi-Al Marj region (Al Jabal Al Akhdar)	Al Faitouri et al. [60]	Tritium and carbon radioisotopes used to estimate recharge rates of groundwater, springs and rain. Stable isotopes (2H/18O) were also applied.	Pumped well water reflects mixing of at least two groundwater systems. Seawater intrusion should be considered in the Ayn Zayanah-Al Coeffiah karstic system, and most Ayn Zayanah spring discharges contain evaporated water.
Al-Sabri area, Benghazi coast (surface coastal water)	Shaltami et al. [61]	Ionic ratios (Cl/Na) and non-sea-salt sulphate (nss-SO4) calculations, with samples normalised to typical seawater composition.	The average Cl/Na ratio (2.2) is higher than the seawater value (1.17), the nss-SO4 indicates an anthropogenic origin, and heavy metals exceed desirable limits.

4.4. Al Jabal Al Akhdar

Table 1i Studies reviewed for Al Jabal Al Akhdar

City / locality	Source	Data and approach	Main findings as reported
Al Jabal Al Akhdar (four hydrogeological units; Benghazi-Al Marj region)	Al Faitouri & Muftah [60]	28 groundwater samples (springs and wells) and 60 rain samples analysed for stable isotopes (2H, 18O) and carbon isotopes (14C, 13C), with tritium used to test for direct infiltration of modern water.	Wells in the Benghazi-Al Marj region pump water from the mixing of at least two groundwater systems. Seawater intrusion should be considered in the Ayn Zayanah-Al Coeffiah karstic system, and most Ayn Zayanah spring discharges contain evaporated water. Miocene waters show increasing aridity, with reduced deuterium excess due to evaporation.
Jabal al-Akhdar aquifer system (regional overview)	Fanack Water (secondary source) [62]	Descriptive synthesis of existing reports on water quality in Libya.	Groundwater quality in the area normally varies between 450 and 3,000 mg/L. The northern coastal area suffers from seawater intrusion as a result of increased exploitation, so coastal aquifer salinity is rising.
Benghazi plain – Al Jabal al Akhdar aquifer system	Libya (n.d.) [63]	National-scale overview of groundwater basins and pressures.	Over-exploitation of the northern aquifers, including the Benghazi plain and Jabal al Akhdar system, is reflected in continuous water-level decline, deteriorating water quality and seawater intrusion along the coast.

4.5. Derna

Table 1j Studies reviewed for Derna

City / locality	Source	Data and approach	Main findings as reported
Derna (Sheha Wells)	Elhassadi [64]	Investigated groundwater salinity in the Sheha well field, Derna, using groundwater quality data.	Elevated groundwater salinity was reported, with TDS concentrations reaching 5,460 mg/L in one well.
Derna	Kotb et al. [65]	Used hydrogeological data from 73 pumping wells and numerical modelling with Visual MODFLOW to evaluate the effects of groundwater abstraction on saltwater intrusion.	Al-Fatayah was identified as a vulnerable area, where intensive groundwater pumping contributed to saltwater up-coning. Simulations predicted up-coning values of 5.68 m and 16 m under pumping rates of 10 and 20 L/s, respectively.

4.6. Tobruk

Table 1k Studies reviewed for Tobruk

City / locality	Source	Data and approach	Main findings as reported
Tobruk city (coastal wells)	Abdulla & Ouki [66]	Physicochemical parameters (Table 1 in the paper) of groundwater samples from coastal wells, within a study of wastewater reuse for irrigation.	Low rainfall, over-pumping of coastal aquifers and seawater encroachment have caused severe water-level decline and quality deterioration. Coastal well samples show high salinity, one sample has high nitrate plus microbial and chemical contaminants, and the groundwater is judged unsuitable for irrigation. Desalinated water (40,000 m^3/day) is almost the sole water resource for the city.
Tobruk city (spatial quality assessment)	Elgali & Khamis [67]	Spatial assessment of groundwater quality for drinking, with spatial analysis tools used to map the distribution of quality parameters.	Groundwater quality was generally poor, with most measured parameters exceeding the permissible limits for drinking water, while pH remained within the acceptable range. Spatial analysis indicated poorer groundwater quality in the northern and northeastern parts of the study area compared with the southern areas. Groundwater was reported as the primary water source for the city, with desalinated seawater also supplying part of the demand.
Al-Dafna coastal plateau east of Tobruk (sabkhas)	Mohammed et al. [68]	Field description, logging and sampling of sabkhas in several wadis, aimed at a hydrodynamic model of sabkha formation.	Sabkhas in the area are subject to flash floods in the wadis and to recharge from tidal flow. Intertidal and supratidal sabkhas develop where tidal pools fill with seawater at high tide.

4.1 What Table 2 shows

Table 2 come from the western coast, from Tripoli and the Jifarah Plain to Zliten. The centre and east are covered by seven small surveys (Sirte, Benghazi, Al-Marj, Jabal al-Akhdar, Derna, Tobruk). Sample sizes range from 5 to 134 wells, sampling years from 2007 to 2023, and the indicators change from study to study. No field dataset was repeated through time. The only temporal information comes from GRACE storage change for 2002–2016 [69], the Zliten water-table history and the Tripoli simulations. A single survey can show that water is saline or contaminated, but not since when or why, and most entries, including the recent ones from Garabulli, Ain Zara and Derna, fall into that category.

5. Critical evaluation of previous studies

5.1 Where, when and how many wells. Location matters more than the word “coastal” suggests. In the 105 × 18 km strip surveyed by Al Farrah et al. [36], fresh water occurred only south of Janzur, while EC reached 15,650 µS/cm about 4 km inland of the Sabratah shoreline and about 10,600 µS/cm at the coast of Tajura. Sebkhas along the shore and gypsum at depth add salt unrelated to the sea, so wells a few kilometres apart can disagree without either being wrong. Both main campaigns fell in dry periods (2007 and 2008), and no dataset covers the wet season. The design itself is good: transects perpendicular to the coast, at roughly one well per 12 to 14 km^2. The weaker point is independence. The 64-well Tripoli set, the 134-well plain-wide set and the 2016 and 2017 papers come from one programme, and the same well codes appear in several of them. Their agreement is one dataset read several times, and the most detailed hydrochemistry for this coast is about eighteen years old. Wells also exist where people farm and live, so “80% of samples” describes the wells that were available.

5.2 Indicators. The same 134 samples support different headlines depending on the criterion: 80% indicative of intrusion on the Stuyfzand classification, 23% strongly affected on Cl/HCO_3, chloride above 250 mg/L in 61% of wells. None is wrong, but they cannot be compared across papers. Magnitude is hidden as well. With the authors’ 645 mmol/L end member, the maximum chloride in the Tripoli (3,155 mg/L) and plain-wide (5,282 mg/L) surveys corresponds to about 14% and 23% seawater (our calculation), in line with the 10–15% from Cl/Br at Tajoura [44]. In most wells the water is still mostly fresh. The newer index-based studies [31,42,47,49] use thresholds calibrated elsewhere, and composite indices built from EC and chloride count the same information twice.

5.3 Separating seawater from other salt. The Jifarah studies do this better than most. They separate lateral intrusion, upconing of deep saline water, sebkha dissolution and gypsum dissolution [28,36,37], and they assign low-chloride, high-SO_4/Cl wells in western Tripoli to gypsum, which rules out intrusion there. Three limits remain. Bromide and isotopes were not measured, so the separation rests on major ions. Lateral intrusion and upconing are told apart by position relative to the drawdown cones, which is inference. And chloride above 250 mg/L in southern Tripoli is attributed to older marine influence, not present intrusion. The authors call the fertiliser and sewage origin of nitrate "probable". Elsewhere (Garabulli, Ain Zara, Tobruk) the chemistry resembles seawater mixing, but other salt sources are not excluded.

5.4 Abstraction and recharge. The abstraction case is strong but circumstantial. Depression cones 25 to 35 m below sea level were mapped around Sabratah and southern Tripoli, chloride and EC rise locally at the cones, and the Tripoli models agree [14,40]. The direct test is missing. At As Swani the cone recovered from about 80 m below sea level in 1996 to 33 m in 2008 once Great Man-Made River water replaced the wellfield, yet chloride in 2008 still followed the cones. Heads respond faster than salinity, and one dry-season snapshot cannot say whether salinity was rising, stable or falling. Pumping on the plain (about 1,200 million m^3 a year, 93% for irrigation) comes from a thesis and other estimates differ widely. Recharge was not estimated independently in the field studies, and low, irregular rainfall (250–350 mm a year against about 1,520 mm potential evaporation) cuts recharge and raises demand in the same dry years. Abstraction is a well-supported mechanism that has not been quantified as a cause, and the supply interruption since 2011 leaves later conditions undocumented.

6. Discussion and research gaps

6.1 Strength of the evidence. In the Tripoli–Sabratah sector, heads below sea level, an Na/Cl ratio below the seawater value, inverse cation exchange and modelled interface migration all agree, but they rest largely on one 2007–2008 dataset. Intrusion is established there as a process and uncertain in rate and trend. Elsewhere the evidence is thinner. A bimodal salinity distribution in 17 east Benghazi samples [58] is a reasonable reading of a small sample. In Jabal al-Akhdar, intrusion is flagged for one karst system only [60]. In Zliten the problem is rising, contaminated groundwater with no link to intrusion in the shallow-well study [50].

6.2 Why salinity differs between sectors. Probably through a mix of abstraction density, aquifer lithology and recharge, but this has been argued more than tested. The Jifarah aquifer is a single unconfined system containing gypsum and bordered by sebkhas, with rainfall falling from more than 300 mm near Tripoli and Garabulli to 150–250 mm toward the southwest. Jabal al-Akhdar is a karstic carbonate plateau with the highest rainfall in the country. The Benghazi plain depends on limited, variable rain. No study tested this across regions, so it remains a testable hypothesis.

6.3 Gaps and proposed work : Table 2 highlights the main research gaps and proposes further work to improve groundwater assessment and management**.**

Table 2 Evidence gaps and suggested work

Gap	What is missing	Suggested work
Change through time	Only the As Swani head history; everything else is a snapshot	15 to 30 sentinel wells on the 2007–08 transects, loggers for level and EC, quarterly sampling including a wet season, a common parameter set (Cl, Br, major ions, NO_3, depth, screen, pumping status), ionic balance within 5%, open data
Source of salt	No Br or isotopes in the Jifarah studies	Cl/Br; $\delta^{18}O$ and $\delta^{2}H$; sulphate isotopes with $^{87}Sr/^{86}Sr$ and $\delta^{11}B$; nitrate isotopes; tritium and ^{14}C for age
Recharge and abstraction	Estimated, not metered; estimates disagree	Satellite-derived irrigated area and crop evapotranspiration as a first abstraction estimate; a water balance including Great Man-Made River supply
Process models	One cross-sectional finite-element model and Tripoli scenarios; no 3D variable-density model found	SEAWAT, first 2D along the 14 km Janzur transect calibrated to 2007–08, then 3D Tripoli–Sabratah; scenarios for current pumping, As Swani reactivation, supply interruption and sea-level rise, with uncertainty
Vulnerability and management	Indices not calibrated against measured chloride	Calibrate GALDIT or DRASTIC against chloride; link models to response functions for pumping limits

7. Conclusions

Groundwater along the Libyan coast is saline and increasingly unfit for use, but the causes and timing of this deterioration remain contested. Most studies rest on a single sampling campaign, and the evidence is not evenly

distributed along the coastline. Salinity is often attributed to seawater intrusion without being distinguished from the dissolution of sabkha and evaporite deposits, evaporation, or relict brines. Where such distinctions were attempted, as in Zliten, Sabratha, and Tripoli, the results were more varied and more informative. Over-abstraction is the driver on which studies agree most, and the drawdown below sea level reported near Tripoli and Sabratha lends this view considerable weight.

Seawater intrusion is therefore established in the Tripoli–Sabratha sector and probable or suspected elsewhere. Salinity along the coast has several sources, and the available record supports a description of present conditions better than an account of trend or cause. Much of the disagreement between studies reflects differences in wells, seasons, years, and indicators rather than differences between aquifers. Excessive abstraction is the best-supported driver, but it has not yet been quantified.

Management should also be guided by the following priorities: abstraction limits and monitoring in the most stressed sectors, and a common sampling protocol that allows results from Sirte to be compared with those from Zawiya.

This review has limitations that should be acknowledged. It draws on abstracts and excerpts available through web searches and is not an exhaustive systematic review, so a gap in this review does not imply a gap in the literature. Arabic-language journals and unpublished reports from the water authorities are the most likely sources of additional evidence.

References

[1] Stein, S., Shalev, E., Sivan, O., & Yechieli, Y. (2023). Challenges and approaches for management of seawater intrusion in coastal aquifers. Hydrogeology Journal, 31(1), 19–22.

[2] Gantayat, R. R., & Elumalai, V. (2024). Salinity-induced changes in heavy metal behavior and mobility in semi-arid coastal aquifers: A comprehensive review. Water, 16(7), 1052.

[3] Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., ... & Kirchner, J. W. (2024). Rapid groundwater decline and some cases of recovery in aquifers globally. Nature, 625(7996), 715–721.

[4] Zhang, J., Liesch, T., & Goldscheider, N. (2025). Impacts of climate change and human activities on global groundwater storage from 2003 to 2022. Journal of Hydrology, 134298.

[5] Werner, A. D., Bakker, M., Post, V. E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., ... & Barry, D. A. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. Advances in Water Resources, 51, 3–26.

[6] Cantelon, J. A., Guimond, J. A., Robinson, C. E., Michael, H. A., & Kurylyk, B. L. (2022). Vertical saltwater intrusion in coastal aquifers driven by episodic flooding: A review. Water Resources Research, 58(11), e2022WR032614.

[7] Giorgi, F. (2006). Climate change hot-spots. Geophysical Research Letters, 33(8).

[8] Taylor, R. G., Scanlon, B. R., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J., Taniguchi, M., Bierkens, M. F. P., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., ... Treidel, H. (2013). Ground water and climate change. Nature Climate Change, 3, 322–329.

[9] Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J.-P., Iglesias, A., ... & Xoplaki, E. (2018). Climate change and interconnected risks to sustainable development in the Mediterranean. Nature Climate Change, 8(11), 972–980.

[10] Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., & Simmons, C. T. (2016). Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. Journal of Hydrology, 535, 235–255.

[11] Pisinaras, V., Paraskevas, C., & Panagopoulos, A. (2021). Investigating the effects of agricultural water management in a Mediterranean coastal aquifer under current and projected climate conditions. Water, 13(1), 108.

[12] Zurqani, H. A. (2025). Introduction to the “Water resources of Libya: Challenges and management”. In Water resources of Libya: Challenges and management (pp. 1–16). Cham: Springer Nature Switzerland.

[13] Alakhal, A. (2025). Changing urban identity and character in Libyan historical cities: A case study of Tripoli (Doctoral dissertation, Birmingham City University).

[14] Sadeg, S., & Karahanoğlu, N. (2001). Numerical assessment of seawater intrusion in the Tripoli region, Libya. Environmental Geology, 40(9), 1151–1168.

[15] Nazeer, M., Amin, G., & Wong, M. S. (2025). Emerging from the depth: Preliminary clues on groundwater upsurge in the coastal city of Zliten, Libya. Geomatics, Natural Hazards and Risk, 16(1), 2475889.

[16] Mourad, K. A., Al-Ghafoud, A. R. I., & Husayn, M. A. (2025). The Zliten groundwater crisis: A threat to community wellbeing and sustainable solutions. Journal of Sustainability, 1(1).

[17] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372.

[18] World Health Organization. (2022). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda. Geneva: WHO. ISBN 978-92-4-004506-4.

[19] Alfarrah, N., Berhane, G., Bakundukize, C., & Walraevens, K. (2017). Degradation of groundwater quality in coastal aquifer of Sabratah area, NW Libya. Environmental Earth Sciences, 76(19), 664. https://doi.org/10.1007/s12665-017-6999-5

[20] Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., & Simmers, I. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological Processes, 20(15), 3335–3370.

[21] Ferguson, G., & Gleeson, T. (2012). Vulnerability of coastal aquifers to groundwater use and climate change. Nature Climate Change, 2(5), 342–345.

[22] Bear, J., Cheng, A. H.-D., Sorek, S., Ouazar, D., & Herrera, I. (Eds.). (1999). Seawater intrusion in coastal aquifers: Concepts, methods and practices. Kluwer Academic Publishers.

[23] Barlow, P. M. (2003). Ground water in freshwater-saltwater environments of the Atlantic coast (Vol. 1262). US Department of the Interior, US Geological Survey.

[24] Appelo, C. A. J., & Postma, D. (2004). Geochemistry, groundwater and pollution. CRC Press.

[25] Alcalá, F. J., & Custodio, E. (2008). Using the Cl/Br ratio as a tracer to identify the origin of salinity in aquifers in Spain and Portugal. Journal of Hydrology, 359(1–2), 189–207.

[26] Aller, L., Bennett, T., Lehr, J., Petty, R. J., & Hackett, G. (1987). DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. US Environmental Protection Agency, Washington, DC, 455.

[27] Chachadi, A. G., & Lobo Ferreira, J. P. C. (2001). Sea water intrusion vulnerability mapping of aquifers using the GALDIT method.

[28] Alfarrah, N., & Walraevens, K. (2018). Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-arid regions. Water, 10(2), 143.

[29] Ben Ghawar, B. M., Elsarat, M. F., Salloum, F. M., & Al Tuwaybi, N. A. (2025). Assessment of groundwater quality in Zelten City, Al Jifara Plain, NW Libya, 162–174.

[30] Elosta, F. (2011). The geological simulation of water shortage from Jifara Plain Basin. In T. Karyotis & D. Gabriels (Eds.), Abstract proceedings of the 6th International Congress of the European Society for Soil Conservation: Innovative Strategies and Policies for Soil Conservation (p. 108). Thessaloniki, Greece.

[31] Boufars, M. S., & Omar, N. (2021). Assessment of seawater intrusion into groundwater using chemical indicators in the Sabratha region. Al-Jamiaa Journal, University of Zawia, 23(3), 409–432.

[32] Khitreesh, M., Shaksham, N., Abuslua, A., & Rhuma, T. (2022). The impact of seawater on groundwater in the coastal area of Joudeim–Sabratha. International Science and Technology Journal, 37(2).

[33] Ganfoud, A. A., & Abouras, G. M. (2018). Groundwater pollution with seawater in Zawia area. The Libyan Journal of Agriculture, 23(1–2), 17–29.

[34] الطاهر، عائشة الأنور معروف. (2026). الآثار البيئية والاقتصادية لتدهور الموارد المائية في مزارع ضواحي مدينة الزاوية خلال الفترة (2000–2024م). مجلة العلوم الشاملة، 10(ملحق 38)، 1527–1541.

[35] Pallas, P. (1980). Water resources of the Socialist People's Libyan Arab Jamahiriya. In M. J. Salem & M. T. Busrewil (Eds.), The geology of Libya (Vol. II, pp. 539–594). Academic Press.

[36] Al Farrah, N., Martens, K., & Walraevens, K. (2011). Hydrochemistry of the upper Miocene-Pliocene-Quaternary aquifer complex of Jifarah Plain, NW-Libya. Geologica Belgica, 14(3–4), 159–174.

[37] Alfarrah, N., Berhane, G., Mjemah, I. C., Van Camp, M., & Walraevens, K. (2016). The origin of high sulfate concentrations and hydrochemistry of the Upper Miocene–Pliocene–Quaternary aquifer complex of Jifarah Plain, NW Libya. Environmental Earth Sciences, 75(20), 1388.

[38] Swaid, F., & Eltariki, I. (2020). Seawater intrusion and nitrate pollution in the Quaternary coastal aquifers of Jefara Plain, northwestern part of Libya. The International Journal of Engineering & Information Technology (IJEIT), 7(1), 57–67.

[39] Abdalla, R., Rinder, T., Dietzel, M., & Leis, A. (2010). Seawater intrusion and groundwater quality of the coastal area in Tripoli region, Libya. Geophysical Research Abstracts, 12, EGU2010-11911.

[40] El Aswed, N. A., Ali, T. A. M., Ghazali, A. H. B., & Yusoff, Z. B. M. (2018). Simulation of different pumping scenarios on the groundwater–sea water intrusion into the Tripoli aquifer, Libya. Journal of Engineering Science and Technology, 13(10), 3419–3431.

[41] Elaswed, N. A., Mohammad, T. A., Ghazali, A. H., & Md Yusoff, Z. (2019). Modelling of groundwater pumping scenarios and their impact on saline water intrusion in a Tripoli coastal aquifer, Libya. Pertanika Journal of Science & Technology, 27(3), 1407–1427.

[42] Ekhmaj, A. I., & Alamari, K. M. (2025). Identify of seawater intrusion using hydrochemical approach and fuzzy logic for the Ain Zara, Libya. Libyan Journal of Ecological & Environmental Sciences and Technology, 7(1), 41–55.

[43] Salem, A. H. M. (2015). Study of seawater intrusion in Tajoura area. Journal of Marine Sciences and Environmental Technologies, 1(2), E35–E50.

[44] Huwaysh, A. M., & El Ahmar, Y. A. (2023). Evaluation of groundwater and seawater intrusion at Tajoura area–NW Libya. International Research Conference (IRC 2023), 36–47.

[45] Okasha, A. Y. (2011). Seawater intrusion along the coastal area between Wadi Libda and Wadi-Kaam, Northwest Libya. Electronic Journal of Environmental, Agricultural and Food Chemistry, 10(7), 2426–2438.

[46] Elyaagubi, F. K., ELNakeib, S. M., Alrabib, M. A., & Abouzed, A. (2019). Assessment of groundwater pollution in different locations of Al-Khums City, Libya. University Bulletin, 5(21).

[47] Mountaser, M. A., Algish, A. M., Abujarir, O. J., & Ashour, F. I. (2025). Assessment of seawater intrusion and associated environmental impacts on the Al-Qarabulli coastal aquifer, Libya. Comprehensive Journal of Science, 10(38), 1085–1092.

[48] Al-Arqat et al. (2020). Al-Arqat, M. A., Al-Abani, A. M., & Bu Fares, M. S. (2020). دراسة ظاهرة تداخل مياه البحر في المياه الجوفية بمنطقة القره بوللي. Journal of Basic Sciences, 33(2), 171–184.

[49] Boufaris, M. S., Al-Ayan, M. A., & Mohammed, N. A. (2022). Evaluation of seawater intrusion with groundwater in Garabolli–Libya. Libyan Journal of Ecological & Environmental Sciences and Technology, Special Issue (Third Conference on Environmental Sciences), 121–129.

[50] Ashmila, A. R., Naji, A. O., Abohamra, A. A., Abogamiza, M. F., & Benzaghta, M. A. (2024). The study of groundwater level rise and its relationship with flow direction and seawater intrusion in Zliten city, Libya. Journal of Basic Sciences, 37(Special Issue 1), 57–76.

[51] Ahmed, H. (2024, February 14). Groundwater upsurge floods homes in Libyan coastal town. Al-Monitor. https://www.al-monitor.com/originals/2024/02/groundwater-upsurge-floods-homes-libyan-coastal-town

[52] Alfji, J. M., & Swaid, F. A. (2016). Evaluation of the shallow groundwater (unconfined aquifer) of some groundwater wells of Misurata region for drinking and irrigation. Journal of Marine Sciences and Environmental Technologies, 2(2), A15–A33.

[53] Ibshir, F. S., & Salim, A. M. (2024). Assessment of groundwater status in Al-Sawawah locality–Misurata in 2021 and its environmental impacts using GIS. The Libyan Journal of Science, 2.

[54] Aboshaala, N. E. A., Grabel, L. M., & Bahroun, N. (2019). Hydrochemical investigation and quality assessment of groundwater in Wadi Jarif, Sirte City, Libya. University Bulletin, 21(3), 49–80.

[55] Amhamed, A. F. R. (2015). Assessment of groundwater quality in Sirte City [Thesis, Ain Shams University].

[56] Gossel, W., Sefelnasr, A., & Wycisk, P. (2010). Modelling of paleo-saltwater intrusion in the northern part of the Nubian Aquifer System, Northeast Africa. Hydrogeology Journal, 18(6), 1447–1463.

[57] Ageel, D. M. (2023). Environmental study about Sirte Sabkhas impact on the surface salinity at western coastal of Libya using MODIS satellite techniques. Journal of Marine Sciences and Environmental Technologies, 9(2), E11–E24.

[58] El Fallah, O. A., Al Faitouri, M. S., & Elmaleky, E. M. (2026). Integrated hydrogeochemical assessment of groundwater quality in eastern Benghazi, northeastern Libya. 109–99), 1(8, المجلة الليبية لعلوم وتكنولوجيا البيئة.

[59] Shaltami, O. R., Fares, F. F., El Faidy, T. M., El Oshebi, F. M., Aljazwi, M. S., & Errishi, H. (2020). Groundwater assessment for drinking and irrigation purposes of Ar Rajmah area, NE Libya. Scientific Journal of the University of Benghazi.

[60] Al Faitouri, M. S. E., Salloum, F. M., & Muftah, A. M. (2019). Hydro-geochemical review of groundwater and rain waters from Al Jabal Al Akhdar, Northeast Libya. Scientific Journal of the Faculty of Science, University of Benghazi, 9(2).

[61] Shaltami, O. R., Fares, F. F., El Oshebi, F. M., Errishi, H., Aljazwi, M. S., Favaloro, R. R., & Rhouma, A. A. (2020). Geochemistry of surface coastal water in Al-Sabri area, Benghazi city, Libya. Libyan Journal of Ecological & Environmental Sciences and Technology, 2(2), 21–25.

[62] Fanack Water. (n.d.). Water quality in Libya. https://water.fanack.com/libya/water-quality-in-libya/

[63] Libya. (n.d.). Country intervention on drought: Libya. United Nations. https://sdgs.un.org/sites/default/files/documents/2136Country_intervention_on_drought_Libya.pdf

[64] Elhassadi, A. (2008). Sea water intrusion in Derna located in the Green Mountain region, Libya—A threatening recurrent phenomenon calling for desalination. Desalination, 220, 189–193. https://doi.org/10.1016/j.desal.2007.05.024

[65] Kotb, A., Hagras, M., & Hassan, N. (2019). Impact of groundwater exploitation on saltwater intrusion in coastal aquifer: Case study: Derna–Libya. Proceedings of the Twenty-Second International Water Technology Conference (IWTC22).

[66] Abdulla, A., & Ouki, S. (2015). The potential of wastewater reuse for agricultural irrigation in Libya: Tobruk as a case study. Global NEST Journal, 17(2), 357–369. https://doi.org/10.30955/gnj.001518

[67] Elgali, J. A., & Khamis, A. A. (2026). Spatial assessment of groundwater quality for drinking purposes in Tobruk City, Libya. Faculty of Arts Journal – Misurata University, (21), 128–138. https://doi.org/10.36602/faj.2026.n21.07

[68] Mohammed, A. A., Anan, T. I., & Gheith, A. M. (2022). Mode of formation of the coastal sabkha sediments in the coastal plain of Al-Dafna Plateau. Scientific Journal for the Faculty of Science – Sirte University, 2(2), 33–37. https://doi.org/10.37375/sjfssu.v2i2.7

[69] Gonçalvès, J., Séraphin, P., Stieglitz, T., Chekireb, A., Hamelin, B., & Deschamps, P. (2021). Coastal aquifer recharge and groundwater–seawater exchanges using downscaled GRACE data: Case study of the Djeffara plain (Libya–Tunisia). Comptes Rendus. Géoscience, 353(1), 297–318.

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